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Enveloping Grasp with a New Detaching Strategy

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Abstract

For enveloping an object placed on a table, human often utilizes the wedge–effect where a simple pushing motion of the bottom part of object makes the object detach from the table. Through grasp experiments by human, we newly found an interesting behavior where human changes his (or her) finger posture from upright to crooked ones after all fingers make contact with the object. This motion is termed as the detaching assist motion (DAM) and greatly contributes to achieving a detaching motion even for an object which is small enough to ensure that such a wedge-effect is not available. We first analyze this motion by utilizing a specially designed force sensing system, and then analytically examined the condition leading to the DAM by using a simple finger-object model. We also implement it into the grasping procedure of a three-fingered robot hand, especially for handling a small size of object.

1 Introduction

Multi–fingered robot hands have potential advantage to perform various skillful tasks like human hands. So far, many works have been done in this field, such as the stability of grasp, the equilibrium grasp, the force closure grasp, and the manipulation of object by utilizing either the rolling or the sliding contact[6]–[20]. Most of works have implicitly assumed that a robot hand already grasps an object. On the other hand, there is another research flow where there is no interaction between a robot hand and an object at the initial phase, and it first approaches and finally grasps an object placed in an environment by applying an appropriate grasping procedure[21]–[25]. This paper is based on the latter approach. For considering the grasp strategy of robot hand, human motion often provides us with a good hint[1]–[5]. Along this research policy, we observed human behavior while he (or she) finally envelops an object placed on a table, as shown in Fig.1. In our former work, we showed that human changes his (her) grasping strategy according to the size of objects, even though they have similar geometry. We called the grasp planning *Scale-Dependent Grasp*. An enveloping grasp can be achieved by three fundamental tasks, detaching an object from a table, lifting up it toward the palm, and firmly grasping.

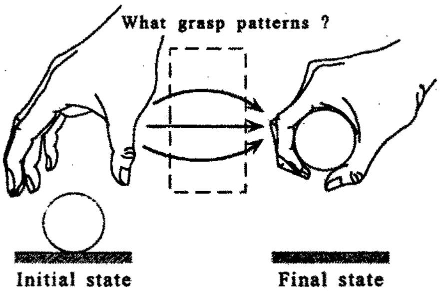
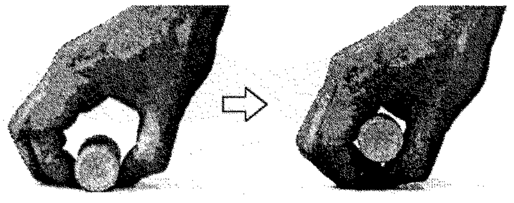


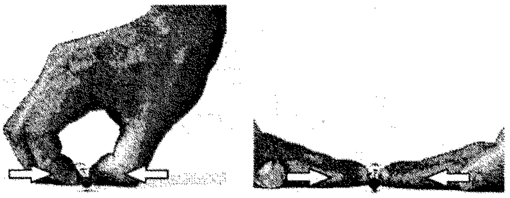
Fig.1 Enveloping grasp for an object placed on a table

For detaching an object from the table, human often utilizes the *wedge–effect* where a simple pushing motion of the bottom part of object makes the object detach from the table as shown in Fig.2(a). Due to its simple motion planning, we can easily implement it into the grasping procedure of a multi–fingered robot hand. Either under significant friction or for an object with small diameter, however, we fail in detaching the object since finger forces balance within the object and do not produce a lifting force any more as shown in Fig.2(b), where two different finger postures are taken for producing the *wedge–effect*. On the other hand, human can easily detach such a small object where we can not expect the *wedge–effect* by a simple pushing motion. Through human observation, we newly found an interesting behavior where human changes his (or her) finger posture from upright to crooked ones, as shown in Fig.2(c). By such a posture change, the object is automatically lifted up from the table through a rolling motion between the object and the finger–tip. This finger motion is termed as the *detaching assist motion (DAM)* and contributes to achieving a detaching motion even for an object which is small enough to ensure that the *wedge–effect* is not expected by a simple pushing motion.

