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Hierarchical Control Method for Manipulating/Grasping Tasks using Multi-fingered Robot Hand

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Abstract

In this paper, we propose a hierarchical control method for manipulation/grasping tasks using multi-fingered robot hands. This method imitates human motion control. Human motion can be divided into two classes, reflex and voluntary movement. Reflex is suppressed by voluntary movement. In the proposed method, a robot hand's grasping control corresponds to human reflex and manipulation control corresponds to voluntary movement. We constructed a controller composed of a manipulation controller, grasping controller and suppresser. The grasping controller has fast feedback but can only execute simple motion. The manipulation controller has slow feedback, and can execute complex motion. Finally, the validity of the hierarchical method is confirmed by computer simulation of various tasks, i.e. grasping, manipulation, and re-grasping motion .

1 Introduction

Robot hands are needed in situations where humans cannot use their own hands directly. Therefore, many robot hands have been developed. Robot hands can be divided into two classes: grippers for industrial use, and robot hands, to imitate the human hand. In precise operations, robot hands with high efficiency and flexibility are required. Therefore, robot hands imitating the human hand are expected. However, the structure of such robot hands is basically very complicated, and control of the robot hand is difficult because hands imitating human's hand have many DOF. Therefore, the establishment of a control method is an important issue in realizing of multi-fingered robot hands, along with the development of hardware.

In the present paper, we define that "robot hand" means "multi-fingered robot hand imitating human's hand".

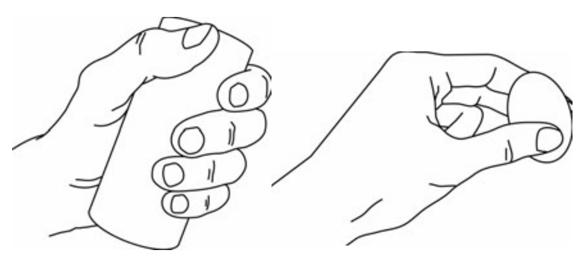
There are two classes in multi-fingered robot hand motion, grasping and manipulation. Grasping is a motion in which the robot hand continues supporting an object stably. Furthermore, grasping is divided into two classes, precision grasping and power grasping, as shown in Fig. 1[1]. In precision grasping, a hand grasps an object by using its fingertips. On the other hand, in power grasping, a hand grasps an object by using both its fingertips and palm. However, power grasping is unsuitable for manipulation, because power grasping takes an optimized form for stable grasping. Therefore, precision grasping is dealt with in this paper.

Manipulation is a motion in which a robot hand changes the position or posture of the manipulating object. Approaches to the object for grasping and re-grasping are included in manipulation.

Yoshikawa proposed an idea, in which the fingertip force is divided into grasping force and manipulation force, which are separately controlled [2]. Many control methods based on the idea of grasping force and manipulation force have been proposed [3][4][5]. Such control methods are effective in manipulation or grasping tasks when the fingers are constantly in contact with an object. Especially, when disturbance is added, a robot hand can continue manipulating/grasping tasks stably because grasping force is determined dynamically. However, the previously mentioned control methods are only applicable for situations when the fingers are in contact with the object throughout the operation. Therefore, the validity of these control methods during re-grasping motion, where fingers do not keep in contact with an object, has not been confirmed.

On the other hand, many studies of re-grasping motion have also been performed [6][7][8]. However, these are only for planning the trajectory of fingertip for re-grasping motion. Therefore, studies on re-grasping motion including dynamic control of robot hands have not been performed.

Nakamura proposed a control method that is not based on the idea of dividing contact force into grasping force and manipulation force [9]. This control method is



(a) Power Grasping (b) Precision Grasping

Fig. 1 : *Two patterns of grasping*

based on the integration theory of reactive behaviors. However, only motion given beforehand is realizable using this control method. Therefore, some motions are unrealizable.

