Scale-Dependent Grasp

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***Abstract*—This paper discusses the scale-dependent grasp. Suppose that a human approaches an object initially placed on a table and finally achieves an enveloping grasp. Under such initial and final conditions, he (or she) unconsciously changes the grasp strategy according to the size of objects, even though they have similar geometry. We call the grasp planning the scale-dependent grasp. We find that grasp patterns are also changed according to the surface friction and the geometry of cross section in addition to the scale of object. Focusing on column objects, we first classify the grasp patterns and extract the essential motions so that we can construct grasp strategies applicable to multifingered robot hands. The grasp strategies constructed for robot hands are verified by experiments. We also consider how a robot hand can recognize the failure mode and how it can switch from one to another.**

***Index Terms*—Grasping strategy, multifingered robot hand, scale-dependent grasp.**

I. Introduction

THERE have been a number of works concerning multifingered robot hands. Most of them address a finger tip grasp, where it is assumed that a part of inner link never makes contact with object [1]–[3]. Enveloping grasp (or power grasp) provides another grasping style, where multiple contacts between one finger and an object are allowed. Such an enveloping grasp can support a large load in nature and is highly stable due to a large number of distributed contact points on the grasped object. We focus on the enveloping grasp in this work. While there are still many works discussing the enveloping grasp, most of them deal with the grasping phase only, such as contact force analysis, robustness of grasp, contact position sensing, and so forth. On the other hand, we are interesting to consider the whole grasping procedure starting from an approach phase. Through experiments for getting the hint of this problem, we found out an interesting human behavior. Suppose that human eventually achieves an enveloping grasp for an object placed on a table, as shown in Fig. 1. Actually, such a situation is often observed in practical environment, e.g., in grasping a table knife, an ice pick, a hammer, a wrench, and so on. In many cases, the tool handle can be modeled as a cylindrical shape. For a cylindrical object having a sufficiently large diameter, human wraps it directly without any regrasping process since the table makes no interference with the finger links at all. As the diameter decreases, human is obliged to utilize a different strategy so that he (or she) may avoid interference caused by the table. By experiments, we show that human chooses a grasp planning according to the size of object, even though they are geometrically similar. We call the grasp planning the *scale-dependent grasp planning*. We would note that the *scale-dependent grasp* does not mean the final grasp style but means the change of grasp patterns observed between the initial and the final states according to the size of objects.

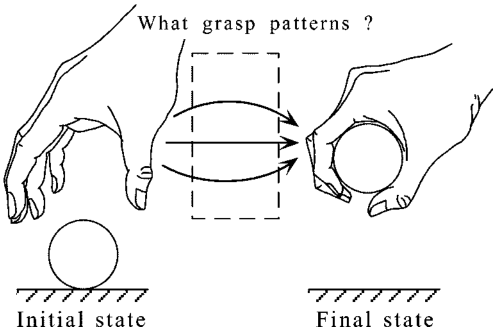

Fig. 1. Enveloping grasp for an object placed on a table.

In this paper, we first observe the human behavior for grasping column objects with different size, shape of cross section, and contact friction. Then, we extract the essential motions (or functions) from human behaviors so that we can apply them to a multifingered robot hand. It should be noted that we do not intend to transfer the exactly same human motions to a robot hand just like a master-slave system. The approach by a master-slave operation may succeed in grasping the object if the robot hand has the same degrees of freedom, configuration, number of fingers, and surface material as those of human. The developed robot hands [4]–[6], however, have their own mechanical configurations and some are too far from that of human hand. Under such a situation, the approach by a master-slave operation may easily fail in grasping an object. This is the reason why we intend to transfer the basic functions instead of the exact motions. In such sense, it is important to extract the basic functions from human grasping patterns. Through human observation, we learn that an enveloping grasp can be achieved by three essential tasks: 1) detaching motion from a table; 2) lifting up motion toward the palm; and 3) firmly grasping. For robot application, we prepare grasping strategies composed of the above three tasks which are changed according to the size, the shape of cross section and the contact friction of object. A question is how a robot chooses an appropriate one among a number of strategies. As for both shape and size of objects, vision sensor is greatly helpful for making decision on choosing an appropriate strategy suitable for them. However, contact friction is not known until a finger tip makes contact with the object. Under such a situation, it should be a natural way that the robot starts to approach an object with the simpler strategy. If it fails in grasping, then it switches to the other one

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depending on the sensor information available. The way for switching is also an important issue in this work.

This paper is organized as follows. In Section II, we briefly review conventional works. In Section III, we observe the human grasping and show that human changes his (or her) grasping strategy depending upon the size, friction, and geometry of objects. In order to obtain the orientation for constructing grasp strategies suitable for a multifingered robot hand, we extract the essential functions from human observation. In Section IV, we discuss the grasping strategies applicable for a general multi-fingered robot hand. We also include the discussion on how to choose an appropriate one among many strategies and how to switch from one to another when the robot hand fails in grasping an object. In Section V, we try to relax some assumptions, so that we can apply the results to more general cases. In Section VI, we conclude our work.

II. Related Work

A. Human Grasping-Based Approach

In robotic hands, there have been a number of papers learned by human behaviors [7]–[10]. Cutkosky [7] 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.* [8] 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 [9] have proposed the *contact web* and the *grasp cohesive index* for automatic classification of human grasping. However, the grasping taxonomy proposed in these works [8], [9] 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.

B. Approach Phase

Jeannerod [11] 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 [12] 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 [13] 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.

C. Enveloping Grasp (or Power Grasp)

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. Mirza and Orin [16] 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. Hirose *et al.* [17] have proposed the *soft gripper* which can always produce constant torque in each joint simultaneously by using only two actuators. Bicchi [18] has showed that internal forces in power grasps can be decomposed into active and passive. Omata and Nagata [19] have analyzed the indeterminate grasp force by considering that sliding directions are constrained in power grasps. Zhang *et al.* [20] have evaluated the robustness of power grasp by utilizing the virtual work rated for all directions of virtual displacements.