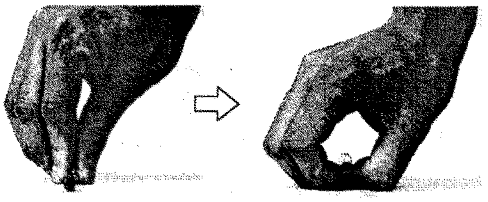
This paper is organized as follows. In section 2, we briefly review conventional works. In section 3, we analyze the magnitude of contact force during the *DAM* by utilizing a specially designed force sensing system. In section 4, we discuss the mechanism and condition



(a) Wedge-effect



(b) Simple pushing motion for a small object (Unsuccessfully)



(c) Detaching a small object with DAM (Successfully)

Fig.2 Grasping motion by human

leading to this motion. In section 5, we also implement it into the grasping procedure of a three-fingered robot hand, and experimentally verify that it is greatly helpful, especially for handling an object with small size. In section 6, we conclude our work.

2 Related Work

Human grasping based approach: In robotic hands, there have been a number of papers learnt by human behaviors[1]–[5]. Cutkosky[1] has analyzed manufacturing grips and correlation with the design of robotic hands by examining grasps used by humans working with tools and metal parts. Bekey et al.[2] have presented the automatic grasp planner which generates an order set of grasp according to task description, heuristics, and geometry of an object. Kang and Ikeuchi[3] have proposed the *contact web* and the *grasp cohesive index* for automatic classification of human grasping. Saito and Nagata have proposed a method to classify and describe grasping and manipulation. It is based on three functions of grasping surfaces and provides simple description for grasping and manipulation. However, the grasping taxonomy proposed in these works[2]–[5] have focused on either the final grasp mode or finding an appropriate grasp posture, while our work focuses on the grasping procedure for size of objects.

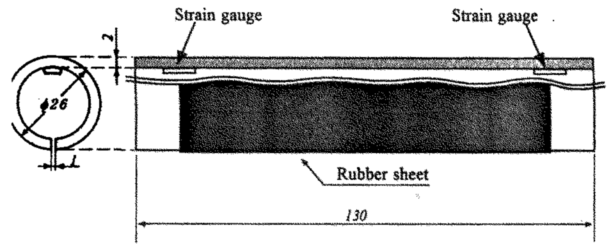
Approach phase: Jeannerod[6] has shown that during the approaching phase of grasping, human hand preshapes in order to prepare the shape matching with the object to be grasped. Bard and Troccaz[7] introduced such a preshaping motion into a robotic hand and proposed a system for preshaping a planar two–fingered hand by utilizing low–level visual data. Kaneko and Honkawa[8] have proposed a method for detecting a local contact point between a robot hand and an object by utilizing the *self–posture changing motion* where a finger link system with compliant joints can change its posture while making contact with an object.

Lifting phase: Trinkle and Paul[9, 10] have proposed the *Initial Grasp Liftability Chart* (IGLIC) to analyze liftable condition for a frictionless object by using several pushers. They have considered grasp planning only for a slippery object, while contact friction generally plays an important role to determine the grasp planning.

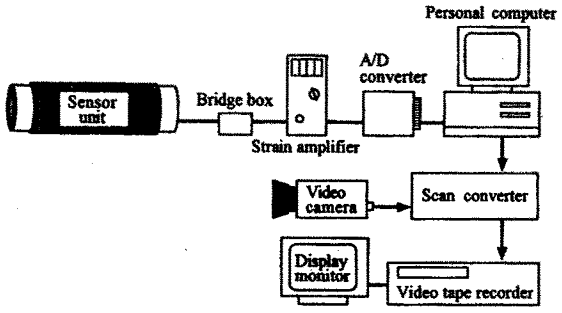
Enveloping grasp (or power grasp): Mirza and Orin[11] have applied a linear programming approach to solve the force distribution problem in power grasps, and showed that the maximum weight of object which a robot hand can grasp increases significantly when the completely enveloping type of power grasp is utilized. Trinkle, Abel and Paul[12] have analyzed planning techniques for enveloping without friction. Hirose et al.[13] have proposed the *soft gripper* which can always produce constant torque in each joint simultaneously by using only two actuators. Salisbury et al.[14, 15] have proposed the Whole–Arm Manipulation (WAM) capable of treating a big and heavy object by using one arm allowing multiple contacts with an object. Bicchi[16] has showed that internal forces in power grasps can be decomposed into active and passive. Omata and Nagata[17] have analyzed the indeterminate grasp force by considering that sliding directions are constrained in power grasps. Zhang et al.[18] have evaluated the robustness of power grasp by utilizing the virtual work rated for all directions of virtual displacements. Kleinmann et al.[19] have showed a couple of approaches for finally achieving the power grasp from the finger tip grasp. Under constant torque control, Kaneko, Higashimori and Tsuji[20] have discussed the transition stability ensuring that the object moves stably from a table to the palm. They have proposed the *force–flow diagram* showing the accelerated direction at the point where the object is placed.

