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Grasping Force Control of Multi-fingered Robot Hand based on Slip Detection Using Tactile Sensor

Daisuke Gunji***, Yoshitomo Mizoguchi*, Seiichi Teshigawara*,
Aiguo Ming*, Akio Namiki**, Masatoshi Ishikawaand** and Makoto Shimojo*

Abstract— **To achieve a human like grasping with a multi-fingered robot hand, the grasping force should be controlled without using information from the grasped object such as its weight and friction coefficient. In this study, we propose a method for detecting the slip of a grasped object using the force output of Center of Pressure (CoP) tactile sensors. CoP sensors can measure the center position of a distributed load and the total load applied on the surface of the sensor, within 1 ms. These sensors are arranged on the fingers of the robot hand, and their effectiveness as slip detecting sensors is confirmed in tests of slip detection during grasping. Finally, we propose a method for controlling grasping force to resist tangential force applied to the grasped object using a feedback control system with the CoP sensor force output.**

I. INTRODUCTION

In order for robots to achieve the same level of precision in manual operation that humans achieve, many researchers are working on highly versatile, multi-fingered robot hands that offer a high degree of freedom. A typical operation of hands is grasping objects. In the past, since it was assumed that robots would grasp specific objects, it was sufficient to use a simple gripper structure as a hand, and to set its grasping force to the required value. However, since each grasped object has a different coefficient of friction and weight, to achieve human-like grasping, it is necessary to set the grasping force appropriately for each object without being aware of this data in advance. Moreover, in order to grasp objects without damaging them, it is desirable to grasp them with the minimum force without slip. Various slip sensors have been proposed to achieve this kind of grasping ability [1].

In human grasping, Johansson et al [2][3] showed that localized slip between the skin and the grasped object is an important factor in adjusting grasping force. Maeno et al [4][5] proposed an elastic finger for distributed sensing using strain gauges with a curved surface, and showed that by imitating the method of grasping objects used by humans, it is possible to pick up any object for which the weight and friction coefficient is not known, at any speed. However, this approach involves the disadvantages of having to produce dedicated fingers, and the requirement for many strain amplifiers to support the arrays of strain gauges. Melchiorri [6] has proposed a method of controlling grasping force by detecting translation and rotational slip using force/torque sensors based on strain gauges, and distributed tactile sensors. However, with this approach the static friction coefficient of the object must be known. Furthermore, since distributed tactile sensors are used, wiring them into the robot is a problem. Ikeda et al [7] have proposed a method of controlling grasping force by measuring the degree of eccentricity of the contact surface using a camera. With methods such as this using vision, how to incorporate cameras in relatively small places such as hands is a problem. Furthermore, processing speed depends on the frame rate of vision, and it is generally difficult to achieve slip detection at high speeds.

This paper shows an approach to slip detection using thin, flexible, lightweight two-dimensional center of pressure tactile sensors (Center of Pressure sensors, hereafter “CoP sensors”) [8][9] that can be mounted on a robot hand. CoP sensors can measure the center position of a distributed load applied to the surface of the sensor and the total load itself within 1(ms). Thus, rapid slip detection can be achieved. Furthermore, only four wires are needed, irrespective of the size of the sensor area, making it easy to mount them on a robot hand. This paper describes slip detection tests using CoP sensors and shows that slip can be detected immediately before it occurs based on the force output of the CoP sensors. Next we show that when force is added to a grasped object causing slip, it is possible to achieve grasp control to resist the force using a force control system with feedback from the force output of the CoP sensors. Finally we propose a method of grasping with optimal grasping force for the object even when its friction coefficient is not known, by adjusting the grasping force based on slip detection using the output of the CoP sensors.

II. STRUCTURE AND FEATURES OF THE SENSOR

A. Structure and Features of the CoP Sensor

CoP sensors can measure the center position of a distributed load and the total load itself [8][9]. The structure of the CoP sensor, as shown in Fig.1, consists of pressure sensitive material sandwiched between two sheets of conductive film, Layers A and B (upper and lower layers respectively). Both edges of the conductive film are electrodes, and we can derive the center position of the current distribution from the potential difference of the electrodes on both conductive film layers. Considering the pressure characteristic of pressure conductive material, it is possible to regard the center position of the current distribution as the center position of

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*Graduate School of Electro-Communications, The University of Electro-Communications.