D. Enveloping Style Manipulation

Trinkle *et al.*[21] have analyzed planning techniques for enveloping without friction. Trinkle and Paul [22], [23] have proposed the *Initial Grasp Liftability Chart* (IGLIC) to analyze liftable condition for a frictionless object by using several pushers. Trinkle *et al.* have discussed the quasi-static, "whole-arm," dexterous manipulation of enveloped slippery workpieces. They have considered grasp planning only under the assumption of low friction, while contact friction generally plays an important role to determine the grasp planning. Under constant torque control, Kaneko *et al.*[25] 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 grasped. Kleinmann *et al.* [26] have showed a couple of approaches for finally achieving the power grasp from the finger tip grasp.

There have been a number of papers discussing finger tip-based manipulation, where we can expect dexterous manipulation by using many degrees of freedom existing in the system. For example, Sarkar *et al.*[27], Cherif and Gupta [28], Kao and Cutkosky [29], and Cole *et al.* [30] discussed the rolling-based manipulation and the sliding-based manipulation. Also, there have been a couple of research groups where they focused on nonprehensile manipulation. For example, pushing manipulation [31], graspless manipulation [32], orientation of planar polygonal parts [33], and toppling manipulation [34].

While there have been many works concerning the grasp, there is no work discussing the grasping strategy based on the *scale-effect* of objects.

III. Observation of Human Grasping

A. Grasp Pattern Classification

In order to observe human behaviors, we asked a subject to achieve enveloping grasp for an object placed on a table, as shown in Fig. 1. For column objects, we observe how human changes his (or her) grasping strategy according to the size, the shape of cross section and the contact friction of object. Fig. 2 shows the objects used in our experiments, where the white and the black surfaces denote that they are covered by a drawing paper and a rubber, respectively, so that we can purposely change the contact friction. Now, suppose two subjects, where they have a big hand and a small hand, respectively. Also, suppose that each subject approaches and grasps the same object. In such a case, the subject with a big hand should feel the object relatively smaller than the subject with a small hand feels. To avoid such scale effect depending on the size of object, we introduce the normalized object size d defined by $d = L_o/L_h$, where L_h and L_o denote the length from the tip of thumb to the tip of index finger, and the

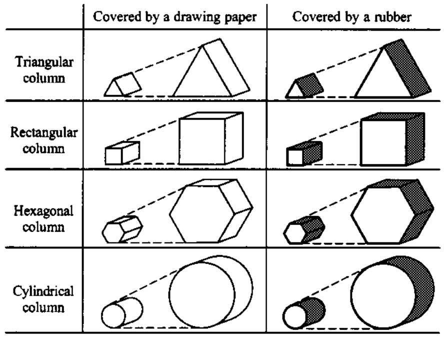

Fig. 2. Column objects used in the experiments.

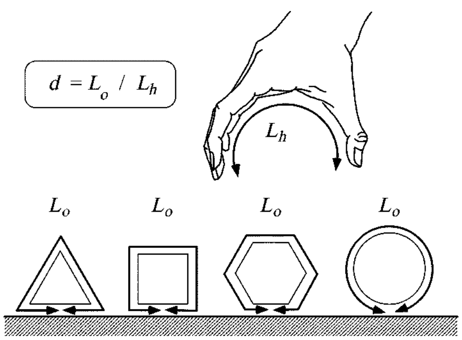

Fig. 3. Explanation of L_o and L_h.

length of the circumference of object, respectively, as shown in Fig. 3. For experiments, we prepared six kinds of objects whose sizes are $2.80 \geq d \geq 0.26$.

Fig. 4 shows the experimental results for column objects, where "No." denotes the number of subjects taking the particular grasp pattern, and the cross section of object is illustrated in the bottom of each figure. Each grasp pattern is explained in the following.

Pattern-1 (*Direct grasp*): Without any re-grasping motion, human directly grasps the object [Fig. 5(a)].

Pattern-2 (*Sliding-based grasp*): This pattern utilizes the sliding motion between the finger link and the object. Finger tips push the part between the bottom of object and the table, such that the object can be lifted up [Fig. 5(b)]. This is what we call the wedge-effect where an object receives quite a big lifting force produced by finger tips inserted into narrow gap between the table and the object.

Pattern-3 (*Rolling-based grasp*): The object is rolled up over the surface of thumb (or index finger). After the object is lifted up from the table, each finger link is closed to achieve an enveloping grasp [Fig. 5(c)].

Pattern-4 (*Regrasping-based grasp*): The object is first picked up by thumb and index (or middle) finger tips. The remaining fingers hook the object and then squeeze it till the finger tip grasping is broken. Finally, the object comes in contact with the palm [Fig. 5(d)].

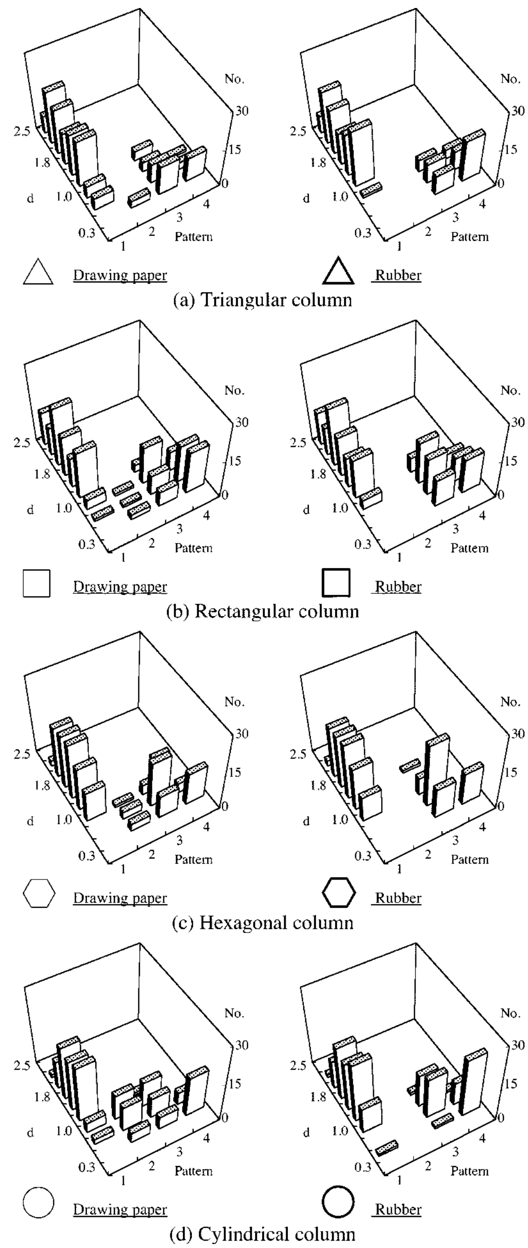

Fig. 4. Grasp pattern classification map.

