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인간의 손의 능력을 응용한 로봇 핸드의 힘 제어

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Control of Grasp Forces for Robotic Hands Based on Human Capabilities

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ABSTRACT

This paper discusses a physiological approach motivated by the study of human hands for robot hand force control. It begins with an analysis of the human's grasping behavior to see how humans determine the grasp forces. The human controls the grasp force by sensing the friction force, that is, the weight of the object which is felt on his hand, but when slip is detected by sensing skin acceleration, the grasp force becomes much greater than the minimum force required for grasping by adding the force which is proportional to the acceleration. And two methods that can predict when and how fingers will slip upon a grasped object are considered. To emulate the human's capabilities, we propose a method for determination of a grasp force, which uses the change in the friction force. Experimental results show that the proposed method can be applied to control of robot hands to grasp objects of arbitrary weight stably without skin-like slip sensors.

1. Introduction

Recently, a large amount of research has been done in the area of dexterous robot hands. The main issue has been how to control mechanical hands so that they can perform manipulation tasks with the same dexterity and sensitivity as the human hands. In general, dexterous robot hands provide versatility for fine motions, and also allow control of gripping forces which provide more efficient grasps. This ranges from securely grasping an object to prevent slipping to grasping a delicate object so that it is not damaged.

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To solve these problems analytical studies of grasping and manipulation by robot hands have been done by many researchers[1]-[6]. Yoshikawa and Nagai[1] divided finger forces into two different forces, a manipulation force and an internal force, and defined the manipulation force, which generates the required external object force. Salisbury[5],[6] defined the internal force which is zero in resultant and can be added when necessary to the manipulation force to prevent sliding or breaking contact.

Another approach to control of robot hands is a physiological approach motivated by the study of human hands[7]-[9]. The human hand is a versatile end effecter that can perform intricate tasks. Thus the study of human grasping has long been an area of interest for hand surgery, for designing prosthetic devices. The study also can lead to a grasp taxonomy that can assist robot hands in choosing an appropriate grasp to perform a specific task and can also be used to design efficient grippers[7]. However, all of these taxonomies function only in limited domains, and also the abilities of the human hands which can apply just the right amount of force for grasping an object, and correct the grasping forces during a grasping operation, have not been successfully imitated in robot hands.

In this paper, we describe a physiological approach to control of a robot hand with enough intelligence to grasp an object of arbitrary weight with the correct force, as humans do. Even though the grasping, manipulation and internal forces were well understood in the previous works, methods for determination of those forces are still inadequate for real time implementation, mainly because of their complexity. Thus to determine the magnitude of the grasping forces during a grasping operation, we analyze the human's grasping characteristics and apply the human's capabilities to robot hand control. However, since the human's grasping behavior is too complex we only deal with limited and simplified cases. We assume Coulomb friction and point contact between the human fingertip and the object. Salisbury and Roth[6] showed that grasping a two-dimensional rigid body is accomplished by two point contacts with friction. And we also choose the prismatic grasp using the thumb and the middle finger for precision aspects of a task[7].

In the following sections, we briefly review analytic studies of grasping and examine the assumptions upon which the analysis rests. We then describe a device to be grasped for measurement of the human's grasping forces and an experimental system which can vary the external force applied to the object and make the object slip on the fingertip. In addition, since slip detection plays a vital role in ability to successfully grasp, we discuss two methods that can predict when and how fingers will slip upon a grasped object. Then based on the analysis of the human's capabilities, we propose a method for determining a grasp force even in the presence of slipping, and show the validity of the proposed method by a robot hand which consists of two parallel fingers.

2. Analysis of grasping

Before we analyze the human's grasping characteristics, we discuss analytic issues such as contact types, number of fingers required to achieve grasps, finger forces, and equilibrium.

