Force Control of a Robot Hand
Emulating Human’s Grasping Motion

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Abstract

This paper describes the force control of the robot hand which is modeled after the grasping characteristics of the human. In the case where the grasped object is moved rapidly, the human precisely changes the grasping forces according to the variations of the fingertip force perpendicular to the grasping direction. The grasping model, which depends on the object's acceleration, is constructed for application to the control system of the robot hand. As a result of the application, it is confirmed that the robot can compensate for the exerted inertial force with not only stable but also efficient and dexterous grasping.

1. Introduction

Stability of precision grasping using robot hands has been an active area of research in the past years. One of the significant issues for performing dexterous manipulations is how to achieve not only stable but also efficient grasping. In the industrial field, there are many cases where stable object manipulation is an important factor. Most industrial robots have been designed for the specified motion under the known environment such as the objects shape and movement span. Therefore little attention has been given to the grasping strategy used for an unexpected force, such as an inertial force which appears when the grasped object is moved quickly. Under the circumstance that the weight or the frictional force of the grasped object is changing, the robot must grasp the object with larger forces beforehand, but it is not ideal when excessive grasping energy is wasted.

It is well-known that the human has the excellent ability to select the optimal grasping force, which is the minimum force used to prevent slipping, through pick and place motions (Westling and Johansson, 1984; Kim et al., 1993; Nakazawa et al., 1996). In dynamic human grasping motion, Flanagan and Wing (1995) investigated the stability of precision grasping forces during cyclic arm movements with a hand-held load. Their research revealed that the grasping forces are modulated in parallel with the load, regardless of the movement frequency and texture of the grasped surface. Kim et al. (1993) also examined the grasping force when a grasped object is shaken and pointed out that the characteristics of strengthening and loosening the grasping force are different with respect to the value of the compensation force.

This paper suggests one method for controlling the robot hand, which is modeled after the grasping characteristics of the human when the inertial force acts on the grasped object. First of all, the characteristics of the human grasping behavior are investigated in the case where the grasped object is moved up and down repeatedly by synchronizing the movement with sounds signals. Next, utilizing the experimental results, the grasping characteristics for compensating the acted inertial force are applied to the force control of the robot hand.

2. Measurement of human grasping behavior

2.1 Experimental device

Figure 1 shows the experimental tool which is used to measure the grasping force. The object is grasped by the thumb and middle finger at points A and B, respectively. Forces are measured by the pasted strain gauges through a low-pass filter [cut off frequency: 200 Hz] and an amplifier. From the values of three laser sensors, it can be found whether the posture of the object is slanted off the horizontal or not. The object position is calculated to be equivalent to height from the floor, the origin is the floor.

2.2 Experimental method and subjects

In the experiment, the subject grasps the object in free space and moves it up and down in the vertical direction periodically. Up and down motions are determined by synchronizing it with the sound signals. The target amplitude is 50mm. The computer makes sound signals in periods of 0.4, 0.55, 0.7, 0.85, 1.0, 1.15, 1.30 and 1.45 seconds. The experiment was practiced for ten times beforehand. The subjects are four male persons whose ages are from 22 to 27 years old.

2.3 Minimal force for grasping

A simple model of the object movement is made to derive the minimal grasping force by which the object can be held. As shown in Figure 2, assuming that the object is moved up with the acceleration α in the vertical direction, the equation of motion is given by

\[ m \alpha = f_1 + f_2 - mg, \]  

where \( f_1 \) and \( f_2 \) are frictional forces, \( m \) is the mass of the object, and \( g \) is the acceleration due to gravity. From the Coulomb friction law, the relationship between the frictional force \( f_1 \) and the grasping force \( F_1 \) is indicated as follows:

\[ |f_1| \leq \mu F_1, \]
where $\mu$ is a static frictional coefficient. Provided that the posture of the grasped object isn’t slanted off the horizontal and the frictional force of both sides are almost equivalent. The frictional force $f_1$ can be expressed by

$$f_1 = \frac{m(g + \alpha)}{2}. \quad (3)$$

So the condition to grasp the object is given by

$$F_1 \geq \frac{m(g + \alpha)}{2\mu}. \quad (4)$$

An equal sign is satisfied when the grasping force is the minimum force required to hold the object. At this moment the grasping force is defined as the minimal grasping force $F_1^*$. Static frictional coefficient $\mu$ is derived from the ratio between the grasping force and the mass of the experimental object at the instant when the object starts to slip down from the fingers. The mass of the object is $0.58\text{kg}$.

