Regrasping Control by Multi-fingered Robot Hand

KAZUHIKO TERASHIMA*, JUAN URBANO*, TAKANORI MIYOSHI*, KAGETOSHI ITO*, TAKASHI IMAMURA*, HIDEO KITAGAWA**

(*) Department of Production Systems Engineering; Toyohashi University of Technology; Hibarigaoka 1-1, Toyohashi; JAPAN,

(**) Department of Electronic Control Engineering Gifu National College of Technology Kamimakuwa, Motosu, Gifu JAPAN

Abstract: In this paper, a smooth regrasping control method of multi-fingered robot hand is proposed. First, four-fingered robot hand with 13 joints was built. Second, manipulation and grasping algorithm of four-fingered robot hand is easily calculated by applying the algorithm made for three-fingered robot hand to the two pairs of three-fingered robot hand. In order to reduce the vibration generated while regrasping, a smooth algorithm for regrasping is presented. Finally, the effectiveness of the present method is demonstrated through experiments.

Keywords: Multi-fingered robot hand, regrasping control, vibration, manipulation.

1 Introduction

Robots are in need in industrial field where tasks and operation are done with high speed and accuracy and in non-industrial fields where assistance to personal and increased convenience are needed. A support robot in non-industrial fields must be able to move multiple ways and get along with human beings.

Previously the developed welfare robot includes a walk support robot, a food tray carrier, and a meal assistance robot. It is difficult, for these robots to manage tasks alone, why humanoid robots were developed. Robot hands making complex moves are actively under study.

Hence, grasping and manipulation by multi-fingered hands have been studied for improvements of the manipulation technology in robotics ([1] - [5]). However, there is very few study on concrete application by using multi-fingered hand. The authors have already studied on development of expert-massage robot for supporting health-care problems. In this field, position control and force control for the motion such as pushing and rubbing are needed.

On the other hand, in addition to the application of multi-fingered hand to health-care and welfare fields, the authors are also interested in the bottle-picking problem in industry. In this problem, a target object must be found by the camera system, and the object is grasped by robot. Then, through transferring the object by robot, the object is inserted in the production machine, and fabricated. The schematic diagram is shown in Fig.1, and the research is now being conducted ([5], [6]).

This technique is highly demanded to establish the flexible manufacturing system and man-free factory. In order to realize this, Japanese factory is actively working to develop the bottle-picking problem like Fanuc Ltd., Kondo Ltd., etc.

However, in any case, gripper or magnetic parts to grasp the object is used. The work is thus limited, and the work capability will be extended if multi-fingered robot hand is applied. For example, it will be possible to flexibly grasp the target object among many parts by humanoid robot hand, and then the regrasping motion enables us to conduct the efficient manipulation.

Under such situation, in this paper, the manipulation and regrasping motion of four-fingered hand is studied. Three-fingered hand is better to realize the stable grasping compared with two-fingered hand. But, three-fingered hand is insufficient, because two-fingered grasping is generated while regrasping. Therefore, four-fingered hand robot is appropriate to conduct the stable grasping, because three-fingered grasping can be maintained while regrasping only one finger. Five-fingered hand has many redundancy. So, in this paper, four-fingered hand is adopted. Up to the present, the grasping control problem for multi-fingered hand has been studied by many researchers, for example [1], and its problem has been almost solved. But, there are still a lot of problems in the field of manipulation and regrasping for multi-fingered hand in experiments. Expecially, the study on dynamitic control for regrasping of multi-fingered hand has scarecely been found, in spite of improtance in real application. Further, when the regrasping motion is instantaneously conducted, the grasping state will become unstable or oscillatory, and therefore the smooth regrasping motion is indispensable.

In this paper, the smooth regrasping control by multi-fingered robot hand to build the flexible bottle-picking problem in near future is proposed. First, in order to treat the formulation of three-fingered and four-fingered hand in the same framework, we consider the state of four-fingered grasping as two pairs of the stable grasping by three-fingers. Then, the algorithm of manipulation and grasping developed for three-fingered hand by T. Yoshikawa, et al ([1]) is used for our purpose. Second, the smooth algorithm for regrasping is presented to avoid the irregular motion generated in regrasping the object. Finally, the effectiveness of the proposed method is demonstrated through experiments, by comparing with the case of the regrasping instantaneously.

