Grasp Control for a Multifingered Hand with Kinematic Redundancy*

(Experiments on Stable Grasp by the Direct Compliance Control Method)

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This paper proposes stable grasp by a robot hand with articulated fingers, each of which has kinematic redundancy. To achieve a stable grasp by such a hand, the following two problems must be considered: (1) the stability of the grasped object and (2) the stability of the finger posture. We first formulate the stability of the grasped object by introducing virtual springs at each fingertip. Secondly, we use the direct compliance control (DCC) method to achieve the stability of the finger posture, in which the stiffness (or compliance) at each fingertip is controlled by adjusting the stiffness independently arranged at each joint with satisfaction of the stability condition for the finger posture. Finally, the effectiveness of the proposed method is confirmed experimentally using a two-fingered plane hand with three-jointed fingers.

Key Words: Multifingered Robot Hand, Stable Grasp, Direct Compliance Control Method, Kinematic Redundancy

1. Introduction

Compared with the human hand, the performance or the functions of a conventional robot hand are extremely limited and they can achieve only simple tasks. Considering that human skill is mostly performed by dextrous finger motions rather than by arm motions, to realize finger functions is indispensable for expanding the ability of robot. With this matter in mind, the number of research activities on the multifingered robot hand has been increasing in these years. When a hand carries out some required tasks, it should grasp the object stably, and control the object position/orientation according to the reference command. This problem has been examined as stable grasp and manipulation control, and some methods have been proposed^{(1)~(3)}.

On the other hand, the dexterity and universality

in manipulation by a multifingered hand greatly depends on the degrees of freedom (d.o.f.) for each finger. For example, the human finger has 3 joints, excepting the thumb. The first joint has 2 d.o.f., the second and third joints have 1 d.o.f.. In total, the human finger has 4 d.o.f., and results in having one redundant d.o.f. for fingertip motion. Although kinematic redundancy is generally effective in expanding the reachable range of the fingertip and can produce obstacle avoidance capabilities, it makes joint control difficult. From this reason, there have been, so far, few research activities for stable grasp or manipulation by multifingered hands with kinematic redundancy.

In this paper, stable grasp by a two-fingered hand with kinematic redundancy in a two-dimensional plane is discussed as preliminary research for achieving object manipulation by a multifingered hand including fingers with kinematic redundancy. We define two kinds of stability which relate to the stability of the grasped object and stability of the finger posture. Stability of the grasped object is discussed based on the grasp theory using the virtual springs at each fingertip, which has already been confirmed in the two-

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fingert hand without kinematic redundancy⁽⁴⁾.

Stability of the finger posture is formulated with stiffness parameters at each finger joint. Regarding the stability of the finger posture with kinematic redundancy, the effectiveness of two stiffness (or compliance) control methods are discussed: the direct compliance control (DCC) method reported in the previous paper⁽⁵⁾, and the Salisbury method⁽⁶⁾. As a result, it is found that adjusting stiffness at the fingertip using the DCC method can achieve both stability of the grasped object and of the finger posture, but the Salisbury method can not provide the stability of the finger posture in the multifingered hand with kinematic redundancy.

These results are experimentally confirmed by a two-fingered plane hand with three-jointed fingers including kinematic redundancy.

Nomenclature

- $d\mathbf{x} \in R^n$: Fingertip displacement
- $d\boldsymbol{\theta} \in R^m$: Joint angular displacement
- $d\hat{\mathbf{x}}, d\hat{\mathbf{y}}, d\hat{\boldsymbol{\theta}}$: Displacement of the grasped object
- e : Potential energy stored at the joint stiffness
- $\mathbf{f} \in R^n$: Force applied at fingertip
- $\mathbf{J} \in R^{n \times m}$: Jacobian matrix of finger
- $\mathbf{K}_e \in R^{n \times n}$: Stiffness matrix in fingertip space
- $\mathbf{K}_j \in R^{m \times m}$: Stiffness matrix in joint space
- k_{xi}, k_{yi} : Stiffness of the virtual springs at the fingertip
- $\hat{k}_x, \hat{k}_y, \hat{k}_\theta$: Stiffness described on the grasped object
- m : Number of d.o.f. for each finger (number of joints)
- n : Number of d.o.f. for fingertip motion
- r_i : Distance between a fingertip and a rotational center of the grasped object
- α : Rotational angle between the absolute coordinate frame and the task coordinate frame
- δ : Initial compression of stiffness k_{xi} at fingertip
- $\boldsymbol{\tau} \in R^m$: Joint torque

2. Theory of Stable Grasp by Multifingered Hand

2.1 Basic concept

In this paper, we consider that there are two kinds of stabilities of grasp by a multifingered hand. One is stability of the grasped object, and the other is stability of the finger posture. When both of these stabilities are satisfied, we consider that the grasp is stable. This can be described in detail as follows.

