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Modelless and Grasping-forceless Control by Robotic Fingers Capable of Mechanically Coupled Movement

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***Abstract*— This paper formulates the dynamics of 5 degrees-of-freedom (DOFs) robotic hand that consists of an index finger and an opposable thumb like the human hand. This system has two geometrical constraints and five velocity constraints generated during the object manipulation task. The three of the velocity constraints are associated with the joint angles of the robot, and are combined to the proposed system on the basis of observations about the fact that the distal two joints of the index finger are mechanically coupled. Based on the equations of motion including these constraints, we perform precise orientation control of a rectangular object grasped by the 5-DOFs robotic hand in the situation that grasping forces are not defined during the manipulation. The manipulation task given is one-finger control (index finger), for which a *serial two-phased* (STP) controller that had previously been proposed is modified. In experiments, we demonstrate that a simple integral controller designed by eliminating the second stage of the STP controller works well in the soft-fingered manipulation. In both simulations and experiments, it is clearly indicated that Jacobian matrices and the grasping forces are not necessarily required in the control law for accomplishing dexterous manipulation tasks. In other words, it is implied that a complete modelless and grasping-forceless control can be achieved in the task-space control.**

I. INTRODUCTION

In conventional approaches associated with robotic hands and dexterous manipulation, an exact model, i.e., robot kinematics and dynamics, of the whole structure of the robot had been required for achieving precise trajectory control and other tasks. In that case, the model error of the robot has often induced a serious failure in the robot motion. On the other hand, in recent studies in terms of manipulation problems by robotic hands, a number of sensor-based planning schemes for the control had been proposed. The motion planning do not necessarily need the accurate model of the robot in practical usages[1], [2]. These researches, however, are yet using the kinematics of the robot in the sense that Jacobian matrices are used in the control law. This paper clearly indicates in the simulation that modelless control of the robot, which has no Jacobian matrices, can be realized by means of a soft-fingered robotic hand. Furthermore, we demonstrate in experiments that encoderless control of the robot, which is capable of achieving object-orientation control, works well when the distal two joints of the robotic finger are mechanically coupled like the human hand [3].

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II. RELATED WORKS AND BACKGROUND

To date, a number of researches and their achievements associated with robotic manipulation have been being presented through theoretical approaches and experimental verifications, which are summarized in the literature [4], [5]. Bicchi defined that *dexterity means the capability of changing the position and orientation of the manipulated object from a given reference configuration to a different one*. In addition, he said that *it is not necessary that the manipulated object can track a given trajectory in position and orientation at every instant during manipulation. Rather, it is sufficient that the object can be brought from the initial to the desired configuration, irrespective of what path it follows in the process.* His observation leads to *virtual trajectory hypothesis* that had been suggested by Hogan *et al.* [6]. On the other hand, the Bicchi's survey is not mentioning any successful examples relating to the object-orientation control that is of the definition of dexterous manipulation, because accurate regulation methods of object orientation had not been completed so far. Even in recent researches, there are few challenges to achieve the orientation control. This fact tells that conventional ways for controlling multi-articulated robotic hands are not available for realizing the dexterous manipulation.

It is important to mimic high-level functionalities of the human in order to create the human-like performance in robots. When the robots take in the capability successfully to the robot-control system, certain simplifications and reductions of the upper-level complicated implementation are anticipated in the robot control. In fact, as indicated in previous studies[7], [9], the robotic hand that usually requires dexterity on the tip of the finger can receive the benefit of avoiding a traditional control method such as the real-time computing process of the robot kinematics and dynamics within a control period.

Based on the above observations, this paper shows a very simple control method for controlling a two-fingered robotic hand that totally having five degrees-of-freedom (DOFs) and consisting of 3-DOFs for the index finger and 2-DOFs for the thumb. This control method does not need the robot kinematics, i.e., Jacobian matrix, that is, the geometrical relationship between the task space and the joint space is not necessary for stable grasping. While grasping forces (internal force) in conventional control strategies had been necessary,