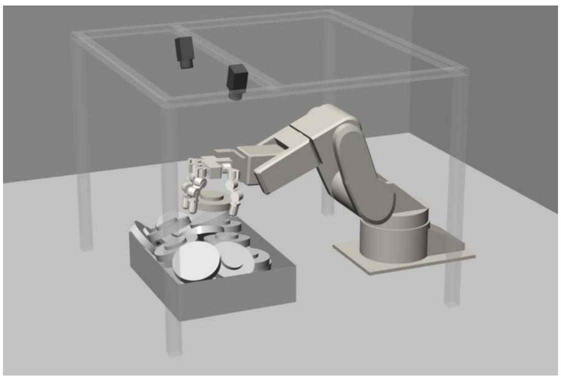

Figure 1: Schematic diagram of Bottle-Picking System by using multi-fingered robot hand

2 Multi-fingered Robot Hands System

The multi-fingered, multi-jointed humanoid robot hand is shown in Fig. 2. It has 4 fingers with 13 joints. The 1^{st} finger (Thumb) has 4 joints, and the 2^{nd} to 4^{th} fingers have 3 joints and are arranged like those of the human hand. The thumb is opposal and redundant. It is 203.9 [mm] length and 222.2 [mm] width, about 1.2 times larger than an adult man's hand.

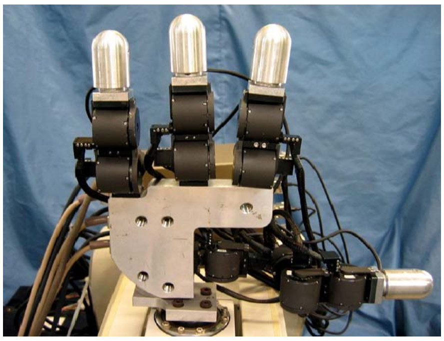

Figure 2: Humanoid Multi-fingered Robot Hand

The small AC servomotor actuator for the robot hands as shown in Fig. 3 is 30 [mm] in diameter, 30 [mm] length, 70 [g] in weight, and generates 1.4 [Watt]. This small sized-motor was manufactured by the Yaskawa Electronic Corporation. The servomotor has an integrated harmonic gear (1/80) and encoder, and directly drives each joint. The fingertip force sensors are the fingertip type of 6-axis force sensors made by BL Autotech Ltd., and is shown in Fig. 4. By using this sensor, three components of force (Fx,Fy,Fz) and three components of momentum (Tx,Ty,Tz) could be measured. Furthermore, user interface and operation environment is shown in Table 1.

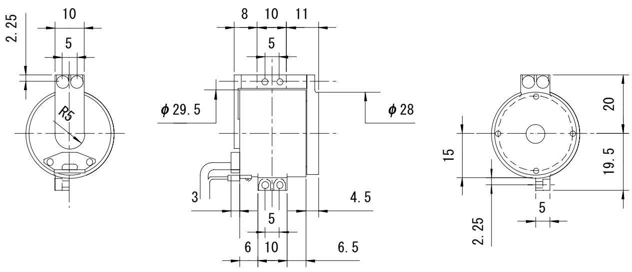

Figure 3: AC servo motor

Figure 4: Force sensor

Table 1:

PC Unit	Processor	Pentium IV 2530 MHz
	Memory	512 MB
	D/A board	Interface PCI-3346A
	A/D board	Interface PCI-3177C
	Counter board	Interface PCI-6205C
Operation Environment	OS	Red hat 7.0
	Sampling time	2 [ms] (500 [Hz])

3 Basic Equation

3.1 Equation of Motion of Mechanism and Object

The equations of motion for each finger is represented by

$$M_f(q)\ddot{q} + \hat{h}_f(q,\dot{q}) + J_f^T F = \tau \quad (1)$$

$$\hat{h}_f(q,\dot{q}) = h_f(q,\dot{q}) + g(q) + f(\dot{q}) \quad (2)$$

,where $\tau = [\tau_1^T, \tau_2^T, \tau_3^T]^T \in R^9$ is a driving torque to finger joint, $F = [f_1^T, f_2^T, f_3^T]^T \in R^9$ is a fingertip force. Here, $M_f$and $\hat{h}_f$ shows the inertia matrix and nonlinear term comprised of centrifugal and Coriolis force. $g(q)$ is gravity term, $f(\dot{q})$is the term of friction force, and q is the joint angle.