Stability of the grasp Suppose that a multifingered hand grasps an object and an external force disturbs the geometrical configuration of the

grasp system. We define that the grasp system is stable if its behavior satisfies both of the following conditions.

(1) Stability of the grasped object

The object can move back to its initial position/orientation when the external disturbance force is removed.

(2) Stability of the finger posture

All fingers can move back to their initial posture when the external disturbance force is removed.

For the multifingered hand without kinematic redundancy, only the stability of the grasped object is important for achieving stable grasp because each finger posture will be uniquely determined by the motion of the grasped object. When, however, each finger has kinematic redundancy, the two requirements of the above-mentioned stability must be considered because the same object position/orientation can produce infinite numbers of finger postures.

We will address the stability of the grasped object in sections 2.2 and 2.3. Generally, the grasp theory has been constructed with the assumption of no friction at the contact between the object and the finger. This results in difficulty in using it in a practical model. With this matter in mind, the stable grasp theory will be discussed with the consideration of friction at the contact.

In sections 3 to 5, we will discuss the stability of the finger posture based on the discussion of stiffness (or compliance) control of the finger.

2.2 Stability of the grasped object

To avoid the complexity of explanation, quasi-static behavior of a grasp system without consideration of dynamic effects will be dealt with. Let us consider a grasped object suspended by virtual springs at the rotational center of the object and located at its initial position/orientation, as shown in Fig. 1(a). When the object is forced to move from its initial position/orientation by something like the external disturbance force, the object will receive some forces/moments from the virtual springs. If the stiffness parameters of all virtual springs are positive, the force/moment moving the object back to its initial position/orientation will be applied. From the definition in section 2.1, this meets the requirement of stability of a grasped object.

Now, let us consider an object grasped by fingers and construct the virtual springs at the fingertip by using compliance control, as shown in Fig. 1(b). As the object motion uniquely results in fingertip motion, we can derive the relationship between the virtual spring parameters in Fig. 1(a) and Fig. 1(b) using the geometrical configuration of the grasp system. This means that we can adjust the virtual springs on

the object by the stiffness parameters of the virtual springs at the fingertip.

Therefore, if the stiffness at the fingertip can be controlled to suspend an object with positive virtual springs in the same way as in Fig.1(a), it is found that stability of a grasped object will be achieved.

2.3 Stable grasp by a two-fingered hand in a two-dimensional plane

We examine stable grasp in detail for two-dimensional grasp using the two-fingered-hand model. To simplify the analysis, we assume that the contact between a fingertip and an object makes point contact. This means that the force is transmitted through the contact point, but moment is not transmitted. In this paper, since we consider the contact friction, it is noted that both the normal and tangential force act between a fingertip and an object.

Stable grasp by a two-fingered hand in a two-dimensional plane is achieved through the three steps shown in Fig. 2. At first, the desired stiffness on the grasped object which consists of three independent virtual springs, translational springs along the x and y axes, and rotational spring along the θ axis, is provided, as shown in Fig. 2(a). If all of the stiffness parameters which are described by the translational stiffness $\hat{k}_x$, $\hat{k}_y$ and rotational stiffness $\hat{k}_\theta$ are posi-

tive, the grasp system will meet the requirement of stability of the grasped object because the object will receive restoring force/moment for the external disturbance.

Next, the desired virtual springs on the object are transformed into the virtual springs k_{xi} and k_{yi} at the fingertip, as shown in Fig. 2(b). The rotational center of the object and fingertips are assumed to be located

(a) Virtual springs suspending object

(b) Virtual springs at fingertip

(a) Virtual springs suspending object

(b) Virtual springs at fingertip

(c) Virtual springs at finger joint

Fig. 1 Basic concept of stable grasp by multifingered hand

Fig. 2 Stable grasp by two-fingered hand in two-dimensional plane

in a straight line, and the distances from the rotational center to each fingertip is described by r_i . Also, it is assumed that each of the virtual springs k_{xi} is initially compressed by δ . If the grasp system in Fig. 2 satisfies the following conditions for small displacement of the object, Fig. 2(a) will be the same as Fig. 2(b).