**Graduate School of Information Science and Technology, The University of Tokyo.

***NSK Ltd, Emerging Techonologies R&D Department.

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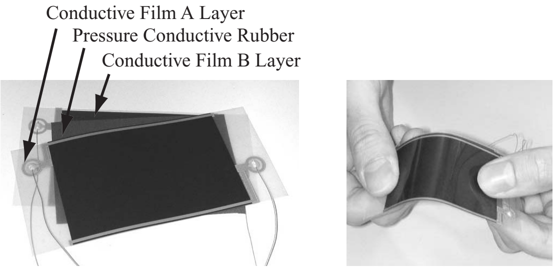


Fig. 1. Structure of CoP Sensor

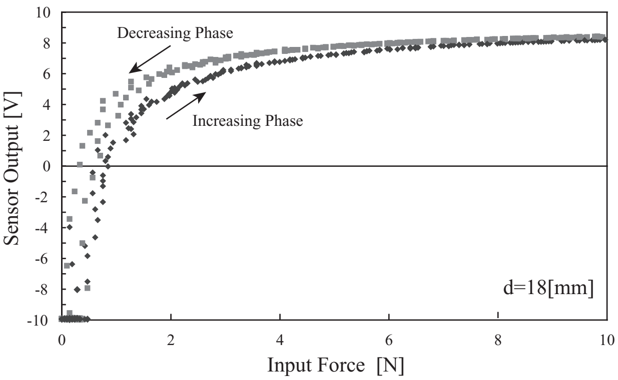


Fig. 3. Total force output characteristics

the load distribution, and the total current which flows circuit as the total load applied to the sensor.

Since CoP sensors consist of thin and flexible materials, they can be used arranged on curved surfaces. Furthermore, they find the center position of load distribution using the potential difference of the electrodes on both conductive film layers, so only four wires are required for the sensors, irrespective of their area, ensuring compact wiring. That is to say, CoP sensors have features that suit them to mounting on robot hands.

The arithmetic processing of the CoP sensors is achieved with simple analog circuits alone. Therefore, the time taken for calculation is very short, thereby achieving a high-speed response within 1(ms). Thus the sensors can be used directly in control loops of 1(kHz).

B. Output Characteristics of CoP Sensor

1) Position and Total Force Output: The position and the total force output characteristics of CoP sensor are shown in Fig.2 and Fig.3 respectively, when arranged on cylinder with diameters of 18(mm) equivalent to the finger-tip of the hand to use for an experiment. The point where pressure is applied and the output voltage of the sensor are in proportional relationship. The results show that as the pressure applied increases, the output of the sensor increases. In addition, with increasing and decreasing pressure the output differs, demonstrating hysteresis properties.

2) Slip Detection: We inspected behavior for tangential force of CoP sensor with the experimental system as shown in Fig.4.Firstly, the two fingers of the hand with the CoP sensors grasped an object.After grasping the object starts, the hand was made to maintain the same joint angle. The grasped object is connected to a DC motor by a wire, and was started to slip vertically downwards due to rotation of the DC motor. Vertical slip displacement of the grasped object was measured with a laser displacement sensor (Omron: ZX-LDA11-N) above the object. The outputs of the sensor and laser displacement sensor were input into a computer via an AD board (Interface: PCI-3168). The control cycle of the hand and the sensor output sampling cycle was 1(ms).

The results of the tests are shown in Fig.5. The figures show the slip displacement of the grasped object measured with a laser displacement sensor and the CoP sensor output (force output and position output). The change in CoP sensor position output due to the occurrence of slip is small with a maximum of 0.3(V). Immediately before slip displacement occurs, the total force output of the CoP sensors falls significantly (the shaded area of sensor force output in Fig.5). Thereafter at the stage where slip displacement is happening, the force output increases again, and during slip, complex changes are indicated. Since these characteristics may change depending on covering material, we performed the same experiment about some materials. As a result, the almost same characteristic was confirmed for all materials. Thus, It

