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

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

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

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

Here, $V_{\mathrm{th}}(>0)(V)$ 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.

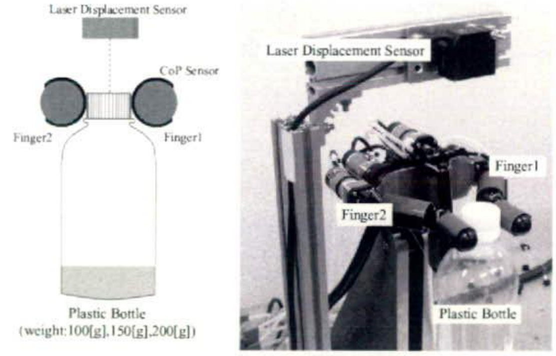

Fig. 10. Experimental system of grasping force control

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 $V_{\mathrm{ref}} = 6.0$(V). The sensor force output voltage when unloaded was -8.0 V. The various parameters were $V_{\mathrm{th}} = 1.0$(V), $c = -30.0$(V/s), $K_{\mathrm{fp}} = 3.0 \times 10^{-3}$, and $K_{\mathrm{fd}} = 5.0 \times 10^{-4}$.

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.

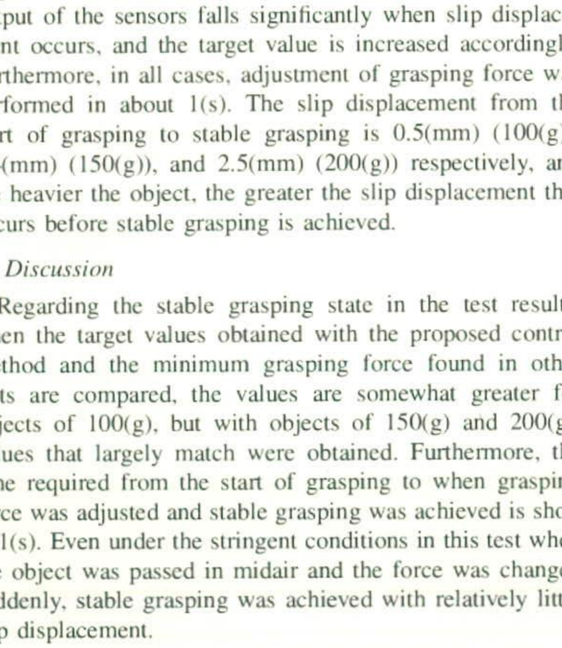

Fig. 11. Experimental result of grasping force control (weight:100g)

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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