Stiffness Control of a Coupled Tendon-Driven Robot Hand

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This paper presents the methods of design and control for a coupled tendon-driven robot hand with stiffness control capability. By using the tendon as a force transmission mechanism, compact design of the robot hand is achieved with the developed controller. Problems specific to the tendon characteristics are considered, such as the slacking problem of tendons when the joint is disturbed, and the tendon elongation problem when the collocated position sensing method is used for compact design. To cope with these problems, two fundamental algorithms are developed and implemented on a laboratory apparatus, the POSTECH Hand II. First, a position estimation algorithm is developed to evaluate the accurate position of the hand, leading to an antagonistic tendon controller. Secondly, an active stiffness control algorithm is developed to control the fingertip force. It is shown that the finger produces excellent linear stiffness characteristics which justifies the effectiveness of the proposed algorithm. The object stiffness control is also implemented to exert desired force to the environment when the hand grasps an object, and is evaluated via experiments.

Introduction

Research on multi-fingered robot hands can, in general, be classified into four research areas: 1) the design of the robot hand; 2) the control accuracy of the robot hand; 3) the optimal force distribution (and stability) of the robot hand when grasping an object; and 4) the application of the robot hand in real situations when a high level of dexterity is desired. The scope of this paper focuses on the design and the control issues of the robot hand. The design of the robot hand is to explore the kinematic design as well as creating a new actuating systems that either enhances the system performance or reduces the actuator package. Many researchers have designed the hand for these purposes [1-16]. Although the designed hands are intended for high industrial performances, methods to obtain a high level of manual dexterity and control accuracy need to be resolved in the laboratory. To solve these problems in the laboratory, robot hands have been built as experimental testbeds, focusing primarily on the evaluation of the feasibility of the control strategy through a set of designed experiments [17-19].

The motivation behind our work is to develop a robot hand as well as increase its control accuracy by using proposed theories. In this paper, design methods and implementation of control algorithms on a planar, 2-fingered robot hand having redundant joint is considered. The POSTECH Hand II possessing a planar, 2 degree-of-freedom (DOF) and three DOF fingers operated by a 2N type actuating system, using DC servo motors with tendon tension sensors, is the focus of this work. The tendon was used as a force transmission mechanism; this allows for a compact design of the robot hand and still maintains the same level of control accuracy when the tendon is not present. On the other hand, with the tendon present, additional problems can arise. Some of the problems that may occur are the nonlinear characteristics: the slacking of the tendons when the joint is perturbed slightly, the elongation of the tendons if a collocated position sensing method is used for a compact design, and the effects of nonlinear friction. To cope with these problems, an active stiffness control method [17], [20-23] is applied to the hand and a position estimating algorithm is developed to evaluate the accurate position of the hand. Then the importance of linearity for the
fingertip stiffness is emphasized when desired positions are applied to the proposed control system continuously, because the linearity will confirm the grasping stability and the realization of a theoretical grasping model in future studies. Finally, the control algorithm, both the joint stiffness control method and the position estimation algorithm, is verified through experiments of object stiffness control with the hand. To confirm the control method more rigorously, we used also another new hand, POSTECH Hand III, having non-collocated position sensors. Using the above methods, the linear characteristics between the displacement and the force of the fingertip are demonstrated with the POSTECH Hand II. The linearity is important for stable grasping and successful implementation of the theoretical results. The final task is to manipulate an object with desired linear stiffness characteristics at the object level. If the object stiffness is properly controlled, the desired trajectory is recovered when the mechanism is disturbed from its nominal trajectory.

Hardware System

Design of Tendon-Driven Hand

The robot hand consists of a thumb (2-DOF) and an index (3-DOF planar redundant) finger, as the human hand, with 2N type actuating configuration (two actuators drive a single joint) to increase flexibility and future expansions. The ratio of link length is $\sqrt{2}:1$ for the thumb, and 5:3:2 (nearly Fibonacci series) for the index finger; these ratios minimize the condition number of $JJ^T$, where $J$ is the standard Jacobian matrix. Fig. 1 shows the photo of the developed coupled tendon-driven robot hand. The 2N configuration [6], [7], [29] provides low antagonistic forces resulting in low-friction and backlash in the tendon-sheath driving system, which ensures more flexibility than other types such as the $N^1$ [1, 4, 5, 8, 9, 11, 12, 15, 16, 18, 19], or $N+1$ [14] type. This can generally be used irrespective of an actuator shape. In order to increase payload capability and to use equal-strength actuators and tendons, a specific tendon transmission mechanism is adapted for our hand [24]. Fig. 2 illustrates the schematics of the tendon transmission mechanism used to drive the second joint.