For a large object $(2.8 \geq d > 1.0)$, human directly grasps it (*Pattern-1*), irrespective of the shape of cross section and the contact friction. As the size of object decreases $(1.0 \geq d \geq 0.5)$, Patterns-2 through 4 appear according to the personal choice as well as the conditions set for the experiment. For this size of object, some subjects take the *sliding-based grasp* (*Pattern-2*), when the surface friction is small. On the other hand, for the object with significant friction, *sliding-based grasp* (*Pattern-2*) disappears and, instead, both *rolling-based grasp* (*Pattern-3*) and *regrasping-based grasp* (*Pattern-4*) become dominant. The change of grasp patterns is naturally understandable, because it is hard to achieve a sliding motion under a significant friction while both rolling and regrasping motions can be realized irrespective of the contact friction. Pattern-4 especially becomes dominant for a small object $(0.5 > d \geq 0.26)$. For such a small object, human tries to avoid interference between the finger tip

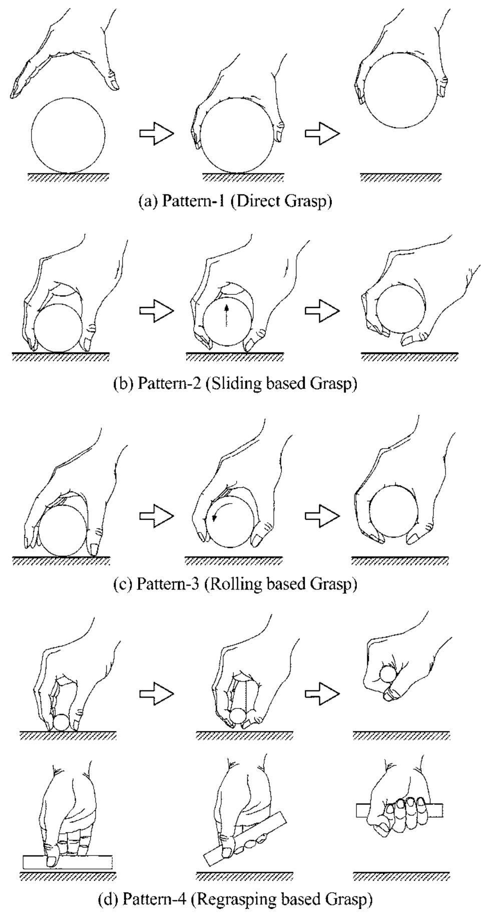

Fig. 5. Grasp patterns.

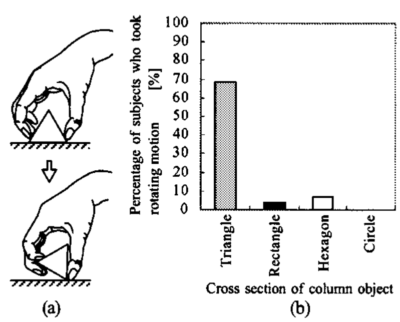

Fig. 6. Initial adjustment motion.

and the table. As a result, human first picks up the object and achieves the target grasp through regrasping process from the finger tip to the enveloping grasps.

An interesting behavior is observed at the initial phase in grasping triangular objects. Almost 70% of subjects first rotate the object around an edge so that a couple of fingers can be inserted in the gap between the object and the table, as shown in Fig. 6(b), where Fig. 6(a) explains the basic motion at the initial phase and Fig. 6(b) shows percentage of subjects utilizing the rotating motion. For grasping a triangular object, such a rotating motion is indispensable for detaching the object from the table. We call this motion *initial adjustment motion*. We note that the *initial adjustment motion* dominantly appears only for triangular objects.

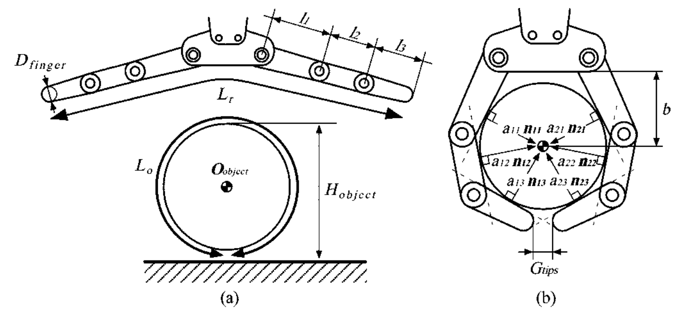

Fig. 7. Relation between the robot hand and the object.

B. Interpretation of Grasping Motions

Human grasping provides a good hint for constructing grasping strategies of a robot hand. However, as mentioned in Introduction, transferring the exact grasping motion to a robot hand may often fail in grasping an object, since each robot hand has its own mechanical configuration and structure. In this section, we provide an interpretation for human grasping, so that we can construct grasping strategies easily applicable to multifingered robot hands. While it is hard to decompose the human behaviors in grasping phase into individual motions, except the direct grasp, we can roughly separate the grasping procedure into the following three tasks.

Task 1 : **Detaching the object from a table and putting it into the robot hand.**
Task 2 : **Lifting up the object within the hand.**
Task 3 : **Grasping the object firmly.**

Detaching the object from a table is the starting motion for further steps. For example, detaching can be achieved by utilizing the wedge-effect or picking up motion or rolling motion. Lifting up can be achieved by sliding motion or rolling motion.

