Motion Analysis of Soft-Fingertip Manipulation Tasks

Byoung-Ho Kim

Abstract: This paper provides a motion analysis of soft-fingertip object manipulation tasks by presenting a dynamic model of multi-fingered object manipulations with soft fingertips. It is fundamentally observed that soft fingertips employed in a multi-fingered hand generate some deformation effects during the manipulation process and also that those effects are closely related to the behavior of the manipulated object. In order to analyze the motion of using soft fingertips, a dynamic manipulation control scheme is presented. Simulation and experimental results demonstrate the motion of soft-fingertips applied in object manipulating tasks and are further used to discuss the characteristics of soft-fingertip motions.

Keywords: Deformation effect, motion analysis, object manipulation, soft fingertip.

1. INTRODUCTION

In grasping and manipulation tasks performed by multi-fingered robotic hands, excessive contact force of a fingertip may negatively impact on the grasped object and/or the finger mechanism. To cope with this difficulty, a compliant contact policy is essential. For instance, some compliance control strategies [1-3] can be used to maintain comfortable contacts. An alternative and very useful approach is to employ a finger with a soft fingertip. In this case, since a soft fingertip has some deformable properties, it is intuitively necessary to consider the deformation characteristics of soft fingertips. For practical soft-fingered manipulating tasks, some type of soft finger and/or soft fingertip should be developed. Since contact models deeply affect the analysis of object manipulation systems, the contact mechanism of soft fingertips must be analyzed. In some cases, we should also consider the materials used in the construction of soft fingertips. There are some valuable research results related to the development of soft fingers and the modeling of soft contact mechanisms. Some compliant materials for robot fingers have been previously reported [4,5]. Shimoga and Goldenberg [6] summarized the conventional viscoelastic models for robot fingertips. Xydas et al. [7,8] presented a model of contact mechanics for soft fingers. Based on their efforts, I have an idea that the deformation of soft fingers will be an important property for effective soft-fingered manipulations. Maeno et al. [9] investigated various types of contact shapes displayed at the contact surface of a finger during human grasping. From their investigation of human grasping and its contact shapes, it was confirmed that the force of each fingertip can be determined by considering the force distribution according to the deformation of soft fingertips. Various tactile sensor modeling methodologies were investigated based on a numerical algorithm [10]. In [11], it was shown that tactile images can be used for estimating the grasping states of a manipulated object during the process of a given manipulation. Recently, a hemispherical soft fingertip was developed by employing a polyurethane compound and further, its model of using a force distribution-based strain mechanism was presented [12].

In relation to the application of soft fingertips to robotic manipulations, some methodologies are worthwhile for manipulating tasks by soft-fingered hands. The rolling property of using deformable fingertips was reported [13]. Arimoto et al. [14] suggested a geometry-based control method for dual soft-fingered manipulations. Doulgeri et al. [15] have considered a soft-tipped finger motion under kinematic uncertainties. The grasping force control scheme of an elastic finger was presented [16]. Also, some researches on the manipulation of deformable objects have been performed [17,18]. On the other hand, a grasp stability algorithm based on an impedance model of soft fingertips was presented for robot hands [19]. From [5] and [20], we can deduce that there exists a certain amount of energy dissipative effects in manipulating with soft fingers. Practically, many types of soft manipulations may suffer from the deformation characteristics. However, the influence of the deformation property of soft fingertips during the object manipulation process has not yet been illustrated.

The main objective of the present paper is to

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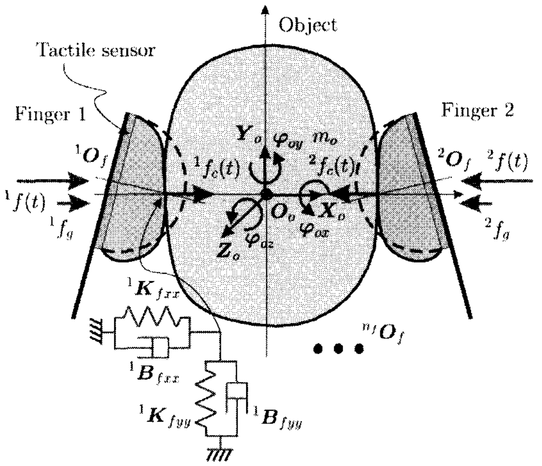

Fig. 1. An object manipulating system by a multi-fingered robot hand with soft fingertips.

analyze the motion of soft-fingertips as they interact with a manipulated object and discuss the motion in terms of softness. This paper is organized as follows. In Section 2, a contact model of soft fingertips is presented in order to properly characterize soft-fingered manipulating tasks. A dynamic model of multi-fingered object manipulations with soft fingertips is also described. In Section 3, a dynamic manipulation control scheme is presented for multi-fingered object manipulations. Simulation and experimental results are shown in Section 4. Finally, concluding remarks are given in Section 5.

2. OBJECT MANIPULATION BY SOFT-FINGERTIP FINGERS

2.1. A contact modeling

Consider an object manipulating system by using a multi-fingered robot hand as shown in Fig. 1. The control performance of an object manipulating system may be affected by the type of the attached fingertip. For the purpose of analyzing the control effect, it is necessary to describe the dynamic relation of a multi-fingered robot hand with soft fingertips. To do that, this section presents the model of soft fingertips in Fig. 1 as a simplified spring and damping model.