In restoring force for small object translation, $d\hat{x}$,

$$\hat{k}_x d\hat{x} = k_{x1}(\delta - d\hat{x}) + k_{x2}(\delta + d\hat{x}). \quad (1)$$

In restoring force for small object translation, $d\hat{y}$,

$$\hat{k}_y d\hat{y} = k_{y1}d\hat{y} + k_{y2}d\hat{y}. \quad (2)$$

In restoring moment for small object rotation, $d\hat{\theta}$

$$\hat{k}_\theta d\hat{\theta} = k_{y1}r_1^2 d\hat{\theta} - k_{x1}\delta r_1 d\hat{\theta} + k_{y2}r_2^2 d\hat{\theta} - k_{x2}\delta r_2 d\hat{\theta}. \quad (3)$$

To decouple the translational/rotational motions,

$$k_{x1}\delta - k_{x2}\delta = 0 \quad (4)$$

$$k_{y1}r_1 d\hat{\theta} - k_{y2}r_2 d\hat{\theta} = 0 \quad (5)$$

From Eqs.(1)~(5), the stiffness parameters at the fingertip and the compression displacement can be expressed as follows using the desired stiffness parameters on the grasped object.

$$k_{x1} = k_{x2} = \hat{k}_x/2 \quad (6)$$

$$k_{y1} = \frac{r_2}{r_1 + r_2} \hat{k}_y \quad (7)$$

$$k_{y2} = \frac{r_1}{r_1 + r_2} \hat{k}_y \quad (8)$$

$$\delta = 2 \frac{r_1 r_2 \hat{k}_y - \hat{k}_\theta}{\hat{k}_x(r_1 + r_2)} \quad (9)$$

Finally, the stiffness at the fingertip will be transformed into the joint stiffness, as shown in Fig. 2(c). There are several ways to transform the stiffness parameters from fingertip space to joint space. The details will be discussed in sections 3 to 5.

3. Stiffness (or Compliance) Control of Finger

3.1 Fundamental formulas

As shown in Eqs.(10)~(13), the fingertip displacement dx , fingertip force f , joint angular displacement $d\theta$ and joint torque τ are related by the stiffness matrices in fingertip space K_e and in joint space K_j , and the Jacobian matrix of the finger J .

$$dx = Jd\theta \quad (10)$$

$$\tau = J^T f \quad (11)$$

$$f = K_e dx \quad (12)$$

$$\tau = K_j d\theta \quad (13)$$

These equations demonstrate the relationship between K_e and K_j . Therefore, we can control the stiffness matrix K_e in fingertip space by adjusting the stiffness matrix K_j in joint space. But since the calculation requires the Jacobian matrix J , the initial finger posture should be previously determined in an appropriate way.

3.2 Stability of the finger posture

To achieve stable grasp by a multifingered hand with kinematic redundancy, stability of the finger posture must be satisfied as well as the stability of the grasped object, as mentioned in section 2.1. This section deals with the stability of the finger posture. In discussion, quasistatic behavior of the finger will be assumed, as it was in section 2.2.

The potential energy e stored at the joint stiffness is expressed as follows:

$$e = d\theta^T K_j d\theta / 2. \quad (14)$$

If the stiffness matrix K_j in joint space is positive definite, potential energy e stored at the joint stiffness will become a minimum of zero at the initial finger posture ($d\theta = 0$), and it will be positive for any finger posture variation. This means that the finger posture disturbed by an external force will move back to the initial posture after the external force is removed, assuming that dynamic transition is ignored.

If stiffness matrices in joint space are positive definite for all fingers, the disturbed configuration of the grasp system will move back to the initial state when the external force is removed. Considering the definition described in section 2.1, this means that the grasp system is quasistatically stable for the finger posture when the stiffness matrices in joint space for all fingers are positive definite.