IV. Application to Robot Hands

For our convenience, we first define several parameters for robot hands, as shown in Fig. 7. We utilize the normalized length $d_{\rm robot}$ defined by $d_{\rm robot} = L_o/L_r$, where L_o and L_r denote the circumference of the object and the length between finger tips, respectively. L_r corresponds to the parameter L_h for human hand. The parameter $H_{\rm object}$ is the height of object, and the corresponding diameter for finger tip is defined by $D_{\rm finger}$. $\boldsymbol{O}_{\rm object}$, $\boldsymbol{n}_{ij}$, a_{ij} and b are the geometrical center of object, a unit normal vector perpendicular to the surface of link j of $i-th$ finger, and the length between the surface of link j of $i-th$ finger and $\boldsymbol{O}_{\rm object}$, and the distance between the palm and $\boldsymbol{O}_{\rm object}$, respectively. $G_{\rm tips}$ is defined by the distance between finger tips, as shown in Fig. 7(b), where we set $G_{\rm tips}=0$ when each finger link has an intersection.

We show several assumptions for simplicity:

(A-1) Objects have column shape and their cross sections are regular polygon where all sides of cross section and angles are equal.

(A-2) Size of the objects are smaller than the size where the robot hand can cover more than the half of the circum-

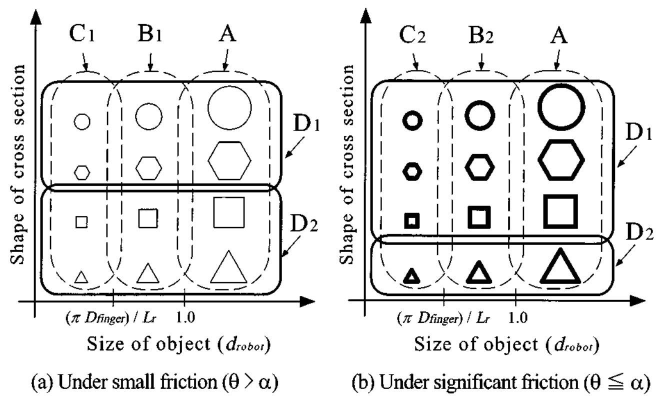

Fig. 8. Map for choosing an appropriate strategy for achieving enveloping grasp.

TABLE I
GROUPS OF GRASPING STRATEGIES

Group	*Grasping strategy*
A	Direct grasp
B_1	Sliding based grasp
B_2	Rolling based grasp
C_1	Regrasping based grasp
C_2	Regrasping based grasp with Rolling motion
D_1	Without Rotating motion
D_2	With Rotating motion

ference, and greater than the size where the robot hand can pick up or achieve a rotating motion on a table.

(A-3) Each finger motion is restricted to a planar motion.

(A-4) Robot hand is attached to the end of an arm. The hand position is measurable.

(A-5) Objects are placed within the reachable area of robot hand.

(A-6) Robot hand includes a joint torque sensor, joint angular sensor and a tactile sensor in the palm.

(A-7) Each joint of robot hand can produce enough torque to manipulate an object.

With both Assumptions (A-4) and (A-6), the robot hand can obtain H_{object}, while it can be detached more easily if it has a vision sensor. The robot hand used in the experiment consists of three same finger units and each finger has three links. The length of each link is $l_1 = 40$ [mm], $l_2 = 25$ [mm], and $l_3 = 30$ [mm], respectively. Rotary encoder is used as an angular sensor. The palm is equipped with ON/OFF type tactile sensor. More precise information on the robot hand will be obtained in our previous work [35]. With these assumptions and the mechanical configuration of the robot hand, we implicitly assume that the study is essentially one of two-dimensional grasping in which object symmetry and, to some extent, hand symmetry is assumed.

Let us now discuss how to realize three tasks given in Section III-B. The simplest way for achieving Task 1 (Detaching the object) is to pick up an object by finger tips. However, if a robot hand regrasps an object from finger tip to an enveloping grasps in the open space in the air, it will often drop the object on the table. If the object is fragile, it will be broken. To avoid such a undesirable scenario, we make the grasp planning so that a part of object can make contact with the table as much as possible until the object is firmly grasped within the hand. Therefore, executing the detaching motion by a robot hand will differ from that of human. Task 2 (Lifting up the object) is achieved either by sliding or rolling motion, depending upon the contact friction over the object's surface as human does. We execute Task 3 (Grasping the object firmly) by constant torque control which is widely used in the research of power grasp [20], [25], [38]. The constant torque control can be achieved by adjusting actuator's current based on the torque sensor output. The control has an advantage where both finger posture and contact force between the finger links and the object are determined automatically according to the command torque. While the grasping motions may differ from those of human and also vary depending upon the mechanical structure of robot hands, the basic tasks constructing the grasping strategy do not change irrespective of the hardware of robot hands.

Fig. 8 shows a guide-line-map for choosing an appropriate strategy according to the size, the shape of cross section and the contact friction of objects. Table I shows the names corresponding each group $A \sim D$ in Fig. 8. Let α and θ be an angle of friction and an angle between the horizontal line and the normal vector $\boldsymbol{n}$ at the contact point, respectively. Fig. 8(a) shows the guide-line-map under the condition that the contact friction between finger links and the object is small $(\theta > \alpha)$, where the horizontal and the vertical axes denote the nondimensional object size d_{robot} and the shape of object, respectively. On the other hand, Fig. 8(b) shows the guide-line-map under the condition where the contact friction is significant $(\theta \leq \alpha)$.

Before proceeding the precise discussion, we define the success condition for achieving an enveloping grasp in our work. Suppose a robot hand having n fingers and m_i links for the $i-th$ finger.

