Soft Contact-based Rigid Object Manipulation
: Planar Case

Byoung-Ho Kim and Shinichi Hirai

†: JSPS Post-doc Fellow, Dept. of Robotics, Ritsumeikan Univ., Kusatsu, Shiga, Japan
◦: Dept. of Robotics, Ritsumeikan Univ., Kusatsu, Shiga, Japan
E-mail: {kbv22006,hirai}@se.ritsumei.ac.jp

Abstract

This paper focuses on the soft contact-based rigid object manipulation. First, a dynamic model of an object manipulation by two-fingered robot hand with soft fingertips is presented. In particular, we deal with a planar case to show certain valuable features in soft-fingertip manipulation tasks. Next, in order to analyze the motion of using soft fingertips, a dynamic manipulation control scheme is employed. Finally, the influence of the dynamic deformation of soft fingertips applied in a rigid object manipulating task is demonstrated by several simulations.

Index Terms—dynamic deformation, object manipulation, soft fingertip.

1 Introduction

In multi-fingered grasping and manipulation tasks, an excessive contact force exerted by the fingertip may have a negative effect on the grasped object and/or the finger mechanism. To prevent such problems, a compliant contact policy is essential. For instance, certain compliance control strategies [1][2] can be used so as to maintain a comfortable contact. A useful alternative is to employ fingers with soft tips. In the latter case, it is, of course, necessary to consider the deformation characteristics of the soft fingertips employed. For practical soft-fingered manipulating tasks, it is desirable to develop certain types of soft fingers and/or soft fingertips, and it is necessary to analyze the contact mechanism of soft fingertips. In some cases, the soft fingertip material needs to be characterized precisely. The development of a soft finger and the modeling of a soft contact mechanism has been covered in the literature. Several compliant materials for constructing robot fingertips have been reported [3][4]. Shimoga and Goldenberg [5] summarized the various viscoelastic models for robot fingertips. Xydas et al. [6][7] presented a model of contact mechanics for soft fingers. Based on their results, we suspect that the deformation of soft fingers will be an important property for effective soft-fingered manipulations. Maeno et al. [8] investigated various type of contact shapes displayed at the contact surface of an elastic finger. Their observations confirmed that each fingertip force can be determined by considering the force distribution according to the deformation of soft fingertips. In [9], a number of tactile sensor modeling methodologies were investigated. These methodologies were based on a numerical algorithm. Since computational load reduction is essentially important for real applications, more simplified contact modeling was necessary. In [10], it was shown that tactile images can be used for estimating the grasping states of a manipulated object during a given manipulation. A hemispherical soft fingertip was recently developed by employing a polyurethane compound, and modeled under a force distribution-based strain mechanism [11].

Related to the application of soft fingertips to robotic manipulations, deformable fingers were employed to exhibit a rolling property [12]. Arimoto et al. [13] proposed a geometry-based control method for dual soft-fingered manipulations. Doulgeri et al. [14] have considered a soft-tipped finger motion under kinematic uncertainties. A grasping force control scheme was proposed for an elastic finger [15]. Also, studies have been conducted on the manipulation of deformable objects [16][17]. Recently, an interesting effort was undertaken to reconstruct the shape of a deformable membrane for a fingertip [18], revealing the deformed images of a fingertip and its reconstruction behavior. An other study developed a grasp stability algorithm based on an impedance model of soft fingertips for robot hands [19]. Shimoga et al. [4] and Akella...
et al. [20] suggest that there exists certain energy dissipative effects in manipulating tasks by soft fingers. However, the dynamic deformation of soft fingertips during an object manipulation has not yet been analyzed.

The main objective of the present paper is to analyze the motion of a rigid object manipulated by a robot hand with soft fingertips and discuss the motion in terms of the softness of fingertips.

2 Soft Contact-based Object Manipulation

2.1 A Soft Contact Modeling

Since the control performance of an object manipulating system can be affected by the type of the attached fingertip, this paper deals with a contact model of a soft-fingertipped object manipulation task. Consider a rigid object manipulating system by a two-fingered robot hand as shown in Fig. 1.