In general, the contact force of the fingertip space of a n_f -fingered hand can be given by

$$T_{fc}=\left[\left({}^1f_c\right)^T \ \left({}^2f_c\right)^T \ \cdots \ \left({}^{n_f}f_c\right)^T\right]^T, \qquad (1)$$

where the superscript T indicates the transpose of a component and $T_{fc} \in R^{m\times 1}$ denotes the fingertip contact force vector in the fingertip space, where the superscript m denotes the total dimension of wrenches of the fingertip space and is given by $4n_f$ for n_f soft fingers [21]. In Fig. 1, the contact force of the i th soft fingertip, ${}^if_c \in R^{4\times 1}$, can be expressed by

$${}^if_c = {}^i\boldsymbol{K}_f\,{}^id_f + {}^i\boldsymbol{B}_f\,{}^i\dot{d}_f, \qquad (2)$$

where the stiffness and damping parameters of the i th soft fingertip, respectively, are given by

$${}^i\boldsymbol{K}_f=\begin{bmatrix} {}^i\boldsymbol{K}_{xx} & {}^i\boldsymbol{K}_{xy} & {}^i\boldsymbol{K}_{xz} & {}^i\boldsymbol{K}_{x\varphi} \\ {}^i\boldsymbol{K}_{yx} & {}^i\boldsymbol{K}_{yy} & {}^i\boldsymbol{K}_{yz} & {}^i\boldsymbol{K}_{y\varphi} \\ {}^i\boldsymbol{K}_{zx} & {}^i\boldsymbol{K}_{zy} & {}^i\boldsymbol{K}_{zz} & {}^i\boldsymbol{K}_{z\varphi} \\ {}^i\boldsymbol{K}_{\varphi x} & {}^i\boldsymbol{K}_{\varphi y} & {}^i\boldsymbol{K}_{\varphi z} & {}^i\boldsymbol{K}_{\varphi\varphi} \end{bmatrix}$$

and

$${}^i\boldsymbol{B}_f=\begin{bmatrix} {}^i\boldsymbol{B}_{xx} & {}^i\boldsymbol{B}_{xy} & {}^i\boldsymbol{B}_{xz} & {}^i\boldsymbol{B}_{x\varphi} \\ {}^i\boldsymbol{B}_{yx} & {}^i\boldsymbol{B}_{yy} & {}^i\boldsymbol{B}_{yz} & {}^i\boldsymbol{B}_{y\varphi} \\ {}^i\boldsymbol{B}_{zx} & {}^i\boldsymbol{B}_{zy} & {}^i\boldsymbol{B}_{zz} & {}^i\boldsymbol{B}_{z\varphi} \\ {}^i\boldsymbol{B}_{\varphi x} & {}^i\boldsymbol{B}_{\varphi y} & {}^i\boldsymbol{B}_{\varphi z} & {}^i\boldsymbol{B}_{\varphi\varphi} \end{bmatrix}.$$

Here, the subscript φ indicates the rotational direction for the normal contact direction of each fingertip. ${}^id_f$ denotes the deformation vector of the i th soft fingertip given by

$${}^id_f=\left[{}^id_x \ \ {}^id_y \ \ {}^id_z \ \ {}^id_\varphi\right]^T$$

and ${}^i\dot{d}_f$ denotes the velocity vector of the deformation of the i th soft fingertip.

In the manipulation process shown in Fig. 1, the position and orientation of an object manipulated by soft fingers can be changed flexibly due to the deformation of the soft fingertips employed. Reversely, the deformation of the soft fingertips depends on the behaviors of the manipulated object and each finger. Thus, the deformation of the fingertip space(f), $d_f \in R^{4n_f\times 1}$, can be expressed as follows:

$$d_f = u_f - \boldsymbol{W}\boldsymbol{R}u_o - \Delta u_o^f, \qquad (3)$$

where

$$d_f=\left[\left({}^1d_f\right)^T \ \left({}^2d_f\right)^T \ \cdots \ \left({}^{n_f}d_f\right)^T\right]^T,$$

$$u_f=\left[\left({}^1u_f\right)^T \ \left({}^2u_f\right)^T \ \cdots \ \left({}^{n_f}u_f\right)^T\right]^T,$$

$${}^iu_f=\left[x_i \ \ y_i \ \ z_i \ \ \varphi_i\right]^T,$$

and

$$u_o=\left[x_o \ \ y_o \ \ z_o \ \ \varphi_{ox} \ \ \varphi_{oy} \ \ \varphi_{oz}\right]^T.$$

Here, x_i, y_i, z_i, and φ_i denote the x-, y- and z-directional linear motions and the rotational motion for the contact normal direction of the ith fingertip space, respectively. x_o, y_o, z_o, φ_{ox}, φ_{oy}, and φ_{oz} represent the x-, y-, z-, and rotational screw motions of the operational space(o), respectively. The wrench transmission matrix from the operational space to the fingertip space, $W \in R^{4n_f \times 6n_f}$, is given by

$$W = \begin{bmatrix} {}^1W & 0 & \cdots & 0 \\ 0 & {}^2W & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & {}^{n_f}W \end{bmatrix}, \quad (4)$$

where ${}^iW \in R^{4\times 6}$ denotes the wrench transmission matrix from the operational space to the ith fingertip space [21].