[Success condition of enveloping grasp]
It is defined that a robot hand completes an enveloping grasp for an object, if the following conditions are satisfied.

$$I_a \leq I_{ae} \ \cap \ I_b \leq I_{be} \ \cap \ G_{\text{tips}} < H_{\text{object}}, \qquad (1)$$

where

$$I_a = \max \left\{ I_{ai} = \sum_{j=1}^{m_i} \frac{|(H_{\text{object}}/2) - a_{ij}|}{H_{\text{object}}}, \quad i = 1, 2, \cdots, n \right\}, \qquad (2)$$

$$I_b = \frac{2b}{H_{\text{object}}}, \qquad (3)$$

I_{ae} and I_{be} are thresholds for I_a and I_b, respectively. I_a is the maximum value among I_{a1} through I_{an}. I_{ai} represents the normalized distance between each link surface and the object surface, and I_b represents the normalized distance between the palm and the representative position of object

For a cylindrical object, $I_a = 0$ and $I_b = 1$ if the object makes contact with all finger links and the palm. However, for a general column object, both $I_a = 0$ and $I_b = 1$ are not kept

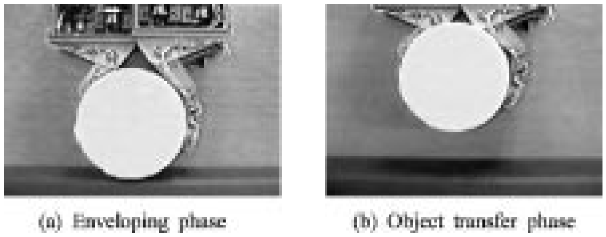

Fig. 9. Direct grasp.

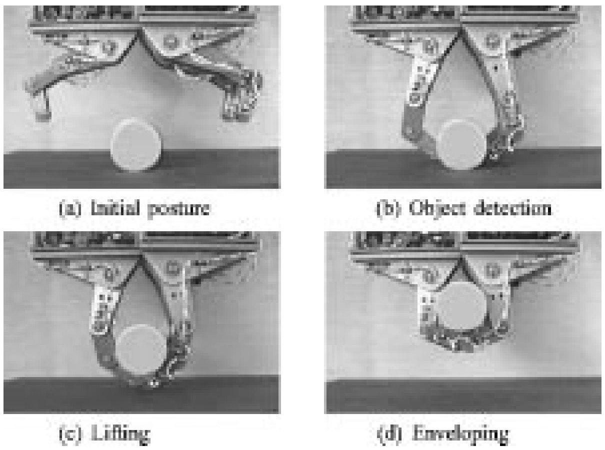

Fig. 10. Sliding-based grasp.

anymore, even if the robot hand fully envelops the object. To cope with this, we have to choose the thresholds (I_{ae}, I_{be}) carefully. For computing I_a and I_b, we need $\boldsymbol{O}_{\mathrm{object}}$. If the robot hand includes a vision sensor, it can directly obtain $\boldsymbol{O}_{\mathrm{object}}$ from the image information. Even if this is not the case, the robot can judge the *success condition of enveloping grasp* by joint angular sensor to some extent, which is described in Appendix.

A. Without Initial Adjustment Motion: Group-D_1

○ $\mathbf{Group-A}$ $(d_{\mathrm{robot}} > 1.0)$: **Direct grasp**

For an object satisfying this condition, constant torque control is applied to each joint after the palm makes contact with the object, as shown in Fig. 9(a). After an enveloping grasp is completed, the robot arm can move the object, as shown in Fig. 9(b). We note that it is not necessary for the hand to realize detaching and lifting motions, since they are achieved by the arm.

Task 1 (**Detaching motion**) :	**no need**
Task 2 (**Lifting motion**) :	**no need**
Task 3 (**Grasping motion**) :	**Constant torque command**

○ $\mathbf{Group-B_1}$

$$((\pi D_{\mathrm{finger}})/L_r \le d_{\mathrm{robot}} < 1.0 \cap \mathit{Contact\ friction\ is\ small})$$

: **Sliding based grasp**

For an object satisfying this condition, the robot hand utilizes a sliding motion between the object and fingers for detaching the object from a table. Initially each finger is opened, as shown in Fig. 10(a) and then approaches the table until the finger tip makes contact with it, where the table detection can be easily checked by torque sensor outputs. In the next step, each finger tip follows along the surface of table until a part of finger link makes contact with the object, as shown in Fig. 10(b). This phase is what we call approach phase. The approach phase is inserted for every strategy except for the *direct grasp*, while we omit the explanation of approach phase in the following discussions. Then, each finger tip pushes the bottom part of object each other, so that we can make the most use of the wedge-effect. The object will be automatically lifted up by slipping over the finger surface, as shown in Fig. 10(c). At the same time, each link is gradually closed to fully constrain the object. In this strategy, constant torque control is also effectively utilized for achieving Tasks 1 through 3. Whether the object really reaches the palm or not strongly depends on how much torque command is imparted to each joint.

Task 1 (**Detaching motion**) :	**Constant torque command**
Task 2 (**Lifting motion**) :	**Constant torque command**
Task 3 (**Grasping motion**) :	**Constant torque command**

Fig. 11 shows the success classification map for a cylindrical object with H_{object} = 32 [mm] and μ = 0.7, where the horizontal and the vertical axes denote the normalized command torque $\tau_1/(mgl_1)$, $\tau_2/(mgl_2)$ for the first and the second joints under $\tau_3/(mgl_3) = \tau_2/(mgl_2)$, respectively, and ○ and the other three marks (×, ■, ◇) correspond to the final grasping postures, as shown in the top of the graph. The judgment of success or failure is achieved by examining I_a and I_b which are also given in Fig. 11. From Fig. 11, we can see that a large area of torque commands is obtained for achieving an enveloping grasp under μ = 0.7.

○ $\mathbf{Group-B_2}$

$$((\pi D_{\mathrm{finger}})/L_r \le d_{\mathrm{robot}} < 1.0 \cap \mathit{Contact\ friction\ is\ large})$$

: **Rolling based grasp**

Fig. 12 shows the success classification map for a cylindrical object $(H_{\mathrm{object}}$ = 32 [mm]) under μ = 1.3. We note that the region(○) where the hand envelops an object successfully, disappears under μ = 1.3. This is because a sliding motion based on wedge-effect is blocked under a significant surface friction. Therefore, we need an alternative strategy for enveloping the object under a significant friction.