3 Experimental Analysis

We design and develop an imitated object as shown in Fig.3(a), where a cylindrical object with the diameter of 26[mm] is made from aluminum pipe covered with rubber sheet to increase the surface friction. It includes two strain gauges, so that we can measure the stress of finger–tip force applied upon the surface of object. Additionally, the finger posture during grasping motion is synchronously recorded by a video system as shown in Fig.3(b).



(a) Sensor unit



(b) Sensor system

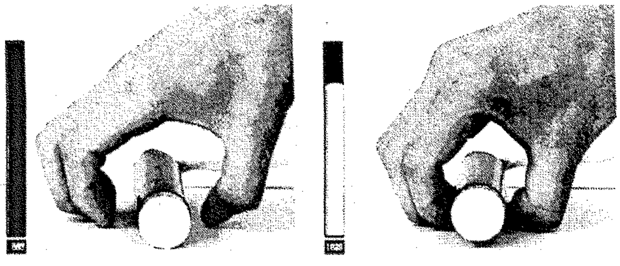
Fig.3 Force sensor system

Fig.4 shows finger postures during grasping experiments, where Fig.4 (a) and (b) are grasp motion without and with the *DAM*, respectively. From these experiments, we can see that human can successfully detach the object from the table in the grasp strategy with the *DAM*, while he can not without the *DAM*. The bar graph shown in the left side of each picture denotes the magnitude of the contact force measured by the strain gauges. We would note that the detaching motion can be easily achieved without any significant contact force in Fig.4(b), while it is avoided even under a large grasping force in Fig.4(a). These results suggest that the *DAM* is greatly effective for achieving the detaching motion under small contact force.

4 Condition leading to the DAM

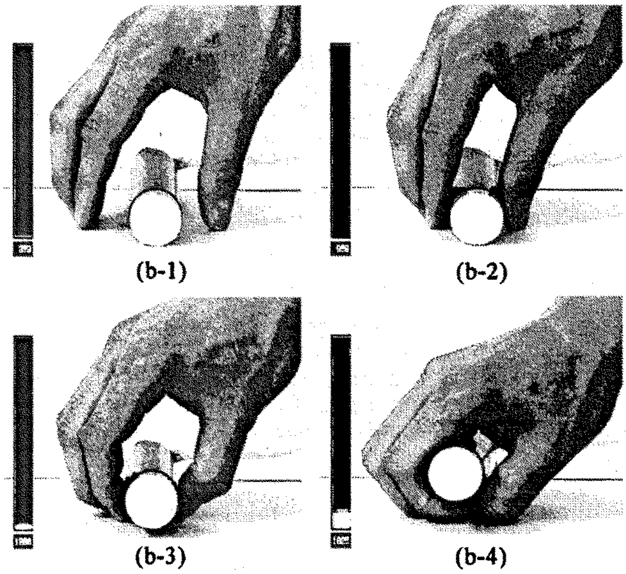
4.1 Working Mechanism of the DAM

Why the *DAM* works effectively for detaching the object from a table? What mechanism exists behind it? In this subsection, we briefly explain the basic working mechanism of *DAM*. For our convenience, we first define several parameters as shown in Fig.5(a). $\boldsymbol{P}_{Si}$ and $\boldsymbol{P}_{Ti}$ are position vectors denoting the center of the distal joint of i-th finger and the finger–tip, respectively, where $\boldsymbol{P}_{Si} = [P_{Six}\ P_{Siy}]^T$, $\boldsymbol{P}_{Ti} = [P_{Tix}\ P_{Tiy}]^T$. θ_{Fi} and f_{xi} are the orientation of finger–tip link and the horizontal force at $\boldsymbol{P}_{Si}$, respectively. $\boldsymbol{n}_i$ and θ_{ni} are a unit normal vector of the surface of object and directing inside of the object, the angle between $\boldsymbol{n}_i$ and horizontal line, respectively. $\boldsymbol{f}_{Ci}$ and θ_{ci} are the contact force produced by i-th finger, the angle between $\boldsymbol{n}_i$ and $\boldsymbol{f}_{ci}$, respectively. l is the vertical line placed at the center of hand. At each contact, we assume a Coulomb friction whose coefficient is given by $\mu = \tan\alpha$, where both static and dynamic frictional coefficients are not distinguished. The finger–tip link can rotate around $\boldsymbol{P}_{Ti}$ and move in the horizontal direction.



