2011 IEEE/RSJ International Conference on
Intelligent Robots and Systems
September 25-30, 2011. San Francisco, CA, USA

Robust Manipulation for Temporary Lack of Sensory Information by a Multi-Fingered Hand-Arm System

Akihiro Kawamura, Kenji Tahara, Ryo Kurazume and Tsutomu Hasegawa

Abstract— **This paper proposes a novel vision-based grasping and manipulation scheme of a multi-fingered hand-arm system robust for a temporary lack of sensory information. Visual information is one of the fundamental components for reliable grasping and manipulation by a multi-fingered hand-arm system. However, in case that visual information such as position and attitude of an object comes to be unavailable due to the occlusion or if the object goes out-of-sight temporarily, unstable and unfavorable behavior is often induced. The proposed method, which utilizes the stable grasping control and the concept of virtual frame, enables to grasp and manipulate an object stably even if the visual information becomes suddenly and temporarily unavailable during manipulation. Firstly, a dynamical model of object grasping using a multi-fingered hand-arm system is formulated. Next, a new control scheme for robust object grasping and manipulation using the virtual frame is proposed. Finally, numerical simulations are performed to verify the usefulness of the proposed method.**

I. Introduction

Visual information is one of the fundamental components for reliable grasping and manipulation by a multi-fingered hand-arm system [1]. However, in some cases, the visual information such as object's position and attitude becomes suddenly and temporarily unavailable due to the occlusion or if the object goes out-of-sight. This causes serious unstable behavior in grasping and manipulation tasks.

To overcome these problems and make the visual servo control more stable against the temporary lack of object information, several methods have been proposed so far. These methods can be classified into two groups.

The method in former group is based on the accurate estimation of the position and attitude of a grasped object in order to compensate the lack of information [2], [3]. Hasegawa *et al.* proposed a manipulation method which is robust against various error of a stereo vision by using a tactile sensor [2]. The position and attitude of a grasped object is estimated by solving a minimization problem to ensure the consistency between vision and tactile information. Yokokohji *et al.* also proposed a control method which is similar to the Hasegawa's method. In addition to that, this method compensated quantization errors related to the sampling period to make a servo loop more stable [3]. However, these methods are valid only for a small and short lack of visual information such as self-occlusion, and not sufficient for the case in which a large amount of information is missed. Additionally, the accurate geometric information of the grasped object such as the size must be provided in advance.

In the method in later group, the robust control input for stable object grasping and manipulation is designed even if the visual information becomes unavailable or unreliable temporarily [4], [5]. Ozawa *et al.* [4] and Cheah *et al.* [5] proposed robust control methods to regulate the position of an end-effector even if visual information obtained by vision sensors contains geometric uncertainty. However, these methods considered some specific tasks such as reaching to the object by an end-effector, and object grasping and manipulation tasks are not considered. Since object grasping and manipulation tasks require not only kinematic information of the robot itself, but also geometrical information of the grasped object, it is difficult to apply the above method directly to the grasping and manipulation tasks.

Meanwhile, Tahara *et al.* have proposed a grasping and manipulation method without external sensing [6]. This method employs the concept of "virtual frame" which is defined by the position of each fingertip instead of an actual object frame. This method is, however, limited to grasp an object which consists of two flat and parallel surfaces.

For arbitrary shaped objects, we have proposed a stable object grasping method and a attitude control method for an arbitrary polyhedral shaped object using a multi-fingered hand-arm system with soft hemispherical fingertips [7], [8]. This method enables stable grasping and attitude control of a grasped object by a sensory feedback control under the condition that the object attitude information is available in real-time. No other information, e.g. the shape of the object and the contact points between fingertips and object surfaces, is required.

In this paper, a novel grasping and manipulation method which is robust for the temporary lack of sensory information is proposed. This method is based on our previous works [7], [8] but the robustness is enhanced by introducing the concept of "virtual frame" [6], [9]. Thanks to this concept, the proposed method enables to regulate position and attitude of a grasped object stably even if the sensory information of the object becomes suddenly and temporarily unavailable during manipulation.

Both the position and the attitude of the virtual frame proposed by Tahara *et al.* and Wimböck *et al.* are defined

This work was partially supported by "Kyushu University Research Superstar Program (SSP)", based on the budget of Kyushu University allocated under President's initiative and Grant-in-Aid for JSPS Fellows.

A. Kawamura is with Graduate School of Information Science and Electrical Engineering, Kyushu University, Fukuoka, 819-0395, JAPAN kawamura@irvs.is.kyushu-u.ac.jp

K. Tahara is with Faculty of Engineering, Kyushu University, Fukuoka, 819-0395, JAPAN tahara@ieee.org

R. Kurazume and T. Hasegawa are with Faculty of Information Science and Electrical Engineering, Kyushu University, Fukuoka, 819-0395, JAPAN {kurazume, hasegawa}@ait.kyushu-u.ac.jp