When the robot recognizes any failure, it switches grasping strategy from sliding to rolling-based strategies after putting down the object on the table. Fig. 13 shows an example of *rolling-based grasp*. More precise motion planning is given in [38].

Task 1 (**Detaching motion**) :	**Rolling motion**
Task 2 (**Lifting motion**) :	**Rolling motion**
Task 3 (**Grasping motion**) :	**Constant torque command**

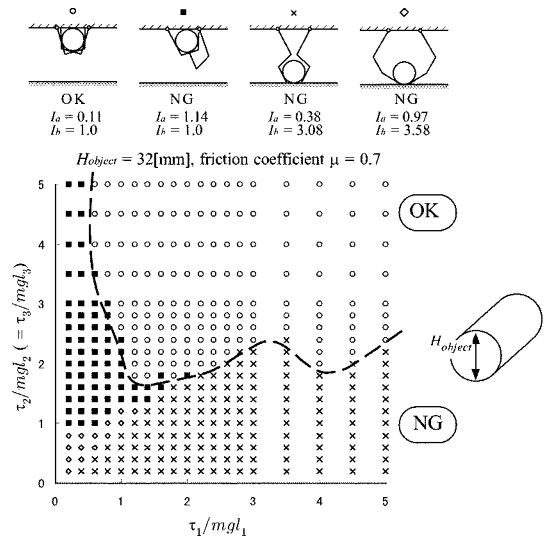

Fig. 11. Success map for a cylindrical object (μ = 0.7).

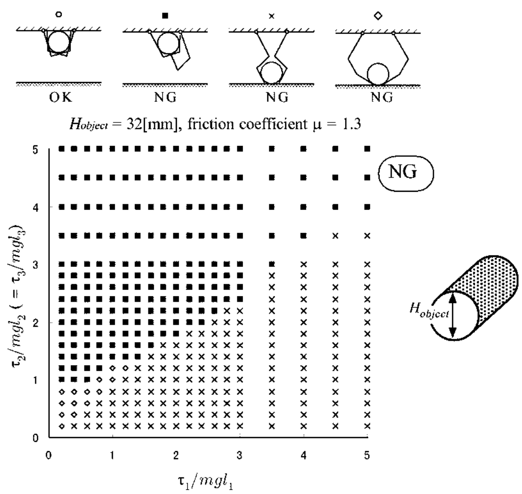

Fig. 12. Success map for a cylindrical object (μ = 1.3).

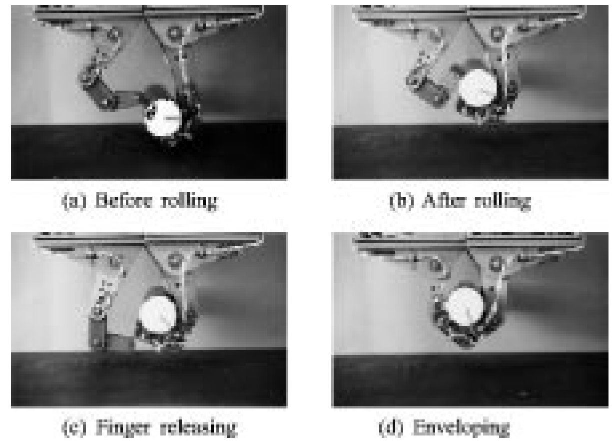

Fig. 13. Rolling-based grasp.

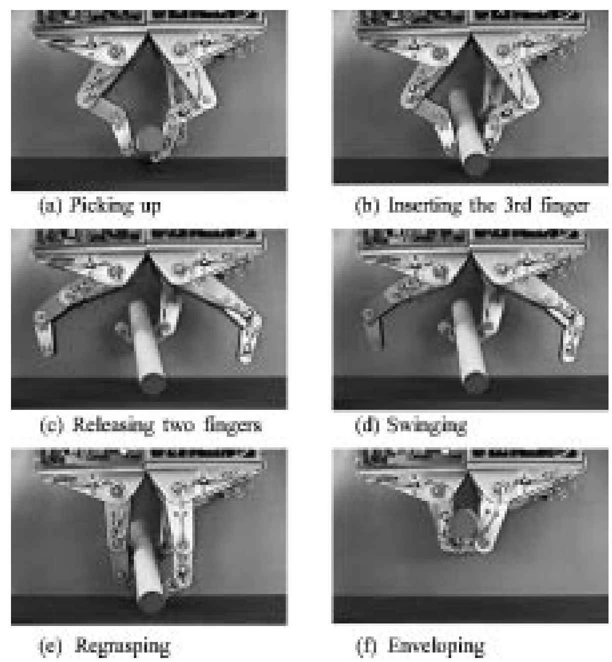

Fig. 14. Regrasping-based grasp.

○ Group − C_1

$$(d_{\text{robot}} < (\pi D_{\text{finger}})/L_r \cap \textit{Contact friction is small})$$

: Regrasping based grasp

For an object whose diameter is small enough to ensure that any finger tip can not be inserted into the bottom part of object, it becomes difficult to utilize the wedge-effect. In such a case, *regrasping-based grasp* may be an appropriate strategy decomposed of two basic motions where one is the motion for picking up the object by using two fingers, as shown in Fig. 14(a), and the other one is the regrasping motion, as shown in Figs. 14(b)–(e). The first motion plays an important role in allowing no interference from the table. In the following motion, the remaining finger hooks the object so that we can make a small gap between the object and the table, as shown in Fig. 14(b), even though two fingers picking up the object are released from the object. After these finger motions, the object is supported by one finger and the table, as shown in Fig. 14(c). We note that under such object's posture we can find an enough space between the object and the table for inserting the released fingers. In the next step, the left finger is swung a bit, as shown in Fig. 14(d) so that both the right and the left fingers may not interfere with each other during the finger closing motion. After every finger is inserted into the bottom of object, as shown in Fig. 14(e), constant torque control is applied for achieving an enveloping grasp, as shown in Fig. 14(f). While human regrasps the object in the air, the robot hand uses the surface of table effectively in order to prevent the object from falling down.