(a-1) (a-2)

(a) Grasp motion without DAM



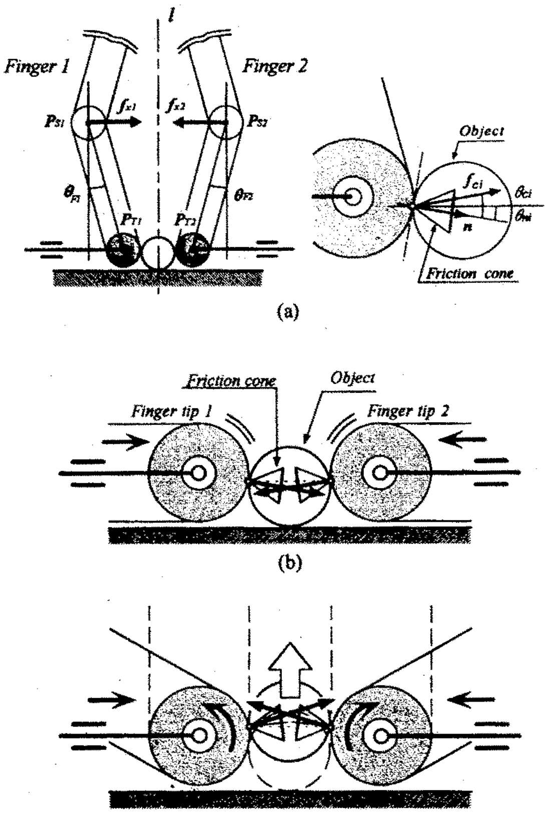
(b-1) (b-2)

(b-3) (b-4)

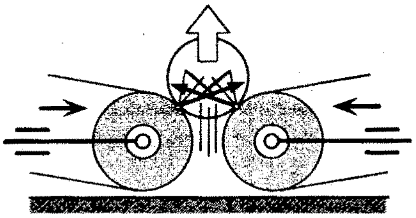
(b) Grasp motion with DAM

Fig.4 Grasping experiment using an imitated object

Let us consider the case where a circular object is pushed by two finger–tips which are also modeled by black circles. We assume that the object is small enough to ensure that a simple pushing motion in the horizontal direction can not lift up the object as shown in Fig.5(b). This means that the *wedge–effect* is not expected at the initial state. Recall the basic motion of *DAM*, namely the change of finger posture from upright to crooked ones. This motion may equivalently produce a rotating motion at the finger–tip level. As a result, the object may be lifted up as shown in Fig.5(c). If a horizontal force is continuously imparted to the object, the object finally slips and moves up at the moment the contact force is away from the boundary of friction cone, as shown in Fig.5(d). This is the outline of the working mechanism of DAM. Thus, the



(c) Rolling-up phase



(d) Slipping-up phase

Fig.5 The basic mechanism of DAM

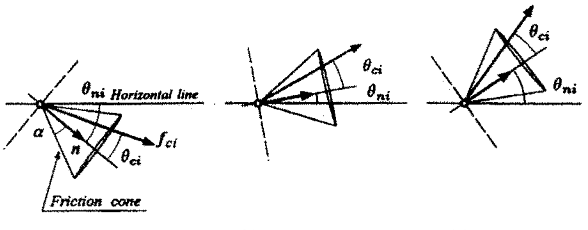
DAM acts an important role for making the geometrical condition enabling the *wedge–effect.*

4.2 Condition for Achieving the DAM

The robot hand can lift up the object when the resultant force has an upward component, i.e.,

$$(\sum_{i=1}^{2} \boldsymbol{f}_{Ci} + m_o \boldsymbol{g}) \cdot (-\boldsymbol{e}_g) > 0, \tag{1}$$

where $\boldsymbol{e}_g$, m_o and $\boldsymbol{g}$ are a unit gravitational vector, mass of the object and gravitational vector, respectively. Now we focus on the i-th finger. There are three patterns for the relationship between the friction cone at the contact point and horizontal line as shown in Fig.6. When the upper boundary of friction cone is lower than horizontal line ($\theta_{ni} \leq -\alpha$) as shown in Fig.6(a), $\boldsymbol{f}_{Ci}$ always pushes down the object toward the table for an increase of horizontal force f_{xi}. In case that the friction cone includes horizontal line ($-\alpha < \theta_{ni} \leq \alpha$) as shown in Fig.6(b), the robot hand can not utilize *wedge–effect* for lifting up the object. In such case, if the robot hand can satisfy following condition,