In the present paper, we propose a hierarchical control method, which realize re-grasping motion and any manipulation. The proposed method can be applied for complex manipulation tasks such as assembly work. We confirm the validity of the hierarchical method through computer simulation.

2 Proposal of Hierarchical Control Method

2.1 Control Structure of Human Motions

Human motions can be divided into two classes according to the relationship between stimulus and action: reflex and voluntary movement. In reflex, a stimulus causes a single reaction. Reflex is a very simple motion with fast feedback. For example, stretch reflex is caused by extension of muscles as shown in Fig. 2. The center of this reflex is the spinal cord. Flexor reflex is caused by an external stimulus as shown in Fig. 3. The center of this reflex is also the spinal cord. Especially, in stretch reflex, reflex signals pass along a single synapse, so the feedback of stretch reflex is very fast.

In voluntary movement, a stimulus causes many candidacies of motion, and a real motion is selected in candidacies. In voluntary movement, signals pass a cerebrum, and intention affects the movement. Therefore, voluntary movement can be very complex, but the feedback of voluntary movement is very slow.

Generally, in human motion, there is a relationship of suppression between reflex and voluntary movement, as shown in Fig. 4. In other words, reflex is suppressed by voluntary movement. There are many studies on the suppression of reflex. For example, in spinal reflex, if a stimulus is given to an animal that is not moving, flexor reflex occurs to avoid the stimulus. However, if a stimulus is given to an animal that is walking, such reflex does not occur. This is the result of suppression. Instructions of the flexor reflex are suppressed by instructions of the voluntary movement when an animal is walking. Generally, mammal neurons, which constitute a nervous reflex system, connect to systems, which come out to higher central nervous system. Examples of central nervous system are motor cortex, supplementary motor cortex or premotor cortex. Therefore, higher central nervous system can suppress reflex.

Humans can execute very complex and smooth motion using this relationship of suppression.

2.2 Hierarchical Control Method

The hierarchical control system is shown in Fig. 5. The hierarchical control system consists of three components, a grasping controller, manipulation controller and suppresser. The role of each controller is described below.

The grasping controller generates torque so that slipping between the fingertip and the object does not occur. The fingertip force generated by the grasping controller is set to add up to zero. Time ceded for the feedback loop of the manipulation controller is very short.

The manipulation controller generates torque to manipulate an object. The time needed for feedback of the manipulation controller is longer than that of the grasping controller.