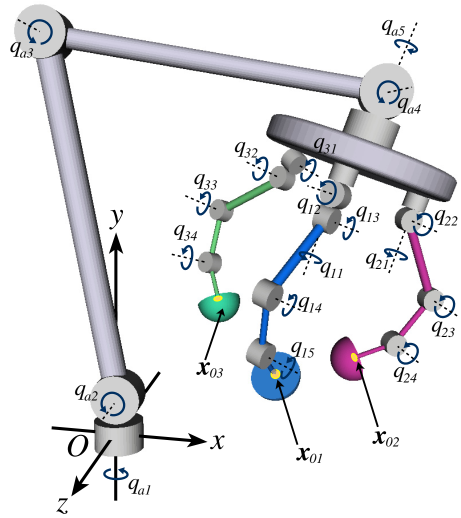

Fig. 1. Multi-fingered hand-arm system

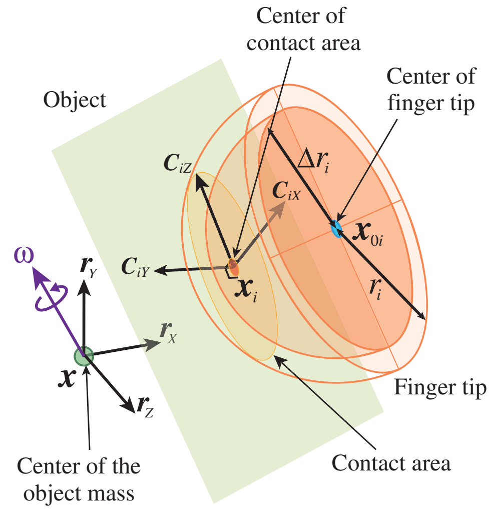

Fig. 2. Contact model at the center of the contact area

based on the center position of each fingertip. Therefore, the attitude control input may interfere with other control inputs which are also based on the center position of each fingertip. For example, the attitude control input and the position control input are interfered each other. To avoid the interference, this paper proposes a new concept of the virtual frame in which the attitude of the virtual frame is defined based on the attitude of each fingertip.

The virtual frame is calculated from joint angles obtained by internal sensors in multi-fingered robotic hand-arm system. By switching the real frame and the virtual frame according to the availability of the sensory information, the proposed method enables to control the object position and attitude even if the sensory information is lacked temporarily.

This paper is organized as follows: Firstly a dynamical model of object grasping using a multi-fingered hand-arm system is formulated in Section II. A new control scheme for robust object grasping and manipulation using new virtual frame is proposed in Section III and IV. In Section V, numerical simulations are performed to verify the usefulness of proposed method.

II. A Multi Fingered Hand Arm System

In this section, we model a hand-arm system composed of an arm and a multi-fingered hand. In our proposed grasping method, we assume that a robotic hand-arm system has enough number of fingers and each finger also has enough number of DOFs, in order to accomplish stable object grasping and attitude control of a grasped object. Namely, there is no limitation of the system configuration, as long as the assumption is satisfied. An example of a multi-fingered hand-arm system treated here is illustrated in Fig. 1. Assume that all fingertips maintain rolling contact with the object surfaces, and do not slip and detach from the surfaces during manipulation. Also assume that fingertips roll within the ranges of its hemispheric surfaces, and they do not deviate from each contact surface. Note that the gravity effect is ignored in this paper for the sake of modeling easily at this stage. As shown in Fig. 1, the symbol O denotes the origin of Cartesian coordinates, and $\boldsymbol{x}_{0i} \in \mathbb{R}^3$ is a position of the center of each fingertip. Hereafter, the subscript of i refers to the i^{th} finger in all equations. The number of DOFs of the arm and the i^{th} finger are represented as N_a and N_i, respectively. A joint angle vector of the arm is expressed by $\boldsymbol{q}_a \in \mathbb{R}^{N_a}$. Similarly, A joint angle vector of the i^{th} finger is expressed by $\boldsymbol{q}_{0i} \in \mathbb{R}^{\mathrm{N}_i}$. Also, $\boldsymbol{q} = (\boldsymbol{q}_a, \boldsymbol{q}_{01}, \boldsymbol{q}_{02}, ..., \boldsymbol{q}_{0N})^{\mathrm{T}}$ denotes a joint angle vector of the arm and all the fingers, where N is the number of the fingers. As shown in Fig. 2, $\boldsymbol{x}_i \in \mathbb{R}^3$ is a position of the center of each contact area. The position of the center of the object mass in Cartesian coordinates is expressed as $\boldsymbol{x} = (x, y, z)^{\mathrm{T}} \in \mathbb{R}^3$. An instantaneous rotational axis of the object at $\boldsymbol{x}$ in Cartesian coordinates is expressed by $\boldsymbol{\omega} = (\omega_x, \omega_y, \omega_z)^{\mathrm{T}} \in \mathbb{R}^3$. An attitude of the object in Cartesian coordinates is expressed by the rotational matrix $\boldsymbol{R} = (\boldsymbol{r}_x, \boldsymbol{r}_y, \boldsymbol{r}_z) \in SO(3)$, where $\boldsymbol{r}_x, \boldsymbol{r}_y, \boldsymbol{r}_z \in \mathbb{R}^3$ are mutually orthonormal vectors on the object frame. In addition, we define contact frames at the center of each contact area by each rotational matrix $\boldsymbol{RR}_{Ci} = (\boldsymbol{C}_{iX}, \boldsymbol{C}_{iY}, \boldsymbol{C}_{iZ})$, and the y-axis of them $\boldsymbol{C}_{iY}$ is taken as normal to the contact surface. For each hemispheric fingertip, r_i is the radius of each fingertip, and Δr_i is the distance between the center of the fingertips and the contact surfaces. Namely, $r_i - \Delta ri$ signifies each fingertip's deformation displacement toward normal to the surface induced by the softness.

