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Task-Based Analysis on Number of Robotic Fingers for Compliant Manipulations

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Abstract

This paper presents a task-based analysis on the number of independent robotic fingers required for compliant manipulations. Based on the stiffness relation between operational space and fingertip space of a multi-fingered object manipulating system, we describe a technique for modulation of the fingertip stiffness without inter-finger coupling so as to achieve the desired stiffness specified in the operational space. Thus, we provides a guideline how many fingers are basically required for successful multi-fingered compliant tasks. Consequently, this paper enables us to assign effectively the number of fingers for various compliant manipulations by robot hands.

Key words : Number of robotic fingers, Compliant manipulation, Multi-fingered robotic hand.

1. Introduction

Many human-friendly and/or industrial service robots [1] require an effective tool such as multi-fingered robot hands [2]- [6]. In order to develop and utilize a robot hand, the number of fingers should be properly determined. Also, we need to employ a control strategy for the robot hand. Especially, compliance control is very useful for compliant manipulations by robot hands.

Related to compliance control, Salisbury [7] presented a compliance control method which utilized a stiffness mapping between the Cartesian space and the joint space. Cutkosky, *et al.* [8] analyzed the effective grasp stiffness by considering the structural compliances in fingers and fingertips, servo gains at the joints of fingers, and small changes in the grasp geometry that may affect grasp forces acting upon the object. Shimoga [9] summarized the conventional grasp synthesis algorithms for robot hands. Also, Kao, *et al.* [10] tried to apply stiffness models usually employed in robotics research to the analysis of human grasping behaviors. To practically apply compliance control algorithms to robot hands, thorough analysis for the grasping geometry, the proper number of fingers, and the structure of fingers should follow [11] [12]. Some researchers have investigated finger structures appropriate for compliance control schemes. The configuration of a serial manipulator or a finger with a kinematically redundant mechanism was considered to implement the desired operational compliance characteristics [13]. Yokoi, *et al.* [14] [15] proposed an independent joint-based compliance control method for redundant arms or manipulators. It is remarked that in order to successfully achieve the given compliance characteristics in the operational space, an employed manipulator or finger should have at least the same number of active joints as the number of independent elements of the desired operational compliance matrix. Yi, *et al.* [16] pointed out that the independent joint-based compliance control via redundantly actuated parallel mechanism was better, in aspect of design, for successful compliance control, in comparison to the case of the kinematically redundant structured fingers or manipulators. In an independent finger and independent joint-based compliance control scheme [17], the authors pointed out that if the inter-finger coupling can be eliminated, each finger can be independently controlled which makes the hand control relatively easy.

In order to investigate the number of fingers for object manipulations based on compliance control, a preliminary study was performed [18]. Based on the previous research, this paper provides a task-based analysis on number of independent robotic fingers required for successful multi-fingered compliant tasks. For the purpose, stiffness mapping for multi-fingered manipulation is presented in Section 2. A useful approach for independent compliance modulation is described in Section 3. In Section 4, the achievable contents of operational compliance characteristics in multi-fingered compliant manipulations are analyzed in the viewpoint of number of fingers. Concluding remarks are finally summarized in Section 5.

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2. Stiffness Mapping for Multi-Fingered Manipulation

It is widely known that the stiffness or compliance can be employed to characterize the grasping and manipulation of robot hands especially when it plays a dominating role as in approximated linear analysis where low velocities and small relative motions lead to small inertial forces [8]. In this paper, we approach the stiffness or compliance control in order to investigate the number of independent fingers that manipulate an object compliantly.

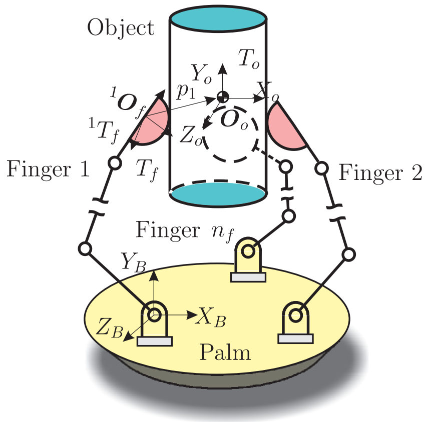


Fig. 1 A multi-fingered object manipulation

Consider a rigid object being manipulated by a n_f-fingered robot hand as shown in Fig. 1, where each finger has ${}^in_j$-joints.