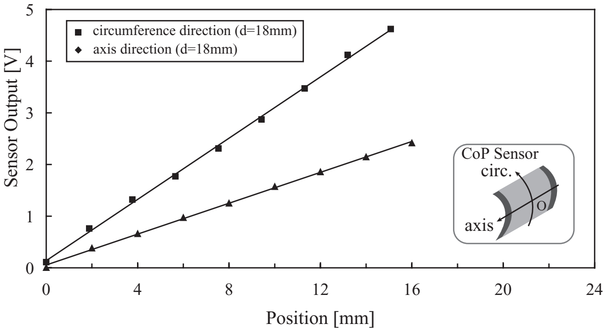


Fig. 2. Position output characteristics

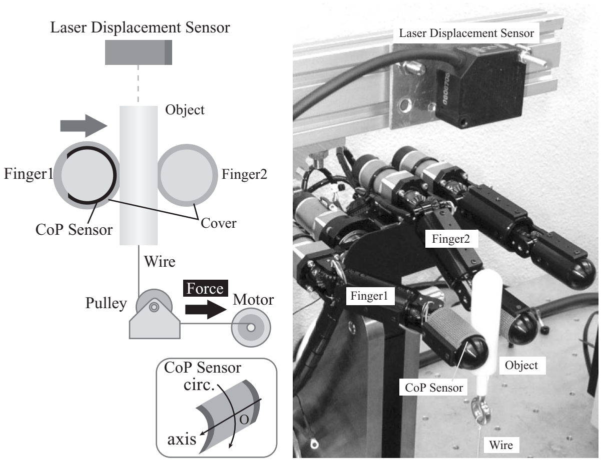


Fig. 4. Experimental system of slip detection on grasping

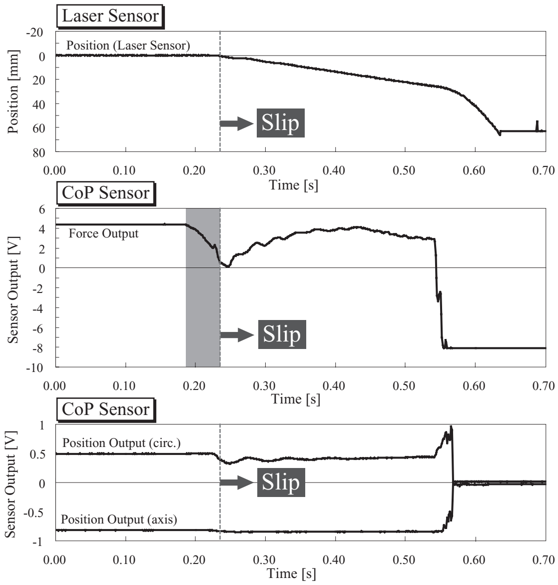


Fig. 5. Experimental result of slip detection on grasping

is thought that falling of total force output of CoP sensor can use slip detection.

III. MULTI-FINGERED ROBOT HAND

In this research we used the high-speed three-fingered hand developed by Namiki et al [10]. This hand has three finger modules with two degrees of freedom, and it comprises joints that swivel the fingers on both sides. The finger modules incorporate an AC servomotor, harmonic drive, and encoder for driving the joints, and each joint is driven with a bevel gear.

Although small and light, this hand can open and close 180 degrees in 100(ms). In addition, it achieves high instantaneous output, obtaining greater grasping force than earlier hands. Furthermore, the hand has the superior characteristic in that backrush in the fingers overall is almost 0.

The maximum torque of the fingertip joints of the finger modules is 0.35(Nm), while that of the basal joints and swivel joints is 2.65(Nm). The control system feeds back the current target joint angle in relation to the target joint angle and sends commands regarding the torque of each joint using PD control. The control system was built on a PC with ART-Linux (kernel-2.4.22-0vl2.11ART) as the OS. The control cycle is 1(ms).

CoP sensors were mounted on each joint of the finger modules. The method used to mount the sensors on the finger modules is shown in Fig.6.

IV. CONTROL OF A MULTI-FINGERED ROBOT HAND TO RESIST SLIP

A. The Basic Concept behind Grasping Force Control

From the test results in Section II-B.2, it is clear that immediately before slip displacement occurs, the CoP sensors show changes in force output. Using this characteristic, we propose a method of control in which grasping force is increased when tangential force causing slip is detected. Hereafter, we will call the proposed control system anti-slip control.