2.1 Contact models

To study the mechanics of constraint and freedom that take effect when two bodies come into contact, we consider the interaction between the fingers and the object being grasped. Salisbury[6] defines three types of contact: point contact, line contact, and plain contact. This formulation is neat, but it does not take into account surface deformation under load in addition to friction and surface geometry. Cutkosky[11] defines a different set of models: point contact, hard curved contact, flat contact, soft curved contact, and very soft contact. In general human fingertips exhibit rolling and deformation, so the model of the human fingertip is soft and curved. However, most analyses consider the point contact with friction, since it is simple to deal with mathematically. The point contact with friction allows that the fingertip is free to rotate about the point of contact, but sliding along its surface is resisted by a friction force. Therefore, the finger can apply normal and tangential forces to the object, but no moments. And the friction force do not exceed the limits imposed by the Coulomb friction law.

To determine how many fingers are required to obtain certain grasps on the object, Salisbury makes use of screw theory. If S_i is the system of screws along the twist which cause motion, to completely immobilize the object it is necessary and sufficient that the intersection of all S_i is null set:

$$S_1 \cap S_2 \cap \cdots \cap S_n = 0 \qquad (1)$$

For planar motion at least four wrenches, which constrain the motion, are needed to completely restrain an object against all disturbance forces in the plane, and a minimum of seven wrenches are needed to restrain an object in a 3-dimensional space. Therefore two point contacts with friction will completely constrain a two-dimensional object.

2.2 Fingertip Forces

When an object is contacted by fingertips at several contact points, the resultant force on the object is dependent on the contact force vectors. Salisbury[6] identifies the external and internal forces acting on the object. Assume n wrenches act on an object in a 3-dimensional space. We form the $6 \times n$ matrix W. Each column of W consists of the six screw coordinates of one of the wrenches.

$$W = [S_1 S_2 \cdots S_n] \tag{2}$$

For an arbitrary net wrench w to be applied to the object we must be able to find a vector c which satisfies

$$Wc = w \tag{3}$$

If the rank of W is 6 and all unisense wrenches have positive intensities, the grasp can resist an arbitrary disturbing wrench w. When we have more than seven wrenches, $n > 7$, solutions to equation (3) have the form

$$c = c_p + \lambda c_h \tag{4}$$

Here c_p is a particular solution to (3) and c_h a homogeneous solution. c_p represents "manipulation force" which will generate the disturbing wrench, including the effect of object weight, without any interaction force components. c_h lies in the null space of W and represents "internal force" which does not affect the object's equilibrium. λ is an arbitrary free variable which determines the magnitude of the internal force. Thus, by properly choosing the magnitude of the internal force we can ensure that contact will be maintained and frictional restraints kept active even in the presence of external force on the object

The problem here is to determine the magnitude of the internal force. Park et. al.[12] and Nakamura et. al.[13] solved numerical optimization problems to find internal force at a given grasping position. However, humans use the minimum force required for grasping the object, thus minimizing effort and avoid object damage. We shall see in the following section how humans determine the internal force.

3. Determination of grasp forces for two-fingered hands

The human hand is a good example to study, as one of the goals of robot hand design is the emulation of some of its functions. We consider a case in which a human hand reaches and safely grasps a target object. Much of the reaching and grasping behavior of humans arises from a knowledge base which is developed and refined through experience beginning in early childhood. As a human hand reaches to grasp an object, the hand shapes into a posture suitable for the interaction. This approach phase consists of the sequence of actions which lead the hand from an arbitrary position and orientation to the vicinity of the object to be grasped. Visual information is used to locate the spatial location and orientation of the object in space and to determine its size and geometric properties. The identification of the object and the goal of the manipulation lead to the choice of grasp. Numerous classifications of human grasps have been proposed. Cutkosky and Wright[9] present the taxonomy of human grasps, which they organized as a hierarchical tree. We can use these taxonomies to design grippers or to assist in selecting a grasp. Once the contacts are in place, the finger forces required to secure the object are calculated. At this time the sensory input changes from visual to tactile sensors. The human hands can use the minimum force required for securely grasping the object. This process requires the ability to sense slippage, so that the force is increased until slippage stops.