The rotational matrix relating the operational space to the fingertip space, $R \in R^{6n_f \times 6}$, is given by

$$R = \begin{bmatrix} {}^1R^T & {}^2R^T & \cdots & {}^{n_f}R^T \end{bmatrix}^T, \quad (5)$$

where

$${}^iR = \begin{bmatrix} {}^iR_o^f & {}^ip_o^f \times {}^iR_o^f \\ 0 & {}^iR_o^f \end{bmatrix}. \quad (6)$$

Here, ${}^ip_o^f$ denotes the 3×1 position vector that locates the origin of the operational space with respect to the ith fingertip space. Also, the initial position and orientation vector relating the fingertip space to the operational space, $\Delta u_o^f \in R^{4n_f \times 1}$, can be expressed as

$$\Delta u_o^f = \begin{bmatrix} \Delta^1 u_o^f(0) & \Delta^2 u_o^f(0) & \cdots & \Delta^{n_f} u_o^f(0) \end{bmatrix}^T, \quad (7)$$

where

$$\Delta^i u_o^f(0) = \begin{bmatrix} {}^iW\,{}^i\delta \end{bmatrix}^T$$

with the initial conditions as follows:

$${}^i\delta = \begin{bmatrix} {}^ix_o^f(0) & {}^iy_o^f(0) & {}^iz_o^f(0) & {}^i\varphi_{ox}^f(0) & {}^i\varphi_{ox}^f(0) & {}^i\varphi_{oz}^f(0) \end{bmatrix}^T,$$

where ${}^ix_o^f(0)$, ${}^iy_o^f(0)$, and ${}^iz_o^f(0)$ denote the translational distance from the ith fingertip space to the operational space under contact without deformation. Similarly, ${}^i\varphi_{ox}^f(0)$, ${}^i\varphi_{oy}^f(0)$, and ${}^i\varphi_{oz}^f(0)$ denote the rotational distance from the ith fingertip space to the operational space under contact without deformation.

By rearranging (3), we get

$$u_f = WRu_o + d_f + \Delta u_o^f \quad (8)$$

and by taking the derivative of (8) with respect to time, the velocity relation between the operational space and the fingertip space of Fig. 1 can be obtained by

$$\dot{u}_f = W\left(\dot{R}u_o + R\dot{u}_o\right) + \dot{d}_f. \quad (9)$$

We can also obtain the following second-order relation in a similar manner:

$$\ddot{u}_f = W\left(R\ddot{u}_o + 2\dot{R}u_o + \ddot{R}u_o\right) + \ddot{d}_f. \quad (10)$$

2.2. A dynamic model of soft-fingertip object manipulations

For a n_f-fingered hand system as shown in Fig. 1, the first-order kinematic relation between the joint space(ϕ) and the fingertip space(f) is given by

$$\dot{u}_f = G_\phi^f \dot{\phi}, \quad (11)$$

where $\dot{\phi} \in R^{n_\phi}$ denotes the velocity vector at the joint space of the hand. $G_\phi^f \in R^{m\times n_\phi}$ (m: the total dimension of wrenches of the fingertip space) represents the Jacobian matrix relating the joint space to the fingertip space.

According to the duality between the velocity vector and the force vector, the force relation between the joint space and the fingertip space is given by

$$\tau_\phi = \left[G_\phi^f\right]^T T_f, \quad (12)$$

where $T_f \in R^{m\times 1}$ and $\tau_\phi \in R^{n_\phi \times 1}$ denote the generalized force vector at the fingertip space and the torque vector at the joint space, respectively.

In general, (11) can be written by

$$\dot{\phi} = G_f^\phi \dot{u}_f, \quad (13)$$

where $G_f^\phi \in R^{n_\phi \times m}$ represents the Jacobian matrix relating the fingertip space to the joint space and it can be determined by the generalized inverse of $\left[G_\phi^f\right]$.

By taking the derivative of (13) with respect to time, the second-order kinematic relation between the fingertip space and the joint space is determined by

$$\ddot{\phi} = G_f^\phi \ddot{u}_f + \left(\dot{u}_f\right)^T H_{ff}^\phi \dot{u}_f, \quad (14)$$

where $\ddot{\phi}$ denotes the acceleration vector at the joint space of the hand, and H_{ff}^{ϕ} implies the second-order kinematic influence coefficient matrix (Hessian description), which is formed by a three-dimensional array [22].

Using the principle of virtual work and D' Alembert's principle, the dynamic model of a multi-fingered hand takes on the following form:

$$I_{\phi\phi}^{*}\ddot{\phi}+\dot{\phi}^{T}P_{\phi\phi\phi}^{*}\dot{\phi}=\tau_{\phi}-\tau_{\phi c}, \quad (15)$$

where $I_{\phi\phi}^{*}$ and $P_{\phi\phi\phi}^{*}$ denote the effective inertia matrix and the inertia power array [22], respectively. $\tau_{\phi c}$ denotes the torque vector of the joint space reflected by the external force including internal grasping forces, and it can be obtained by

$$\tau_{\phi c}=\left[G_{\phi}^{f}\right]^{T}T_{fc}, \quad (16)$$

where T_{fc} is defined by (1).

By substituting (14) into (15), the dynamic model relating the fingertip space to the joint space of a multi-fingered hand can be expressed as:

$$I_{\phi ff}^{*}\ddot{u}_{f}+\left(\dot{u}_{f}\right)^{T}P_{\phi fff}^{*}\dot{u}_{f}=\tau_{\phi}-\tau_{\phi c}, \quad (17)$$

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

$$I_{\phi ff}^{*}=I_{\phi\phi}^{*}G_{f}^{\phi} \quad (18)$$

and

$$P_{\phi fff}^{*}=\left(I_{\phi\phi}^{*}\circ H_{ff}^{\phi}\right)I_{ff}^{*}+\left[G_{f}^{\phi}\right]^{T}P_{\phi\phi\phi}^{*}G_{f}^{\phi}, \quad (19)$$

where the operator '∘' represents the generalized scalar dot product, which yields the product of a matrix and a three-dimensional array [22,23].