4. Salisbury Method of Stiffness Control

Salisbury proposed one of the stiffness control methods for manipulators by adjusting stiffness in joint space⁽⁶⁾. We examine the effectiveness of his method in the finger with kinematic redundancy. In his method, from Eqs.(10)~(13), the desired stiffness matrix K_e in fingertip space is transformed to the stiffness matrix K_j in joint space as follows.

$$K_j = J^T K_e J \quad (15)$$

In a previous paper⁽⁴⁾, we reported that stable grasp using a two-fingered hand without kinematic redundancy was successfully achieved by using the Salisbury method for stiffness control of a finger. But the Salisbury method is not suitable for fingers with kinematic redundancy because stability of the finger posture is not achieved.

Using the method introduced in section 3.2, we examined this through the analysis of the definiteness of a stiffness matrix in joint space. Considering that the number of d.o.f. at the fingertip is n and that the number of joints is m , the Jacobian matrix J and stiffness matrix K_e in fingertip space are $n \times m$ and $n \times n$ matrices, respectively. According to Eq.(15), the rank of the stiffness matrix K_j in joint space will maximally be n because the rank of J and K_e are maximally n . On the other hand, K_j is a $m \times m$ matrix

and $n < m$ because of the kinematic redundancy of the finger. Thus, the stiffness matrix $\mathbf{K}_j$ in joint space is found to be nonpositive definite. As mentioned in section 3.2, this means that the finger will not move back to the initial posture after removing the external force applied at the fingertip.

From the above discussion, it is found that the Salisbury method cannot be used to keep the finger posture stable when fingers with kinematic redundancy are employed.

5. Direct Compliance Control (DCC) Method

5.1 Fundamental formulas

Kaneko et al. proposed the direct compliance control (DCC) method⁽⁵⁾ which enables the desired stiffness condition at the end of the manipulator to be obtained by adjusting the stiffness at each joint independently. From Eqs.(10)~(13), the relation between the stiffness matrices in fingertip space $\mathbf{K}_e$ and in joint space $\mathbf{K}_j$ are derived as follows:

$$\mathbf{K}_e^{-1} = \mathbf{J} \mathbf{K}_j^{-1} \mathbf{J}^t. \quad (16)$$

Suppose there are n d.o.f. at the fingertip. This finger will have a $n \times n$ stiffness matrix $\mathbf{K}_e$ in fingertip space. Generally, $\mathbf{K}_e$ is symmetric; therefore $\mathbf{K}_e$ has $n(n+1)/2$ independent components. If the number of joints is the same as the number of independent components of $\mathbf{K}_e$, we can determine joint stiffness parameters uniquely from the desired stiffness matrix in fingertip space because the same number of equations as the number of joints can be obtained from Eq.(16). This means that by giving a desired stiffness matrix $\mathbf{K}_e$ in fingertip space, the stiffness matrix $\mathbf{K}_j$ in joint space can be determined as a diagonal matrix. Using $\mathbf{K}_j$, therefore, a torque control law will be constructed independently at each joint.

Let us apply the DCC method to a finger of an experimentally used two-fingered hand which has three joints. In this finger, we have $n=2$ and $m=3$, and Eq.(16) can be written as follows:

$$\begin{bmatrix} k_{j11}^{-1} \\ k_{j22}^{-1} \\ k_{j33}^{-1} \end{bmatrix} = \det(\mathbf{K}_e)^{-1} \begin{bmatrix} j_{11}^2 & j_{12}^2 & j_{13}^2 \\ j_{21}^2 & j_{22}^2 & j_{23}^2 \\ j_{31}^2 & j_{32}^2 & j_{33}^2 \end{bmatrix}^{-1} \begin{bmatrix} k_{e22} \\ k_{e11} \\ -k_{e12} \end{bmatrix}. \quad (17)$$

where

$$\mathbf{K}_e = \begin{bmatrix} k_{e11} & k_{e12} \\ k_{e12} & k_{e22} \end{bmatrix} \quad \mathbf{K}_j = \text{diag}[k_{j11}, k_{j22}, k_{j33}]$$

$$\mathbf{J} = \begin{bmatrix} j_{11} & j_{12} & j_{13} \\ j_{21} & j_{22} & j_{23} \end{bmatrix}.$$

Equation(17) above will provide information on how to control the stiffness at the fingertip for the articulated finger through independently adjusting the stiffness at each joint.