The relation between the generalized force vector in the operational space and the fingertip force vector is given by

$$T_o = [\boldsymbol{G}_o^f]^T T_f, \tag{1}$$

where $T_o \in \mathcal{R}^{n\times 1}$ denotes the generalized force vector in the operational space$(_o)$ including inertial load, gravity load of the system, and external load, and $T_f \in \mathcal{R}^{m\times 1}$ denoting the fingertip force vector in the fingertip space$(_f)$ is expressed as

$$T_f = \left[\begin{array}{cccc} ({}^1T_f)^T & ({}^2T_f)^T & \cdots & ({}^{n_f}T_f)^T \end{array}\right]^T, \tag{2}$$

and the Jacobian matrix relating the operational space to the fingertip space $\boldsymbol{G}_o^f \in \mathcal{R}^{m\times n}$ is given by

$$\boldsymbol{G}_o^f = \left[\begin{array}{cccc} [{}^1\boldsymbol{G}_o^f]^T & [{}^2\boldsymbol{G}_o^f]^T & \cdots & [{}^{n_f}\boldsymbol{G}_o^f]^T \end{array}\right]^T \tag{3}$$

with

$${}^i\boldsymbol{G}_o^f = \left[\begin{array}{cc} {}^f_o\boldsymbol{R}_i & p_i \times {}^f_o\boldsymbol{R}_i \\ 0 & {}^f_o\boldsymbol{R}_i \end{array}\right], \; i = 1, 2, \cdots, n_f. \tag{4}$$

Here, ${}^f_o\boldsymbol{R}_i$ and p_i denotes the rotation matrix and the position vector from the operational space to the fingertip space of the ith finger, respectively. m denotes the total dimension of wrenches applied to the grasped object by n_f fingers and it is given by $\sum_{i=1}^{n_f} {}^in_{fp}$, where ${}^in_{fp}$ denotes the dimension of the ith finger's wrench applied to the grasped object.

In general, the $n \times n$ stiffness matrix $\boldsymbol{K}_o^*$ in the operational space of a multi-fingered object manipulation system can be expressed as follows [17]:

$$\boldsymbol{K}_o^* = [\boldsymbol{G}_o^f]^T[\boldsymbol{K}_f][\boldsymbol{G}_o^f] - ((T_f)^T \circ [\boldsymbol{H}_{oo}^f]) \tag{5}$$

where $\boldsymbol{K}_f$, representing the $m \times m$ stiffness matrix in the fingertip space, is expressed as

$$\boldsymbol{K}_f = \left[\begin{array}{cccc} {}^1\boldsymbol{K}_f & {}^{12}\boldsymbol{K}_f & \cdots & {}^{1n_f}\boldsymbol{K}_f \\ {}^{21}\boldsymbol{K}_f & {}^2\boldsymbol{K}_f & \cdots & {}^{2n_f}\boldsymbol{K}_f \\ \vdots & \vdots & \ddots & \vdots \\ {}^{n_f1}\boldsymbol{K}_f & {}^{n_f2}\boldsymbol{K}_f & \cdots & {}^{n_f}\boldsymbol{K}_f \end{array}\right], \tag{6}$$

in which ${}^i\boldsymbol{K}_f$ and ${}^{ij}\boldsymbol{K}_f$ are, respectively, given by

$${}^i\boldsymbol{K}_f = \left[\begin{array}{cccc} {}^i\boldsymbol{K}_{fxx} & {}^i\boldsymbol{K}_{fxy} & {}^i\boldsymbol{K}_{fxz} & {}^i\boldsymbol{K}_{fx\varphi} \\ {}^i\boldsymbol{K}_{fyx} & {}^i\boldsymbol{K}_{fyy} & {}^i\boldsymbol{K}_{fyz} & {}^i\boldsymbol{K}_{fy\varphi} \\ {}^i\boldsymbol{K}_{fzx} & {}^i\boldsymbol{K}_{fzy} & {}^i\boldsymbol{K}_{fzz} & {}^i\boldsymbol{K}_{fz\varphi} \\ {}^i\boldsymbol{K}_{f\varphi x} & {}^i\boldsymbol{K}_{f\varphi y} & {}^i\boldsymbol{K}_{f\varphi z} & {}^i\boldsymbol{K}_{f\varphi\varphi} \end{array}\right] \tag{7}$$