A. Constraints

A 3-dimentional rolling constraint with area contact [7] can be expressed as a Pfaffian constraint as

$$\begin{bmatrix} \boldsymbol{X}_{iq} \\ \boldsymbol{Z}_{iq} \end{bmatrix} \dot{\boldsymbol{q}} + \begin{bmatrix} \boldsymbol{X}_{ix} \\ \boldsymbol{Z}_{ix} \end{bmatrix} \dot{\boldsymbol{x}} + \begin{bmatrix} \boldsymbol{X}_{i\omega} \\ \boldsymbol{Z}_{i\omega} \end{bmatrix} \boldsymbol{\omega} = \boldsymbol{0}, \tag{1}$$

where

$$\left[\begin{array}{l} \boldsymbol{X}_{iq} = \Delta r_i \boldsymbol{C}_{iZ}^{\mathrm{T}} \boldsymbol{J}_{\Omega i} - \boldsymbol{C}_{iX}^{\mathrm{T}} \boldsymbol{J}_{0i} \\ \boldsymbol{X}_{ix} = \boldsymbol{C}_{iX}^{\mathrm{T}} \\ \boldsymbol{X}_{i\omega} = \{\boldsymbol{C}_{iX} \times (\boldsymbol{x} - \boldsymbol{x}_{0i})\}^{\mathrm{T}} - \Delta r_i \boldsymbol{C}_{iZ}^{\mathrm{T}} \\ \boldsymbol{Z}_{iq} = -\Delta r_i \boldsymbol{C}_{iX}^{\mathrm{T}} \boldsymbol{J}_{\Omega i} - \boldsymbol{C}_{iZ}^{\mathrm{T}} \boldsymbol{J}_{0i} \\ \boldsymbol{Z}_{ix} = \boldsymbol{C}_{iZ}^{\mathrm{T}} \\ \boldsymbol{Z}_{i\omega} = \{\boldsymbol{C}_{iZ} \times (\boldsymbol{x} - \boldsymbol{x}_{0i})\}^{\mathrm{T}} + \Delta r_i \boldsymbol{C}_{iX}^{\mathrm{T}}, \end{array}\right. \tag{2}$$

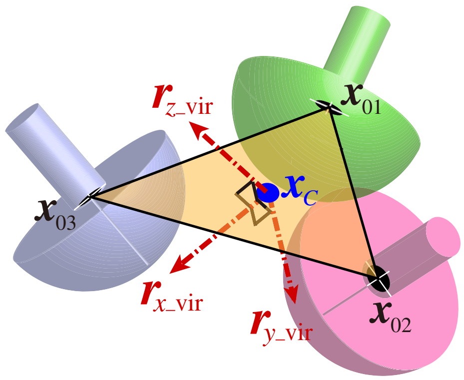

Fig. 3. Virtual frame

and $\boldsymbol{J}_{\Omega_i} \in \mathbb{R}^{3\times\left(N_a+\sum_{i=1}^{N} N_i\right)}$ is the Jacobian matrix for the attitude angular velocity of each fingertip with respect to the joint angular velocity $\dot{\boldsymbol{q}} \in \mathbb{R}^{N_a+\sum_{i=1}^{N} N_i}$. Moreover, $\boldsymbol{J}_{0i} \in \mathbb{R}^{3\times\left(N_a+\sum_{i=1}^{N} N_i\right)}$ is the Jacobian matrix for the center of each fingertip $\boldsymbol{x}_{0i}$ with respect to the joint angular velocity $\dot{\boldsymbol{q}}$.

B. Overall Dynamics

Given the constraints shown by (1), Lagrange's equations of motion of the overall system are given by applying the variational principle as follows:
For the multi-fingered hand-arm system:

$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \left\{\frac{1}{2}\dot{\boldsymbol{H}}(\boldsymbol{q}) + \boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}})\right\}\dot{\boldsymbol{q}} + \sum_{i=1}^{N}\frac{\partial T_i}{\partial \dot{\boldsymbol{q}}}^{\mathrm{T}} + \sum_{i=1}^{N}\left(\boldsymbol{J}_{0i}^{\mathrm{T}}\boldsymbol{C}_{iY}f_i + \boldsymbol{X}_{iq}^{\mathrm{T}}\lambda_{iX} + \boldsymbol{Z}_{iq}^{\mathrm{T}}\lambda_{iZ}\right) = \boldsymbol{u}, \quad (3)$$

For the object:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \sum_{i=1}^{N}\left(-f_i\boldsymbol{C}_{iY} + \boldsymbol{X}_{ix}^{\mathrm{T}}\lambda_{iX} + \boldsymbol{Z}_{ix}^{\mathrm{T}}\lambda_{iZ}\right) = \boldsymbol{0} \quad (4)$$

$$\boldsymbol{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega}\times\boldsymbol{I}\boldsymbol{\omega} - \sum_{i=1}^{N}\{\boldsymbol{C}_{iY}\times(\boldsymbol{x}-\boldsymbol{x}_{0i})\}f_i + \sum_{i=1}^{N}\frac{\partial T_i}{\partial \boldsymbol{\omega}}^{\mathrm{T}} + \sum_{i=1}^{N}\left(\boldsymbol{X}_{i\omega}^{\mathrm{T}}\lambda_{iX} + \boldsymbol{Z}_{i\omega}^{\mathrm{T}}\lambda_{iZ}\right) = \boldsymbol{0} \quad (5)$$

where in (3), $\boldsymbol{H} \in \mathbb{R}^{\left(N_a+\sum_{i=1}^{N} N_i\right)\times\left(N_a+\sum_{i=1}^{N} N_i\right)}$ is an inertia matrix for the arm and each finger, $\boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is a skew-symmetric matrix, and $\boldsymbol{u} \in \mathbb{R}^{N_a+\sum_{i=1}^{N} N_i}$ is a vector of the input torque. In (5), $\boldsymbol{M} = \mathrm{diag}(m,m,m)$ is a mass of the object, $\boldsymbol{I} = \boldsymbol{R}\bar{\boldsymbol{I}}\boldsymbol{R}^{\mathrm{T}}$, and $\bar{\boldsymbol{I}} \in \mathbb{R}^{3\times3}$ is an inertia tensor for the object represented by the principal axes of inertia. In addition, f_i is a reproducing force in the normal direction to the object surface at the center of each contact area, T_i is an energy dissipation function which acts as a viscosity between fingertips and object surfaces in twist direction. Also λ_{iX} and λ_{iZ} denote Lagrange's multipliers.