On the other hand, the equation of motion for object assuming as rigid body is represented by

$$M_o(r)\ddot{r} + h_o(r,\mathbf{v}) = T \quad (3)$$

$$T = J_o^T F \quad (4)$$

Here, r is a position and a posture of the object, and $T = [f^T, N^T]^T \in R^6$ is a resultant force, where

$$f = \sum_{i=1}^{3} f_i \quad (5)$$

$$N = \sum_{i=1}^{3} ({}^oP_i \times f_i) \quad (6)$$

Further, $M_o(r)$ is the inertia matrix, $h_o(r,\mathbf{v})$ is nonlinear term comprised of a centrifugal, Coriolis and gravity. $J_o \in R^{9\times 6}$ is a matrix determined by the grasping position to the object, and ${}^oP_i$ is a position vector from the origin of object coordination to each contact point C_i.

3.2 Constraints Condition

In this paper, grasping and manipulation is assumed to be point-contact between finger and object, and it is assumed that slipping phenomenon is not generated.

Translation velocity $\dot{P}_i$ of the object at each grasping point C_i in the standard coordination $\sum_b$ is given by

$$\dot{P}_i = \dot{r}_p + \omega_o({}^bR_o\,{}^oP_i) \quad (7)$$

,where ${}^oP_i$ is a position vector from the origin of object coordination to each contact point C_i. Here, r_p is a position vector from the origin of standard coordination $\sum_b$ to the origin of object coordination $\sum_o$, and ω_o is the angular velocity of object seen from the standard coordination $\sum_b$. ${}^bR_o$ is a transition matrix to transform from the standard coordination to the object coordination.

On the other hand, the velocity $\dot{P}_i^{f_i}$ of each finger is represented by using Jacobi matrix J_{f_i} of each finger as follows:

$$\dot{P}_i^{f_i} = J_{f_i}\dot{q}_i \tag{8}$$

,where $\dot{P}_i^{f_i}$ is the translation velocity of finger f_i at the contact point C_i seen from the coordination of the *i*-th finger, and J_{f_i} is a Jacobi matrix with respect to the *i*-th finger, where $J_{f_i} \in R^{3\times 3}(i = 1, 2, 3)$.

In order that each finger is operated for the object with no slip and no detouch, the velocity $v = [\dot{r}_p^T, \omega^T]^T \in R^6$ of the object and the joint velocity $\dot{q} = [\dot{q}_1^T, \dot{q}_2^T, \dot{q}_3^T] \in R^9$ consisted of the joint velocity $\dot{q}_i \in R^3(i = 1, 2, 3)$ of each finger must be agreed as follows.

$$J_o v = J_f \dot{q} \tag{9}$$

,where J_f is a Jacobian matrix, comorised of $J_f = diag[J_{f1}, J_{f2}, J_{f3}] \in R^{9\times 9}$.

4 Control System

In this paper, control system of grasping and manipulation for the object uses the method of Yoshikawa, et al ([1]). Following to the literature ([1]), the main idea and algorithm for three fingers is summarized as follows:

Grasping force $F_g = [f_{g1}^T, f_{g2}^T, f_{g3}^T] \in R^9$ is defined as the finger force satisfying the following two conditions. (1) $J_o^T F_g = 0$, that is, a resultant force is not given to the object. (2) The limitation of static friction at the contact point is satisfied as

$$\frac{F_{gi}^T a_i}{\|f_i\|} \geq \frac{1}{\sqrt{1+\mu_i^2}}, \quad (i = 1, 2, 3) \tag{10}$$

, where a_i and μ_i is respectively the interior-directed normal vector of the surface of the object and the static friction coefficient. As the concept of the grasping force, the basis vector is given by B_g, and the magnitude between each contact point is given by h_g of the grasping parameter ([1]).