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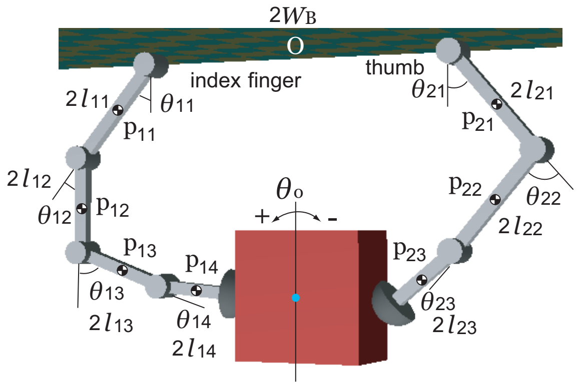
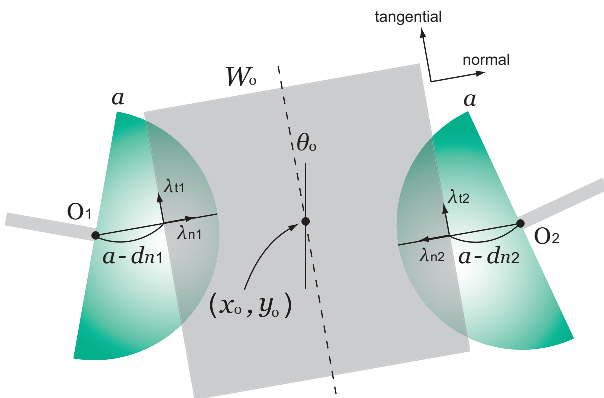


(a) overview of a two-fingered robotic hand



(b) soft-fingered manipulation

Fig. 1. It shows geometrical relationship between two soft fingers and a grasped object. This configuration contains a pair of geometrical constraints normal to the contacting face of the object and a pair of velocity constraints tangential to the face, which are not integrable because rolling motion, in general, depends on the passed history of the motion.

our researches treating soft-fingered manipulation recently have indicated that the passive deformation of soft fingers, which is induced by the two-fingered grasping, contributes to stable manipulation without the grasping forces [10]. Eventually, the relationship of statics between the task space and the joint space of the robot, i.e., $\boldsymbol{\tau} = \boldsymbol{J}^{-1}\boldsymbol{f}$, can be eliminated in the control law by using no Jacobian matrices and no grasping forces. In this paper, we show in a simulation that one-fingered control of a pinched object can be realized by implementing a proposed control method. In this case, the other finger acts as that for only maintaining the stable grasping. Finally, we demonstrate that the object-orientation control can be carried out experimentally, and that the robotic hand can be controlled with no encoder readings and no grasping forces.

III. GEOMETRICAL AND VELOCITY CONSTRAINTS IN GRASPS

First, we represent a geometrical configuration model of the two-fingered robotic hand and a grasped object before describing dynamics of the robot, which is shown in Fig. 1-(a).

Let $\theta_{\rm o}$ be the object orientation, $\theta_{\rm ij}$ be the j-th joint angle of the i-th finger, and $2l_{ij}$ be the length of each link respectively. In an enlarged view of the two fingers and the object shown in Fig. 1-(b), let O_i be the i-th fingertip origin, a be the fingertip radius, $d_{{\rm n}i}$ be the maximum displacement for a direction normal to the contacting face, and $W_{\rm o}$ be the width of the grasped object. In addition, let $2W_{\rm B}$ be the base distance of the both fingers, O be the origin of a base coordinate of the robotic hand, and p_{ij} be the position of the center of gravity. Then, the position of O_1 with respect to the coordinate system can be expressed as

$$\mathrm{O}_{ix} = (-1)^i W_{\rm B} + 2\sum_{j=1}^{r}\left\{l_{ij}\sin\left(\sum_{k=1}^{j}\theta_{ik}\right)\right\}, \quad (1)$$

$$\mathrm{O}_{iy} = 2\sum_{k=1}^{r}\left\{l_{ij}\cos\left(\sum_{k=1}^{j}\theta_{ik}\right)\right\}, \quad (2)$$

where $r = 4$ and $r = 3$ when $i = 1$ (index finger), $i = 2$ (thumb) respectively.