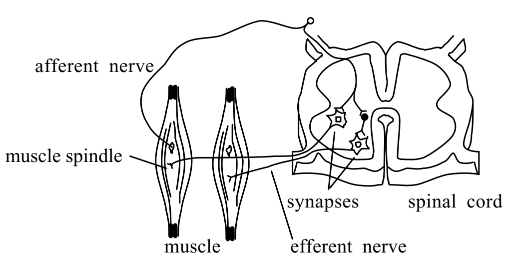


Fig. 2 : *Stretch Reflex*

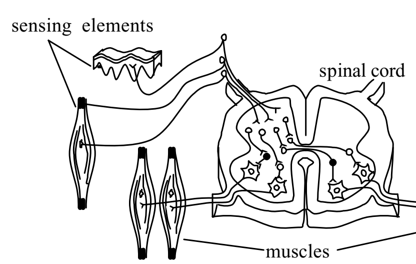


Fig. 3 : *Flexor Reflex*

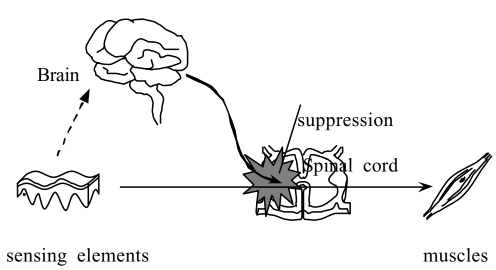


Fig. 4 : *Relationship of suppression*

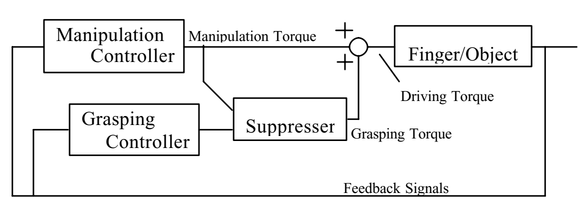


Fig. 5 : *Hierarchical control method*

In some manipulation tasks such as re-grasping, lifting a finger from an object becomes necessary. In this occasion, the manipulation controller generates force to lift the finger from the object, and the grasping controller generates force to maintain the fingers' contact with the object. These two forces may possibly to conflict.

In the hierarchical method, the suppresser is introduced in order to avoid such confliction. The suppresser controls the output of the grasping controller according to the output of the manipulation controller.

2.3 Validities of the method

Validities of the hierarchical control method are shown below.

First, the hierarchical control method can realize re-grasping motion because the suppresser controls the output of the grasping controller. Second, because the feedback loop of the manipulation controller is slow, the hierarchical control method can realize complex manipulation that requires very long time to calculate. Thus, the intended manipulation task can be executed. In addition, hierarchical controller realizes grasping that overcomes external disturbance, because feedback of grasping controller is very fast.

3 Simulation model

The effectiveness of the hierarchical control method is demonstrated through computational simulation. The model of a robot hand is shown in Fig. 6. This model is expressed in a two-dimensional plane. Each finger has three DOF and touches the object with a circular fingertip. To realize re-grasping motion, the robot hand has three fingers. We constructed a dynamical model and the controller model. In this section, details of the models are described.

3.1 Construction of Dynamical Model

The dynamical model simulates motion of the fingers and the object and consists of three models, the finger model, the object model, and the contact model.

The object model simulates motion of an object manipulated by the robot hand. The dynamic equation is given by

$$f = m\ddot{x}$$

$$^{O}\mathrm{N} = {}^{O}\mathrm{I}\,{}^{O}\dot{\omega} + {}^{O}\omega \times \left({}^{O}\mathrm{I}\,{}^{O}\omega\right)$$

where, f is the external force, m is the mass of the object, x is the position of the object, $^{O}\mathrm{N}$ is the external moment, $^{O}\mathrm{I}$ is the inertia of the object, $^{O}\omega$ is the angular velocity of the object. Note that $^{O}\mathrm{N}$, $^{O}\mathrm{I}$ and $^{O}\omega$ are expressed in the object's coordinate system.

In this model, the dynamic equation is integrated numerically by Euler's method. Euler's method is a first-order method. However in this case, the contact model requires a small time-step, which enables us to obtain accurate results using the simulation.

The finger model simulates the motion of the robot fingers. In the finger model, the finger's dynamic equation is calculated numerically, and then integrated numerically. In the finger model, the dynamic equation is calculated by using the Newton-Euler formulation. The dynamic equation is given by,

$$\mathbf{f} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q},\dot{\mathbf{q}})$$

where, **M** is the inertia matrix of robot hand, **h** is the vector of viscous force and coriolis force, **f** is the vector of torque working on joints in generalized coordinates, and **q** is the position of joints in generalized coordinates. In the Newton-Euler formulation, **M**, **h** and **f** are calculated numerically. The dynamic equation is integrated by using the Euler's method. One time step is 0.1 ms in both models.

The contact model simulates the contact between fingers and an object. In the contact model, a surface of an object is approximated as a set of points. The simulation uses a contact model with springs and dampers under the influence of friction, as shown in Fig. 7. In this model, we can consider stick or slip conditions. If a fingertip is in contact with an object, first, we calculate the contact force by using the spring and