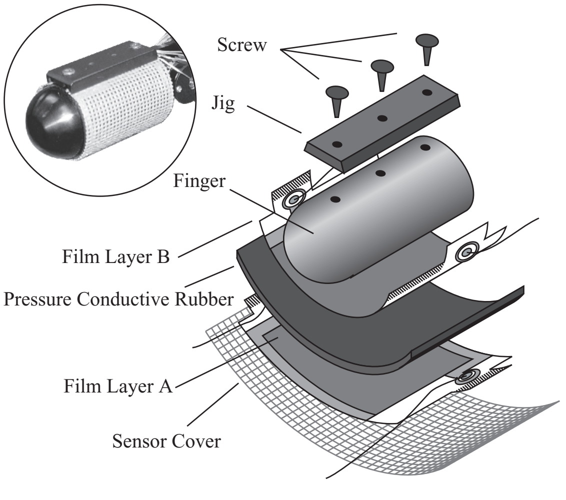


Fig. 6. Installation of CoP sensor

In the test described in Section II-B.2, vertical downward force was applied to the grasped object therefore there should be no change in normal force even at the stage when CoP sensor force output is changing. That is to say, force output of the CoP sensors actually shows a smaller value than for normal force. In relation to this, we considered control that achieves a certain sensor force output. If the sensor force output falls due to the occurrence of slip, control works to increase the force output. As a result, it is supposed that as an amount of slip force increases, the grasping force also increases through control.

In other words, with only a force control system that feeds back the CoP sensor force output, grasping force control that resists tangential force without any special control should be possible.

The proposed anti-slip control can be achieved with just a simple force control system, and no information about the grasped object whatsoever is required. However, if there is no margin in the target grasping force for the limits of friction, or if strong tangential force is applied, it is possible that increased grasping force from the control system will be insufficient and slip will occur.

B. Control System

As described in the previous section, with only a force control system that feeds back the CoP sensor force output, grasping force control that resists tangential force is possible. So damping control as shown in formula (1) was added to the PD control of the joint angle of the hand as anti-slip control.

$$\theta_{\mathrm{ref}} = \hat{\theta}_{\mathrm{ref}} + \hat{A}\int (V_{\mathrm{ext}} - V_{\mathrm{ref}})\,dt \tag{1}$$

Here, $\hat{\theta}$ is the target joint angle, $\hat{A}$ is the coefficient, V_{ext} is the CoP sensor force output, V_{ref} is the target value for sensor force output, and θ_{ref} is the new target joint angle. Normally,

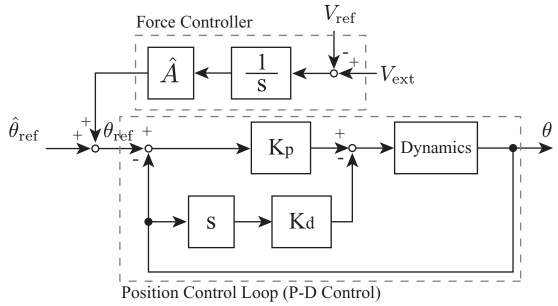


Fig. 7. Control system of muti-fingered robot hand

the force output of the CoP sensors and the relevant target values should be converted from voltage levels to force, but here for the sake of simplicity, the voltage levels themselves are used as is. Also for simplicity's sake, the position of the hand is not considered. Fig.7 shows the configuration of the control system.

C. Test Method

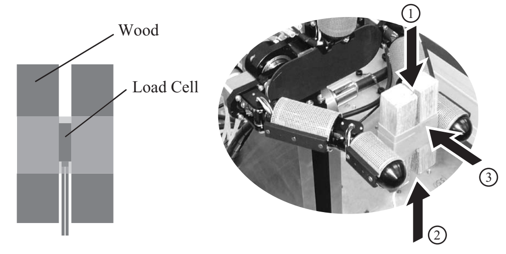
The hand grasped an object and when tangential force was applied to the grasped object, changes in the grasping force were measured.

As shown in Fig.8 (a), an object with a load cell built into it was grasped by the fingertip joints of the hand.Anti-slip control was only applied to the basal joints of the fingers grasping the object. The target value of the sensor force output was $V_{\mathrm{ref}} = 3.0(V)$.