In the multifingered robot hand, a tendon tension sensor is an indispensable tool in avoiding high antagonistic forces caused by the opposing actuators, and also to realize fine force control for a tendon-driven robot hand where the actuators are normally placed on the forearm of the manipulator [6], [14], [18], [19]. Individual tendon-tension sensors were developed which can be mounted close to the joints for accurate torque control. Fig. 3 shows this sensor. Each sensor is calibrated to give an analog voltage which corresponds to the tension of the tendon.

Overall Hardware Description

The overall system structure of the two-fingered hand is illustrated in Fig. 4. To allow flexibility for the control algorithm, the controller is implemented as a digital system composed of target computers in a VMEbus card cage, and a host workstation. The system has 16 channels of D/A conversion and 16 channels of differential A/D conversion to accommodate future expansion. All software is developed on a workstation in the UNIX environment using a real-time software development tool.

The position sensing system is connected to the digital I/O ports through a multiplexer and is designed to count the pulses.
of encoders. Position feedback is derived from incremental optical encoders mounted directly on the motor shaft. The servo rate for each tendon force controller is 500Hz and the stiffness management loop runs at 50Hz.

The analog control system implements 10 torque servo systems, and 10 tension sensing systems. The torque servo system is designed so that the servo inputs have a linear relation with the actuator currents. The actuators, with a 50:1 harmonic gear and a PWM torque amplifier, drive the joints via flexion and extension tendons which are routed over pulleys. The tension sensing system offers pre-scaled analog voltages to the digital system.

Stiffness Control

Since the robot hand handles objects using position data that are not known exactly, the hybrid position/force control method which requires precise trajectory is difficult to apply. The stiffness control method, on the other hand, can be used for handling objects without knowing the exact trajectory of position or force. Fig. 5 illustrates the concept of the stiffness control. In the stiffness control method, the endpoint force $F$ is given by

$$F = K_c \delta x$$

where $K_c$ is the desired spring constant in Cartesian coordinates, and $\delta x$ is the virtual displacement of the endpoint. The stiffness control method only requires specifying the spring constant $K_c$ and generating $F$ according to $\delta x$. This simplicity can offset the complexities of a multi-fingered robot hand. Salisbury [14] applied a stiffness control method for a robot manipulator to the three-fingered Stanford/JPL hand having a collocated position sensor (see [32] for details). Kaneko expanded the work systematically [17], [18] followed by Maekawa [19] and Starr [35]. Although these works are very interesting for stiffness control of robot hands, there are some limitations: 1) the works are restricted to non-redundant finger (2 degree-of-freedom); 2) they used the tendon-sheath driving systems, deteriorating control accuracy and causing a hysteresis effect (see [26]); and 3) they used the collocated position sensing method without any compensation [14], [35]. Developing a general stiffness control method and an accurate position sensing system are required to overcome the limitations.

Active Stiffness Control

Many researchers proposed active stiffness control methods [17], [20-23]. In the case of the non-redundant manipulator, the joint torque $\tau$ is related to virtual joint displacement $\delta q$ by the joint level stiffness matrix $K_q$ [22]

$$\tau = K_q \delta q \quad (2)$$

The joint level stiffness matrix is given by

$$K_q = J^T K_c J + hN \quad (3)$$

where $J$ is the Jacobian matrix which maps velocities in the joint space to those in Cartesian space. For a redundant manipulator, the following formulation [21] is used:

$$K_q = J^T K_c J + hN \quad (4)$$

where $N$ is an orthogonal matrix with respect to $J^T K_c J$ and $h$ is an arbitrary variable. The reason for using (4) rather than (3) is because $K_q$ of (3) is always degenerate in the redundant manipulator. For example, in a planar 3 DOF manipulator, the rank of $K_q \in \mathbb{R}^{3x3}$ should be three to stabilize the manipulator. However, the rank of $K_c \in \mathbb{R}^{2x2}$ (which can be specified) is only two, causing instabilities. In order to control our hand which has a redundant degree of freedom, the method was modified appropriately.