III. Construction of the Virtual Frame

In this method, basically a real object frame which is available from visual sensors is manipulated to a desired frame, and if a real object frame becomes unavailable, a virtual frame instead of the real object frame is utilized to manipulate the grasped object. The concept of the virtual frame has been reported by Wimböck *et al.* [9] and Tahara *et al.* [6]. In their methods, the virtual frame is defined by a relative position vector between each fingertip, and a control input to regulate the attitude of the object is designed to generate a task-space artificial potential energy according to a desired attitude. However, the attitude of their virtual frame is defined based on the center position of each fingertip similar to the definition of the virtual object position, and thereby the object attitude control input might cause an interference with other control inputs, such as the stable object grasping control input, or the object position control input which are also based on the center position of each fingertip. In this section, a new virtual frame which is defined based on the attitude of each fingertip is proposed. In this formulation based on the attitude of each fingertip, there is no interference of the attitude control input with other control inputs. Firstly, the position of the virtual frame $\boldsymbol{x}_c$ is designed as

$$\boldsymbol{x}_c = \frac{1}{N}\sum_{i=1}^{N}\boldsymbol{x}_{0i}. \quad (6)$$

Next, we define the virtual frame at $\boldsymbol{x}_c$ by a rotational matrix $\boldsymbol{R}_{\mathrm{vir}}$ as shown in Fig. 3. It is given as

$$\boldsymbol{R}_{\mathrm{vir}} = \left(\boldsymbol{r}_{x_{\mathrm{vir}}}, \boldsymbol{r}_{y_{\mathrm{vir}}}, \boldsymbol{r}_{z_{\mathrm{vir}}}\right), \quad (7)$$

where

$$\boldsymbol{r}_{x_{\mathrm{vir}}} = \frac{\tilde{\boldsymbol{r}}_{x_{\mathrm{vir}}}}{\|\tilde{\boldsymbol{r}}_{x_{\mathrm{vir}}}\|}, \quad \left(\tilde{\boldsymbol{r}}_{x_{\mathrm{vir}}} = \sum_{i=1}^{N}\boldsymbol{r}_{x_{\mathrm{f}i}}\right) \quad (8)$$

$$\boldsymbol{r}_{y_{\mathrm{vir}}} = \frac{\tilde{\boldsymbol{r}}_{x_{\mathrm{vir}}}\times\tilde{\boldsymbol{r}}_{y_{\mathrm{vir}}}}{\|\tilde{\boldsymbol{r}}_{x_{\mathrm{vir}}}\times\tilde{\boldsymbol{r}}_{y_{\mathrm{vir}}}\|}, \quad \left(\tilde{\boldsymbol{r}}_{y_{\mathrm{vir}}} = \sum_{i=1}^{N}\boldsymbol{r}_{y_{\mathrm{f}i}}\right) \quad (9)$$

$$\boldsymbol{r}_{z_{\mathrm{vir}}} = \boldsymbol{r}_{x_{\mathrm{vir}}}\times\boldsymbol{r}_{y_{\mathrm{vir}}}. \quad (10)$$

In (8) and (9), $\boldsymbol{r}_{x_{\mathrm{f}i}}$ and $\boldsymbol{r}_{y_{\mathrm{f}i}}$ in the rotational matrix $\boldsymbol{R}_{\mathrm{f}i}$ are mutually orthonormal vectors, and this rotational matrix expresses the attitude of each fingertip.

IV. Control Scheme

Let us design a switching control scheme which depends on whether the geometrical information of the grasped object is available or not. Assume that the accurate position and attitude of the object is available in an initial state. The procedural steps are shown as follows:

1) The object is manipulated using a real object frame.
2) The real object frame is NOT available.
3) The controlled target (the real object frame) is changed to the virtual object frame.
4) The real frame is available again.
5) Return to 1).

The flow chart of these steps is shown in Fig. 4. Each step of the procedure is explained in the following sections.

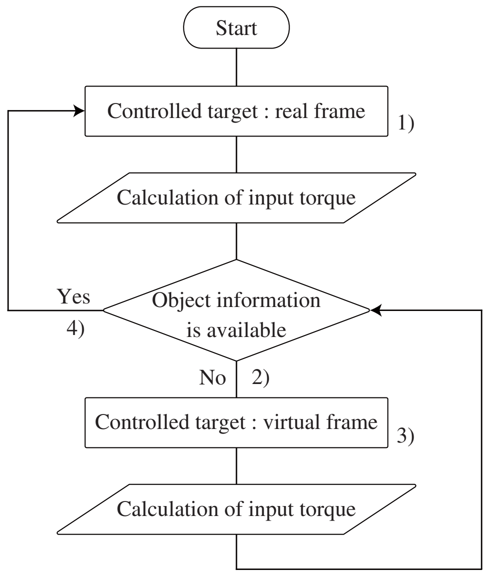

Fig. 4. Flow chart of the switching control scheme

A. *Step* 1)

In this step, an accurate position and attitude of the object is given from some visual sensors. The input torque $\boldsymbol{u}$ is given as