Task 1 (Detaching motion) :	**Alternative finger insert–ing motion**
Task 2 (Lifting motion) :	**Constant torque command**
Task 3 (Grasping motion) :	**Constant torque command**

○ Group − C_2

$$(d_{\text{robot}} < (\pi D_{\text{finger}})/L_r \cap \textit{Contact friction is large})$$

: Regrasping based grasp with Rolling motion

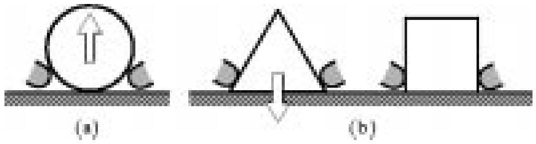

Fig. 15. Examples of objects where the upward force (a) is expected and (b) is not expected by a simple pushing motion.

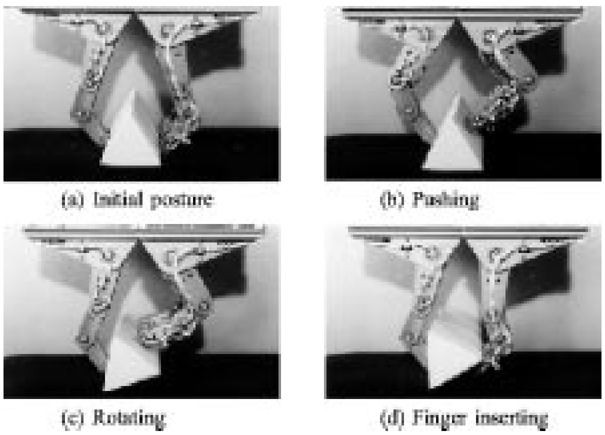

Fig. 16. Initial adjustment motion (rotating motion).

For an object satisfying this condition, the regrasping motion just same as the motion for Group-C_1 (*Regrasping-based grasp*) can be applied for detaching the object from the table and inserting the finger into the bottom of object. However, the object can not slide over the finger link surface under a large contact friction. Thus, after detaching the object from the table, a rolling motion utilized in Group-B_2 (*Rolling-based grasp*) is applied for carrying the object to the palm.

Task 1 (Detachingmotion) :	**Alternative finger insert−ing motion**
Task 2 (Liftingmotion) :	**Rolling motion**
Task 3 (Grasping motion) :	**Constant torque command**

B. With Initial Adjustment Motion: Group-D_2

For an object whose cross section is circle, as shown in Fig. 15(a), an upward force can be produced by pushing the bottom of the object toward the horizontal direction. For an object whose cross section is triangle or rectangle, as shown in Fig. 15(b), the finger tip forces may produce a downward force or balance each other within the object. Under such a situation, the lifting force is not produced even though the contact force is increased. From grasp experiments by human, the rotating motion is obviously a key for detaching an object from the table if it has rectangular or triangular cross section. For either object, a robot hand also conveniently utilizes the rotating motion for producing a space for inserting fingers between the object and the table. For this *initial adjustment motion* we can also apply the toppling manipulation where the rotating motion is guaranteed by just one finger [34]. Fig. 16 shows an example of the *initial adjustment motion*. Once a sufficient gap is produced,as shown in Fig. 16(c), one finger is removed away from the object's surface and inserted into the gap, as shown in Fig. 16(d). After the finger tip is inserted into the gap between the object and the table, we apply the same grasping mode as those taken for cylindrical objects.

C. The Switching Algorithm among Strategies

We now discuss how to choose an appropriate one from various strategies prepared according to the size, the shape of cross section, and the contact friction of objects, and how to switch from one to another when a robot hand fails in grasping an object. First of all, a robot hand needs to know the size of object, so that it can choose a strategy appropriate for the scale. An appropriate candidate is to utilize a tactile sensor installed in the palm. Suppose that each finger is fully opened initially and we make the hand come down until either the palm sensor or the finger link makes contact with an object. By this contact, the robot can detect the height of object $H_{\rm object}$ and $d_{\rm robot}$ computed by $\pi H_{\rm object}/L_r$. While $\pi H_{\rm object}$ does not provide the circumference of object in general, it denotes the exact one for a cylindrical object. Anyway, the robot can roughly estimate the size of object by $\pi H_{\rm object}/L_r$. Even for two objects having the same $d_{\rm robot}$, there are some cases where two different strategies exist. In such a case, we take the idea of Easier-Strategy-Comes-First which starts from the easier strategy and switches into the other one when an easy one fails. Fig. 17 shows the flow-diagram of the grasping strategies, where relatively complicated strategies are placed in lower parts and strategies surrounded by a bold line entail the *initial adjustment motion*.

The strategy block-I consists of *direct grasp*. It is difficult that the robot hand lifts up a triangular or a rectangular object from the table by *direct grasp without rotating motion*, except for the case that the contact friction is large. In such a case, the robot hand applies the *direct grasp with rotating motion*. When the robot hand fails in grasping the object, it estimates that the object is small for achieving the *direct grasp*, then it switches the block-I to the block-II.

The strategy block-II consists of *sliding* and *rolling-based grasps*. At first, the robot hand tries the *sliding-based grasp* since it is simpler than the *rolling-based grasp*. When the contact friction is large, the robot hand can not utilize the *sliding-based grasp*. When the cross section of object has triangle or rectangle, the robot hand needs the *initial adjustment motion* before further steps. Based on the *success condition*, the robot hand recognizes the failure. In either case that the object has triangular or rectangular cross section, the *initial adjustment motion* is necessary before starting Tasks 1 through 3. Therefore, the robot hand needs the information concerning the shape of cross section of the object when it recognizes the failure. While the robot needs the bottom shape of object, it is not necessary for the robot to know the full shape of cross section for choosing an appropriate strategy. The bottom shape of object can be estimated by measuring width W_f and W_t, where W_f and W_t are the width at the bottom and the width at a bit higher position, as shown in Fig. 17, respectively. If $W_f < W_t$, cross sections are, for example, pentagon, hexagon, circle, and so on. When the robot fails in grasping under $W_f < W_t$, it judges a large contact friction of object. Based on this estimation, the robot hand chooses the *rolling-based grasp*. On the other hand, if $W_f \geq W_t$, the shape of cross section should be triangle or