This soft-fingered hand system has a pair of geometrical constraints induced by the grasping. As shown in Fig. 1-(b), it can be expressed by considering the deformation to the direction normal to contacting faces as follows:

$$C_{{\rm n}i} = -(-1)^i(x_{\rm o} - \mathrm{O}_{ix})\cos\theta_{\rm o} + (-1)^i(y_{\rm o} - \mathrm{O}_{iy})\sin\theta_{\rm o} - a + d_{{\rm n}i} - \frac{W_{\rm o}}{2} = 0. \quad (3)$$

On the other hand, a pair of velocity constraints induced by the object rotation on both fingertips can be expressed as

$$\dot{C}_{{\rm t}i} = \frac{\rm d}{{\rm d}t}\Big((x_{\rm o} - \mathrm{O}_{ix})\sin\theta_{\rm o} + (y_{\rm o} - \mathrm{O}_{iy})\cos\theta_{\rm o}\Big) - a\left(\sum_{k=1}^{r}\dot{\theta}_{ik} + (-1)^i\dot{\theta}_{\rm o}\right) - \dot{d}_{{\rm t}i} = 0, \quad (4)$$

where $r = 4$ and $r = 3$ when $i = 1$ (index finger), $i = 2$ (thumb) respectively. Note that this constraint involves not only angular velocities of the object and the joints but also velocity of the tangential deformation of the fingertip, $d_{{\rm t}i}$.

IV. FORMULATION OF A 5-DOF ROBOTIC HAND

Let us recall the equations of motion of robotic hand system in general form, then these can shortly be expressed as a vector form:

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{f}_{\rm p} - \boldsymbol{\Phi}^{\rm T}\boldsymbol{\lambda} = \boldsymbol{f}_{\rm ext} + \boldsymbol{u}, \quad (5)$$

where definitions of the physical parameters are listed in Table I. Note that the generalized coordinate has twelve variables, that is, $\boldsymbol{q} = [\boldsymbol{p}_{\rm o}, \boldsymbol{\theta}, \boldsymbol{d}]$. Each vector form is also detailed in Table I. In addition, the generalized potential force, $\boldsymbol{f}_{\rm p}$, includes not only gravitational force to the total system but also elastic forces/moments induced by the deformation of the fingertip. The constraint matrix, $\boldsymbol{\Phi} \in \mathcal{R}^{4\times 12}$, consists of components obtained by partially differentiating $C_{{\rm n}i}$ and $\dot{C}_{{\rm t}i}$ with respect to $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$ respectively, and is eventually

TABLE I

DEFINITIONS OF PARAMETERS.

parameter	definition
$\boldsymbol{M}$	inertia matrix
$\boldsymbol{q}$	generalized coordinate, $[\boldsymbol{p}_{\rm o}, \boldsymbol{\theta}, \boldsymbol{d}]$
$\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})$	Coriolis force, nonlinear frictions, and viscous resistance of soft fingertip
$\boldsymbol{f}_{\rm p}$	generalized potential force
$\boldsymbol{\Phi}$	constraint matrix, $[C_{\rm n1}, C_{\rm n2}, C_{\rm t1}, C_{\rm t2}]$
$\boldsymbol{\lambda}$	constraint force, $[\lambda_{\rm n1}, \lambda_{\rm n2}, \lambda_{\rm t1}, \lambda_{\rm t2}]$
$\boldsymbol{f}_{\rm ext}$	generalized external force
$\boldsymbol{u}$	control input
$\boldsymbol{p}_{\rm o}$	$[x_{\rm o}, y_{\rm o}, \theta_{\rm o}]$
$\boldsymbol{\theta}$	$[\theta_{11}, \theta_{12}, \theta_{13}, \theta_{21}, \theta_{22}]$
$\boldsymbol{d}$	$[d_{\rm n1}, d_{\rm n2}, d_{\rm t1}, d_{\rm t2}]$

TABLE II

MECHANICAL AND SIMULATION PARAMETERS, AND INITIAL VALUES

Parameters	Values	Parameters	Values
$K_{\rm P1}$	50	a	10 mm
$K_{\rm P2}$	12	E	0.232 MPa
$K_{\rm D}$	1 Nm·s	$m_{11}, m_{12}, m_{13}, m_{21}, m_{22}$	88 g
$K_{\rm I}$	0.0002	m_{14}, m_{23}	60 g
$W_{\rm o}$	51.7 mm	$2l_{11}, 2l_{21}, 2l_{22}$	50 mm
$M_{\rm o}$	86 g	$2l_{12}, 2l_{13}$	40 mm
$2W_{\rm B}$	130 mm	$2l_{14}, 2l_{23}$	30 mm
θ_{11}	$-40°$	θ_{12}	40°
θ_{13}	70°	θ_{21}	$-40°$
θ_{22}	80°	$\theta_{\rm o}$	0°