For an $n$-DOF redundant manipulator, when the manipulator Jacobian $J$ has full row rank $m$, the general equation for torque $\tau$ can be written as

$$\tau = \tau_{\text{min}} + \tau_{\text{null}} = J^T F + (I - J^T J) \tau_0 \quad (5)$$

where $\tau_{\text{min}}$ denotes the equivalent joint torque corresponding to the endpoint force $F$, $\tau_{\text{null}}$ is the null torque determining the null motion of the manipulator without any motion of the fingertip, to is an arbitrary vector, $J^T = J(J^T J)^{-1}$ is the pseudoinverse of $J$, and

$$F = K_c \delta x \quad (6)$$

$$\delta x = J \delta q \quad (7)$$

In (5), the frictionless joint mechanism was assumed and gravity and any other torques were assumed negligible.

In (5) through (7), the following conditions are met:
1. $\tau = 0$ when $\delta q = 0$ (the joint torque is zero at equilibrium condition) and
2. $\tau_{\text{min}}$ and $\tau_{\text{null}}$ are independent (that is, the null motion does not depend on the endpoint force).

Mathematically, the above conditions can be restated as
1. $\tau \to 0$ as $\delta q \to 0$ and

The terms $K_{\text{min}}$ and $K_{\text{null}}$ are defined as
\[ \tau = K_q \delta q \]  
\[ K_q = K_{\text{min}} + K_{\text{null}} \]  
where
\[ K_{\text{null}} = [I - JK_0] \]  
and the weighted pseudoinverse of $J$ (for a weighting matrix $W$) is given by $J^+ = W^T(JW)^+$. The second constraint given above for $T_{\text{min}}$ and $T_{\text{null}}$ is satisfied for the symmetric positive definite weighting matrix $W$ because $W$ is selected as $W^T = W$ because it preserves the symmetric configuration of $K_{\text{null}}$. The final equations for the joint torque needed to control the manipulator are
\[ \tau = J^T K_{\text{null}} [I - J_{\text{null}} J] K_0 \]  
with
\[ K_{\text{null}} = [I - J_{\text{null}} J] K_0 \]  
where $K_q$ is always symmetric positive definite, and $J_{\text{null}}$ denotes the $K_0$ weighted pseudoinverse. The above equations are similar to the Combined Compliance Control scheme of (16), differing by the term $K_0 J^T (J K_0 J^T)^{-1} J K_0$. Considering the bias force $F_0$ used to specify the tip force directly and a damping gain $K_0$, which guarantees critically damped motion of the end point, (12) can be modified to
\[ \tau = J^T K_{\text{null}} [I - J_{\text{null}} J] K_0 (q_d - q_m) \]  
+ $J^T K_0 J (q_d - q_m) + J^T F_0$  
where $q_d$ and $q_m$ are the desired and the measured joint space displacement, respectively. The above equation is referred to as the Unified Active Stiffness Control method for a general planar $n$-DOF robot manipulator.

Next, the desired tendon tension $f_d$ which is required to control the hand by a low-level stiffness controller can be computed from the desired joint torque $\tau$. The relation between the joint torque $\tau$ and the tendon tension $f_d$ is written as
\[ \tau = D f_d \]  
where $\tau = \tau_1 \cdots \tau_n, f = f_1 \cdots f_n$, and $D \in \mathbb{R}^{n \times 2n}$ is a constant matrix determined by the geometry of the hand. For example, in the case of the 3-DOF POSTECH Hand II index finger,
\[ D = \begin{bmatrix} 0 & \cdots & 0 & r & \cdots & r & r & \cdots & r \\ 0 & \cdots & 0 & -r & \cdots & -r & -r & \cdots & -r \end{bmatrix} \]  
where $r$ is the radii of joint pulleys. From the assumption of quasi-static motion and tension minimization, the desired tendon tension can be computed according to
\[ f_d = D_{\text{null}} \tau + [I - D_{\text{null}} D] f_0 \]  
where $f_0$ denotes bias tension, $W \in \mathbb{R}^{2n \times 2n}$ is a symmetric positive definite matrix, and $D_{\text{null}} \in \mathbb{R}^{2n \times 2n}$ is the weighted pseudoinverse of $D$. If the tension is to be evenly distributed for all tendons, $W$ can be selected as the identity matrix. Applying the constraint condition of
\[ f_d \geq f_{\text{null}}, > 0 \]  
to prevent the tendons from slacking, the modified tendon tension can be computed simply.