On the other hand, manipulation force of fingertip, $F_m = [F_{m1}, F_{m2}, F_{m3}]^T \in R^9$, is the force to give from each fingertip to the object. Manipulation force satisfies the following three conditions:

1. The specified composite force is given to the object.
2. The manipulation force does not direct the opposite side against the grasping force.
3. The manipulation force does not have the component of the grasping force.

Here, the manipulation parameter h_m represents the magnitude of its force. Then, the following relation holds:

$$F = F_g + F_m \tag{11}$$

$$F_g = B_g h_g, \quad B_g \in R^{9\times 3} \tag{12}$$

$$h_g = [h_{g1}, h_{g2}, h_{g3}]^T, \quad h_{gi} \geq 0, \quad (i = 1, 2, 3)$$

$$F_m = B_m h_m, \quad B_m \in R^{9\times 6} \tag{13}$$

$$h_m = [h_{m1}, \cdots h_{m6}]^T, \quad h_{mi} \geq 0, \quad (i = 1, 2, \cdots 6)$$

Here, when the resultant force T from fingertip to the object is given, h_m becomes

$$h_m = (J_o^T B_m)^{-1} T \tag{14}$$

Then, it follows that

$$F_m = B_m (J_o^T B_m)^{-1} T \tag{15}$$

The manipulation/grasping control system is represented by the diagram as shown in Fig. 5.

By the linearized compensator, the original nonlinear system is linearized in the following:

$$\left.\begin{array}{l} \ddot{r} = u_1 \\ h_g = u_2 \end{array}\right\} \tag{16}$$

,where $u_1 \in R^6$ and $u_2 \in R^3$ is respectively control input to the linearized compensator.

In order to compensate the model uncertainty and disturbance, servo controller is also applied to Eq.(16) as follows:

$$u_1 = \ddot{r}_d + K_P e + K_I \int e dt + K_D \dot{e} \tag{17}$$

$$e = r_d - r \tag{18}$$

$$u_2 = h_{gd} + K_F \int (h_{gd} - h_g) dt \tag{19}$$

, where r_d is a reference of position and posture for the object, and h_{gd} is a reference of the grasping parameter, $\{K_P, K_i, K_D\}$ are control gains of PID controller.

In what follows, PID gain was obtained in the trial and error method as $K_P = 1500$, $K_D = 30$, and $K_I = 20$, where sampling time is 2 [ms].

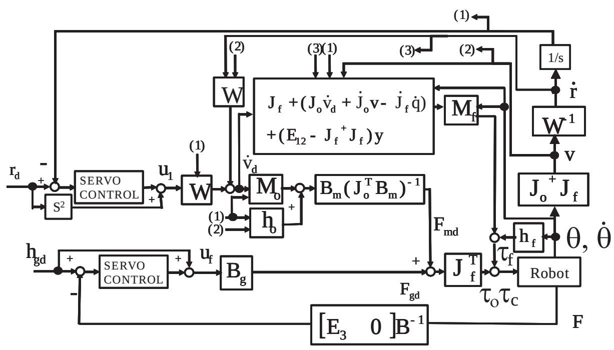

Figure 5: Block diagram of control system for grasping/manipulation

5 Manipulation/Grasping Control Considering Regrasping Motion

5.1 Proposed algorithm for smooth regrasping

In case of four-fingered hand, it becomes easier to realize the stable grasping by always using for grasping three fingers and using for regrasping one finger. Then the four-fingered system can be considered as the composition of two pairs of three fingers.

Namely, before regrasping, we will assume that grasping is conducted by using the finger C_1, C_2 and C_3 (We call it as State B). Then after regrasping, the object is grasped by the finger C_1, C_2 and C_4 (We call it as State A).

The one method of regrasping is to change the grasping state instantaneously from the state (A) to the State (B). However, in this method, unsmooth grasping state, or unstable state will be generated, due to the sudden motion, and then inappropriate vibration phenomenon will be occurred. So, in this section, we will consider the method to realize the smooth regrasping motion. In order to simplify the algorithm of regrasping, in this paper, the grasping with three fingers is assumed during the steady grasping, and then it is assumed that the grasping with four fingers is utilized only while regrasping the finger.

While only regrasping, the state (A) and (B) coexists, and the stable grasping will be able to be achieved by gradually shifting from the grasping of the state (A) to that of the state (B), when the time goes.