3. **Human grasping behavior for compensation of the inertial force**

3.1 **Experimental results**

The experimental result of the subject A is shown in Figure 3. As shown in this figure, while the grasped object is moved up and down periodically, the human changes the grasping force simultaneously. The two time trajectories are sinusoidal and their phase difference is approximately 180 degrees. Figure 4(a) and (b) show the time trajectories of the grasping force and its theoretical minimum value which is derived from equation (4). The periods of shaking are 1.0 and 0.4sec. As shown in these figures, it is found that the grasping force is controlled by matching the theoretical force, regardless of the shaking speed. Even though the shaking motion is very quick, the human controls the grasping force to compensate for the inertial force. If the cycle of sound signals is shorter than 0.4sec, it is so quick that a human cannot synchronize the cycle of shaking with the sound signal. The safety factor in the figures are equivalent to: $N$ as follows:

$$N = \frac{F_t}{F_t^*}. \quad (5)$$

It is the ratio between the human grasping force $F_t$ and its theoretical minimum force $F_t^*$. When the period is 1.0 sec, the safety factor is almost constant. In the case of 0.4 sec, the safety factor changes periodically. When the grasping force becomes the maximal value, the safety factor keeps constant value, which is about 1.3. Considering that the value of the force is compensated for, the characteristics of increasing the grasping force differs from that of decreasing. In the case where the frictional force on the fingertips becomes smaller by the inertial force temporarily, the theoretical force is also decreased but the human doesn’t reduce the grasping force positively.

3.2 **Analysis**

For detailed analysis, the grasping force $F_t$ and $F_t^*$ are approximated by using the following equation $F_{fit}$:

$$F_{fit} = F_{amp} \sin \{\omega (t + \frac{\phi}{\omega})\} + F_{mass} \quad (6)$$

where $\omega$ is frequency, given by $2\pi/T$ ($T$ is a period of time). $F_{amp}$, $F_{mass}$, $\phi$ are appropriate parameters. The first term in equation (6) expresses the compensation for the inertial force, and the second term is the center of amplitude. Here, to derive the approximate parameters, the Levenberg Marquardt method is used to derive the parameters of equation (6). In Figure 4, dotted sine waves express the result of fitting the measured force and theoretical value. The amplitude of the parameter $F_{amp}$, and the delay time are shown in Figure 5. The delay time is dependent
on the difference of $\phi/\omega$ in equation (6) between the theoretical force and the measured force. Note that the amplitude of theoretical force (triangle marks) becomes smaller as the period of shaking time increases. As shown in this figure, the amplitude of measured force (black circle marks) is changed according to the value of the inertial force. As the period becomes longer, the delay time is increased while the amplitude of the measured force is reduced. In quick shaking motion, the delay time cannot be observed, so up and down motions are performed with grasping motion of increasing and decreasing simultaneously. It is considered that this dexterous behavior is not only based on sensing the inertial force, but also predicting them. If the shaking motion is slower, the delay time is about 0.2 sec longer. The parameter $F_{max}$ is shown in Figure 6. Note that the center of amplitude of the theoretical force is constant with no relation to the shaking speed. When the period of shaking is 0.4 and 0.55 sec, the center of amplitude of the measured data $F_{max}$ is approximately two times as large as the center of amplitude of the theoretical force. However, if the period is more than 0.7 sec, its values become slightly greater than the theoretical one. Namely, the human controls the grasping force efficiently with the minimum grasping energy during slow shaking. On the other hand, in quick shaking motion, the task of moving the object and adjusting the grasping force at the same time is performed without any feedback of sensing.