5.2 Examination on stability of the finger posture

In the DCC method, the stiffness matrix $\mathbf{K}_j$ in joint space is diagonal. It is positive definite if all diagonal components are positive. In such a case, the finger will move back to the initial posture because the potential energy stored at the joint stiffness of Eq. (14) is a minimum of zero at the initial posture. Thus, introducing the DCC method, the condition to achieve the stability of the finger posture is expressed as follows:

$$k_{jii} > 0 \quad (1 \leq i \leq m)$$

$$\mathbf{K}_j = \text{diag}[k_{j11}, k_{j22}, \dots, k_{jmm}]. \quad (18)$$

6. Experimental Results

A two-fingered plane hand with three joints in each finger is used for the experiments⁽⁷⁾. Each joint has a position and torque sensor, and we can control the joint stiffness (or compliance) by controlling the joint torque according to the joint angular displacement. Figure 3 and Fig.4 are experimental results of the grasp operation, which show the behavior of the grasp system when external disturbance force is applied and removed.

Figure 3 shows results of a grasp operation achieved using the DCC method to control the stiffness

Initial and final posture

Under disturbance

Fig. 3 Experimental grasp by the DCC method
($\hat{k}_x = 300 \text{ N/m}$, $\hat{k}_y = 1200 \text{ N/m}$, $\hat{k}_\theta = 1.4 \text{ Nm/rad}$)

at the fingertip. In the experiments, positive values were used for stiffness on the object $\hat{k}_x, \hat{k}_y$ and $\hat{k}_\theta$. For this reason, object could receive restoring force/moment from fingers for the disturbance, resulting in stability of the grasped object. As all the joints were also controlled to keep all of their stiffness parameters positive, stability of the finger posture was achieved. Satisfaction of both stability conditions is confirmed in the figure because the finger posture moved back to the initial state, as well as the object, after removing external force. This confirms that the DCC method can be effectively used to control the multifingered hand with kinematic redundancy.

Figure 4 shows the result of a grasp operation obtained using the Salisbury method to control the stiffness at the fingertip. In this experiment, the positive desired stiffness on the object was used in the same way as in Fig. 3. From the observation of the finger posture in Fig. 4, the stability of the grasped object is confirmed. However, the stability of finger posture is not achieved because the finger posture cannot move back to the initial posture after removal of the external force, as mentioned in section 4. This causes instability of grasp and results in a disadvantage of the Salisbury method for the hand with kinematic redundancy.

Fig. 4 Experimental grasp by the Salisbury method ($\hat{k}_x=300$ N/m, $\hat{k}_y=1\,200$ N/m, $\hat{k}_\theta=1.4$ Nm/rad)

7. Limitation of Stiffness at Fingertip in DCC Method

In the DCC method, the joint stiffness determined according to Eq.(16) does not always satisfy the stable condition of finger posture at Eq.(18) because some stiffness at the fingertip or finger posture may force the introduction of unstable joint stiffness parameters.

This is simulated by employing the three-jointed-plane finger model with the same structure and posture in experiment, as shown in Fig. 5. In Fig. 5(a), the task coordinate frame at the fingertip is oriented by α in the absolute coordinate frame, and the stiffness parameters k_x and k_y at the fingertip are provided in the task coordinate frame. Figure 5(b) shows a simulation result of stability of the finger posture. The shadowed area corresponds to the region where all joint stiffnesses are positive, and the finger posture is kept stable when the DCC method is used. To obtain the experimental result in Fig. 3, the

(a) Arrangement of stiffness parameters at fingertip

(b) Stability of the finger posture depending on the stiffness at fingertip

Fig. 5 Limitation of stiffness at fingertip in the DCC method

stiffness at the fingertip corresponding to point A in Fig. 5(b) was selected. It is found that selections of stiffness parameters at the fingertip are limited to satisfy the stability of the finger posture.

8. Conclusions

Through the analyses and experiments concerning grasp by a multifingered hand with kinematic redundancy, we obtained the following results.

(1) It was confirmed that stable grasp by a multifingered hand was successfully achieved by introducing the control of stiffness at the fingertip.

(2) It was found that finger posture became unstable in a multifingered hand with kinematic redundancy when the Salisbury method was used to control the stiffness at the fingertip.

(3) The direct compliance control (DCC) method is effective for achieving the stability of finger posture in the multifingered hand with kinematic redundancy.

(4) The use of the DCC method enables obtaining the stability of finger posture. However, limitations of adjustable stiffness at fingertip are produced.

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