After the object was grasped, tangential force was applied by human hand to the grasped object. As shown in Fig.8 (b), tangential force was applied to the grasped object from three different directions in the tests, from above, from below, and from the front.

D. Test Result

Fig.9 shows the grasping force measured from the sensor force output and load cell with anti-slip control. The time shown shaded in the figure is when tangential force is applied. Furthermore, the numbers shown in circles indicate the direction of tangential force, corresponding to Fig.8(b). Irrespective of the direction in which the tangential force is applied, it is apparent that the load output of the CoP sensors falls significantly at the same time as tangential force is applied.



(a) Grasping object (b) Tangential force direction

Fig. 8. Experimental result (without anti-slip control)

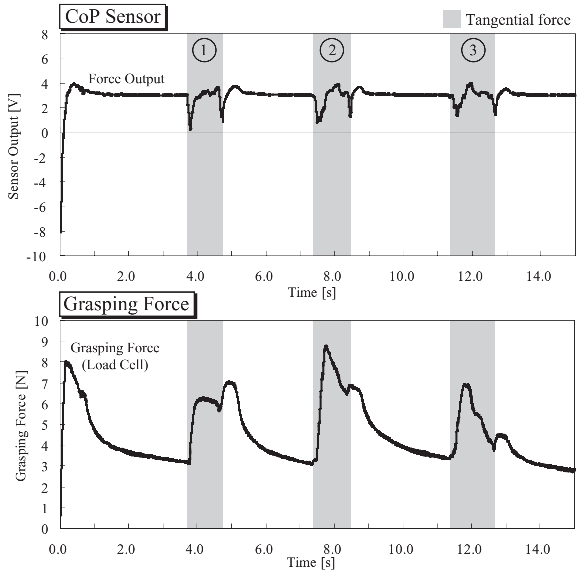


Fig. 9. Experimental result (top:without anti-slip control / bottom:anti-slip control)

When anti-slip control is applied, grasping force increases significantly as soon as tangential force is applied. Furthermore, it is apparent that in all cases grasping force increases, irrespective of the direction of tangential force.

Therefore, the speed at which grasping force increases, in other words the responsiveness to the application of tangential force, changes with the gain of the control system. The influence of integration gain $\hat{A}$ in particular can be thought to be significant. The greater $\hat{A}$ is, the faster the response, but there is a greater possibility that instantaneous grasping force will be excessive, breaking the object.

The results of the tests show that with simple force control that feeds back the CoP sensor force output, it is possible to achieve grasping force control that resists tangential force.

V. MULTI-FINGERED ROBOT HAND GRIP CONTROL BASED ON SLIP DETECTION

A. Basic Concept

As one of the necessary sufficient conditions for a multi-fingered robot hand to be able to grasp an object in a still state there exists the condition that the power of each fingertip of the hand is within the friction cone [11]. Based on this, it is possible to prevent slip if control is performed so that fingertip power always remains within the friction cone. However, for this control a static friction coefficient is required as a parameter. In order to avoid restrictions on the objects that can be grasped, an approach is required that allows control even when the static friction coefficient is unknown. Therefore this paper proposes a method of control in which appropriate grasping force for the grasped object can be achieved even when the coefficient of friction and weight of the grasped object are unknown, using the force output of CoP sensors.

The basic concept of the proposed approach is as follows. When a hand grasps an object, if the grasping force is too weak, the object will slip. However, if this slip is detected and the grasping force is increased slightly, when the required grasping force is reached, slip no longer occurs. In the above process, all that is required is detection of slip and a corresponding increase in grasping force, and no information about the grasped object is required whatsoever. This approach is similar to the control method that humans may be supposed to use.

From the test results in Section II-B.2, it is clear that immediately before slip displacement of the grasped object occurs, the force output of the CoP sensors falls. Therefore, we propose a control method that regards this change in output as occurrence of slip, and increases the grasping force with a target in accordance with the occurrence of slip. With the proposed method, grasping force is controlled based only on sensor output, so no information about the grasped object such as the coefficient of friction is required whatsoever. Furthermore, since changes in sensor output can be obtained immediately before slip displacement occurs, if the hand operates fast enough, it should be possible to adjust grasping force before slip displacement occurs in most cases.