4. Force control of robot hand emulating human grasping behavior

The previous section showed the characteristics of human grasping behavior when the inertial force acts on the grasped object. In this section, the obtained
Table 1 Parameters $\kappa$ and $T$ of four subjects.

<table>
<thead>
<tr>
<th>subject</th>
<th>$\kappa$</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.51</td>
<td>0.0482</td>
</tr>
<tr>
<td>B</td>
<td>1.29</td>
<td>0.0427</td>
</tr>
<tr>
<td>C</td>
<td>1.83</td>
<td>0.0325</td>
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<tr>
<td>D</td>
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<td>0.0388</td>
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</table>

characteristics are applied to the force control of a robot hand. It can be considered that the control system for compensating the inertial force is separated into two types. One type is based on the planned displacement. If the path planning of the grasped object is determined, the inertial force can be derived by differentiating the planned displacement before performing the movement. Considering the situation above, the control system is constructed with the feed-forward loop of the displacement through the differential controller. The other type depends on the observed acceleration when the path cannot be specified, such as master-slave manipulation. Here, the unplanned movement of the grasped object is considered. The latter type is applied to the control system.

4.1 Control of the grasping force

Figure 7 shows the relationship between the acted acceleration of the grasped object and the safety factor $N$ in the case of subject B. Note that the positive and negative accelerations represent the lower and upper directional movements, respectively. As shown in this figure, while the acceleration is increased in the positive range, the parameter $N$ stays constant. On the other hand, for negative acceleration, the safety factor $N$ decreases as the acceleration increases. It can be confirmed that the characteristics of grasping behavior for compensation of the inertial force are different according to the direction of the acceleration, namely the direction of the movement. This characteristic is approximated as follows:

$$N(\alpha) = \begin{cases} \kappa & (\alpha \geq 0) \\ \frac{T}{\alpha^2} + \kappa & (\alpha < 0) \end{cases}$$

where $\kappa$ and $T$ are parameters, and $\alpha$ is object acceleration. The equation above is indicated with a broken line in Figure 7. Table 1 shows the parameters $\kappa$ and $T$ of the four subjects. Each subject has its own value of the safety factor, which depends on the complicated factors such as the individuals fingertip sensitivity (Westling and Johansson, 1987), the frictional coefficient of the fingertips (Shimada et al., 1996), and their own experiences (Forssverg et al., 1991). But their characteristics have the same qualitative trend and it can be represented by using the model above. Here, this approximated model is used to determine the force of the robot hand.

4.2 Robot hand and control system

The robot hand, to which the human characteristics are applied, is shown in Figure 8. Two fingers are moved by DC servo motors through the ball screw, and each finger can be shifted in one direction. Grasping forces are measured by the pasted strain gauges. Figure 9 shows the control system for the robot hand. To observe the acceleration of the moving robot hand, the accelerometer is attached on the robot hand. The control block diagram is shown in Figure 10. $F(\alpha)$ represents the grasping force to compensate for the inertial force which is calculated from the observed acceleration. The sum of the reference input $F_d$ and disturbance $F(\alpha)$ is applied to the controlled element after being multiplied by the safety factor $N(\alpha)$, which is changed by the acceleration and expressed by equation (7). Involving the influence of the inertia, the desired force $F_i(t)$ is defined as follows:

$$F_i(t) = N(\alpha, t)\{F_d + F(\alpha, t)\}.$$  

(8)

Input $u(t)$ can be expressed by

$$u(t) = K_p\{F_i(t) - F(t)\},$$  

(9)
where $F(t)$ is output, or the measured grasping force and $K_p$ indicates the proportional gain. In the experiment, the robot hand is moved up and down repeatedly in the Z direction (see Figure 8) by using PUMA (Kawasaki Heavy Industries: PH561). The grasped object is 0.28kg, and the parameter $K$ is 1.7, $T$ is 0.0427.