$$\boldsymbol{u} = \boldsymbol{u}_s + \boldsymbol{u}_p + \boldsymbol{u}_o, \tag{11}$$

where $\boldsymbol{u}_s$ is for stable object grasping, $\boldsymbol{u}_p$ is for position control of the object, and $\boldsymbol{u}_o$ is for attitude control of the object, respectively. The control input for stable grasping $\boldsymbol{u}_s$ is designed so that the center of each fingertip approaches each other [7]. It is given as

$$\boldsymbol{u}_s = \frac{f_d}{\sum_{i=1}^{N} r_i} \sum_{j=1}^{N} \boldsymbol{J}_{0j}^{\mathrm{T}} (\boldsymbol{x}_c - \boldsymbol{x}_{0j}) - \boldsymbol{C}\dot{\boldsymbol{q}}, \tag{12}$$

where $\boldsymbol{C} \in \mathbb{R}^{\left(N_a + \sum_{i=1}^{N} N_i\right) \times \left(N_a + \sum_{i=1}^{N} N_i\right)} > 0$ is a positive definite diagonal matrix that expresses the damping gain for each joint, and f_d is the nominal desired grasping force. The control input for the object position control $\boldsymbol{u}_p$ is given as

$$\boldsymbol{u}_p = K_p \sum_{j=1}^{N} \boldsymbol{J}_{0j}^{\mathrm{T}} (\boldsymbol{x}_d - \boldsymbol{x}), \tag{13}$$

where K_p is a positive scalar constant and $\boldsymbol{x}_d$ is a desired position of the object. The control input for attitude control of the object $\boldsymbol{u}_o$ [8] is given as

$$\begin{aligned} \boldsymbol{u}_o \;=\; & K_o \sum_{j=1}^{N} \boldsymbol{J}_{\Omega j}^{\mathrm{T}} \left\{ (\boldsymbol{r}_x \times \boldsymbol{r}_{xd}) \right. \\ & \left. + (\boldsymbol{r}_y \times \boldsymbol{r}_{yd}) + (\boldsymbol{r}_z \times \boldsymbol{r}_{zd}) \right\}, \end{aligned} \tag{14}$$

where $K_o > 0$ is a positive scalar constant. A desired real object frame is expressed by a rotational matrix $\boldsymbol{R}_d = (\boldsymbol{r}_{xd}, \boldsymbol{r}_{yd}, \boldsymbol{r}_{zd})$. Each cross product in the right-hand side of (14), e.g. $\boldsymbol{r}_x \times \boldsymbol{r}_{xd}$, signifies an attitude error for each axis between the present attitude and the disired attitude of the object. Namely, the summation of each cross product indicates a desired instantaneous rotational axis of the object. Eventually, a desired attitude of the object can be realized by adding the moment torque to the grasped object from each fingertip around this desired instantaneous rotational axis.

B. *Step* 2)

In the case that the position and attitude information of the grasped object is unavailable, the control target is switched from the real object frame to the virtual object frame, immediately. At this moment, the last real information of the grasped object acquired from some visual sensors is stored. Then, we configure the desired virtual frame $\boldsymbol{x}_{d_{\mathrm{vir}}}$, $\boldsymbol{R}_{d_{\mathrm{vir}}}$ using the last obtained object information. It is given as follows:

$$\boldsymbol{x}_{d_{\mathrm{vir}}} = \boldsymbol{x}_{c_{\mathrm{last}}} + (\boldsymbol{x}_d - \boldsymbol{x}_{\mathrm{last}}) \tag{15}$$

$$\boldsymbol{R}_{d_{\mathrm{vir}}} = \boldsymbol{R}_d \boldsymbol{R}_{\mathrm{last}}^{\mathrm{T}} \boldsymbol{R}_{\mathrm{vir}_{\mathrm{last}}}, \tag{16}$$

where $\boldsymbol{x}_{c_{\mathrm{last}}}$ is the position of the virtual object frame at the last moment, and $\boldsymbol{x}_{\mathrm{last}}$ is the position of the real object frame at the last moment. Similarly, $\boldsymbol{R}_{\mathrm{vir}_{\mathrm{last}}}$ is the rotational matrix which expresses the virtual frame at the last moment, and $\boldsymbol{R}_{\mathrm{last}}$ is the real object frame at the last moment. Namely, the desired virtual frame, which reflects a relative position and attitude of the object between the real object frame and the desired real object frame, is designed. Eventually, this method can avoid a discontinuity of an input torque to each joint which may be induced by the switching operation.