Note that the grasp geometry-based Jacobian relation between the fingertip space and the operational space of a soft-fingered object manipulation system may not be available because soft fingertips will undergo deformation upon contact.

Thus, in order to derive a dynamic model of soft-fingered manipulations, one has to consider the deformation relation given by (9) and (10).

By combining (9), (10), and (17), we finally derive a dynamic model of soft-fingered manipulations that incorporates 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:

$$\begin{aligned}&I_{\phi oo1}^{*}\ddot{u}_{o}+2I_{\phi oo2}^{*}\dot{u}_{o}+I_{\phi oo3}^{*}u_{o}+\left(\dot{u}_{o}\right)^{T}P_{\phi ooo1}^{*}\dot{u}_{o}\\&+\left(\dot{u}_{o}\right)^{T}P_{\phi ooo2}^{*}u_{o}+\left(u_{o}\right)^{T}P_{\phi ooo3}^{*}u_{o}\\&=\tau_{\phi}-\tau_{\phi c}-\gamma,\end{aligned} \quad (20)$$

where $I_{\phi ooj}^{*}(j=1,2,3)$ and $P_{\phi oooj}^{*}(j=1,2,3)$ denote the effective inertia matrices and the inertia power array mappings relating the operational space to the joint space, respectively;

$$I_{\phi oo1}^{*}=I_{\phi ff}^{*}WR, \quad (21)$$

$$I_{\phi oo2}^{*}=I_{\phi ff}^{*}W\dot{R}, \quad (22)$$

$$I_{\phi oo3}^{*}=I_{\phi ff}^{*}W\ddot{R}, \quad (23)$$

$$P_{\phi ooo1}^{*}=R^{T}W^{T}P_{\phi fff}^{*}WR, \quad (24)$$

$$P_{\phi ooo2}^{*}=\left[R^{T}W^{T}P_{\phi fff}^{*}+\dot{R}W^{T}\left[P_{\phi fff}^{*}\right]^{T}\right]W\dot{R}, \quad (25)$$

and

$$P_{\phi ooo3}^{*}=\dot{R}^{T}W^{T}P_{\phi fff}^{*}W\dot{R}. \quad (26)$$

The γ term in (20) is composed of three terms given by

$$\gamma=\gamma_{1}+\gamma_{2}+\gamma_{3}, \quad (27)$$

where

$$\gamma_{1}=I_{\phi ff}^{*}\ddot{d}_{f}, \quad (28)$$

$$\gamma_{2}=\left(\dot{d}_{f}\right)^{T}P_{\phi fff}^{*}\dot{d}_{f}, \quad (29)$$

and

$$\gamma_{3}=\left(\dot{d}_{f}\right)^{T}P_{\phi fff1}^{*}\dot{u}_{o}+\left(\dot{d}_{f}\right)^{T}P_{\phi fff2}^{*}u_{o}. \quad (30)$$

Here, $P_{\phi fff1}^{*}$ and $P_{\phi fff2}^{*}$ denote the inertia power array mappings relating the fingertip force to the joint torque:

$$P_{\phi fff1}^{*}=\left[P_{\phi fff}^{*}+\left[P_{\phi fff}^{*}\right]^{T}\right]WR \quad (31)$$

and

$$P_{\phi fff2}^{*}=\left[P_{\phi fff}^{*}+\left[P_{\phi fff}^{*}\right]^{T}\right]W\dot{R}. \quad (32)$$

Through the dynamic model, it is noted that the terms γ_1 and γ_2 are dependent on the acceleration and the velocity of the deformation of the soft fingertips, respectively. The γ_3 term depends on the velocity of the deformation of the soft fingertips as well as that of the manipulated object. That is, equations (27~32) reveal that the γ term is entirely dependent upon the behavior of soft fingertips and the manipulated object as well as the dynamic characteristics of the hand. The γ term actually reflects some torque disturbances influenced by the deformation of soft fingertips as well as the actual behavior of the manipulated object.

3. A DYNAMIC 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. 2, 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 prompts the resultant torque command for driving all joints of the hand for the given manipulating task. The parameters given by α and β are determined by considering the dynamic parameters of the fingers, the soft-fingertips, and the object. In Fig. 2, the manipulation control strategy is described by

$$\tau_\phi = \alpha\left(\ddot{u}_o^d + \boldsymbol{K}_v\dot{e}_o + \boldsymbol{K}_p e_o\right) + \beta + \tau_{\phi c}, \qquad (33)$$

where α is given by (21). The term β is represented by

$$\beta = 2\boldsymbol{I}^*_{\phi oo2}\dot{u}_o + \boldsymbol{I}^*_{\phi oo3}u_o + \left(\dot{u}_o\right)^T \boldsymbol{P}^*_{\phi ooo1}\dot{u}_o + \left(\dot{u}_o\right)^T \boldsymbol{P}^*_{\phi ooo2}u_o + \left(u_o\right)^T \boldsymbol{P}^*_{\phi ooo3}u_o .$$

$\boldsymbol{K}_p$ and $\boldsymbol{K}_v$ denote the position and velocity gainm atrices at the operational space, respectively. e_o is th e position error vector of the manipulated object defin ed as $u_o^d - u_o$ so that $\dot{e}_o = \dot{u}_o^d - \dot{u}_o$ and $\ddot{e}_o = \ddot{u}_o^d - \ddot{u}_o$. The $\tau_{\phi c}$ term is given by (16).