(a) $\theta_{ni} \leq -\alpha$ (b) $-\alpha < \theta_{ni} \leq \alpha$ (c) $\theta_{ni} > \alpha$

Fig.6 The relationship between friction cone and horizontal line

$$f_{xi} > \frac{m_o g/2}{\tan(\theta_{ni} + \alpha)} \tag{2}$$

it can produce upward force for the object and keep the rolling contact between the object and the finger links. In case that the lower boundary of friction cone is higher than horizontal line ($\theta_{ni} > \alpha$) as shown in Fig.6(c), the robot hand can utilize *wedge–effect.* In such case, if the robot hand can satisfy following condition,

$$f_{xi} > \frac{m_o g/2}{tan(\theta_{ni} - \alpha)}, \tag{3}$$

the robot hand can lift up the object from the surface of table by utilizing the *wedge–effect.* Even if the robot hand can not satisfy the condition (3), it can produce upward force to the object and keep a rolling contact when it can satisfy the condition (2).

The necessary condition for achieving the *DAM* is to impart a horizontal force satisfying the condition (2). Under the condition, if the tip of each finger is rotated geometrically as shown in Fig.5(c), it is guaranteed that the object is lifted up with a rolling motion.

5 Grasp Experiments by a Multi–fingered Robot Hand

Let us explain how to implement the *DAM* for multi–fingered robot hand. Each finger–tip joint is rotated from upright ($\theta_{Fi} = 0[rad]$) to crooked ($\theta_{Fi} = \pi/2[rad]$) by utilizing the position control. The remaining joints are controlled so that the following conditions can be satisfied.

1. The height of finger–tip i P_{Tiy} from the surface of table does not change.
2. The horizontal force f_{xi} is applied at $\boldsymbol{P}_{Si}$ for lifting up the object.

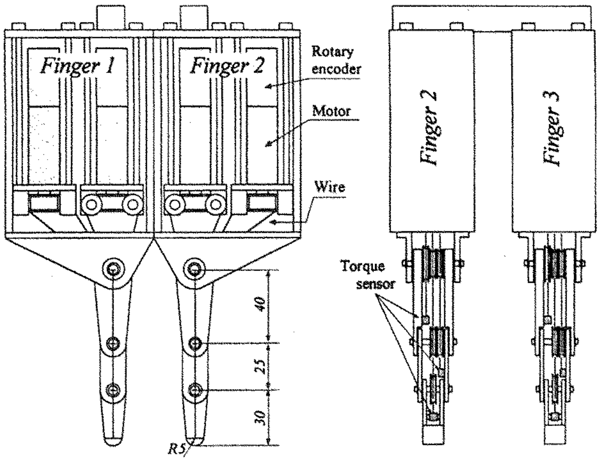


Fig.7 Structure of the robot hand

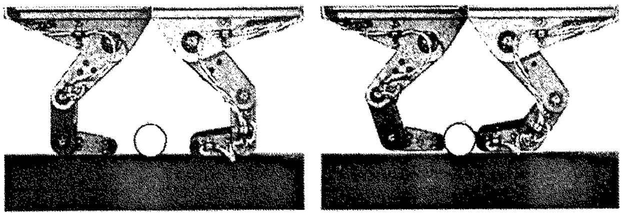


Fig.8 The experimental result by applying the Wedge-effect

For the object not to move away from the center of hand, the horizontal force f_{xi} is given by

$$f_{xi} = K_{tip}L_i \tag{4}$$

where K_{tip} and L_i are the spring constant and the distance between l to $\boldsymbol{P}_{Si}$.

We implement the *DAM* into the grasping procedure and execute the whole grasping experiment for an object placed on a table. The robot hand used in the experiment consists of three same finger units and each finger has three links as shown in Fig.7. The length of each link is $l_1 = 40[mm]$, $l_2 = 25[mm]$, and $l_3 = 30[mm]$, respectively, and the radius of each finger–tip is $5[mm]$. The finger links are driven by wire and a torque sensor is included in each joint. Rotary encoder is used as an angular sensor. More precise information on the robot hand will be obtained in our previous works[26, 27].