This paper does not attempt to deal with all of these problems; rather, it discusses some of the issues involved in grasping force control. Thus, the finger-object contact is modeled as a simple point contact with friction. The object to be grasped is a two-dimensional rigid body. And we also choose the prismatic grasp using the thumb and the middle finger for precision aspects of a task.

3.1 Measurement of the Human's Grasping Forces

We design a simple experimental device as shown in Fig.1, to measure the human's grasp and friction forces simultaneously as it is grasped.

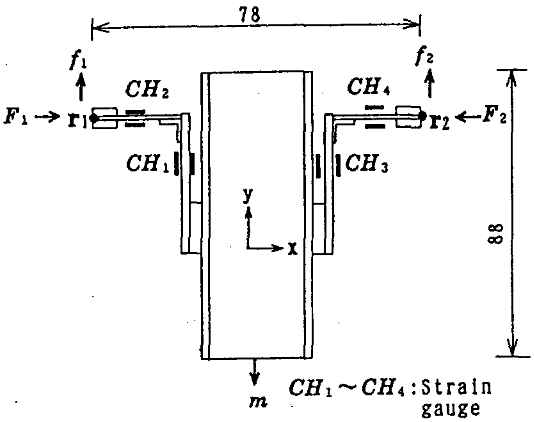

Fig.1 A device for measuring grasp and friction forces

CH_1, CH_3 are force sensors using strain gauges for measurement of grasp forces and CH_2, CH_4 are for friction forces.

Based on assumptions described above, we consider two-fingered hands with planar motion. Let $\boldsymbol{F}_1=[F_1, 0]^T$ and $\boldsymbol{F}_2=[-F_2, 0]^T$ denote the grasp forces applied by the i th finger ($i=1, 2$) on the object in the $x-y$ plane, and let $r_1=[-x, y]^T$ and $r_2=[-x, y]^T$ denote the positions of contact points of fingers. For static equilibrium we have

$$WF = 0 \qquad (5)$$

where

$$W = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -y & -x & -y & x \end{bmatrix} \quad \text{and}$$

$$\boldsymbol{F} = \begin{bmatrix} F_1 \\ 0 \\ -F_2 \\ 0 \end{bmatrix}$$

Then the solution of equation (5) will be

$$F_1 = F_2 \qquad (6)$$

Therefore, the grasp force $\boldsymbol{F} = [\ \boldsymbol{F}_1{}^T,\ \boldsymbol{F}_2{}^T\ ]^T$ satisfies the condition of internal force. In the following experiment we will see how humans determine the magnitude of the grasp force, i.e. F_i.

The friction force f_i satisfies the Coulomb friction law:

$$f_i \leq \mu\ F_i \qquad (7)$$

where μ is the coefficient of friction. Combining (6) and (7) gives

$$F_1 = F_2,\ \ f_1 = f_2$$
$$mg = f_1 + f_2 \leq 2\mu F_1 \qquad (9)$$

where m is the weight of the object.

Since slip detection plays a vital role in ability to successfully grasp, we are interested in knowing when a finger will slip. Using (7) we compute the ratio of a friction force f to a grasp force F :

$$\frac{f}{F} \leq \mu \qquad (10)$$

Note that $(f\,/F)$ equals to be μ as the finger starts to slip.

Another way to look at the onset of slipping is to construct an index, V, and to define the change in V as

$$V = f - \mu F$$
$$\delta V = \delta f - \mu \delta F \qquad (11)$$

which indicates whether a given force applied to the grasped object will cause it to move closer or farther from the edge of slip, and how fast. Therefore if δV is plus, the finger is progressing toward the edge.

Fig.2 shows the experimental system which can vary the external force applied to the object and make the object slip on the fingertip.

We use the following procedure. The object presented in Fig.1 is put on the table, which is attached to a ball screw. And one slightly contacts the object at points $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ with the thumb and the middle finger. Then the table is moved down with acceleration to be commanded, and the human grasps the object with information only from the cutaneous sensors. The force sensor outputs and the position of the table are simultaneously recorded with a computer and A/D converter every 10 msec. The weight of the object is 0.35 kg and the frictional coefficient of fingertip is 0.47 by experiment.