The concept of regrasping is shown in Fig.6. In Fig.6, f_{ai} and f_{bi} are respectively the fingertip force in each state (A) and (B), and $f_i = f_{ai} + f_{bi} (i = 1, 2)$.

Then, the smooth regrasing is achieved by linearly shifting the grasping parameter, and thus the following equation is presented:

$$h_g^a(t) = \frac{t_f - t}{t_f} h_g^a(t_0) \tag{20}$$

$$h_g^b(t) = \frac{t}{t_f} h_g^b(t_f) \tag{21}$$

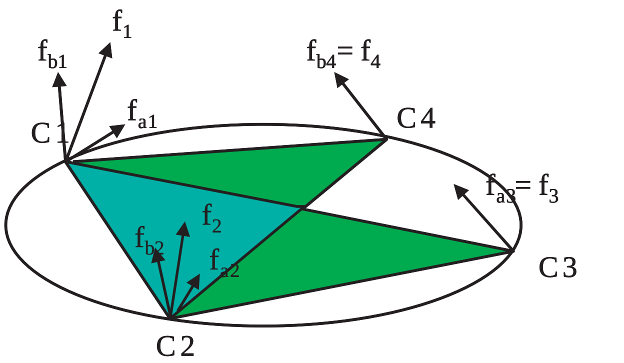

Figure 6: Concept of manipulating force during regrasping

,where $h_g^a(t_0)$ is the grasping parameter in the state (A) before regrasping, and $h_g^b(t_f)$ is the grasping parameter in the state (B) after regrasping, and $h_g^a(t)$ and $h_g^b(t)$ is respectively the grasping parameter for the change of time while regrasping, where t_0 and t_f are the start and end time of regrasping, respectively.

5.2 Decomposition of Fingertip Force for Feedback Control of Reference Grasping Parameter

As shown in Eq.(20) and (21), the reference grasping parameter $h_g^a(t)$ and $h_g^b(t)$ are changed with time, and then feedback control of the output value of grasping parameter are conducted for the reference grasping parameter.

As seen from Fig. 6, fingertip force f_1 and f_2 are composed of the two states (A) and (B).

Here, the stable grasping is respectively designed to be realized for each state (A) and (B), following to the algorithm explained in section IV. Namely, the state (A) and (B) are independently designed such as satisfy the assumption of grasping/manipulation. Therefore, each force f_{a1} and f_{b1} in each state must be independently measured. However, by force sensor, only the resultant force $f_i (i = 1, 2)$ is measured. Hence, decomposition of fingertip force $f_i (i = 1, 2)$ must be conducted for f_{ai} and f_{bi}. Namely, by measuring the $f_i (i = 1, 2)$, both of f_{ai} and f_{bi} must be estimated.

Let us explain on the force decomposition for the finger when the grasping state changes from the state (A) comprised of finger 1st, 2^{nd} and 4^{th} to the state (B) comprised of finger 1^{st}, 2^{nd} and 3^{rd}.

As seen in Fig.7, the composite force measured in the i-th fingertip is calculated by

$$\left.\begin{array}{l} F_x^i = a_i e_{14x} + b_i e_{13x} + c_i e_{12x} \\ F_y^i = a_i e_{14y} + b_i e_{13y} + c_i e_{12y} \\ F_z^i = a_i e_{14z} + b_i e_{13z} + c_i e_{12z} \end{array}\right\} \tag{22}$$

(i=1, 2)

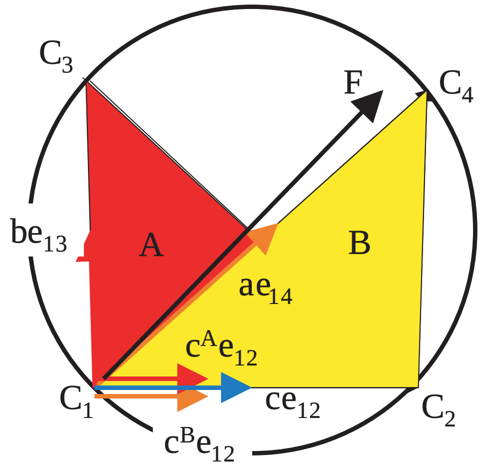

Figure 7: Manipulating force during regrasping

Here, e_{ij} denotes an unit vector from contact point of i-th finger to contact point of j-th finger, and $\{x, y, z\}$ and $\{a, b, c\}$ denote the direction and the magnitude of vector, respectively.