described as

$$\Phi_{ij} = \begin{bmatrix} \frac{\partial C_{\rm n1}}{\partial q_1} & \frac{\partial C_{\rm n1}}{\partial q_2} & \cdots & \frac{\partial C_{\rm n1}}{\partial q_{12}} \\ \frac{\partial C_{\rm n2}}{\partial q_1} & \frac{\partial C_{\rm n2}}{\partial q_2} & \cdots & \frac{\partial C_{\rm n2}}{\partial q_{12}} \\ \frac{\partial C_{\rm t1}}{\partial q_1} & \frac{\partial C_{\rm t1}}{\partial q_2} & \cdots & \frac{\partial C_{\rm t1}}{\partial q_{12}} \\ \frac{\partial C_{\rm t2}}{\partial q_1} & \frac{\partial C_{\rm t2}}{\partial q_2} & \cdots & \frac{\partial C_{\rm t2}}{\partial q_{12}} \end{bmatrix} \in \mathcal{R}^{4\times 12} \tag{6}$$

Furthermore, the constraint force, $\boldsymbol{\lambda}$, corresponds to internal forces that counteract all together. As a result, the forces do not work in this system, resulting in the fact that the energy due to the constraint force is always zero. That is, the last term of Lagrangian of the system, $\mathcal{L} = K - P + \boldsymbol{C}_{\rm n}^{\rm T}\boldsymbol{\lambda}_{\rm n}$, becomes zero, where K and P are defined as kinetic energy and potential energy of the total system, and $\boldsymbol{C}_{\rm n} = [C_{\rm n1}, C_{\rm n2}]$ and $\boldsymbol{\lambda}_{\rm n} = [\lambda_{\rm n1}, \lambda_{\rm n2}]$ are satisfied. Therefore, each component of Eq. (6) corresponds to the direction and moment arm in terms of the constraint forces.

Next, let us describe the Lagrangian of the 5-DOFs robotic hand system, and then it can be expressed using vector $\boldsymbol{p}$, mass of the link m_{ij}, inertia of the link I_{ij}, acceleration of gravity g, Young's modulus E of the soft fingertip, as

$$\begin{aligned} \mathcal{L} &= \frac{1}{2}\sum_{j}^{3} m_{1j}\dot{\boldsymbol{p}}_{1j}^2 + \frac{1}{2}\sum_{j}^{2} m_{2j}\dot{\boldsymbol{p}}_{2j}^2 + \frac{1}{2}I_{11}\dot{\theta}_{11}^2 \\ &+ \frac{1}{2}I_{12}(\dot{\theta}_{11}+\dot{\theta}_{12})^2 + \frac{1}{2}I_{13}(\dot{\theta}_{11}+\dot{\theta}_{12}+\dot{\theta}_{13})^2 \\ &+ \frac{1}{2}I_{21}\dot{\theta}_{21}^2 + \frac{1}{2}I_{22}(\dot{\theta}_{21}+\dot{\theta}_{22})^2 \\ &- g\sum_{j}^{3} m_{1j}p_{1jy} - g\sum_{j}^{2} m_{2j}p_{2jy} \\ &- \pi E\sum_{i}^{2}\left\{\frac{d_{\rm ni}^3}{3\cos^2\theta_{\rm pi}} + d_{\rm ni}^2 d_{\rm ti}\tan\theta_{\rm pi} + d_{\rm ni}d_{\rm ti}^2\right\} \\ &+ \sum_{i}^{2} C_{\rm ni}\lambda_{\rm ni}. \end{aligned} \tag{7}$$

In the above equation, $\theta_{{\rm p}i}$ is shortened such that $\sum_{k=1}^{r}\theta_{ik} + (-1)^i\theta_{\rm o}$ when $i = 1 : r = 4$ (index finger) and $i = 2 : r = 3$ (thumb), as well as Eq. (4). The previous term from the end of Eq. (7) corresponds to the elastic potential energy induced by the deformation of soft fingertips, whose basic model had been formulated in the literature [10]. Note that the last term is substantially zero because of $C_{{\rm n}i} = 0$ expressed in Eq. (3). Finally, the left-hand side equation of Eq. (5) can be described from Eq. (7).