3.2 Experimental Results and Discussion

When the acceleration applied to the object is 2.0 m/sec ^{2} , the experimental result is presented in Fig.3, where F, f are the measured grasp and friction forces, and F_0 is the force calculated by substituting f into equation (7). Thus F_0 is the minimum grasp force required for grasping the object without no slippage. We also present plots of f/F and δV . Note that at time t_1 , f/F is close to μ, and also δV is plus. This indicates there has been slippage on the fingertip. Then the grasp force F is much greater than the minimum force F_0 . But there is no slippage at time t_2 as f/F is far from μ. And F is a little greater than F_0 . From these results, we can see that humans control the grasp force by sensing the friction force, that is, the weight of the object which is felt on his hand. But acceleration on the fingertip, the grasp force becomes much greater than the minimum force by applying the additional force which is proportional to the acceleration.

For determination of appropriate grasp forces it is necessary to detect the magnitude of the slippage as well as the onset of slip. However, work in designing when slip is detected by sensing skin

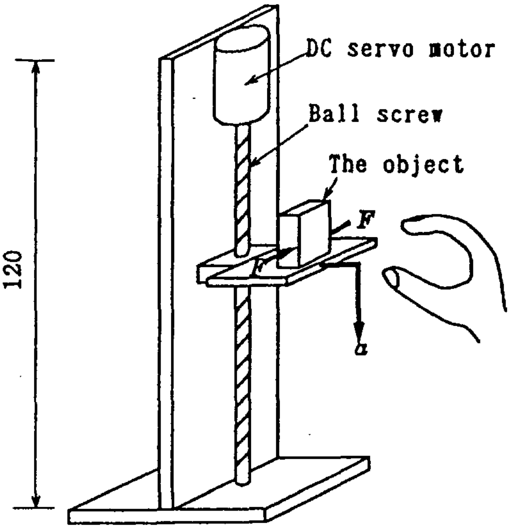

Fig.2 Experimental system

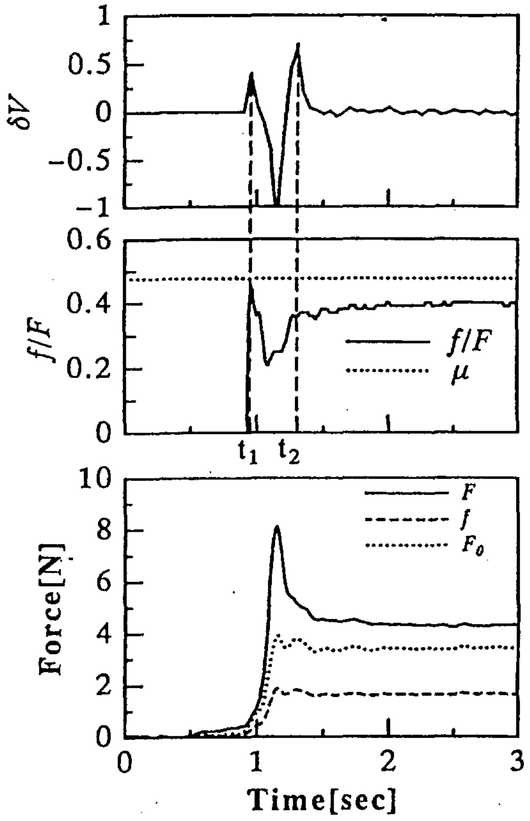

Fig.3 Human grasping characteristics

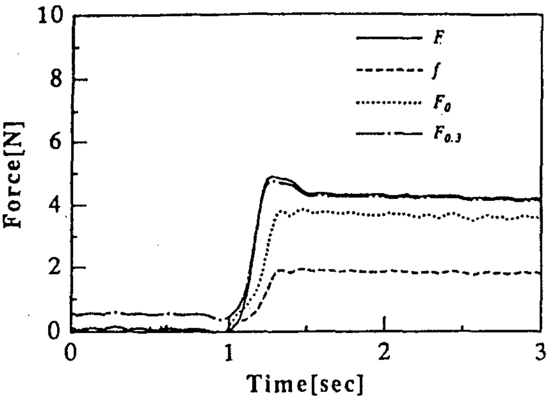

Fig.4 Comparison of actual grasp forces with simulation forces ($a=0.3$ m/sec ^{2})