While regrasping, Ce_{12} is the sum of $C^B e_{12}$ in the state (B) and $C^A e_{12}$ in the state (A) as seen from Fig.7. Then, it is easily understood to achieve the decomposition exactly by putting $C^A = \frac{t}{t_f} C$, and $C^B = \frac{t_f - t}{t_f} C$.

The state (A) and (B) is a pair of set for regrasping. There are four pairs of combination in order to transit from the stable three-fingered grasping state to the stable three-fingered grasping state via four-fingered grasping state during regrasping, and all cases are calculated in the same way.

5.3 Experimental Results and Discussion

Simulation and experiments have been done to assure the usefulness of the proposed method with respect to the regrasping motion. Sampling time is 2 [ms]. Cylindrical pipe made by a polyvinyl chloride was used as the object for grasping, where the weight 218.2 [g], the diameter 70 [mm], and the length 135 [mm]. The static friction coefficient between robot finger and the object was measured as $\mu = 0.686$ by experiments.

Firstly, simulation to lift the object up to the 20 [mm] in the X-direction were conducted. Grasping parameter h_g was given by 1.5 [N]. Then, Fig. 8 shows the angle of joint for 1^{st} finger. Output results well agree with reference ones, and object was lifted up to the 20 [mm] in the upper direction. Fig. 9 shows the friction angle while lifting the object.

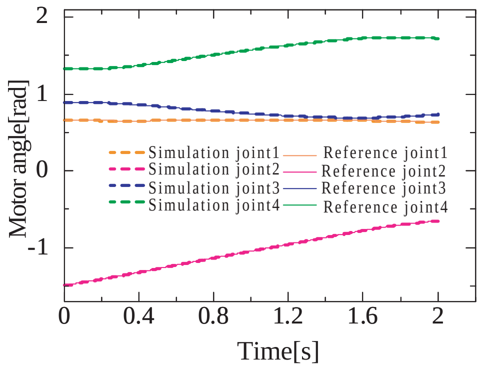

Figure 8: Manipulation simulation result of the 1^{st} finger by lift motion

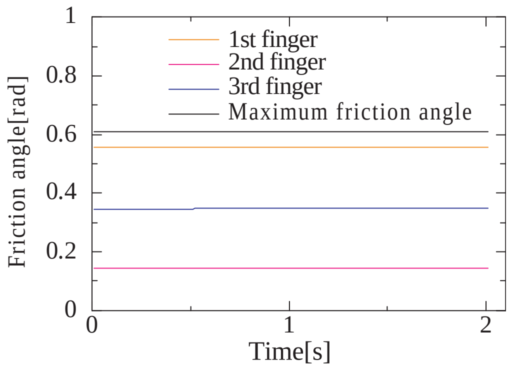

Figure 9: Friction angle of lift motion

In order to achieve the stable grasping, grasping force's direction must enter within the friction cone. In this case, the maximum allowable friction angle is 0.61 [rad], where friction coefficient is $\mu = 0.69$. As seen in Fig. 9, the friction angle of each finger is smaller than the maximum friction angle, and thus the stable grasping was achieved.

Next, the regrasping experiments have been done. First, in order to compare with the proposed method, the experiments have been conducted to instantaneously regrasp from three-finger to another three-finger.

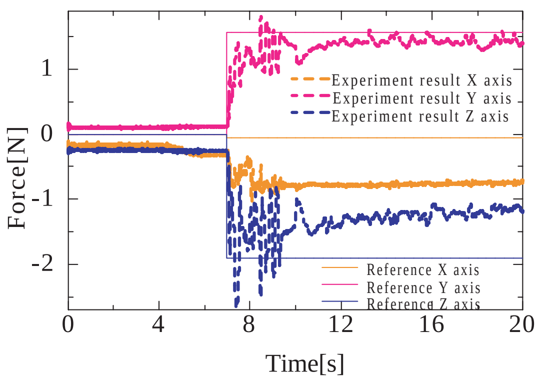

Figure 10: Grasping force of 3^{rd} finger during regrasping

Fig. 10 ~ Fig.12 shows the experimental results by instantaneously regrasping. In the beginning, the grasping is done by using finger 1^{st}, 2^{nd} and 4^{th}, and at time of 7 sec, the grasping is instantaneously switched by using finger 1^{st}, 2^{nd} and 3^{rd}.