Figs.8 and 9 show the experimental results where the robot hand utilizes the *wedge–effect* and the *DAM* for detaching a cylindrical object from the table. The robot hand grasps the cylindrical object ($\phi 12[mm]$) which is covered with rubber sheet in order to increase the surface friction. The robot hand can not lift up the object by utilizing the *wedge–effect* as shown in Fig.8 since the contact forces balance within the object, while it can lift up the object by utilizing the *DAM* as shown in Fig.9. Initially each finger–tip is opened as shown in Fig.9(a) and then it follows along the surface of table until a part of finger link makes contact with the object as shown in Fig.9(b). As each finger–tip link rotates from $\theta_{Fi} = 0[rad]$ to $\theta_{Fi} = \pi/2[rad]$, the robot hand lifts up the object from the surface of table as shown in Fig.9(c). When the condition of sliding contact between the finger link and the object is satisfied, the *wedge–effect* occurs as show in Fig.9(d). After every finger–tip link lies horizontally as shown in Fig.9(e), the constant torque control is applied for achieving an enveloping grasp as shown in Fig.9(f).

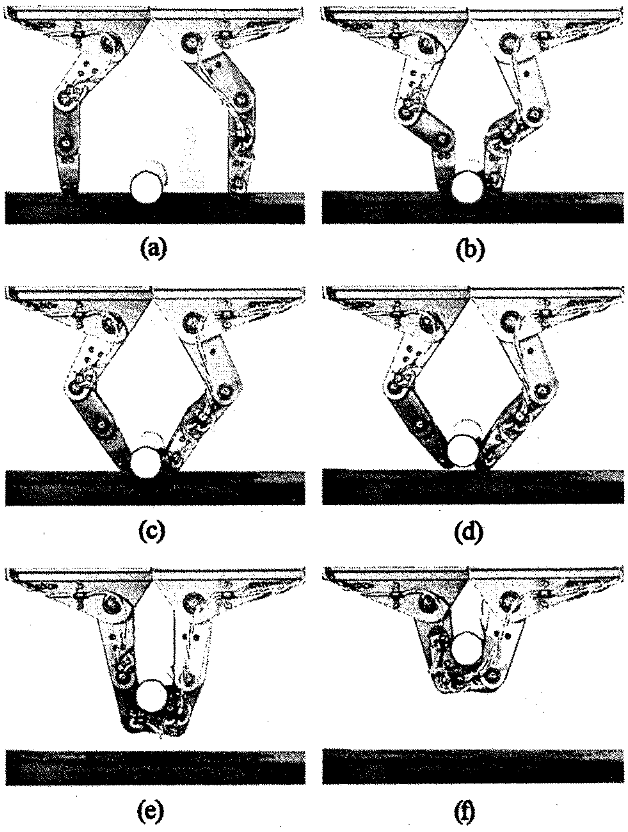


Fig.9 The experimental result by using the DAM

6 Conclusions

We newly found the *DAM* through the observation of human grasping. We made clear that the *DAM* greatly contributes to achieving the detaching motion, even though the object is small enough to be difficult to expect the *wedge-effect*. We analytically examined the condition leading to the *DAM* by using a simple finger-object model. We also implemented the *DAM* into the grasp procedure of a multi–fingered robot hand and verified experimentally its effectiveness.

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References

[1] M. Cutkosky: "On Grasp Choice, Grasp Models, and the Design of Hands for Manufacturing Tasks," IEEE Trans. on Robotics and Automation, Vol. 5, No. 3, JUNE, pp. 269–279, 1989.

[2] G.A. Bekey, H. Liu, R. Tomovic, and W. Karplus: "Knowledge-Based Control of Grasping in Robot Hands Using heuristics from human motor skills," IEEE Trans. on Robotics and Automation, Vol. 9, No. 6, DECEMBER, pp. 709–722, 1993.

[3] S.B. Kang and K. Ikeuchi: "Toward Automatic Robot Instruction from Perception—Recognizing a Grasp from Observation," IEEE Trans. on Robotics and Automation, Vol. 9, No. 4, AUGUST, pp. 432–443, 1993.

[4] T. Iberall, J. Jackson, L. Labbe, and R. Zampano: "Knowledge-Based Prehension: Capturing Human Dexterity," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 82–87, 1988.