and

$${}^{ij}\boldsymbol{K}_f = \left[\begin{array}{cccc} {}^{ij}\boldsymbol{K}_{fxx} & {}^{ij}\boldsymbol{K}_{fxy} & {}^{ij}\boldsymbol{K}_{fxz} & {}^{ij}\boldsymbol{K}_{fx\varphi} \\ {}^{ij}\boldsymbol{K}_{fyx} & {}^{ij}\boldsymbol{K}_{fyy} & {}^{ij}\boldsymbol{K}_{fyz} & {}^{ij}\boldsymbol{K}_{fy\varphi} \\ {}^{ij}\boldsymbol{K}_{fzx} & {}^{ij}\boldsymbol{K}_{fzy} & {}^{ij}\boldsymbol{K}_{fzz} & {}^{ij}\boldsymbol{K}_{fz\varphi} \\ {}^{ij}\boldsymbol{K}_{f\varphi x} & {}^{ij}\boldsymbol{K}_{f\varphi y} & {}^{ij}\boldsymbol{K}_{f\varphi z} & {}^{ij}\boldsymbol{K}_{f\varphi\varphi} \end{array}\right] \tag{8}$$

for the case of soft finger contact. Here, ${}^i\boldsymbol{K}_{fkl}$ denotes the coupling stiffness elements between the k- and l-direction in the ith fingertip space. ${}^{ij}\boldsymbol{K}_f$ denotes the inter-finger coupling stiffness matrix between the ith finger and the jth finger. The subscript φ indicates the rotational direction for the contact normal direction of each fingertip. The operator of $(\circ)$ represents the generalized scalar dot product, which yields the product of a matrix and a three-dimensional array [19]. For example, let A and B represent a $p \times q$ matrix and a $q \times m \times n$ three-dimensional array, respectively. The operation $A \circ B$ would then yield a $p \times m \times n$ three-dimensional array. $\boldsymbol{H}_{oo}^f$ denotes the second-order kinematic influence coefficient matrix that implies the change of $\boldsymbol{G}_o^f$ with respect to contact configuration.

Finally, the effective stiffness in the operational space considering the effects generated by changes in the grasp configuration can be represented as

$$\boldsymbol{K}_o = [\boldsymbol{G}_o^f]^T[\boldsymbol{K}_f][\boldsymbol{G}_o^f] \tag{9}$$

where the effective stiffness $\boldsymbol{K}_o$ is also symmetric since the second term of (5) becomes symmetric when linear fingertip forces are applied.

It is noted from (9) that the geometric configuration of a given grasp is associated with the stiffness distribution relating the operational space to the fingertip space.

3. Independent Compliance Modulation

In a common robot hand system, there exists inter-finger coupling. If the inter-finger coupling can be eliminated, each finger can be independently controlled which makes the hand control relatively easy. This section describes a technique for modulation of the fingertip stiffness without inter-finger coupling so as to achieve the desired stiffness specified in the operational space. For convenience, we particularly illustrate a compliance control by a two-fingered robot hand with soft fingertips as shown in Fig. 2.

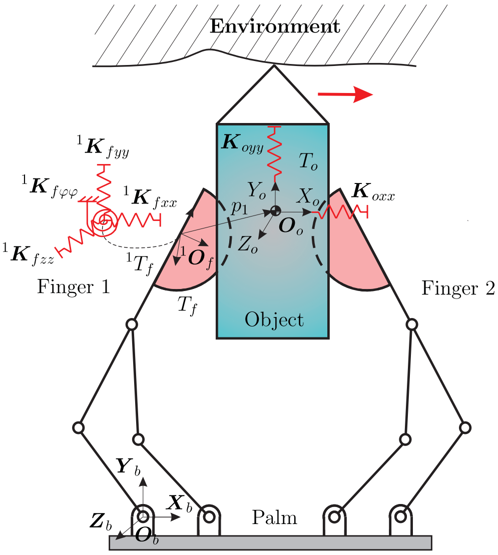


Fig. 2 Compliance control by two-fingers

In the case of two-fingered compliant tasks shown in Fig. 2, a 2 × 2 object stiffness matrix in the operational space can be considered as

$$\boldsymbol{K}_o = \begin{bmatrix} \boldsymbol{K}_{oxx} & \boldsymbol{K}_{oxy} \\ \boldsymbol{K}_{oyx} & \boldsymbol{K}_{oyy} \end{bmatrix} \tag{10}$$

and the 8 × 8 stiffness matrix in the fingertip space is generally represented by

$$\boldsymbol{K}_f = \left[\begin{array}{c|c} {}^1\boldsymbol{K}_f & {}^{12}\boldsymbol{K}_f \\ \hline {}^{21}\boldsymbol{K}_f & {}^2\boldsymbol{K}_f \end{array}\right] \tag{11}$$

where ${}^i\boldsymbol{K}_f$ and ${}^{ij}\boldsymbol{K}_f$ are defined in (7) and (8), respectively.