V. SIMULATION STUDY

In this simulation, let us consider a case that the 5-DOFs robotic hand proposed in this paper performs orientation control of a grasped object, as shown in Fig. 1-(a). Here, we introduce a very simple controller for achieving precise object manipulation, which is named *serial two-phase (STP)* controller in this paper [7], [8]. It was verified that this controller works well in the case of presence of large time delay of visual feedback processes. This method had been applied to the visual feedback system by using two fingers of the robotic hand. In this paper, we attempt to carry out the same object orientation control using only one-finger of the robot. That is, while the STP controller is applied only to the index finger, traditional and straightforward PD controller for joint angles is implemented to the thumb. Such a unique controller can be represented as a two-phase structure:

$$\theta_{11}^{\rm d} = K_{\rm I}\int(\theta_{\rm o}^{\rm d} - \theta_{\rm o})\,{\rm d}t, \tag{8}$$

$$u_{11} = -K_{\rm P1}(\theta_{11} - \theta_{11}^{\rm d}) - K_{\rm D}\dot{\theta}_{11}, \tag{9}$$

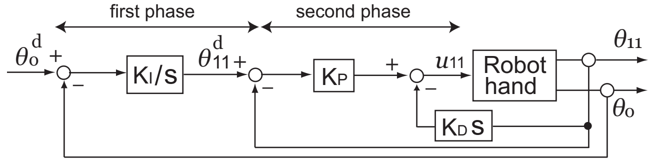
$$u_{21} = -K_{\rm P2}(\theta_{21} - \theta_{21}^{\rm d}) - K_{\rm D}\dot{\theta}_{21}. \tag{10}$$

Therefore, the second stage controller for the thumb (Eq. (10)) is not engaged in the orientation control of the object. In this case, $\theta_{21}^{\rm d}$ can arbitrarily be set to be a neighborhood value from the initial joint θ_{21} of the thumb, as shown in Table II. This controller design can be clearly known from block diagrams illustrated as Fig. 2. It is obvious that the controller for the thumb does not act directly as that for object orientation control.

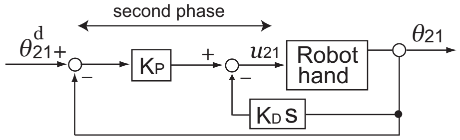
In addition, we assume that three joints of the robot satisfy constraint conditions relating to angular velocity in order to ensure the task such as activating the two base joints, θ_{11} and θ_{21}, only. These constraints are expressed as

$$\dot{\theta}_{11} = \dot{\theta}_{12}, \quad \dot{\theta}_{12} = \dot{\theta}_{13}, \quad \dot{\theta}_{21} = \dot{\theta}_{22}. \tag{11}$$

Note that the final joints in both fingers, θ_{14} and θ_{23}, were introduced only for grasping the object as perpendicularly as possible, as shown in Fig. 1-(a). Therefore, these joints are

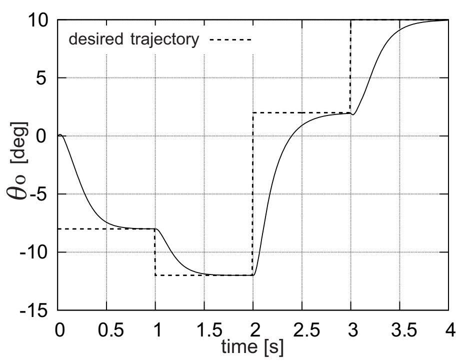


(a) for index finger

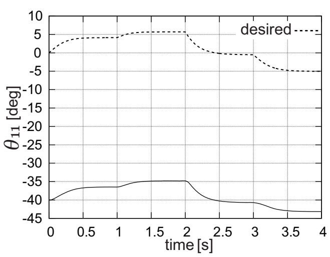


(b) for thumb

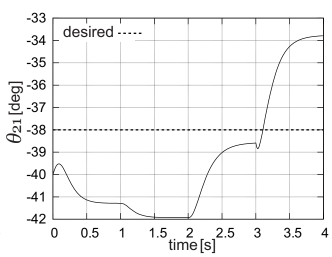
Fig. 2. It shows two kinds of block diagrams. The upper figure corresponds to the STP controller, and the control law in the lower figure is a simple PD controller applied to the thumb. The first stage of the STP controller is eliminated in the lower figure.