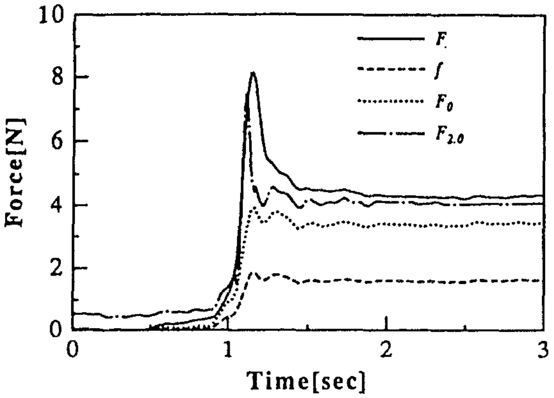

Fig.5 Comparison of actual grasp forces with simulation forces ($a=2.0$ m/sec ^{2})

skin-like slip sensors, such as that presented by Howe et. al.[10], has not yet been applied to building practical devices. Thus full exploitation of human functions has not yet been accomplished, mainly because of the lack of adequate contact sensing technology. But, from δV, which utilizes the change in f we can predict how fast the finger moves towards the edge of slip. So δf will give information about the magnitude of the slip. Using δf we present a method for determination of a grasp force:

$$F = (f + \delta f \cdot k) \cdot \frac{1}{\mu} + F_i \qquad (12)$$

where δf is the change in f, F_i is a contact force and k is a constant. The contact force and the constant were chosen as $F_i = 0.5$ N and $k=8.0$ heuristically. When the accelerations applied on the object are 0.3 and 2.0 m/sec ^{2}, the grasp forces computed from (12) are presented in Fig.4 and Fig.5, where $F_{0.3}$ and $F_{2.0}$ are the calculated forces at each acceleration, and F, f are the measured forces. The calculated forces $F_{0.3}$ and $F_{2.0}$ are almost identical with the measured force F. These results suggest that the proposed method can be applied to robot hands for detemination of grasp forces without skin-like slip sensors.

4. Robot Hand Control

To show the validity of the proposed method for determining the grasp force during a grasping operation, we construct a robot hand which consists of two parallel fingers. The hand is operated by a DC servo motor with harmonic drive