C. *Step* 3)

The grasped object is manipulated by the use of the virtual frame and the desired virtual frame. The control input $\boldsymbol{u}$ is switched to the following form that is using the virtual frame.

$$\boldsymbol{u} = \boldsymbol{u}_s + \boldsymbol{u}_{p_{\mathrm{vir}}} + \boldsymbol{u}_{o_{\mathrm{vir}}} \tag{17}$$

The control input for position control of the virtual frame $\boldsymbol{u}_{p_{\mathrm{vir}}}$ is designed as

$$\boldsymbol{u}_{p_{\mathrm{vir}}} \;=\; K_p \sum_{j=1}^{N} \boldsymbol{J}_{0j}^{\mathrm{T}} (\boldsymbol{x}_{d_{\mathrm{vir}}} - \boldsymbol{x}_c). \tag{18}$$

The control input for attitude control of the virtual frame $\boldsymbol{u}_{o_{\mathrm{vir}}}$ is expressed as

$$\begin{aligned} \boldsymbol{u}_{o_{\mathrm{vir}}} \;=\; & K_o \sum_{i=1}^{N} \boldsymbol{J}_{\Omega i}^{\mathrm{T}} \left\{ (\boldsymbol{r}_{x_{\mathrm{vir}}} \times \boldsymbol{r}_{xd_{\mathrm{vir}}}) \right. \\ & \left. + (\boldsymbol{r}_{y_{\mathrm{vir}}} \times \boldsymbol{r}_{yd_{\mathrm{vir}}}) + (\boldsymbol{r}_{z_{\mathrm{vir}}} \times \boldsymbol{r}_{zd_{\mathrm{vir}}}) \right\}. \end{aligned} \tag{19}$$

D. *Step* 4)

If the real object frame is available again, the control input is return to the initial one. In that case, a small discontinuity of the control input may be induced. However, we can assume that in this case the virtual frame has already been regulated to the desired one sufficiently, and then the real object frame is assumed to be near the desired one. Therefore, its torque jump might be small enough. In addition, this state can be regarded as another initial condition of the manipulation, and the stability of the closed-loop system has already been verified theoretically by our previous reports

TABLE I

PHYSICAL PARAMETERS

Triple-fingered hand-arm system

1^{st} link length	l_{a1}	1.300[m]	l_{i1}	0.300[m]
2^{nd} link length	l_{a2}	1.000[m]	l_{i2}	0.200[m]
3^{rd} link length	l_{a3}	0.175[m]	l_{i3}	0.140[m]
1^{st} mass center	l_{ga1}	0.650[m]	l_{gi1}	0.150[m]
2^{nd} mass center	l_{ga2}	0.500[m]	l_{gi2}	0.100[m]
3^{rd} mass center	l_{ga3}	0.0875[m]	l_{gi3}	0.070[m]
1^{st} mass	m_{a1}	1.300[kg]	m_{i1}	0.250[kg]
2^{nd} mass	m_{a2}	1.000[kg]	m_{i2}	0.150[kg]
3^{rd} mass	m_{a3}	0.400[kg]	m_{i3}	0.100[kg]
1^{st} Inertia $\boldsymbol{I}_{a1}$	$\mathrm{diag}(7.453, 7.453, 0.260)\times10^{-1}$[kg·m^2]			
2^{nd} Inertia $\boldsymbol{I}_{a2}$	$\mathrm{diag}(3.397, 3.397, 0.128)\times10^{-1}$[kg·m^2]			
3^{rd} Inertia $\boldsymbol{I}_{a3}$	$\mathrm{diag}(0.291, 0.291, 0.500)\times10^{-1}$[kg·m^2]			
1^{st} Inertia $\boldsymbol{I}_{i1}$	$\mathrm{diag}(7.725, 7.725, 0.450)\times10^{-3}$[kg·m^2]			
2^{nd} Inertia $\boldsymbol{I}_{i2}$	$\mathrm{diag}(2.060, 2.060, 0.120)\times10^{-3}$[kg·m^2]			
3^{rd} Inertia $\boldsymbol{I}_{i3}$	$\mathrm{diag}(0.538, 0.538, 0.031)\times10^{-3}$[kg·m^2]			
Radius of fingertip r_i	0.070[m]			
Stiffness coefficient k_i	1.000×10^5[N/m^2]			
Damping function ξ_i	$1.000\times\left(r_i^2-\Delta r_i^2\right)\pi$[Ns/m^2]			

Object

Mass m	0.037[kg]
Y_1	0.092[m]
Y_2	0.048[m]
Y_3	0.048[m]
θ_{t1}	1.833[rad]
θ_{t2}	1.833[rad]
θ_{t3}	2.618[rad]
Inertia $\boldsymbol{I}$	$\mathrm{diag}\,(1.273, 0.193, 1.148)\times10^{-3}[\mathrm{kg}\cdot\mathrm{m}^2]$

TABLE II

DESIRED GRASPING FORCE AND GAINS

f_d	10.0[N]
K_p	4.762
K_o	0.238
$\boldsymbol{C}_a$	$\mathrm{diag}(1.003, 0.651, 0.735, 0.278, 0.177)\times10^{-1}$[Ns·m/rad]
$\boldsymbol{C}_1$	$\mathrm{diag}(0.606, 0.687, 0.786, 0.642, 0.198)\times10^{-2}$[Ns·m/rad]
$\boldsymbol{C}_2$	$\mathrm{diag}(0.468, 0.780, 0.318, 0.099)\times10^{-2}$[Ns·m/rad]
$\boldsymbol{C}_3$	$\mathrm{diag}(0.648, 0.780, 0.318, 0.099)\times10^{-2}$[Ns·m/rad]
$\boldsymbol{x}_d$	$(0.100, 0.500, 0.700)^{\mathrm{T}}$ [m]
$\boldsymbol{R}_d$	$\begin{bmatrix} 0.88 & -0.32 & -0.34 \\ 0.34 & 0.94 & 0.00 \\ 0.32 & -0.12 & 0.94 \end{bmatrix}$

[7], [8]. Therefore, the stability of the overall system can be ensured in all likelihood, but it must be analyzed more carefully in the next work.