The grip Jacobian matrix relating the operational space to the fingertip space of Fig. 2 can be given by

$$\boldsymbol{G}_o^f = \begin{bmatrix} {}^1\boldsymbol{G}_o^f \\ {}^2\boldsymbol{G}_o^f \end{bmatrix} \tag{12}$$

where ${}^1\boldsymbol{G}_o^f$ and ${}^2\boldsymbol{G}_o^f$ denote the grip Jacobian matrices relating the operational space to each fingertip space of the two fingers, and those components are dependently determined by the grasping geometry.

In order to eliminate inter-finger couplings as well as the coupling of the fingertip space for effective hybrid(force and position) control in the fingertip space, the fingertip stiffness matrix of the assigned task is firstly set up as

$$\boldsymbol{K}_f = \left[\begin{array}{c|c} {}^1\boldsymbol{K}_f^d & {}^{12}\boldsymbol{K}_f^d \\ \hline {}^{21}\boldsymbol{K}_f^d & {}^2\boldsymbol{K}_f^d \end{array}\right] \tag{13}$$

where the desired fingertip stiffness ${}^i\boldsymbol{K}_f^d (i = 1, 2)$ can be assigned by

$${}^i\boldsymbol{K}_f^d = \begin{bmatrix} {}^i\boldsymbol{K}_{fxx} & 0 & 0 & 0 \\ 0 & {}^i\boldsymbol{K}_{fyy} & 0 & 0 \\ 0 & 0 & {}^i\boldsymbol{K}_{fzz} & 0 \\ 0 & 0 & 0 & {}^i\boldsymbol{K}_{f\varphi\varphi} \end{bmatrix} \tag{14}$$

with only the diagonal stiffness terms in (7) and

$${}^{ij}\boldsymbol{K}_f^d = {}^{ji}\boldsymbol{K}_f^d = \boldsymbol{0}. \tag{15}$$

For the purpose of this study, it is useful to rearrange (9) as a vector form:

$$K_{oo} = [\boldsymbol{B}_f^o]\, K_{ff} \tag{16}$$

where

$$K_{oo} = \begin{bmatrix} \boldsymbol{K}_{oxx} & \boldsymbol{K}_{oxy} & \boldsymbol{K}_{oyy} \end{bmatrix}^T, \tag{17}$$

$$\begin{aligned} K_{ff} = \big[&{}^1\boldsymbol{K}_{fxx}\ {}^1\boldsymbol{K}_{fyy}\ {}^1\boldsymbol{K}_{fzz}\ {}^1\boldsymbol{K}_{f\varphi\varphi} \\ &{}^2\boldsymbol{K}_{fxx}\ {}^2\boldsymbol{K}_{fyy}\ {}^2\boldsymbol{K}_{fzz}\ {}^2\boldsymbol{K}_{f\varphi\varphi}\big]^T, \end{aligned} \tag{18}$$

and

$$\boldsymbol{B}_f^o = \begin{bmatrix} {}^1\boldsymbol{B}_f^o & {}^2\boldsymbol{B}_f^o \end{bmatrix} \tag{19}$$

where ${}^1\boldsymbol{B}_f^o$ and ${}^2\boldsymbol{B}_f^o$ represent the relationship matrices relating each fingertip space of the two fingers to the operational space, and they are actually driven by the independent compliance modulation. Note that the components of $\boldsymbol{B}_f^o$ are dependent on the grasping geometry.

As a result, the independent fingertip stiffness for a given operational stiffness can be obtained by solving (16).

4. Necessary Fingers as Compliant Tasks

It is widely known that determining the number of fingers is essential for optimal design and effective manipulations. Based on compliance control, this section analyzes on necessary fingers for successful compliant tasks. We also considers some primitive compliant tasks performed by a human hand for bio-mimetic considerations.