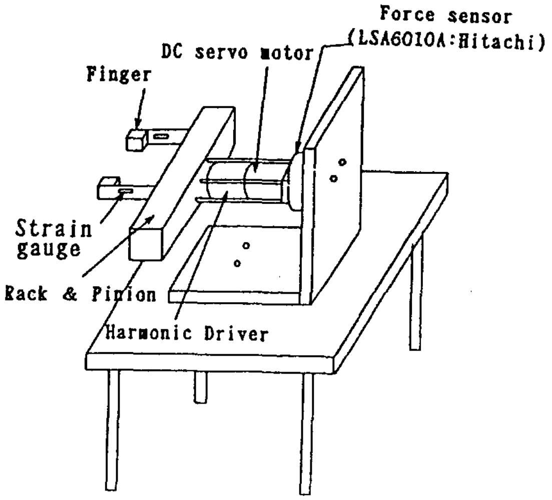

Fig.6 A robot hand with force sensors

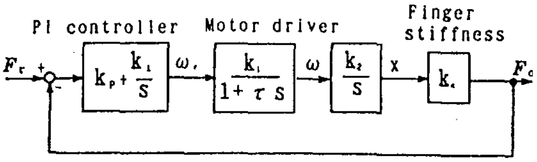

Fig.7 Block diagram of grasp force controller

through rack-pinion as shown in Fig.6. The friction force on the fingertip is detected by employing a 6-axis force/torque sensor which measures the weight of an object to be grasped. A block diagram of the force control loop is shown in Fig.7. The motor driver is modeled as a simple first-order system, where τ is the motor time constant, k_1 is the velocity control gain and ω is the motor shaft velocity. And k_2 is a constant relating the motor shaft position to the finger position x. The finger stiffness k_x relates finger position x to finger grasp force F_o, and hence defines the elasticity of the finger. The proportional gain k_p is calculated in order to keep the response of the force servo approximately critically damped. The integral term is included to remove steady-state errors due to friction. Equation (12) is used to command reference grasp force F_r. We have conducted the experiment for the robot hand to grasp an object of arbitrary weight which is put on the table in the same way of the previous human grasping. Fig.8 and Fig.9 show the experimental results at $a=0.3$ and $a=2.0$ m/sec ^{2}, where $F_i=1.0$ N, $\mu=0.4$ and $m=0.2$ kg. The object can be grasped with approprate grasp forces by the hand without dropping even in the presence of slippage. These experimental results show that the proposed method works successfully.

5. Conclusions

When an object is contacted by fingertips at several points, the finger forces are divided into a manipulation force and an internal force. The magnitude of the internal force can be determined by solving numerical optimization problems. However, humans use the minimum force required for grasping the object, thus minimizing effort and avoid object damage. Thus, we have analyzed the human's grasping behavior to see how humans determine the grasp forces.

Humans determine the grasp forces by

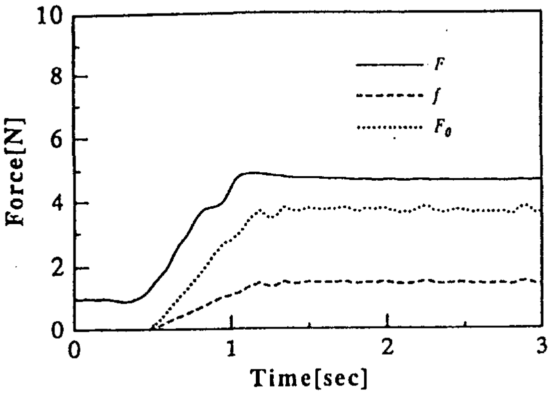

Fig.8 Experimental results of force control with the robot hand ($a=0.3$ m/sec ^{2})

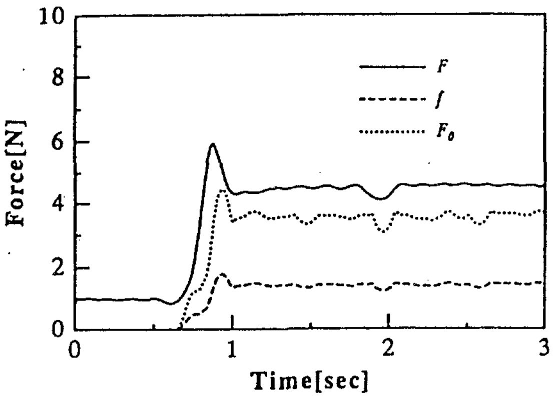

Fig.9 Experimental results of force control with the robot hand ($a=2.0$ m/sec ^{2})

sensing the friction force, that is, the weight of the object which is felt on his hand. But when slip is detected by sensing skin acceleration on the fingertip, the grasp force becomes much greater than the minimum force required for grasping the object. To emulate the human's capabilities, we have presented a method for determination of a grasp force, which utilizes the change in the friction force. Experimental results show that the proposed method can be applied to control of a robot hand to grasp objects of arbitrary weight stably without skin-like slip sensors.

We have discussed preliminary experimental results on human's grasping capabilities based on force control. For more stable grasp operations it will be necessary to consider friction force sensors on the fingertip or skin-like slip sensors.

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