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 for determining proper internal grasping forces can be provided by

$$T_{fc}(0) = \begin{bmatrix} {}^1f_g(0) \\ {}^2f_g(0) \end{bmatrix} = \begin{bmatrix} {}^1\boldsymbol{K}_{xx} & 0 \\ 0 & {}^2\boldsymbol{K}_{xx} \end{bmatrix} \begin{bmatrix} {}^1d_x(0) \\ {}^2d_x(0) \end{bmatrix}, \qquad (34)$$

where ${}^if_g(0)$ and ${}^id_x(0)$ denote the internal grasping force and the initial deformation vectors of the x-direction of the i th soft fingertip, respectively.

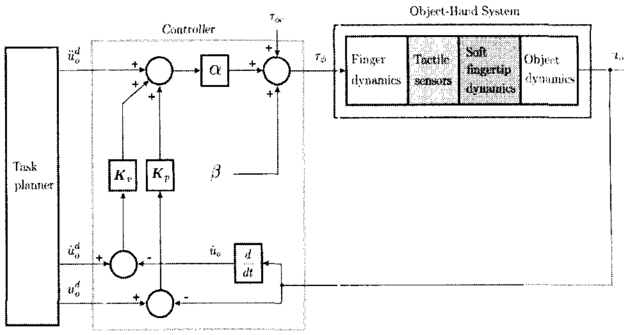

Fig. 2. An object manipulation control scheme by soft-fingered hands.

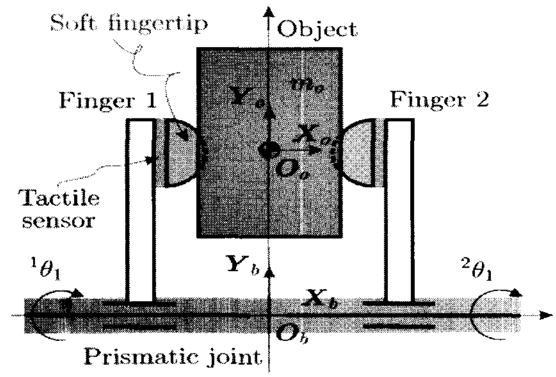

Fig. 3. An object manipulating system by a two-fingered robot hand with soft fingertips.

Moreover, 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. IMPLEMENTATION

4.1. Simulation results

In order to analyze the motion of soft-fingertips, preliminary simulation studies are performed by a two-fingered robotic hand with deformable fingertips. For the simulations, examples are considered in planar space. It is assumed that the employed object is rigid and the slip at the contact surface is ignored. The first simulation is an attempt to demonstrate some of the deformation characteristics of soft fingertips applied in a planar soft-fingered object manipulation.

Consider an object manipulation task by a dual soft-fingered hand as shown in Fig. 3. The given task is to control the position of the rigid object along a given horizontal trajectory. The control block diagram shown in Fig. 2 is used for the given task. The kinematic and dynamic parameters of the hand are described in section 4.2. Initially, the task planner in Fig. 2 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

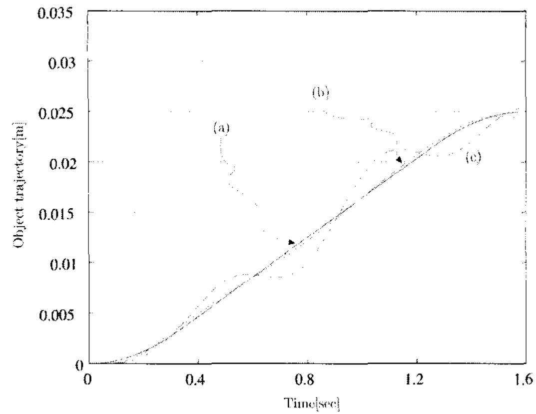

Fig. 4. Trajectory of object: (a) desired trajectory, (b) actual trajectory obtained by considering the γ term, and (c) actual trajectory obtained without considering the γ term; ${}^{i}\boldsymbol{K}_{xx}$(i=1,2)=500 N/m.

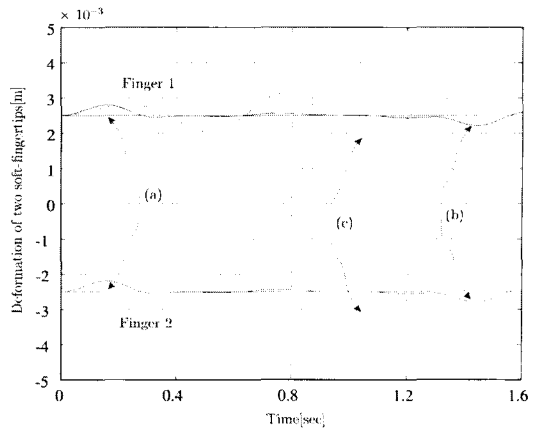

Fig. 5. Deformation of soft fingertips: (a) initial state, (b) when the γ term is considered, and (c) when the γ term is not considered; ${}^{i}\boldsymbol{K}_{xx}$(i=1,2)=500 N/m.