### 4.3 Experimental results

Figure 11(a), (b) show the experimental results performed by the robot hand. In this experiment, the parameters $K_p$ is set to 0.5, and the period is 0.7sec. In Figure 11(a), the safety factor $N$, by which the desired force is multiplied for stable grasping, is constant ($N=1.7$). It can be confirmed that observing the acceleration of the grasped object enables the robot to control the grasping force for compensating the exerted inertial force, just like a human. However, at the time of reaching the minimal value of theoretical force, there are some possibilities for the grasped object to be dropped because the difference between the controlled force and theoretical force becomes smaller. In the case of a human, when the inertial force is exerted in the upper direction, the grasping force is not excessively reduced. So the parameter $N$ is set to be changed by the value of the acceleration. The experimental results are shown in Figure 11(b). Note that the variation of the safety factor depends on the objects acceleration, and its time trajectory has peaks when the object reaches the upper most position during shaking. Compared with the case where the parameter $N$ is constant, the active motions of reducing the grasping force are avoided. It can be confirmed that modeling after the human characteristics will produce both stable and efficient manipulation of robot hand.

The used hand has various dynamics with respect to the mechanical structure. The delay time between the desired force and the current one occurs naturally. As for a human, the fingertips consist of elastic component and the flexible hand has many de-

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**Fig. 11** Experimental results of controlling the grasping force when performed by a robot hand (Period is 0.7 sec).

**Fig. 12** Experimental results of controlling the grasping force when performed by a robot hand (Period is 0.4 sec).

**Fig. 13** Control block diagram with PD feedback loops.
degrees of freedom, therefore there is a probability that the delay time will occur when the grasping force is strengthened or loosened. The experimental results of the subjects showed that the delay time occurs in slow shaking motion, but when the human shakes the grasped object very quickly, the delay time cannot be observed. As the shaking motion becomes faster, improving the control system of the robot hand is required in order to avoid delay. Figure 12(a) shows the experimental results under the condition that the period of time is 0.4sec. In this experiment, the robot hand was fixed, that is, standstill, and only the accelerometer was shaken by the subject. Therefore the inertial force cannot act on the grasped object, and when the time trajectory of the grasping force crosses that of the theoretical force, it can be assumed that the grasped object is slipping down. With only a proportional feedback loop, when the two time trajectories intersect, there is a possibility that the grasped object will be dropped. Even though the proportional gain is increased, the delay time cannot be improved. To solve this problem, the differential feedback loop is added to the control system as shown in Figure 13. Input $u(t)$ can be given by

$$u(t) = K_p \{ F(t) - F(t) \} - K_d \frac{dF(t)}{dt},$$ \hspace{1cm} (10)$$

where $K_d$ indicates differential gain. Figure 12(b) shows the experimental result in the case where the control system includes the differential feedback loop. Parameters $K_p$ and $K_d$ are set to 0.5 and 0.07, respectively. For the case of adding a differential feedback loop, the delay time is improved and the stability for grasping can be secured. If the parameter $K_d$ is a higher value, the force for compensating the inertial force is larger, and it is necessary to select the optimal parameter $K_d$.

5. Conclusion

In this paper, the human characteristics of controlling the grasping force was investigated, and applied to the control system of the robot hand as one of the new grasping strategies. When the grasped object was moved up and down repeatedly, the human precisely controlled the grasping force according to the variations of the fingertip force in the tangential direction to the tip surface. The characteristics of strengthening and loosening the grasping force were different with respect to the ratio between the minimal force and the applied force. From the obtained characteristics, the model for determination of the grasping force, which depends on the acceleration of the grasped object, was made for controlling the grasping force of the robot hand. As a result of the application, it could be confirmed that the robot manipulation was performed with no excessive force but with stable grasping to prevent dropping an object, just like a human.

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