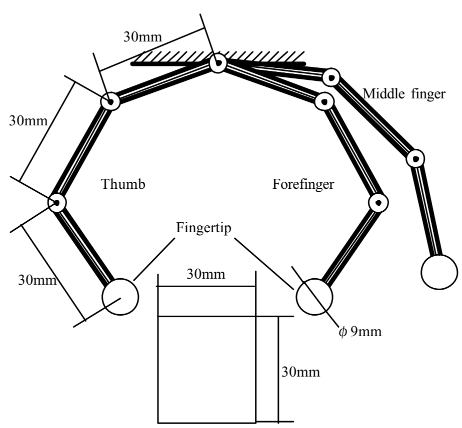


Fig. 6 : *Model of Robot Hand*

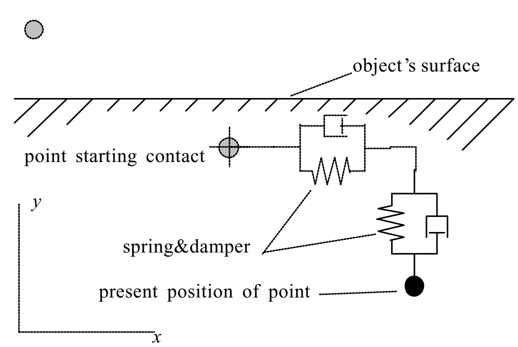


Fig. 7 : *Model of Contact*

damper. Normal contact force f_n is

$$f_n = (x - x_0)\, k_n + u\, c_n$$

and tangent contact force f_t is

$$f_t = (y - y_0)\, k_t + v\, c_t$$

where, x and y are the present positions of a point that constitutes the surface of the object, x_0 and y_0 are the positions of the point starting contact, u is the velocity of a point in the x direction, v is the velocity of a point in the y direction, k_n and k are the elastic coefficients between the point and the object, c_n and c_t are the viscous coefficients between the point and the object. Second, we consider the stick or slip condition. If f_n and f_t fulfill the condition,

$$f_t < \mu_s f_n$$

where, μ_s is the static friction coefficient, then, the finger and the object sticks. In this case, f_n and f_t are true contact forces. However, if f_n and f_t do not fulfill the condition above, then state between the point and the object changes to slip. In such a case, we have to consider the dynamic friction coefficient. In other words, f_t must be re-calculated as

$$f_t = \mu_d f_n$$

where, μ_d is a dynamic friction coefficient.

3.2 Construction of Controller Model

A controller model simulates the controller.

The algorithm of the grasping controller is shown as follows. First, from the position of the fingertips, the grasping controller calculates and finds the inner force. The sum of inner force does not affect the position and posture of the object. Second, the inner force is adjusted so that the condition of static friction may be fulfilled, with the ratio of each fingertip force maintained. The calculated fingertip force is converted into target motor torque. The target torque is realized by I control. The feedback cycle of grasping controller is 1 ms.

In the manipulation controller, the trajectory of the fingertip is known beforehand. Hence, the finger is controlled to follow the trajectory. In this paper, for control simplicity, we use PD control as position control in each joint. The feedback cycle of manipulation controller is 10 ms.

As shown in Fig. 5, the suppresser controls and suppresses the output torque of the grasping controller, based on the output torque of the manipulation controller. For example, if the output torque of the manipulation controller is small, the suppression by the suppresser becomes weak. On the contrary, if the output torque of the manipulation controller is large, then, the suppression by the suppresser becomes strong. Output of the suppresser τ_g' is calculated by

$$\tau_g' = \tau_g \cdot sigmoid\left(S_\alpha \left(S_b - \tau_m\right)\right)$$

where, τ_g is an output of the grasping controller, S_α and S_b are the signals for adjustment of suppression, and τ_m is an output of the manipulation controller. The sigmoid function is shown in Fig. 8, and is expressed by the following equation:

$$sigmoid(x) = \frac{1}{1 + \exp(-x)}$$

The output of the suppresser τ_g' and the output of manipulation controller are added and inputted to the actuator as a torque command.