(a) trajectory of the object orientation



(b) error of θ_{11}

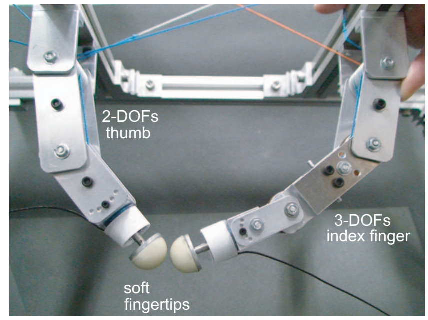


(c) error of θ_{21}

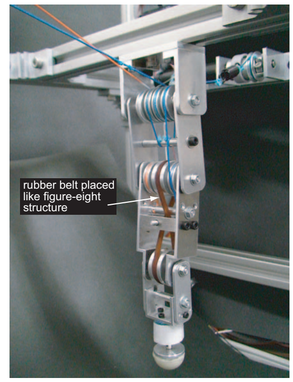
Fig. 3. It shows successful trajectory tracking of object orientation, which is grasped by two fingers. No error remains in each time step of the trajectory. On the other hand, the STP controller proposed in this paper generates extremely large errors during the manipulation. However, these discrepancies are not fatal error for achieving the object orientation control.

assumed to be fixed at constant angle, that is, $\theta_{14} = 15^\circ$ and $\theta_{23} = 10^\circ$ are fulfilled during this simulation study.

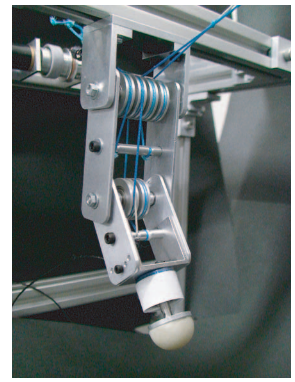
Fig. 3 shows a simulation result, in which the dotted line of the upper figure is desired orientation of the object. It is clearly indicated that the object trajectory converges to the desired one with no error in each time step. Figs. 3-(b) and (c) show that extremely large errors between $(\theta_{11}, \theta_{21})$ and $(\theta_{11}^{\rm d}, \theta_{21}^{\rm d})$ remain throughout the manipulation task. This result implies that the discrepancy of both joints is not important for object orientation control, and is admissible errors. Hence, we conclude that the orientation of grasped object can be precisely controlled by only one finger in the sense that $\theta_{\rm o}^{\rm d}$ is not involved at the controller for the thumb.



(a) overall view of 5-DOFs robotic hand



(b) index finger robot



(c) thumb robot

Fig. 4. The index-finger robot has a figure-eight structure by setting a cylindrical rubber belt between the DIP joint and the PIP joint. This system has 8 DC motors, totally 12 idle-revolution pulleys and 2 fixed pulleys, and 2 soft fingertips mounted at both ends of the finger.

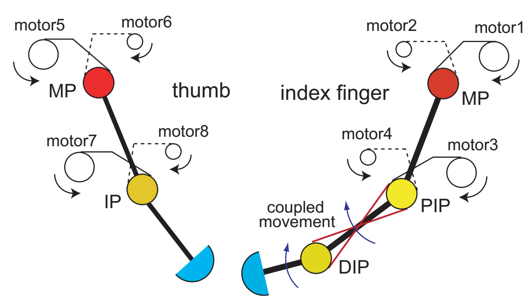


Fig. 5. A schematic view of motor configuration and wire connections. Odd number motors drive the finger toward grasping the object, and even number motors move the finger toward the counter direction.

One reason why we consider such a finger movement is that the index finger and the thumb of the human hand manipulate an object smoothly by making extension and flexion movements alternately at the fingers. Furthermore, each of the fingers can roll the object dexterously, where the other finger acts for only maintaining stable grasping. This kind of natural movement had not been achieved so far by conventional robot mechanisms and their control methods.