B. Control Method

The basic control system is the anti-slip control proposed in Section IV. Here, grasping force is adjusted by changing the target value for sensor force output V_{ref} in relation to the sensor output. Hereafter, we will simply call the target value for sensor force output V_{ref} the "target valu".

In the proposed method, a low value is first set for V_{ref}, and grasping of the object starts. After grasping starts, V_{ref} is changed in accordance with formulas (2) and (3). Δt is the control cycle.

When $V_{\text{ref}}(t) - V_{\text{ext}}(t) > V_{\text{th}}$

$$V_{\text{ref}}(t+\Delta t) = V_{\text{ref}}(t) + K_{\text{fp}}\{V_{\text{ref}}(t) - V_{\text{ext}}(t)\} \tag{2}$$

When $\dot{V}_{\text{ext}} < c$ and $V_{\text{ref}}(t) - V_{\text{ext}}(t) > 0$

$$V_{\text{ref}}(t+\Delta t) = V_{\text{ref}}(t) - K_{\text{fd}}\dot{V}_{\text{ext}} \tag{3}$$

Here, $V_{\text{th}}(>0)(V)$ and $c(<0)(V/s)$ are appropriate threshold values, and K_{fp} and K_{fd} are coefficients.

It can be said that the smaller the threshold value V_{th} and c in each conditions, the greater the sensitivity to slip. However, if the threshold value is too low, even if slip is not occurring, the target value will be increased, and the grasping force will be excessive. In addition, since the bigger the coefficients K_{fp} and K_{fd}, the faster the target value is increased, it is possible to reduce the occurrence of slip displacement, but at the same, the possibility that grasping force becomes excessive also increases. Therefore, it is necessary to set appropriate values for these parameters, taking into account the responsiveness of the multi-fingered robot hand used for grasping.

C. Test Method

We tested the proposed control method on the multi-fingered robot hand, grasping an object for which the coefficient of friction and mass were unknown. The experimental system is shown in Fig.10.

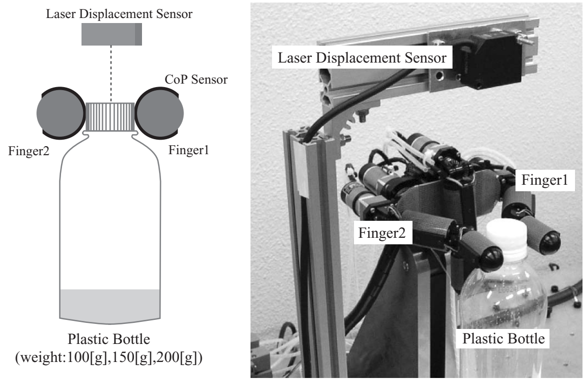


Fig. 10. Experimental system of grasping force control

The grasped object is a plastic bottle with water in it. By changing the amount of water in the bottle, its weight was set at 100(g), 150(g), and 200(g), and testing was conducted with each weight. Slip displacement of the bottle was measured with a laser displacement sensor (Omron: ZX-LDA11-N) above the object. The outputs of the sensor and laser displacement sensor were input into a computer via an AD board (Interface: PCI-3168). The control cycle of the hand and the sensor output sampling cycle was 1(ms).

First, the robot hand was made grasp the plastic bottle held by a human. After the hand grasped the bottle, the human let go of it so that only the hand was holding it.

Grasping control was only applied to the basal joints of the fingers grasping the bottle. Slip-resistant mesh (approx. 1(mm) lattice, thickness 0.5(mm)) was used to coat the surface of the sensors. The initial target value was $V_{\text{ref}} = 6.0$(V). The sensor force output voltage when unloaded was -8.0 V. The various parameters were $V_{\text{th}} = 1.0$(V), $c = -30.0$(V/s), $K_{\text{fp}} = 3.0 \times 10^{-3}$, and $K_{\text{fd}} = 5.0 \times 10^{-4}$.

Separately from the above test, we also examined the minimum grasping force that can be used to grasp the same object as in the test above without slip, in order to evaluate the proposed control method. Using the anti-slip control proposed in Section IV, we repeatedly changed the target value Vref in increments of 0.5 V for each weight of the grasped object until the hand grasped it without slip. The results for the minimum necessary grasping force were target values of -1.5 V (100 g), 1.0 V (150 g), and 3.5 V (200 g) respectively.