In this paper, we model the soft fingertips applied to Fig. 1 as a spring simplified as shown in Fig. 2. Then, the contact force of the $i$th soft fingertip in Fig. 2 can be described by

$$f_c^i = K_{xx}^i d_x^i(t)$$

(1)

where $K_{jk}$ and $d_j(t)$ denote the $jk$-directional stiffness and the $j$-directional deformation parameters of the $i$th soft fingertip, respectively. The deformation of each fingertip can be represented by

$$\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} x_o(t) \\ -r_1 - l_1 \\ r_2 + l_2 \end{bmatrix}$$

(2)

where $d_x(t)$ and $x_i(t)$ denote the $x$-directional deformation and position of the $i$th soft fingertip, respectively. And $x_o(t)$, $r_i$, and $l_i$ represent the actual position of the manipulated object, the radius of the $i$th soft fingertip, and the length parameter between the origin of the operational space and the contact surface of the $i$th finger, respectively.

By taking the derivative of (2) with respect to time, the velocity relationship between the operational space ($o$) and the fingertip space ($f$) of Fig. 2 can be expressed as the following form:

$$\dot{u}_f = B_o \dot{u}_o + \ddot{d}_f$$

(3)

where

$$\dot{u}_f = \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix}, \quad \ddot{d}_f = \begin{bmatrix} \ddot{d}_x(t) \\ \ddot{d}_y(t) \end{bmatrix}, \quad B_o = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

and

$$\dot{u}_o = \begin{bmatrix} \dot{x}_o(t) \\ \dot{x}_o(t) \end{bmatrix}.$$
where $\dot{\phi} \in \mathbb{R}^{n_\phi}$ denotes the velocity vector at the joint space of the hand. $G_f^\phi \in \mathbb{R}^{n_\phi \times m}$ ($m$: the total dimension of wrenches of the fingertip space) can be calculated by the generalized pseudo-inverse of $G_f^\phi$ which represents the Jacobian matrix relating the joint space and the fingertip space. The force relation between the joint space and the fingertip space is given by

$$\tau_\phi = [G_f^\phi]^T T_f$$  \hspace{1cm} (6)

where $T_f \in \mathbb{R}^{m \times 1}$ and $\tau_\phi \in \mathbb{R}^{n_\phi \times 1}$ denote the generalized force vector at the fingertip space and the torque vector at the joint space, respectively. And $[G_f^\phi]^T$ is the transpose of the Jacobian matrix $[G_f^\phi]$.

By taking the derivative of (5) with respect to time, the second-order kinematic relation between the fingertip space and the joint space is determined by

$$\ddot{\phi} = G_f^\phi \ddot{u}_f + \dot{u}_f^T H_f^\phi \ddot{u}_f$$  \hspace{1cm} (7)

where $\ddot{\phi}$ denotes the acceleration vector at the joint space of the hand, and $H_f^\phi$ implies the second-order kinematic influence coefficient matrix which is formed by a three-dimensional array.

In general, the dynamic model of a multi-fingered hand with rigid fingertips has the following form [21]:

$$I_\phi^* \ddot{\phi} + \dot{\phi}^T P_{\phi\phi}^* \dot{\phi} = \tau_\phi - \tau_{fc}$$  \hspace{1cm} (8)

where $I_\phi^*$ and $P_{\phi\phi}^*$ denote the effective inertia matrix and the inertia power array, respectively. And $\tau_{fc}$ implies the torque vector at the joint space considering the contact force of the fingertip space which is generated by the external force including internal grasping forces and it can be obtained from (6) as follows:

$$\tau_{fc} = [G_f^\phi]^T T_{fc}$$  \hspace{1cm} (9)

where the contact force vector at the fingertip space, $T_{fc}$, is given by

$$T_{fc} = \begin{bmatrix} (l_{f1}^e)^T & (l_{f2}^e)^T & \cdots & (l_{fn}^e)^T \end{bmatrix}^T.$$  \hspace{1cm} (10)

By substituting (7) into (8), the dynamic model relating the fingertip space to the joint space of a multi-fingered hand can be expressed by

$$I_{\phi ff}^* \ddot{u}_f + \dot{u}_f^T P_{\phi ff}^* \ddot{u}_f = \tau_\phi - \tau_{fc}$$  \hspace{1cm} (11)

where $I_{\phi ff}^*$ and $P_{\phi ff}^*$ denote the effective inertia matrix and the inertia power array relating the fingertip space to the joint space, respectively;

$$I_{\phi ff}^* = I_{\phi \phi}^* G_f^\phi$$  \hspace{1cm} (12)

and

$$P_{\phi ff}^* = (I_{\phi \phi}^* \odot H_f^\phi) + [G_f^\phi]^T P_{\phi \phi}^* G_f^\phi$$  \hspace{1cm} (13)

where the operator of “$\odot$” represents the generalized scalar dot product which provides the result of multiplication between a matrix and a three-dimensional array. For example, let $A$ and $B$ represent a $p \times q$ matrix and a $q \times m \times n$ three-dimensional array, respectively, and the operation of $A \odot B$ resultantly makes a $p \times m \times n$ three-dimensional array.