4.1 Approach

For the purpose of analyzing on necessary fingers for compliant tasks, it is actually useful to investigate the dimension of (16). In n-dimensional space, K_{oo} in (16) denotes $n(n+1)/2 \times 1$ vector consisting of independent elements of $\boldsymbol{K}_o$, and K_{ff} denotes $m \times 1$ vector consisting of independent elements of $\boldsymbol{K}_f$ without coupling. Also, $\boldsymbol{B}_f^o$ denotes the $n(n+1)/2 \times m$ matrix relating the independent elements of the object stiffness matrix to those of the decoupled fingertip stiffness matrix. Therefore, by checking the dimension of (16), we can resultantly justify the number of independent fingers for successful implementation of compliant manipulating tasks by multi-fingered robot hands. In practice, in a robotic hand manipulating system as shown in Fig. 1, the components of the wrench transmitted through the contact between the fingertip and the contact point of the object are limited by the contact constraint defined according to the contact types [11]. It is therefore very important to determine the number of fingers and the number of joints for implementation of the desired compliance characteristic given in the operational space. In this paper, the operational stiffness matrix is assumed to be symmetric, and soft finger contact is considered.

4.2 Task-Based Effective Fingers

Consider a typical hybrid control task by a two-fingered hand in Fig. 2. If the purpose of this task is to follow a given trajectory on the environment maintaining a desired contact force to the contact normal direction of the object, a 2×2 stiffness characteristic matrix in the operational space of the manipulating system can be assigned. Then, let's check the fundamental structure of the assigned stiffness matrix to judge the number of independent fingers required for the task. It is easily known that a specified 2×2 object stiffness matrix consists of three independent elements, and the dimension of the fingertip stiffness matrix is considered as 8×8, which has totally thirty six independent stiffness elements and twenty eight coupling elements exist among them. If those coupling elements are to be zero for an independent finger-based compliance control without coupling, eight independent stiffness elements that consist of the diagonal components in (13) are only available. Thus, we can notice that the dimension of $\boldsymbol{B}_f^o$ is 3×8. This implies that eight input parameters are resultantly enough to solve for the three equations given in (16). It is therefore confirmed that a two-fingered hand involving soft contacts can implement a 2×2 object stiffness characteristic in the two-dimensional space. In this sense, the number of independent fingers for various compliant tasks represented by the dimension of $\boldsymbol{K}_o$ can be investigated as Table 1, where (a) and (b) denote the necessary number of independent elements of $\boldsymbol{K}_f$ without coupling and the number of independent elements according to the assigned $\boldsymbol{K}_o$, respectively. $(c)(=(a)-(b))$ represents the remaining degree of freedom for $\boldsymbol{K}_f$.

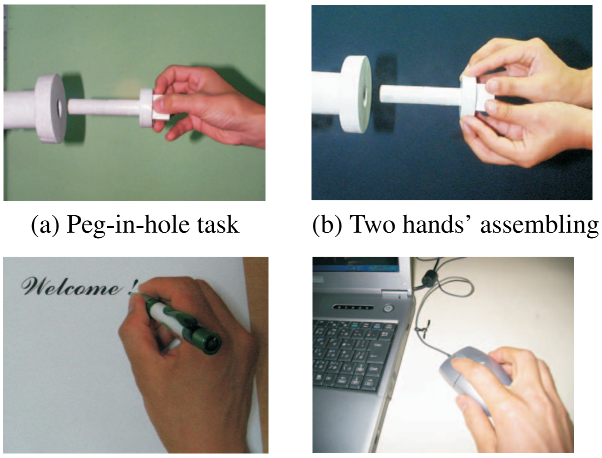
Table 1. Necessary independent fingers as compliant tasks (○ : Available, ×: Impossible)

Fingers	(a)	(b)	(c)	Dimension of $\boldsymbol{K}_o$	Remarks
2	8	3	5	2×2	○
		6	2	3×3	○
		10	-2	4×4	×
		15	-7	5×5	×
		21	-13	6×6	×
3	12	3	9	2×2	○
		6	6	3×3	○
		10	2	4×4	○
		15	-3	5×5	×
		21	-9	6×6	×
4	16	3	13	2×2	○
		6	10	3×3	○
		10	6	4×4	○
		15	1	5×5	○
		21	-5	6×6	×
5	20	3	17	2×2	○
		6	14	3×3	○
		10	10	4×4	○
		15	5	5×5	○
		21	-1	6×6	×

Also, we can consider higher-ordered tasks given by 3×3 or 4×4 operational stiffness characteristics, etc. It is confirmed from Table 1 that a two-fingered hand can implement a contact task requiring a 3×3 operational stiffness characteristic. However, it is not enough to satisfy a 4×4 operational stiffness. Hence, a robot hand should have at least three fingers in order to handle a compliant task represented by a 4×4 operational stiffness matrix.