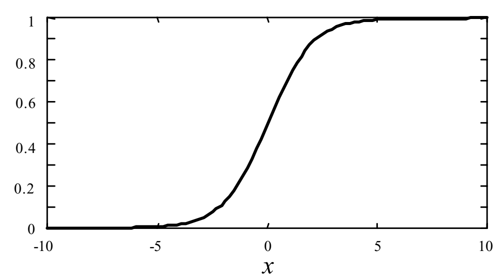


Fig. 8 : *The sigmoid Function*

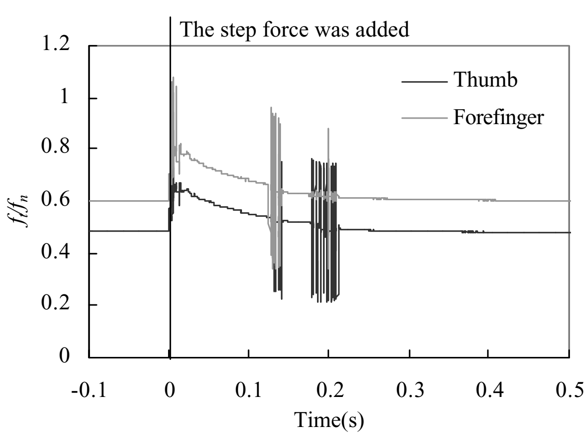


Fig. 9 : *History of f_n/f_t in Result of Grasping (Thumb and Forefinger)*

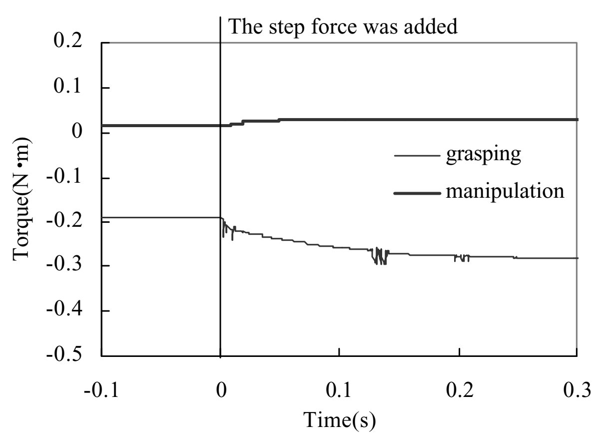


Fig. 10 : *History of torques in Result of Grasping (MP Joint of Forefinger)*

the grasping controller controls torque so that f_n/f_t is 0.6 or less.

The result of the grasping simulation is shown in Fig. 9 and Fig. 10. In Fig. 9, the history of f_n/f_t is shown, where f_n is a normal fingertip force, and f_t is a tangental fingertip force. The history of torque generated by the grasping controller and the manipulation controller is shown in Fig. 10. When external disturbance is added, f_n/f_t increases, but later gradually decreases due to the working of the controller, as shown in Fig. 9. The grasping controller began to work sooner than manipulation controller because the feedback of the grasping controller is faster than the feedback of the manipulation controller, as shown in Fig. 10. Therefore, it was confirmed by the simulation that in the hierarchical control method, a controller realizes stable grasping by fast feedback of the grasping controller.

4 Results and Discussions

The validity of the controller in grasping, manipulation and re-grasping motion in verified in this section. General state is shown below. The value of the static friction coefficient μ_s between the fingers and the object is 1.0, and the value of the dynamical friction coefficient μ_d is 0.9. The mass of the object is 0.3[kg], and the size of the object and the fingers are shown in Fig. 6.