D. Test Results

Fig.11 shows the slip displacement of the grasped object with weight of 100(g), the sensor force output, and the target value. Table I shows the grasped object with weights of 150(g) and 200(g), with the target grasping force at the point when stable grasping was achieved V_{ref}(V), the minimum necessary grasping force V_{ref} (Min) (V), the displacement that occurred up to stable grasping, and the time required up to that point.

The results of the test show that for all weights of object, grasping force was adjusted in accordance with the weight of the object using the proposed control method. When slip

TABLE I

EXPERIMENTAL RESULT OF GRASPING FORCE CONTROL

	Weight		
	100 (g)	150 (g)	200 (g)
V_{ref} (V)	-0.24	1.4	3.7
V_{ref} (Min) (V)	-1.5	1.0	3.5
Slip (mm)	0.54	1.4	2.5
Adjustment time (s)	0.60	1.09	0.83

displacement and sensor force output are compared, the force output of the sensors falls significantly when slip displacement occurs, and the target value is increased accordingly. Furthermore, in all cases, adjustment of grasping force was performed in about 1(s). The slip displacement from the start of grasping to stable grasping is 0.5(mm) (100(g)), 1.4(mm) (150(g)), and 2.5(mm) (200(g)) respectively, and the heavier the object, the greater the slip displacement that occurs before stable grasping is achieved.

E. Discussion

Regarding the stable grasping state in the test results, when the target values obtained with the proposed control method and the minimum grasping force found in other tests are compared, the values are somewhat greater for objects of 100(g), but with objects of 150(g) and 200(g), values that largely match were obtained. Furthermore, the time required from the start of grasping to when grasping force was adjusted and stable grasping was achieved is short at 1(s). Even under the stringent conditions in this test when the object was passed in midair and the force was changed suddenly, stable grasping was achieved with relatively little slip displacement.

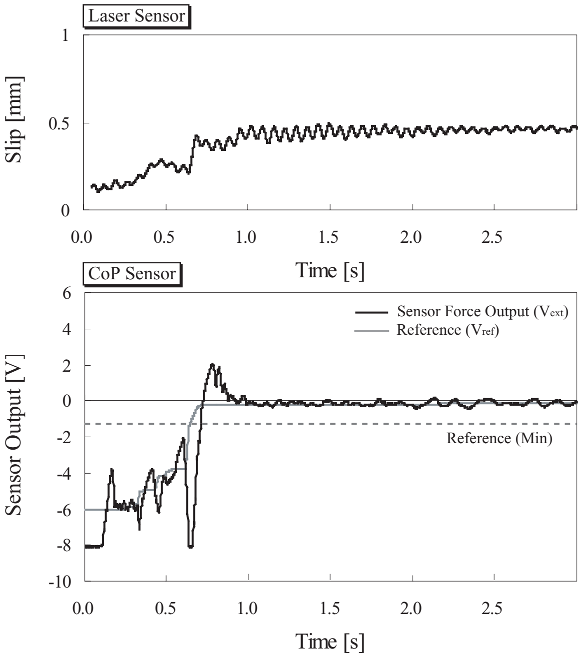


Fig. 11. Experimental result of grasping force control (weight:100g)

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper we proposed an anti-slip control method using these characteristic force output changes, and confirmed the effectiveness of the proposed method through testing. Furthermore, we proposed a method of adjusting grasping force in response to slip detected using sensor force output, and in testing using the proposed method, we showed that optimum grasping force can be obtained even when no information about the grasped object is known.

B. Future Works

The reasons for the occurrence of the characteristic changes in sensor force output immediately before slipping occurs must be clarified. In addition, by covering the sensor surface with appropriate material, it should be possible to infer the direction of slip of an object from changes in the sensor position output. We will confirm these matters in future testing.

This paper describes tests with a relatively simple grasping position, but the proposed control method can probably also be applied to more complex grasping positions such as power grasps. Therefore in future we will examine control methods that take grasping position into consideration, with the aim of achieving dexterous grasping similar to that of humans.

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