Estimation of Joint Angle
As mentioned previously, the POSTECH Hand II uses a 2N coupled type mechanism and collocated position sensing method. The relation between joint angle $q$ and tendon displacement $y$ can be written (with zero initial conditions) as:
\[ y = D^T q \]  
where $D$ is the same as that of (16). The minimum norm least square solution of (21) becomes
\[ q = (D^T y)^+ \]  
where $(D^T y)^+$ is the pseudoinverse of $D^T$. (22) is used to compute the joint displacements from the measured tendon displacements.

To minimize the position error caused by unwanted system compliance, an effective tendon compliance is introduced. Assuming that the tendon displacement can be expressed as
where \( f_{\text{measured}} \) and \( y_{\text{measured}} \) are the measured tension and measured tendon displacement, respectively, the least square solution (22) is modified to

\[
q \approx (D^T D)^{-1} (D^T y_{\text{measured}} - C_{\text{ten}} f_{\text{measured}})
\]

where \( C_{\text{ten}} \) denotes effective tendon compliance. The value of \( C_{\text{ten}} \) obtained from experimental data is given approximately by 0.03mm/N, as shown in Fig. 6 (the result was obtained by: all the joints were fixed, and both the tension \( f_1 \) and the tendon displacement \( y_1 \) of the first joint were measured). The hysteresis effects are assumed negligible in our case compared to other robot hands [18], [19], [35] using the tendon-sheath transmission mechanism. Other researchers that have used the tendon-sheath transmission mechanism observed a rather strong nonlinear hysteresis effect [26].

Since \( C_{\text{ten}} \) includes components such as actuator compliance, environmental compliance, and finger compliance, the overall compliance can vary with environmental conditions, although the tendon compliance is a dominant factor when compared with the others. To cope with this variation, \( C_{\text{ten}} \) is assumed to be 0.03mm/N. The effective tendon compliance \( C_{\text{ten}} \) is then updated accurately through experiments with stiffness control active, from the following equations (derived from (24)):

\[
C_{\text{ten}} = (y_{\text{measured}} - D^T \hat{q}_{\text{desired}}) f_{\text{measured}}
\]

where \( \hat{q}_{\text{desired}} \) is the desired joint angle used in the experiment, \( y_{\text{measured}} \) is the measured actuator displacement, and \( f_{\text{measured}} \) is the measured tendon tension. This procedure is verified in the following section. This position estimation procedure is referred to as the compliance compensated position estimation method.

Low-level Tension Control

The most basic element in controlling the robot hand is the tendon tension control. For the POSTECH Hand-II, the tension of each tendon is controlled with a feedforward term and a linear regulator. Also, the controller includes an integral term that removes steady-state errors due to friction. The \( j \)th actuator torque is evaluated using

\[
\tau_j = K_F f_{err} + K_f f_d + K_i \int f_{err} dt + K_V \dot{\theta}_{err} \times r
\]

with

\[
f_{err} = f_d - f_m \]

\[
\theta_{err} = \theta_{\text{desired}} - \theta_m
\]

where \( r \) is the radii of the driving pulleys, \( f_d \) and \( f_m \) are the desired and the measured tension of \( j \)th tendon, and \( \theta_{\text{desired}} \) and \( \theta_m \) are the

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**Table 1:** Allowable ranges of the variables used in the tension controller.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_F )</td>
<td>15 ~ 35</td>
</tr>
<tr>
<td>( K_V )</td>
<td>150 ~ 350</td>
</tr>
<tr>
<td>( K_I )</td>
<td>100</td>
</tr>
<tr>
<td>( K_F )</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Overview of Stiffness Controller

The hand control system (joint stiffness controller) is shown in Fig. 8. The controller is composed of a trajectory planner which generates a joint space trajectory for a given Cartesian space trajectory, a tendon management logic described in (15) and (18), 2n low-level tendon tension controllers as in (27), and a joint angle estimation logic as in (24). To resolve the kinematic redundancy of the 3 DOF index finger, a constraint known as the distal curling effect or obstacle avoidance was used according to the object configuration and the tasks. The stiffness controller is partitioned into two parts for parallel processing: One handles stiffness management for trajectory planning, grasping, and stiffness conversion from Cartesian to joint space, while the other controls the low-level tension. The stiffness management portion runs at 50Hz, and the low-level tension control portion runs at 500Hz.