As a general rule, full stiffness implementation is possible when (c) in Table 1 is equal to or greater than zero.

For instance, when we employ the independent compliance modulation technique above, some coupling stiffness elements in the operational space can be planned zero according to the grasp positions of fingers as well as the RCC(Remote Compliance Center) point. Particularly, in a peg-in-hole task of Fig. 3(a), the actual number of independent stiffness elements required in the operational space can be reduced and planned by fifteen primary components [20]. In this case, we can get at least six surplus mobility which is not necessary in the task and thus it can be managed by four soft fingers. It is noticeable from Table 1 that five fingers are not enough to implement a 6×6 operational stiffness characteristic. A normal human has two hands and each hand has five fingers. So, it is remarked that a human may suffer from the lack of mobility to manipulate an object by only five fingers. This problem can be coped by using a proper cooperation of two hands as shown in Fig. 3(b).



(a) Peg-in-hole task (b) Two hands' assembling

(c) Writing (d) Mouse manipulation

Fig. 3 Multi-fingered compliant manipulations

A writing task in Fig. 3(c) is an another useful example for intelligent service robots [1]. The feature of this task is that the translational and rotational motions of the grasped pen are dominantly necessary to write a character. Of course, the selection of a useful grasp style is very important to stably write a character. As the tail of the pen is constrained by the saddle between the thumb and index finger, especially shown in Fig. 3(c), we can intuitively see that the motion of the grasped pen can be easily balanced during the writing process. Usually, we can find that many people prefer this grasp style for writing a precision character. It actually allows that certain motions can be modulated by the combination of translational and rotational motions. Thus, a resultant stiffness elements required in the operational space for a writing task can be defined as mainly eight elements in a 6×6 matrix [20]. That is, a writing task can be done by at least two soft fingers with the grasp style that utilizes the constraint made by the saddle. In the viewpoint of stability, three fingers are recommendable for a writing task as shown in Fig. 3(c).

In the case of handling a mouse as shown in Fig. 3(d), three-directional motions, such as the planar and/or rotational motions, are basically utilized. In this case, six independent stiffness elements in the operational space can be specified for the task. Therefore, the mouse can be manipulated by two soft fingers. Usually, a human hand uses the index finger for additional purposes such as clicking the mouse.

In practice, many robotic hands consist of four [2] [4] or five fingers [3] [5] [6]. Through the above analysis, it is possible to estimate their feasibility. From Table 1, it is remarkable that those hands with four or five fingers can be applied to various compliant manipulation tasks with the maximum fifteen degrees of freedom, but a hand with five fingers has four more degrees of freedom for a given task. The redundancy in a five-fingered hand can be favorably used to a regrasping operation for dextrous object manipulations as shown in Fig. 4.

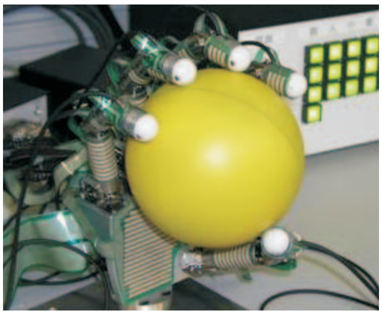


Fig. 4 Regrasping task by a Gifu hand [5]

5. Concluding Remarks

A task-based analysis on the number of independent robotic fingers required for compliant manipulations has been presented. In particular, based on an independent compliance modulation, a sufficient guideline to justify the number of independent robotic fingers for compliant manipulating tasks was provided. As a result, this analysis can be applied to determine how many fingers are fundamentally necessary to successfully implement various compliant manipulating tasks by robot hands.

In addition, since the geometric configuration of a given grasp is associated with the stiffness distribution from the operational space to the fingertip space, it is remarkable that a grasp planning is closely related to achieve the performance of a compliance control scheme. Of course, the structure and driving mechanism of fingers are practically very important for implementing the associated stiffness relating the fingertip space to joint space.

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