V. NUMERICAL SIMULATION

In this section, we report the simulation result. The robotic hand-arm system used in this simulation is a triple-fingered hand-arm system. It consists of an arm part which has 5 DOFs and a triple-fingered hand part which has one 5 DOFs finger and two 4 DOFs fingers. The grasped object is triangular prism. Specific parameters of the triple-fingered hand-arm system and the grasped object are shown in Table I. In this Table, Y_i is a perpendicular distance from the center of the object mass $O_{c.m.}$ to each surface of the object, and θ_{ti} is the external angle of a cross-sectional triangle of the object. Table II shows the desired nominal grasping force and gains. An initial condition of the overall system is shown in Table III. Figure 5 shows the transient responses of the real object frame and the virtual object frame. The column of "Object Information" indicates whether the position and attitude information of the grasped object is available or not. Namely, in this simulation, the real information of the object is lacked from 1.5[s] to 5[s], and it is acquired in other periods. The column of "Control Target" indicates the present control target at that moment, the real object frame or the virtual object frame. Several solid lines in this figure mean transient responses of the control targets and the desired values. In particular in this figure, only values with respect to $\boldsymbol{r}_x$ from the rotational matrix $\boldsymbol{R}$ are shown. We can see from this figure that all elements of $\boldsymbol{R}$ converge to each desired value. Figure 6 shows snapshots of the simulation. In this figure, each image includes two contents. The left-hand side of each image shows the overall view, and a translucent red object indicates the desired object position and attitude, and a solid blue object indicates the real object position and attitude. The right-hand side of each image shows all frames which are available at that moment. During 1.5 [s] to 5.0 [s], the virtual frame is utilized for the control target, and therefore, the real object position and attitude converge not to the desired real object position and attitude, but the desired virutal object position and attitude. Of course, there is the difference between the desired real object frame and the desired virtual object frame. However, they are quite near each other and the stability of the overall system is held during this period. After the real object information is available again, both the real position and attitude of the object converge to each desired value respectively at the final state.

TABLE III

INITIAL CONDITION

$\dot{\boldsymbol{q}}$	$\boldsymbol{0}$[rad/s]
$\boldsymbol{q}_a$	$(-0.183, -1.369, 1.898, 1.343, -0.787)^{\mathrm{T}}$ [rad]
$\boldsymbol{q}_{01}$	$(1.007, 0.235, -0.771, 1.338, 0.328)^{\mathrm{T}}$ [rad]
$\boldsymbol{q}_{02}$	$(0.242, -0.733, 1.122, 0.754)^{\mathrm{T}}$ [rad]
$\boldsymbol{q}_{03}$	$(2.019, -0.924, 0.912, 1.088)^{\mathrm{T}}$ [rad]
$\dot{\boldsymbol{x}}$	$\boldsymbol{0}$ [m/s]
$\boldsymbol{x}$	$(0.158, 0.501, 0.681)^{\mathrm{T}}$ [m]
$\boldsymbol{\omega}$	$\boldsymbol{0}$ [rad/s]
$\boldsymbol{R}$	$\begin{bmatrix} 1.00 & 0.00 & 0.00 \\ 0.00 & 1.00 & 0.00 \\ 0.00 & 0.00 & 1.00 \end{bmatrix}$

From these figures, we can conclude that the object grasping and manipulation can be realized well by our proposed method.

VI. CONCLUSION

This paper presented a robust object grasping and manipulation method against the temporary lack of geometrical information of the grasped object during manipulation. Firstly, the overall system dynamics was modeled. Next, the new virtual frame in which its attitude is defined based on the attitude of each fingertip was introduced. After that, the robust object manipulation scheme, which utilizes the real frame and the virtual frame of the object effectively, was designed. This method was designed so that the hand-arm system works well even if the geometrical object information is completely unavailable during manipulation. Finally, we confirmed through the numerical simulation result that our proposed method realized desired position and attitude of the grasped object in stable, even though the geometrical object information is suddenly lacked during manipulation.