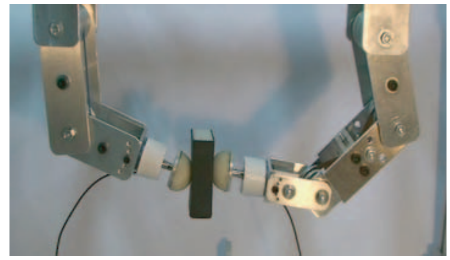
VI. EXPERIMENTS

For experiments, we designed a 5-DOFs wire-driven robotic hand shown in Fig. 4-(a). This robot has totally 8 DC motors, and a pair of the motors drive each angular joint, as illustrated in Fig. 5. The index finger consists of 6 pulleys for idle revolution around the metacarpophalangeal(MP) and proximal interphalangeal(PIP) joints and 2 pulleys fixed at the PIP and distal interphalangeal(DIP) joints, as shown in Figs. 4-(b) and 5. The pair of 2 pulleys are placed in order to implement a figure-eight structure capable of achieving coupled movements of the DIP and PIP joints of the human. The thumb robot has also 6 idle-revolution pulleys for wires, but the figure-eight structure is not introduced in this design. In both ends of the robot, hemispherical soft fingertips are mounted, as shown in Fig. 4-(a). As shown in Fig. 5, odd number motors drive the finger so that its joint moves to the direction where the grasping force increases. On the other hand, even number motors move the finger joint toward the counter direction. We placed large torque motors for the inward motion (i.e., motor1,3,5,7) rather than the motors used for the outward motion of the finger (i.e., motor2,4,6,8). In this experiment, we gave a more simpler integral controller than that of the simulation (Eqs. (8), (9), and (10)) for realizing orientation control of the grasped object, and is then expressed as

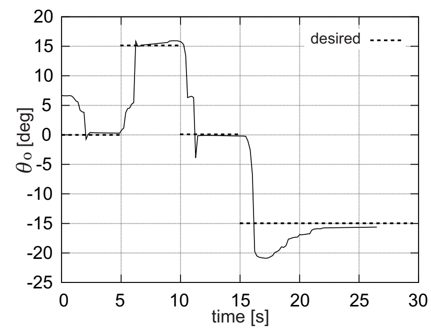
$$u_{i2} = -(-1)^i K_{\rm I} \int (\theta_{\rm o}^{\rm d} - \theta_{\rm o})\,{\rm d}t + \tau_{i2}, \tag{12}$$

where the last term is named *biased torque*, and it works so as to maintain initial secure grasping before the actual control task. Note that the left-hand side of Eq. (12) corresponds to the torque applied to two joints, θ_{12} (PIP) and θ_{22} (IP), as shown in Fig. 5. Therefore, both fingers are sustained by the motors (number 1,2,5,6) to which the only biased torque is applied. Fig. 6 shows an experimental result, in which the desired object trajectory is given at the interval of 5 seconds. It clearly shows that the actual trajectory robustly converges to the desired value, and as a result, indicates that the simple integral controller applied to the IP and PIP joints performs well to decrease orientation errors in each time step.

We notice that the straightforward control law expressed in Eq. (12) does not involve the Jacobian matrix, despite the fact that the first term of the right-hand side of Eq. (12) is described as a workspace control. This non-Jacobian control method naturally enables to eliminate the joint angles that are sensed in real time, that is, the encoder sensing is not necessary for the robotic manipulation. Eventually, this result suggests that a certain kind of modelless and grasping-forceless control can be realized if certain mechanical constraints associated with the musculoskeletal structure are involved in the robot mechanism.



(a) manipulation test



(b) result

Fig. 6. It shows a snapshot of dexterous manipulation by 5-DOFs robotic hand, and that the object orientation converges to the desired trajectory, and its error remains small.

VII. CONCLUDING REMARKS

This paper had proposed a straightforward control model capable of realizing precise and secure manipulation by means of a 5-DOFs two-fingered robotic hand. This control law does not involve Jacobian matrices and grasping forces that had been usually required in the robotic manipulation. In particular, it had been clearly indicated that even a unique controller in which encoders are not used works well for achieving object orientation control in an experiment. These results imply that various inner models such as robot dynamics and kinematics, in fact, are not necessary if the robot system has similar structure and performance to the human fingers. That is, an antagonistic wire-driven mechanism and a soft-finger structure are enabling to mimic the biomechanical characteristics. We conclude that such a human-like robot can comply with nonlinear properties (e.g., the gravitational force, the Coulomb friction, and so on) without the complicated robot model, and namely that a complete sensor-based control scheme could be constructed in environmental robotics.

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