Fig. 10 and Fig. 11 show the grasping force of 3^{rd} and 4^{th} finger during grasping, respectively. Because regrasping is occurred at time of 7 [s] suddenly, the behavior of force after 7 [s] is vibrated, and then smooth regrasping is not achieved. Fig. 12 shows the grasping parameter between each finger. After regrasping, the grasping parameter is largely vibrated. This means that the object is being moved during grasping.

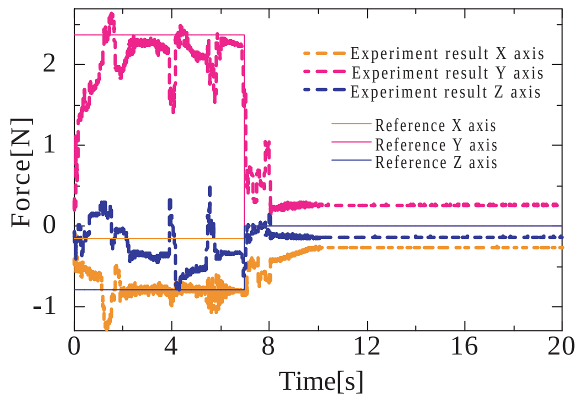

Figure 11: Grasping force of 4^{th} finger during regrasping

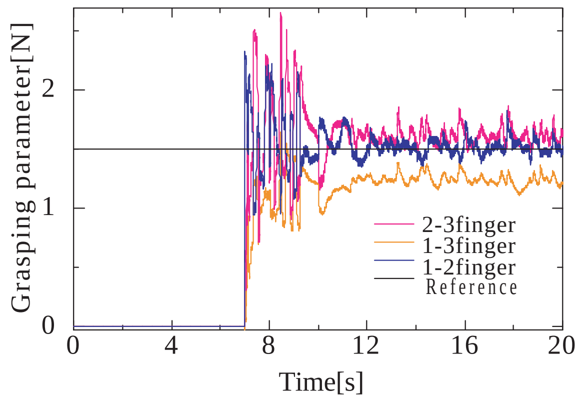

Figure 12: Grasping parameter of 1^{st}, 2^{nd} and 3^{rd} finger after regrasping

On the other hand, Fig.13, 14 and 15 show experimental results of the smooth regrasping case proposed in this paper.

First, the grasping is conducted by using finger 1^{st}, 2^{nd} and 4^{th} until 6 sec, and the smooth regrasping from 4^{th} finger to 3^{rd} finger is conducted during 6~ 8 [s]. Namely, during 6~ 8 [s], the grasping with four fingers is conducted. Then, after 8 [s], the grasping by using finger 1^{st}, 2^{nd} and 3^{rd} is done. During both of grasping and regrasping, the stable grasping and regrasping were achieved, and after regrasping, the vibration of the grasping force is reduced. Furthermore, grasping parameter after regrasping is stable, compared with the instantaneous regrasping, as seen from Fig.12 and Fig.15.

Through these simulation and experimental results, the usefulness of the proposed method was shown.

In this paper, simple regrasping cases were discussed as the basic research. Now, we are preparing in experiments the more complex regrasping case such as conducts simultaneous motion comprised of the both of regrasping the finger and rotating the object. Furthermore, a bottle-picking problem by integrating the regrasping/manipulation control of multi-fingered hand in this paper and vision system [6] developed in authors group will be presented in the near future.