4.1 Grasping Task

In the grasping, task, the thumb and forefinger are initially in contact with the object. When the state of the fingers and object is stable, step force was added as an external disturbance. The controller has to generate torque to resist this external disturbance. In this simulation, the static friction coefficient between the fingers and the object was given. Due to the safety ratio,

4.2 Manipulation Task

In the manipulation task, the thumb and the forefinger change the position and posture of the object. In this

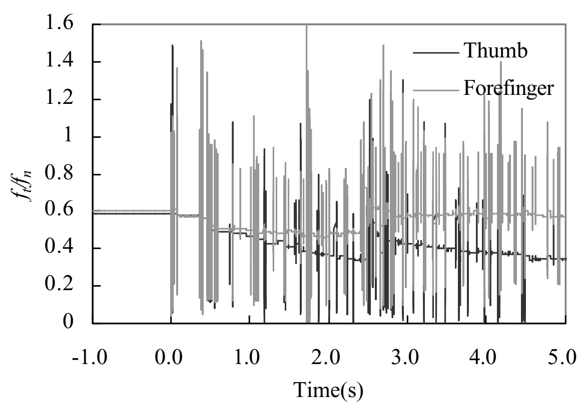


***Fig.11 :** History of f_n/f_t in Result of Manipulation (Thumb and Forefinger)*

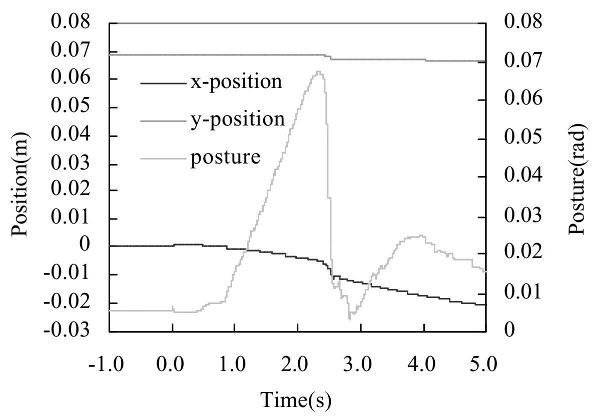


***Fig. 12 :** History of object's position and posture in Result of Manipulation*

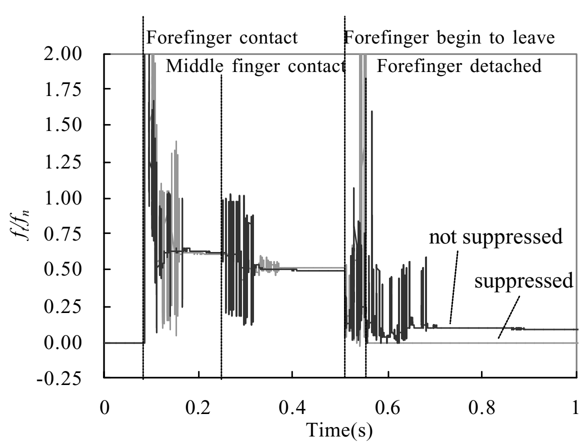


***Fig. 13 :** History of f_n/f_t in Result of Re-grasping motion (Forefinger)*

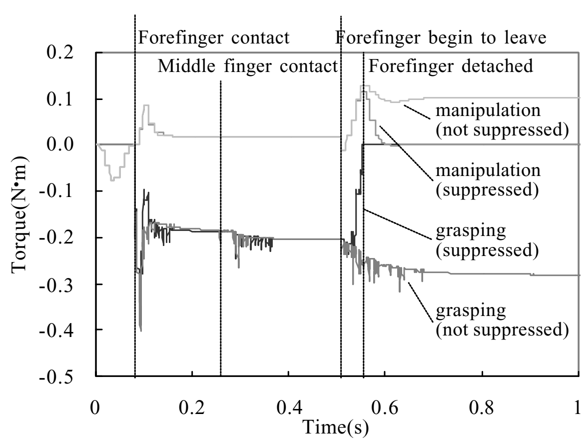


***Fig. 14 :** History of grasping torque and manipulation torque in Result of Re-grasping motion (MP Joint of Forefinger)*

simulation, trajectory of fingers when changing position and posture of the object were given beforehand.