Experiments

Cartesian Stiffness Control

The purpose of stiffness control is to obtain linear characteristics of the stiffness, for any disturbance, either in Cartesian space or in joint space. To evaluate the developed two-fingered hand from the viewpoint of stiffness controllability, the relations between virtual Cartesian displacement and fingertip force were measured. Fig. 9 illustrates the experimental procedure. The fingertip was placed against a hard surface at a Cartesian position, and then the desired fingertip position was programmed to follow a trajectory along the y direction. During the traverse process,\( K_C \) was fixed. Both the tendon tensions and the joint displacements were measured by the tension sensor (installed inside the finger) and the encoder (installed on the actuator), respectively. The displacement of the fingertip was calculated using (24), and the fingertip forces were obtained from the tendon tensions measured by tension sensors.

Fig. 10 shows the experimental results of Cartesian stiffness control for the different stiffness gain \( K_C \). The stiffness \( K_C \) used were

\[
K_C = \begin{bmatrix} K_1 & 0 \\ 0 & K_1 \end{bmatrix}
\]

(30)

\[ K_1 = 75, 150, 300 \text{ (N/m)} \]

(31)

\( K_1 \) increased, the fingertip stiffness fell below the expected value. These results reveal that the tendon-driven robot finger with the collocated position sensor does not generate the desired tip stiffness.

We need an updating algorithm for \( C_{en} \) as described in the previous section. The updated effective tendon compliance, \( C_{en} \), was 0.06mm/N from (25). Fig. 11 shows the results when \( C_{en} = 0.06 \text{mm/N} \) was used. The system compliance was completely compensated with the compliance adjustment. A summary of the procedure for estimating \( C_{en} \) is given:

Procedure:
1. Assume an effective tendon compliance \( C_{en} \) of 0.03mm/N.
2. Select \( K_C \) to be 150N/m (or 75, 300, ...) so that the finger is stable.
3. Perform experiments as illustrated in Fig. 9.

5. If $|C_{ten}' - C_{ten}| > \text{error}$,
then set $C_{ten} \leftarrow C_{ten}'$ and then goto step 2.
The results of this procedure are listed in Table 2.

### Table 2: Fingertip stiffness characteristics when the effective tendon compliance is 0.03mm/N (Non-updated) or 0.06mm/N (Updated).

<table>
<thead>
<tr>
<th>Desired (N/m)</th>
<th>Non-updated</th>
<th>Updated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>75</td>
<td>70 (93%)</td>
</tr>
<tr>
<td>$K_2$</td>
<td>150</td>
<td>125 (83%)</td>
</tr>
<tr>
<td>$K_3$</td>
<td>300</td>
<td>220 (73%)</td>
</tr>
</tbody>
</table>

**Object Stiffness Control**

The final goal of the stiffness control is to generate a desired stiffness for an object that has been grasped. With linear stiffness characteristics of the hand, we can specify object stiffness to the hand as

$$K_C = g(J_bK_b)$$

where $K_b$ is the object stiffness, $J_b$ is the Jacobian which maps the velocities of the tip in Cartesian space to those in the object space, $K_C$ is the fingertip stiffness, and $g(\cdot)$ is an operator that transforms the object stiffness to the fingertip stiffness.

To obtain an expression relating the object stiffness, the fingertip stiffness, and the grasp force, the following assumptions are made:

1. The fingertip is modeled as a hard point contact with friction.
2. The structural compliance caused by the fingertip and transmission is assumed negligible.
3. Contact points are predetermined and cannot be changed during the manipulation.
4. Quasi-static manipulation is assumed.