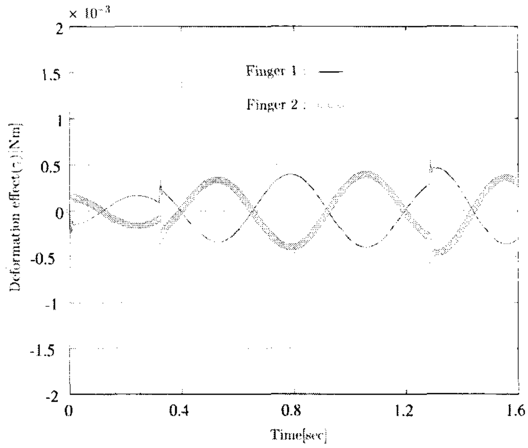

Fig. 6. Deformation effect of soft fingertips: ${}^{i}\boldsymbol{K}_{xx}$(i=1,2)=500 N/m.

the object is planned by a trapezoidal velocity profile for the total time of 1.6 sec, where the average velocity is set as 0.02 m/sec. The geometrical structure of the grasp is symmetric. The control signal is updated every 2 msec.
The object in Fig. 3 is actuated by

$$T_o(t) = m_o \ddot{x}_o(t), \tag{35}$$

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 soft fingertips is set as 0.01 m. In particular, the deformation of each soft fingertip is initialized as ${}^{1}d_x(0)$=0.0025 m and ${}^{2}d_x(0)$=-0.0025 m, respectively. The actual contact force between the object and each soft fingertip is obtained by (2), where the deformation of each soft fingertip is calculated by (3). The stiffness parameter of the i th soft fingertip is assigned by

$${}^{1}\boldsymbol{K}_{xx} = {}^{2}\boldsymbol{K}_{xx} = 500 \text{ N/m}. \tag{36}$$

The joint motion of each finger is governed by (33) and the position and velocity gains at the operational space are chosen by $\boldsymbol{K}_p = 50$ and $\boldsymbol{K}_v = 0.012$.
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 γ 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 γ term intrinsic in t he manipulation process obtained when the object is manipulated by the proposed manipulation control sch eme without considering the γ term. The second sim ulation characterizes the deformation effect according to the softness of the fingertips employed.

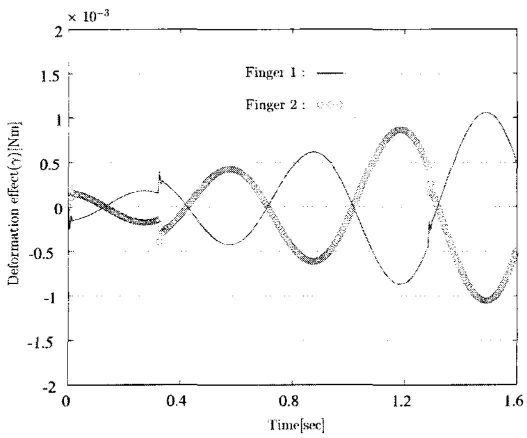

Fig. 7. Deformation effect of soft fingertips: ${}^{i}\boldsymbol{K}_{xx}$(i=1,2)=425 N/m.

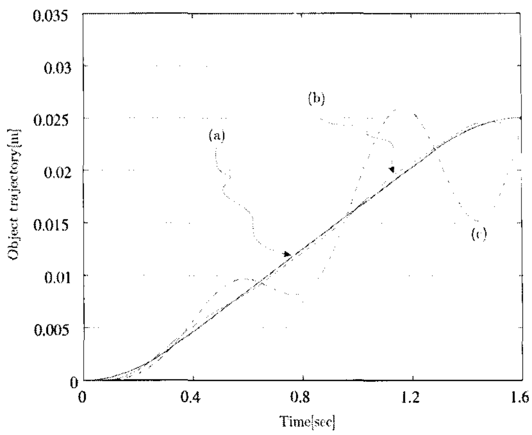

Fig. 8. Trajectory of object: (a) desired trajectory, (b) actual trajectory when the γ term is considered, and (c) actual trajectory when the γ term is not considered; ${}^{i}\boldsymbol{K}_{xx}$(i=1,2)=425 N/m.

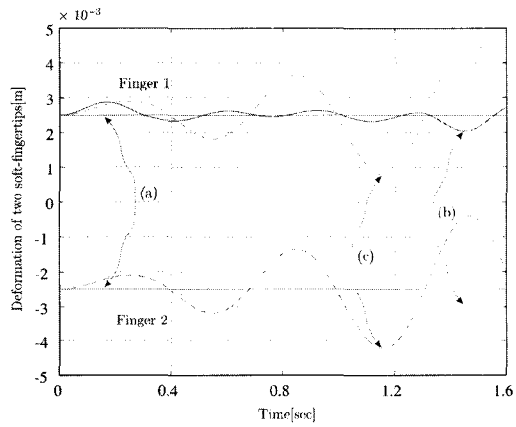

Fig. 9. Deformation of soft fingertips: (a) initial state, (b) when the γ term is considered, and (c) when the γ term is ignored; ${}^{i}\boldsymbol{K}_{xx}$(i=1,2)=425 N/m.

In this stage, the previous soft fingertips are changed to the new soft fingertips given by

$$ {}^{1}\boldsymbol{K}_{xx} = {}^{2}\boldsymbol{K}_{xx} = 425 \text{ N/m}. \tag{37}$$

Physically, this means that the new soft fingertips are 15% softer than those in the previous simulation.

Similar to the preceding simulation, the fundamental γ profile of this case is illustrated in Fig. 7. The following trajectory 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 γ term is considered in the manipulation process. In particular, the deformational oscillation of each fingertip greatly exceeds that shown in Fig. 5(c), with 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. To compensate for this effect, it is desirable that the deformation outcome is properly considered in a given manipulation task.