[5] F. Saito and K. Nagata: "Interpretation of Grasp and Manipulation from Functional Surfaces," Proc. of Robotics Syumposia, pp. 113–120, 1999. (In Japanese)

[6] M. Jeannerod: "Attention and Performance," chapter Intersegmental coordination during reaching at natural visual objects, pp. 153-168, Erlbaum, Hillsdale, 1981.

[7] C. Bard and J. Troccaz: "Automatic Preshaping for a Dexterous Hand from a Simple Description of Objects," Proc. of the IEEE Int. Workshop on Intelligent Robots and Systems, pp. 865-872, 1990.

[8] M. Kaneko and K. Honkawa: "Contact Point and Force Sensing for Inner Link Based Grasps," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 2809–2814, 1994.

[9] J.C. Trinkle and R.P. Paul: "Planning for Dexterous Manipulation with Sliding Contacts," J. of Robotics Research, Vol. 9, No. 3, pp. 24–48, 1990.

[10] J.C. Trinkle and R.P. Paul: "The Initial Grasp Liftability Chart," IEEE Trans. on Robotics and Automation, Vol. 5, No. 1, FEBRUARY, pp. 47–52, 1989.

[11] K. Mirza and D.E. Orin: "Control of Force Distribution for Power Grasp in the DIGITS System," Proc. of the IEEE 29th CDC Conf., pp. 1960–1965, 1990.

[12] J.C. Trinkle, J.M. Abel and R.P. Paul: "Enveloping, Frictionless Planar Grasping," Proc. of the IEEE Int. Conf. on Robotics and Automation, 1987.

[13] S. Hirose: "The Development of Soft Gripper for Versatile Robot Hand," Mechanism and Machine Theory, Pergamon Press, 13, pp. 351–359, 1978.

[14] J.K. Salisbury: "Whole-Arm Manipulation," Proc. of the 4th Int. Symp. of Robotics Research, Santa Cruz, CA, 1987. Published by the MIT Press, Cambridge MA.

[15] J.K. Salisbury, W. Townsend, B. Eberman and D. Dipietro: "Preliminary Design of a Whole-Arm Manipulation System (WAMS)," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 254, 1988.

[16] A. Bicchi: "Force Distribution in Multiple Whole-Limb Manipulation," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 196–201, 1993.

[17] T. Omata and K. Nagata: "Rigid Body Analysis of the Indeterminate Grasp Force in Power Grasps," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 1787–1794, 1996.

[18] X-Y. Zhang, Y. Nakamura, K. Goda, and K. Yoshimoto: "Robustness of Power Grasp," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 2828–2835, 1994.

[19] K.P. Kleinmann, J. Henning, C. Ruhm, and H. Tolle: "Object Manipulation by a Multifingered Gripper: On the transition from precision to power grasp," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 2761–2766, 1996.

[20] M. Kaneko, M. Higashimori and T. Tsuji: "Transition Stability of Enveloping Grasps," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 3040–3046, 1998.

[21] M. Kaneko, Y. Tanaka and T. Tsuji: "Scale-dependent Grasp," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 2131–2136, 1996.

[22] M. Kaneko, Y. Hino and T. Tsuji: "On Three Phases for Achieving Enveloping Grasps," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp. 385–390, 1997.

[23] M. Kaneko, N. Thaiprasert and T. Tsuji: "Experimental Approach on Enveloping Grasp for Column Objects," Preprint of Experimental Robotics, pp. 17–27, 1997.

[24] T. Shirai, M. Kaneko, K. Harada, T. Tsuji: "Scale-Dependent Grasps," Proc. of the Int. Conf. on Advanced Mechatronics, pp. 197–202, 1998.

[25] M. Kaneko and T. Tsuji: "Realization of Enveloping Grasp," 1997 IEEE Int. Conf. on Robotics and Automation(Video Proceeding), 1997.

[26] M. Kaneko: "Development of a Dexterous Multifingered Robot Hand", Journal of the Robotics Society of Japan, Vol. 16, No. 5, pp. 41–43, 1998. (in Japanese)

[27] N. Imamura, M. Kaneko, T. Tsuji: "Development of Three-Fingered Robot Hand with a New Design Concept," Proc. of the 6th IASTED Int. Conf. on Robotics and Manufacturing, pp. 44–49, 1998.