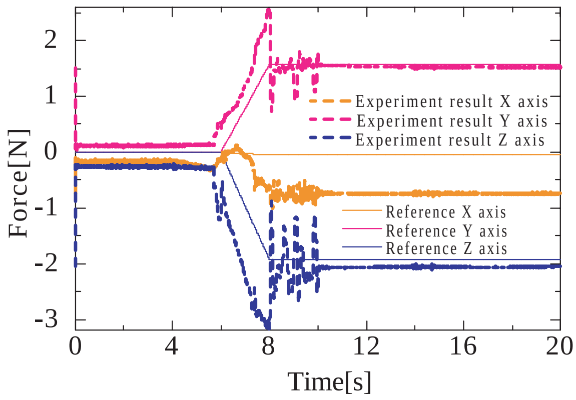

Figure 13: Grasping force of 3^{rd} finger during regrasping

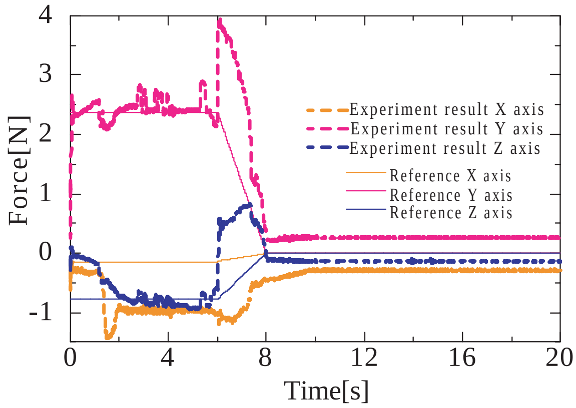

Figure 14: Grasping force of 4^{th} finger during regrasping

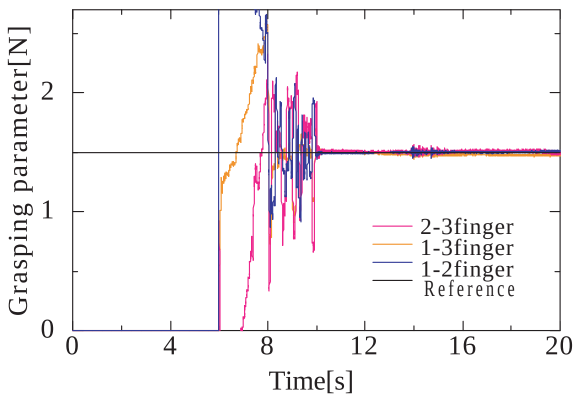

Figure 15: Grasping parameter of 1^{st}, 2^{nd} and 3^{rd} finger after regrasping

6 Conclusions

The contribution of this paper is summarized as follows:

1. The four-fingered robot hand with 13 joints was built.

2. The algorithm for the smooth regrasping of four-fingered hand comprised of two pairs of three-fingered hand systems was presented. Furthermore, a decomposition method of composite fingertip force was presented for realizing feedback control of the grasping parameter.

3. It was demonstrated by experiments that the proposed smooth regrasping method was useful.

References:

[1] T. Yoshikawa K. Nagai, Dynamic Manipulation/grasping ping Control of Multi-fingered Robot Hands, The Society of Instrument and Control Engineering, vol. 30, no. 1, 1994, pp. 39-47.

[2] T. Komatsu and H. Kawasaki, Humanoid Type Robot hand with Built-in Servo Motor, Proc. Meeting of Robotics and Machatronics Meeting of Japan Society of Mechanical Engineering, Tokyo, 1998.

[3] H. Kitagawa, T. Terai, P. Minyong and K. Terashima, Application of Neural Network to Teaching of Massage Using Multi-Fingered Robot Hand, Journal of Robotics and Mechatronics, vol. 14, no. 2, 2002, pp. 162-169.

[4] P. Minyong, H. Kitagawa, and K. Terashima, Expert Massage Motion Control by Multi-fingered Robot Hand, Proc. of The 2003 IEEE, RSJ International Conference on Intelligent Robots and Systems (IROS), Las Vegas, October, 2003, pp. 3035-3040.

[5] K. Terashima, T. Miyoshi, et al, Sense feedback control of Anthropomorphic Robot For Medical and Welfare Support, Proc. of the First Symp. on Intelligent Human Sensing(IHSS2003), Mar. 13, Toyohashi, Japan, 2003, pp. 199-206.

[6] J. Doi, T. Miyake, et al, Shape Modeling from Prototypical Solid Using Silhouettes and Stripe Projection, The 4^{th} IASTED International Conference on Visualization, Imaging, and Image Processing, VIIP 2004.