Note that the grasp geometry-based Jacobian relation between the fingertip space and the operational space in soft-fingered object manipulating systems may not available any more because soft fingertips have some deformation properties. Accordingly, it is necessary to consider the deformation relation given by (3) and (4) for the purpose of deriving a dynamic model of soft-fingertipped manipulations.

By combining (3), (4), and (11), we finally derive a new dynamic model of soft-fingered manipulations including deformation characteristics. The resultant dynamic model relating the operational space to the joint space of an object-hand system as shown in Fig. 1 can be described as follows:

$$I_{\phi oo}^* \ddot{u}_o + \ddot{u}_f^T P_{\phi oo}^* \ddot{u}_o = \tau_\phi - \tau_{fc} - \gamma$$  \hspace{1cm} (14)

where $I_{\phi oo}^*$ and $P_{\phi oo}^*$ denote the effective inertia matrix and the inertia power array relating the operational space to the joint space, respectively;

$$I_{\phi oo}^* = I_{\phi ff}^* B_\phi$$ and $P_{\phi oo}^* = B_\phi^T P_{\phi ff}^* B_\phi$.

The $\gamma$ term implies the torque effect influenced by the deformation of the employed soft fingertips and it is given by

$$\gamma = I_{\phi ff}^* \ddot{d}_f + \ddot{d}_f^T P_{\phi ff}^* \ddot{d}_f + \ddot{d}_f^T P_{\phi ff}^* B_\phi \ddot{u}_o$$  \hspace{1cm} (15)

where $P_{\phi ff}^*$ denotes the power array mapping relating the fingertip force and the velocity of the object to the joint torque given by

$$P_{\phi ff}^* = [P_{\phi ff}^* + [P_{\phi ff}^*]^T] B_\phi.$$  \hspace{1cm} (16)

Through the dynamic model, we can find some valuable points in soft-fingered manipulations as follows. When a finger employs a soft material on its fingertip, it may possible to grasp an object comfortably than that of using a hard fingertip. It is because a soft fingertip can utilize the torsional effect formed by the deformation of the soft fingertip. Even though such a soft fingertip can provide some positive effects,
this paper specifies some considerable issues in soft-fingered manipulations that the $\gamma$ term depends on the acceleration and the velocity of the deformation of soft fingertips as well as the velocity of the manipulated object. It can be recognized comprehensively as the energy dissipative effects in manipulating with soft fingers [20]. On the other hand, the $\gamma$ term results in some torque disturbances. This is, the behavior of the manipulated object in a soft-fingered manipulation is fundamentally related to the $\gamma$ term.

3 A Manipulation Control Scheme

This section presents a dynamic manipulation control scheme so as to confirm the behavior of an object manipulated by multi-fingered hands. In Fig. 3, the task planner provides the necessary parameters related to the trajectory planning of the object, the dynamic parameters of soft fingertips, the dynamic parameters of fingers, and so on. The controller block makes the resultant torque command for driving all joints of the hand for the given manipulating task. The parameters given by $\alpha$ and $\beta$ are determined by considering the dynamic parameters of the fingers, the soft-fingertips, and the object. For the purpose of implementation, some tactile sensors can be employed to detect the contact forces of soft fingertips.

When an object is being stably manipulated by a multi-fingered hand, the contact between the object and each finger should be guaranteed during the manipulation process. For this purpose, proper internal grasping forces can be considered, and for a two-fingered robotic hand, a guideline of determining proper internal grasping forces can be given by

$$T_{fc}(0) = \begin{bmatrix} \hat{K}_{xx} & 0 \\ 0 & 2\hat{K}_{xx} \end{bmatrix} \begin{bmatrix} d_x(0) \\ 2d_x(0) \end{bmatrix}$$

where $f_y(0)$ and $d_x(0)$ denote the internal grasping force and the initial deformation vectors of the $x$-direction of the $i$th soft fingertip, respectively. Also, the magnitude of the internal forces is decided in such a way as to satisfy the friction at the contact surface of each finger.