Let me now elaborate on the oscillatory deformationobserved in each soft fingertip. Even though the deformations shown in Figs. 5(b) and 9(b) are well-controlled, the response of the deformations still fluctuates to a certain extent. This is because the soft fingertip employed was modeled as a spring given by (36) and (37). If, in addition, a damping property is considered in modeling a soft fingertip, the oscillatory deformation may be alleviated. Then, let me consider the previous task with ${}^{1}\boldsymbol{K}_{xx} = {}^{2}\boldsymbol{K}_{xx} = 425$ N/m, for which additional damping parameters are assigned by ${}^{1}\boldsymbol{B}_{xx} = {}^{2}\boldsymbol{B}_{xx} = 10$ Nsec/m, where the γ term is not considered.

Figs. 10 and 11 show the results of a planar manipulation taking into account the damping effect due to the soft fingertips. As a result, Figs. 10 and 11 indicate that the oscillatory responses in Figs. 8 and 9, respectively, become more moderate. This indicates that the oscillatory perturbation of the spring-like model of a soft fingertip can be properly stabilized by considering the damping characteristics of the soft fingertip. Thus, the damping property may allow the control performance of the assigned task to stabilize.

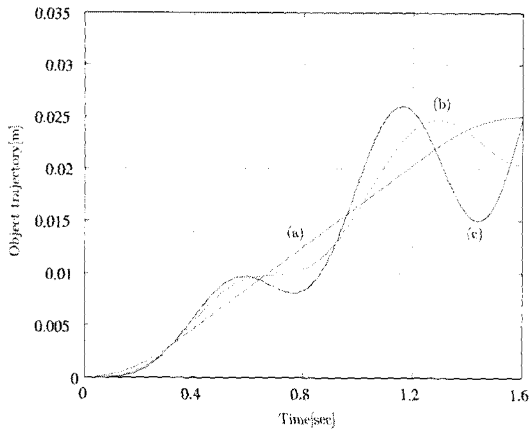

Fig. 10. Trajectory of object: (a) desired trajectory, (b) actual trajectory when the damping term is considered, and (c) actual trajectory when the damping term is not considered.

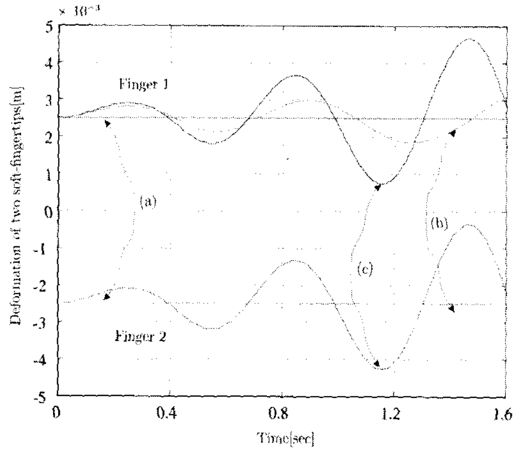

Fig. 11. Deformation of soft fingertips: (a) initial state, (b) when the damping term is considered, and (c) when the damping term is ignored.

4.2. Experiment results

In order to experimentally implement object manipulation, a two-fingered hand with soft fingertips and a hand control system were developed as shown in Fig. 12. Each finger has one prismatic joint that is driven by a DC micromotor (Model No. 2342-024CR) with an encoder, Model No. HEDM-5500J14, of Koshindenki Inc. The motor driver employed is a TITech driver with Model No. PC-0121-2 developed by Okazaki Industrial Inc. and the power supply is given by Model No. LCA50S-24 of the Cosel company. The length of dual fingers is 0.092 m, and each finger has a tactile sensor, Model No. I-SCAN10 $\times$ 10 developed by Nitta Ltd., which is attached on the bottom side of each fingertip.

The effective inertia matrix, $I^*_{\phi\phi}$ in (15), of the hand involving the inertia terms of the used motors is driven by

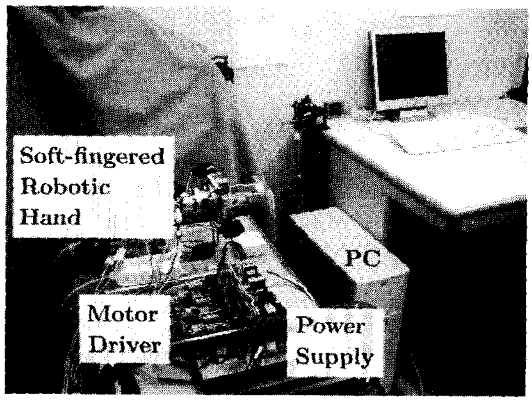

Fig. 12. A developed two-fingered hand with soft fingertips and its control system.

$$I^*_{\phi\phi} = \begin{bmatrix} {}^1I_m + m_1(D_1)^2 & 0 \\ 0 & {}^2I_m + m_2(D_2)^2 \end{bmatrix}, \quad (38)$$

where the mass parameters of each finger are given by $m_1 = m_2 = 0.1025$ Kg and the inertia terms of the used motors are given by ${}^1I_m = {}^2I_m$ = 7.83×10^{-7} Kg(m/rad)^2. $D_i (i = 1,2)$, given by 1.59 $\times 10^{-4}$ m/rad, represents the transmission ratio between the prismatic joint and the driving motor of the i th finger.