In Fig. 12, an illustration of the grasp model is replaced by a set of virtual springs. Usually, the fingertip coordinate frames are chosen so that: the $z_2$ axis is along the surface normal to the object, the $x_2$ axis is in the tangential plane along the object's surface, and the $y_2$ axis is perpendicular to both the axes based on the right-handed coordinate rule. For an object grasped by $m$ fingers, the static force equilibrium (if gravity forces are deemed negligible) is given by

$$F_b = J_bF_C$$

with

$$J_b = \left[ J_{b1} \ldots J_{bm} \right]^T$$

$$F_C = \left[ F_{c1} \ldots F_{cm} \right]^T$$

where $F_b \in \mathbb{R}^{6 \times 1}$ is the generalized resultant force acting on the object, $J_b \in \mathbb{R}^{6 \times n}$ ($n$ is the number of constraints at the point of contact; in 3D, $n = 3$) is a coordinate transformation matrix from the $i$th fingertip space to the object space, and $F_C \in \mathbb{R}^{6 \times 1}$ is the $i$th fingertip force. In general, displacement of the object, $\delta x_b$, is related to that at the fingertips by

$$\delta x_C = J_b \delta x_b + \frac{\partial J_b}{\partial x_b} \delta x_b + \cdots$$

The reaction forces at each of the fingers are then transmitted to the object and given by

$$F_b = J_b^T F_C$$

$$= J_b^T \left[ K_C(\delta x_C) + F_0 \right]$$

$$= J_b^T \left[ -K_C(J_b \delta x_b + \frac{\partial J_b}{\partial x_b} \delta x_b + \cdots) + F_0 \right]$$

$$= -J_b^T K_C J_b \delta x_b + J_b^T F_0 - J_b^T K_C \frac{\partial J_b}{\partial x_b} \delta x_b + \cdots$$

where $F_0$ is the bias force. It should clear here that $J_b$ is evaluated at the current (measured) position. Since the object stiffness $K_b$ is defined as $-\partial F_b / \partial x_b$ and quasi-static manipulation is assumed, one can see that

$$K_b = J_b^T K_C J_b + \Delta K_b$$

where

$$\Delta K_b = J_b^T K_C \frac{\partial J_b}{\partial x_b} \delta x_b + \text{higher order terms}$$

The above term was proposed in [20] and is known as the additional stiffness induced by configuration change and force as expressed in Equation (42). This additional stiffness introduces instability when the position of the object deviates from the desired position. To obtain the fingertip stiffness specifying the given object stiffness, (41) is to be resolved for $K_C$. Since the
number of controllable stiffness elements are \( mn(n+1)/2 \), the given problem is simplified to a problem of computing the \( Kc_i \) elements from the 21 elements of \( Kb \in R^{6 \times 6} \). Although cases are different depending on the number of fingers, it usually corresponds to an ill-posed problem and does not have an exact solution. The orthogonal stiffness model of \( Kc_i = \text{diag}(k_{xi}, k_{yi}, k_{zi}) \), however, can simplify the problem, where \( k_{xi}, k_{yi} \) and \( k_{zi} \) denote the orthogonal stiffness elements of \( Kc_i \). Thus, (41) can be reconstructed as a linear equation in the manner

\[
Bk = h
\]

where \( B \in R^{21 \times mn} \) is the coefficient matrix of the linear equation, \( k \in R^{mn} \) is a fingertip stiffness vector defined by

\[
k = [k_{x1} \ k_{y1} \ ... \ k_{xm} \ k_{ym} \ k_{zm}]^T,
\]

and \( h \in R^{21} \) denotes the vector composed of \( Kc \)'s elements. Combining (43) and the constraints, it comes to a constrained least square problem.

To demonstrate object stiffness control, a grasped object was allowed to move along a prescribed trajectory, and then the object was disturbed manually at a certain position. If the object stiffness is properly controlled, the trajectory is recovered automatically. The object stiffness is given in

\[
Kb = \begin{bmatrix}
k_x & 0 & 0 \\
0 & k_y & 0 \\
0 & 0 & k_0
\end{bmatrix}
\]

and the null stiffness \( K_0 \) is given by (heuristically)

\[
Bk = h
\]
multiplied by the deviation from the nominal trajectory (about 5%mm in Fig. 15).

Conclusion

The design of a two-fingered robot hand with stiffness control capability and the development of a stiffness controller were presented. Since collocated position sensing can cause position uncertainty by the finger compliance, a stiffness controller having an estimation procedure to compensate for the compliance was proposed. For the index finger with a redundant degree of freedom, a simple unified active stiffness control method was proposed with the specification of null stiffness and the low-level tension controller. The experimental results for the POSTECH Hand II and III showed that the stiffness controlled robot finger exhibits good linear stiffness characteristics in Cartesian stiffness control and the object can exert the desired force to the environment in object stiffness control.

References