Results of the manipulation are shown in Fig. 11 and Fig. 12. The history of f_n/f_t is shown in Fig. 11, and the history of the position and posture of an object is shown in Fig. 12. During manipulation, f_n/f_t were kept at 0.6 or less by the grasping controller, as shown in Fig. 11. And, the robot hand could change the position and posture of an object, as shown in Fig. 12. Therefore, by using this hierarchical method, robot hands can change the position and posture of objects to any position and posture when given proper trajectory of the fingertips. In this hierarchical method, feedback of the manipulation controller is slow, which gives enough time to calculate proper trajectory of the fingertips.

4.3 Re-grasping Task

The re-grasping motion task is as follows.

1) The hand grasps an object with its thumb and forefinger.
2) The middle finger comes into contact with an object.
3) The forefinger separates from an object.

To confirm the validity of our hierarchical control method, this simulation was done using the hierarchical controller and a controller that has no suppresser.

Results of re-grasping are shown in Fig. 13 and Fig. 14. The history of f_n/f_t is shown in Fig. 13, and the history of grasping torque and manipulation torque is shown in Fig. 14. The value of f_n/f_t is defined to be 0 if the finger is not in contact with an object.

In the case of a suppresser enabled system, the forefinger separated from an object at 0.55[s]. However, in the case of the suppresser being disabled, the forefinger would not separate from the object, as shown in Fig. 13. When the suppression enabled system, the grasping torque decreases as the manipulation torque increases, as shown in Fig. 14. This is due to suppression. However, when the suppression is disabled, the manipulation torque increases as the grasping torque increases. This is the result of conflict between the manipulation controller and grasping controller.

Therefore, we can conclude that the suppression of this hierarchical control method is useful for realizing re-grasping motion.

5 Conclusions

We presented a hierarchical control method for manipulation/grasping tasks using multi-fingered robot hands. This method emulates the human motion control. We showed the effectiveness of the method using dynamical simulation, and confirmed that this method can execute stable grasping, any manipulation and re-grasping.

References

[1] Mark R. Cutkosky : "On Grasp Choice, Grasp Models, and the Design of Hands for Manufacturing Tasks", IEEE Transactions on Robotics and Automation, vol.16, no.6, pp.652-662, 2000

[2] T. Yoshikawa and K. Nagai : "Manipulating and Grasping Forces in Manipulation by Multifingered Robot Hands", Int. J. Robotics and Automation, vol.7, no. 1, pp.66-67, 1991

[3] H. Maekawa, K. Yokoi, K. Tanie, M. Kaneko, N. Kimura and N. Imamura : "Development of a Three Fingered Robot Hand with Stiffness Control Capability", Mechatronics, vol.2, no.5, pp.483-494, 1992

[4] H. Maekawa, K. Tanie and K. Komoriya : "Dynamic Grasping Force Control Using Tactile Feedback for Grasp of Multifingered Hand", Proc. IEEE Int. Conf. on Robotics and Automation, pp.2462-2469, 1996

[5] T. Yoshikawa and K. Nagai : "Dynamic Manipulation / Grasping Control of Multifingered Robot Hands", Proc. IEEE Int. Conf. on Robotics and Automation, pp.1027-1033, 1993

[6] Y. Hasegawa, K. Mase and T. Fukuda : "Re-grasping Behavior Acquisition by Evolutionary Programming", proc. of Congress on Evolutionary Computation, 1999

[7] K. Kitano and K. Terashima, "Manipulation Control of an Object by Multifingered Robot Hand Considering the Regrasping Motion", Proc. of FAN symposium of JSME, vol.6, pp418-419, 1996

[8] H. Yoshikawa, A. Sakawaki and T. Watanabe : "Scheme of Rotating Slippery Object by Regrasp Utilizing the Gravity", Proc. of Conf. of the Robotics Society of Japan (in Japanese), pp265-266, 2001

[9] Y. Nakamura and T. Yamazaki : "The Integration Theory of Reactive Behaviors and Its Application to Reactive Grasp by a Multi-Fingered Hand", Journal of the Robotics Society of Japan (in Japanese), vol.15, no.3, pp.448-459, 1997