4 Simulation Results

In order to analyze the motion of a soft-fingertipped object manipulation task, an object manipulation task by a dual soft-fingered hand as shown in Fig. 1 is considered. Each finger of the hand is actuated by a prismatic joint which is driven by a DC motor connected with certain transmission between the prismatic joint and the driving joint. The parameters of the hand is illustrated in Table 1. In this paper, we performed three simulations by employing different soft fingertips. It is assumed that the manipulated object is rigid and the slip at the contact surface is ignored.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of finger</td>
<td>0.092 m</td>
</tr>
<tr>
<td>Mass of finger</td>
<td>0.1025 Kg</td>
</tr>
<tr>
<td>Transmission ratio</td>
<td>$1.59 \times 10^{-4}$ m/rad</td>
</tr>
</tbody>
</table>

The first simulation is an attempt to show some deformation characteristics of soft fingertips applied in a planar soft-fingered object manipulation. The given task is to control the position of the rigid object along a given horizontal trajectory. The control block diagram shown in Fig. 3 is used for the given task. Initially, the task planner in Fig. 3 defines the necessary parameters related to the desired horizontal trajectory of the object, the dynamic parameters of soft fingertips, the dynamic parameters of fingers, and so on. The horizontal velocity of the object is planned by a trapezoidal velocity profile for the total time, 1.6
sec, where the average velocity is set as 0.02 m/sec. The geometrical structure of the grasp is symmetric. And the control signal is updated every 2 msec.

The object of Fig. 1 is manipulated by

$$T_o(t) = m_o \ddot{x}_o(t)$$

where $T_o(t)$ denotes the generalized force applied to the object and it is determined by the deformation forces of soft fingertips. The parameter $\ddot{x}_o(t)$ denotes the $x$-directional actual acceleration of the manipulated object. Especially, the parameters of the object such as width($l_1 = l_2$), height($h$), and mass($m_o$) are chosen by 0.03 m, 0.1 m, and 2.2 Kg, respectively. The radius of the used rigid fingertips is set as 0.01 m. In particular, the deformation of each soft fingertip is initialized as $^1d_x(0) = 0.0025$ m and $^2d_x(0) = -0.0025$ m, respectively. The actual contact force between the object and each soft fingertip is obtained by (1), where the deformation of each soft fingertip is calculated by (2). The stiffness parameter of the $i$th soft fingertip is assigned by

$$^1K_{xx}(i = 1, 2) = 500 \text{ N/m}.$$  

The joint motion of each finger is governed by (16) and the position and velocity gains at the operational space are chosen by $K_P = 50$ and $K_D = 0.012$.

Fig. 4. Trajectory of object: (a) desired trajectory, (b) actual trajectory obtained by considering the $\gamma$ term, and (c) actual trajectory obtained without considering the $\gamma$ term; $^1K_{xx}(i = 1, 2) = 500 \text{ N/m}$.

Figs. 4 and 5 show the results of trajectory followings of the manipulated object and the deformation profiles of the two soft fingertips, respectively. We can observe from the figures that the trajectory of the object and the deformation of each finger are properly controlled when the deformation effect given by the $\gamma$ term is considered in the manipulation process, while these responses are not well-controlled when the deformation effect is ignored. More specifically, in the latter case, the deformation of each soft fingertip oscillates greatly with time. Since it is desirable for the deformation profile during the manipulation process to be traceable to the initial deformation determined by internal grasping forces, this tendency for vibrational deformation may lead the manipulation system to become unstable. Fig. 6 shows the fundamental $\gamma$ term intrinsic in the manipulation process obtained when the object is manipulated by the proposed manipulation control scheme without considering the $\gamma$ term.

The second simulation characterizes the motion of the given manipulation task according to the softness of the fingertips employed. In this stage, the previous soft fingertips are changed to the new soft fingertips

![Fig. 5. Deformation of soft fingertips: (a) initial state, (b) when the $\gamma$ term is considered, and (c) when the $\gamma$ term is not considered; $^1K_{xx}(i = 1, 2) = 500 \text{ N/m}$.](image)

![Fig. 6. Deformation effect of soft fingertips: $^1K_{xx}(i = 1, 2) = 500 \text{ N/m}$.](image)
given by

\[ K_{xx} = 425 \text{ N/m}. \]  \hspace{1cm} (20)

Fig. 7. Deformation effect of soft fingertips: \( K_{xx} (i = 1, 2) = 425 \text{ N/m} \).