The robot hand is controlled by the developed PC-based hand control system. Here, a Pentium-IV (1.9GHz) computer with Linux is used in the experiment. The contact force activating the manipulated object is measured by using the tactile sensor. The control algorithms are coded in C language. The control signal update and the data feedback for each joint are executed every 2 msec with the aid of the real-time operating system, RTX [24]. In this experiment, the given task of the object in Fig. 13 is to control the position along the x-direction and maintain the grasping properly, where the grasped object is made of wood. The grasping force to the x-direction is assigned by 4.0 N for finger 1 and by -4.0 N for finger 2. The softness of used fingertips is experimentally estimated by ${}^1\boldsymbol{K}_{xx}$ =2500 Nm and ${}^2\boldsymbol{K}_{xx}$=2300 Nm. The position and velocity gains at the operational space are chosen by $\boldsymbol{K}_p$= 300 and $\boldsymbol{K}_v$ = 2.5, respectively.

The performances of position tracking are shown to be satisfactory in Figs. 14 and 15. Though a small change in the deformation of soft fingertips exists during the manipulation process, it is observed from Fig. 16 that the contact during the manipulation is successfully maintained. Since constructing an appropriate transmission mechanism for driving fingers

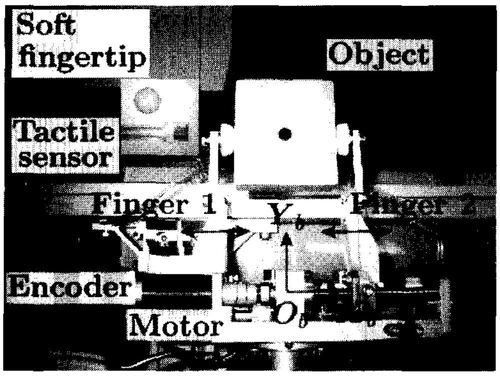

Fig. 13. An object manipulation task by a two fingered robotic hand with soft fingertips.

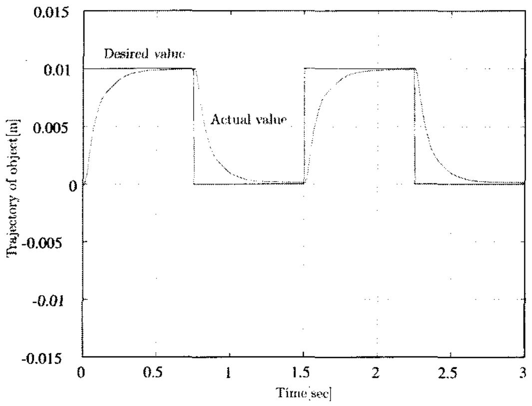

Fig. 14. Trajectory of object.

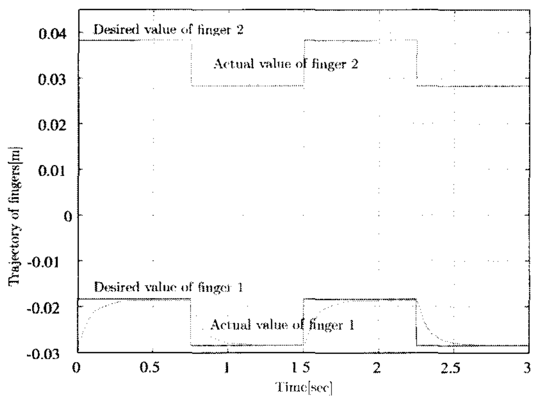

Fig. 15. Trajectory of two fingers.

and inserting the damping effect in a control loop can reduce the influence of the deformation of soft fingertips, it can be expected that they may assist in the motion behavior of soft-fingertip manipulation tasks.

5. CONCLUDING REMARKS

The motion of soft-fingertip object manipulation tasks tasks has been analyzed in this study. From a dynamic modeling of soft-fingertip object manipulations, this

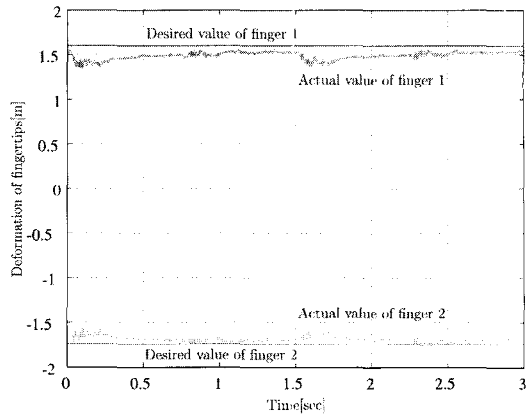

Fig. 16. Deformation of soft fingertips.

work substantially showed the influence of the deformation property of soft fingertips by employing two types of soft fingertips. Through the simulation and experimental works performed by using a two-fingered hand with soft fingertips, the behavior of soft-fingertip manipulating tasks has been demonstrated and also analyzed in terms of the characteristics of fingertips. As a result, the defor-mation effect represented by the γ term varies with the elasticity of the fingertips employed in soft-fingered manipulations. The softer the fingertip is, the more critical the influence of its deformation behavior becomes. After all, the motion of soft-fingertip manipulations can be affected by the deformation influence and its significance depends on the softness of the employed fingertips. Accordingly, the control of soft-fingertip manipulation tasks can be facilitated by considering the deformation effect. In this sense, a manipulation control method that incorporates the deformation effect can be usefully applied to soft-fingered manipulations. In addition, in order to compensate for the influence of the deformation of soft fingertips, it is necessary to consider a proper transmission mechanism for driving fingers in the finger design aspect, and include some damping property in the control viewpoint.

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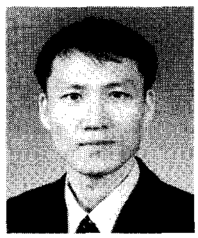

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