In our future works, we have to consider what is the

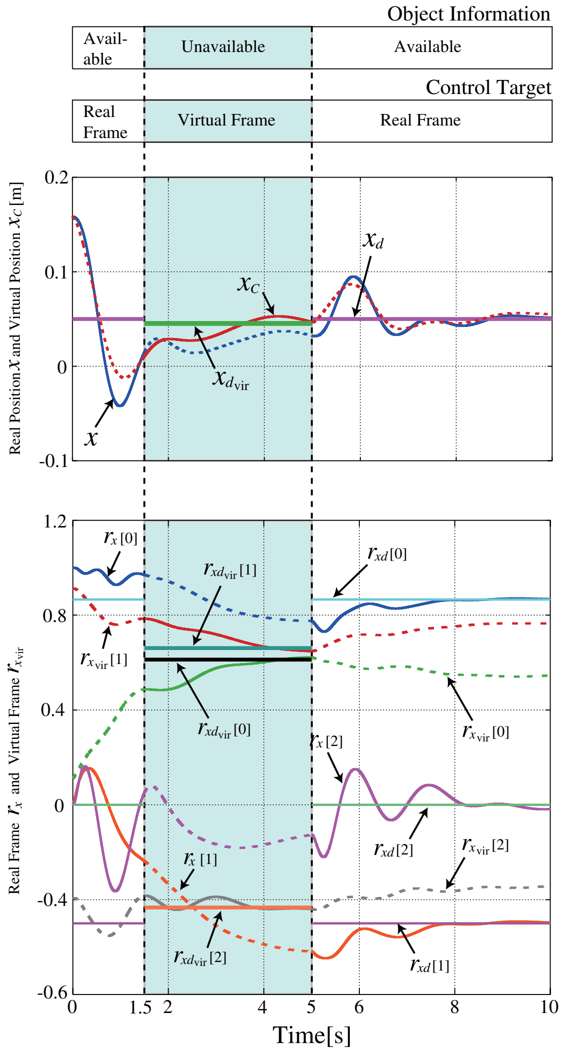

Fig. 5. Transient responses of the real frame and the virtual frame

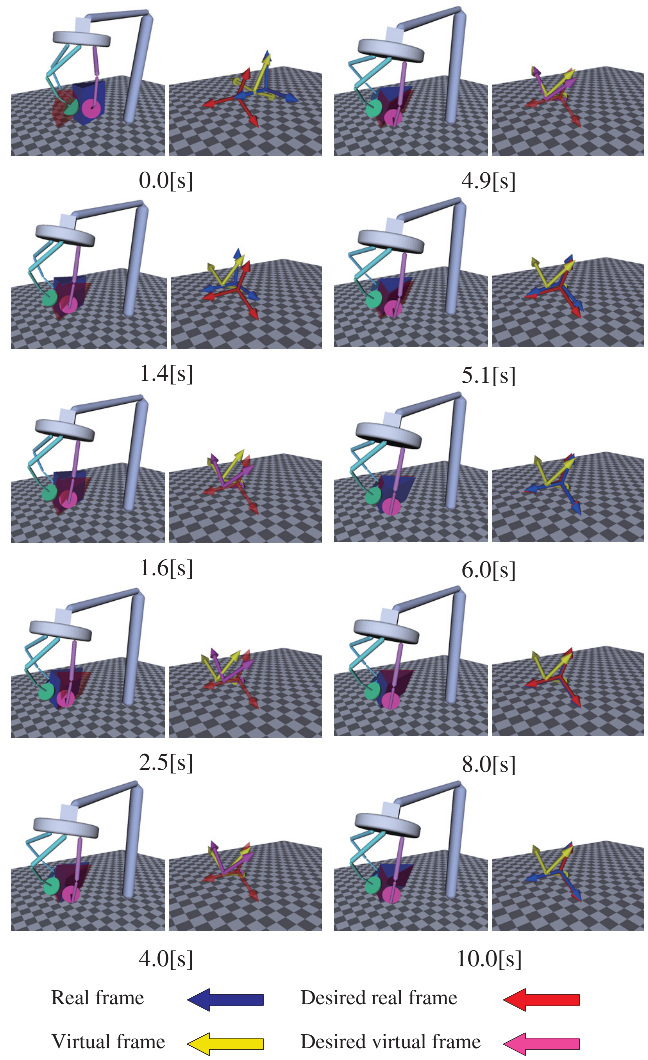

Fig. 6. Snapshots of the simulation

best timing to switch the real frame and virtual frame for the manipulation task. We also have to analyze the stability of the overall system including switching the controllers. In addition, we would like to conduct experiments using a prototype to confirm the usefulness of our proposed method.

ACKNOWLEDGMENT

This work was partially supported by "the Kyushu University Research Superstar Program (SSP)", based on the budget of Kyushu University allocated under President's initiative and Grant-in-Aid for JSPS Fellows.

REFERENCES

[1] S. Hutchinson, G. D. Hager and P. I. Corke, "A tutorial on visual servo control," *IEEE Trans. on Robot. and Automation,* Vol. 12, No. 5, pp. 651–670, 1996.

[2] K. Honda, T. Hasegawa, T. Kiriki and T. Matsuoka, "Real-time pose estimation of an objet manipulated by multi-fingered hand using 3D stereo vision and tactile sensing," *1998 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 1814–1819, Victoria, B.C., Canada, 1998.

[3] Y. Yokokohji, M. Sakamoto and T. Yoshikawa, "Vision-aided object manipulation by a multifingered hand with soft fingertips," *Proc. IEEE Int. Conf. Robot. Automat.*, pp. 3201–3208, Detroit, Michigan, May 1999.

[4] R. Ozawa and Y. Oobayashi, "Adaptive task-space PD control for manipulators by the implicit visual feedback", *Proc. of the 27th Annual Conf. of the Robotics Society of Japan*, 3M1-01, Yokohama, Japan, 2009 (in japanese).

[5] C. C. Cheah and J. J. E. Slotine, "Task-space Setpoint Control of Robots with Dual Task-space Information," *Proc. of the 2009 IEEE Int. Conf. Robot. Automat.*, pp. 3706–3711, Kobe, Japan, 2009.

[6] K. Tahara, S. Arimoto and M. Yoshida, "Dynamic object manipulation using a virtual frame by a triple soft-fingered robotic hand," *Proc. IEEE Int. Conf. Robot. Automat.*, pp. 4322–4327, Anchorage, AK, May 2010.

[7] A. Kawamura, K. Tahara, R. Kurazume and T. Hasegawa, "Dynamic grasping for an arbitrary polyhedral object by a multi-fingered hand-arm system," *2009 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2264–2270, St. Louis, Missouri, 2009.

[8] A. Kawamura, K. Tahara, R. Kurazume and T. Hasegawa, "Dexterous object manipulation by a human-like hand-arm system with unified controller," *Proc. IEEE Int. Conf. Robot. Biomim.,* pp. 1542–1548, Tianjin, China, 2010.

[9] T. Wimböck, C. Ott, and G. Hirzinger, "Passivity-based Object-Level Impedance Control for a Multifingered Hand," *Proc. of the 2006 IEEE/RSJ on Intelligent Robots and Systems*, pp. 4621–4627, Beijing, China, 2006.