Similar to the previous simulation, the fundamental \( \gamma \) profile of this case is illustrated in Fig. 7. The trajectory following results of the manipulated object and the deformation profiles of the two soft fingertips are shown in Figs. 8 and 9, respectively. These figures reveal that the trajectory and the deformation performances are satisfactory only when the \( \gamma \) term is considered in the manipulation process. In particular, the deformational oscillation of each fingertip greatly exceeds that shown in Fig. 5(c), the oscillation increasing gradually during the manipulation process. This is because the deformation effect strongly depends on the elasticity of the fingertips: the dynamic deformation becomes prone to fluctuation if the elasticity of fingertips increases. Moreover, the deformation effect can be amplified by the tracking error of the manipulated object, and vice versa. Practically, this trend implies that the behavior of the manipulated object becomes unstable due to the deformational oscillation of soft fingertips.

In addition, let me consider the same task using more harder fingertips assigned by

\[ K_{xx} = 650 \text{ N/m}. \]  \hspace{1cm} (21)

The trajectory following results of the manipulated object and the deformation profiles of the two soft fingertips of the third case are shown in Figs. 10 and 11, respectively.

Through the analysis, the simulation results can be summarized as Table 2. In Table 2, we can address that the fingertips used in case 2 are physically 15% softer than those of case 1, while those of case 3 are 30% harder than the first case. As a result, we can observe the trend that the more a fingertip is soft, the more the trajectory following performance is not satisfactory. Also, the deformation is increased gradually. Especially, when the \( \gamma \) term is not considered in the manipulation process, the maximum error of trajectory in case 2 is increased by 222.8% compared with the first case. However, it is decreased by 62.7% in case 3. The deformation performance of each finger is also largely varied according to the softness of fingertips. On the other hand, when the \( \gamma \) term is considered in the manipulation process, the trajectory and the deformation performances are changed as a low rate relatively. Consequently, it is concluded that the
trajectory and the deformation performances closely depend on the softness of fingertips employed in the given task.

5 Concluding Remarks

This paper analyzed the fundamental characteristics on a rigid object manipulation by a robot hand with soft fingertips. We showed certain influence of the deformation of soft fingertips through a dynamic modeling of soft-fingertipped object manipulations and several simulations. As a result, the softer the fingertip is, the more critical the influence of its deformation behavior becomes. Thus, the motion of soft contact-based manipulations can eventually be affected by the deformation influence of the employed fingertips. In this sense, a manipulation control method that incorporates the deformation effect can be usefully applied to soft-fingered manipulations. Practically, a proper transmission mechanism for driving fingers in the design aspect and some damping property in the control viewpoint are helpful for compensating the deformation effect.

ACKNOWLEDGMENTS

This work was supported by the research fund of Japan Society for the Promotion of Science.

References

Table 2. Control performance of the soft-fingertipped manipulation task (×: the case that γ is not considered, ○: the case that γ is considered).

<table>
<thead>
<tr>
<th>Item</th>
<th>Softness ((^1K_{xx} = ^2K_{xx} , \text{N/m}))</th>
<th>Max. error of object (mm)</th>
<th>Max. deformation of fingertip 1 (mm)</th>
<th>Max. deformation of fingertip 2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>500</td>
<td>2.866</td>
<td>0.663</td>
<td>3.151</td>
</tr>
<tr>
<td>Case 2</td>
<td>425</td>
<td>9.252</td>
<td>0.952</td>
<td>4.661</td>
</tr>
<tr>
<td>Case 3</td>
<td>650</td>
<td>1.070</td>
<td>0.414</td>
<td>2.742</td>
</tr>
<tr>
<td>(\frac{\text{Case2–Case1}}{\text{Case1}} \times 100%)</td>
<td>-15</td>
<td>222.8</td>
<td>43.6</td>
<td>47.9</td>
</tr>
<tr>
<td>(\frac{\text{Case3–Case1}}{\text{Case1}} \times 100%)</td>
<td>30</td>
<td>-62.7</td>
<td>-37.6</td>
<td>-13.0</td>
</tr>
</tbody>
</table>