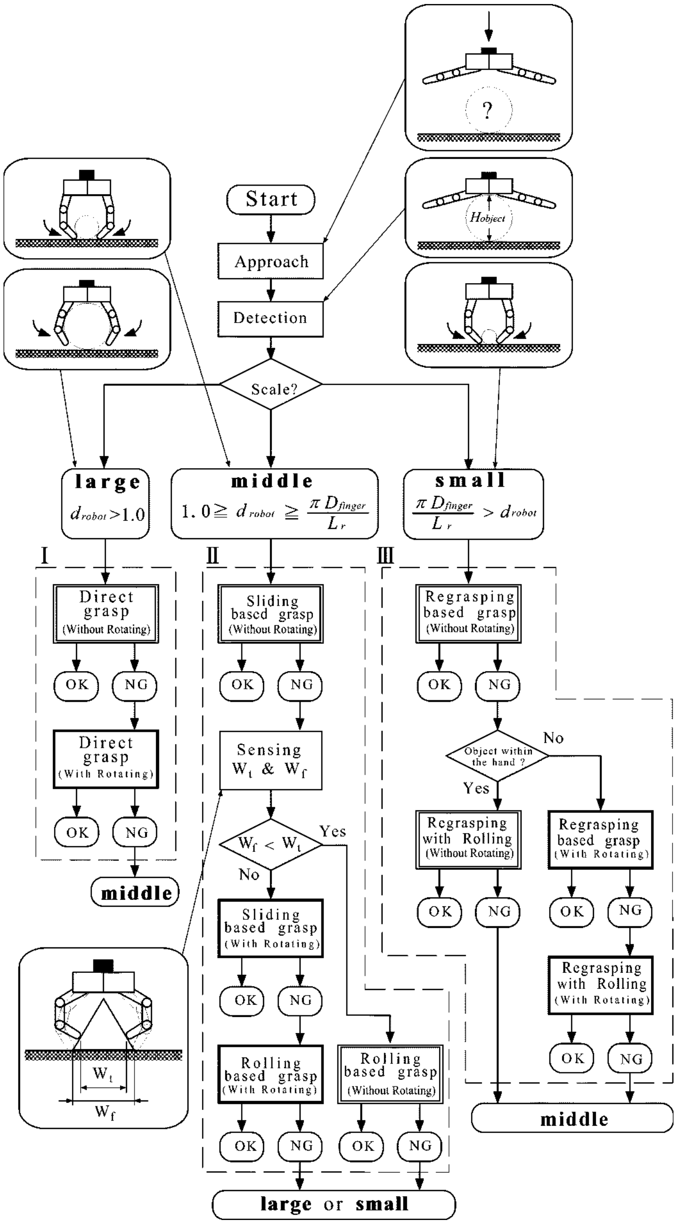

Fig. 17. Strategy flow diagram.

rectangle. In case of $W_f \geq W_t$, the robot hand chooses the *sliding-based grasp with rotating motion*. If both approaches in block-II do not work successfully, the robot hand switches the strategy block to either block-I or block-III.

The strategy block-III consists of *regrasping-based grasp*. First, the robot hand tries *regrasping-based grasp*. When the robot hand fails in grasping, it checks the status where the object is. When the object is in the robot hand, it switches the strategy to *regrasping-based grasp with rolling motion* according to the reasoning that the contact friction is too large for lifting up the object by utilizing constant torque control. On the other hand, when the object is not detached from the table, the robot hand switches the strategy to *regrasping-based grasp with rotating motion* according to the reasoning that the object is triangular or rectangular column. When all strategies in block-III do not work appropriately, the robot hand switches the strategy block to the block-II.

Fig. 17 is-based on tactile information, each block becomes much simpler under a vision sensor. The video proceeding [39] contains the experiments based on this switching algorithm.

V. Discussion

As for the generality issue, we first try to relax the assumption given in Section IV and consider the following cases, toward general column objects, a new robot hand, and a new task. We also discuss the torque determination in theoretical sense.

A. Toward General Column Objects

For general column objects, the most important point is to confirm whether the robot hand can detach the object from the table or not (Task 1).

While the switching in the strategy flow diagram given in Let β_1 and β_2 be angles between an edge of the object and the table, as shown in Fig. 18. We classify general column objects into three groups, as shown in Fig. 18, where both β_1 and β_2 are greater than $\pi/2$ [rad] in Fig. 18(a), either β_1 or β_2 is greater than $\pi/2$ [rad] in Fig. 18(b), and both β_1 and β_2 are less than $\pi/2$ [rad], respectively. For an object shown in Fig. 18(a), we can apply the same grasping strategy as those used for a cylindrical object. The objects classified into Fig. 18(b) are not included in the strategy flow diagram. Now, suppose that two fingers push the bottom part of object, as shown in Fig. 19(a). While the right finger does not contribute to lifting up the object, the left finger produces the wedge-effect and rotates the object around one edge of the object, as shown in Fig. 19(b). If the surface friction is small enough, the hand will lift up the object by sliding motion and finally complete an enveloping grasp. Thus, the object shown in Fig. 18(b) can be included in the same group which can be achieved by a *sliding-based grasp* if the contact friction is small. Now, let us consider an object classified into the group in Fig. 18(c). Such an object needs an *initial adjustment motion* requested for either a triangular or a rectangular objects. For achieving the *initial adjustment motion*, the robot has to detect P_c where the rotating moment is produced as far as the contact friction is not zero. Since P_c does not always exist for general column objects, the robot often meets an object where P_c is not found. In such a case, the robot anyway pushes at P_c' where P_c' denotes the top of object, as shown in Fig. 18(c). When the robot can not rotate the object, it gives up grasping the object.

As far as the surface friction is large enough, the robot hand can not grasp the object whose shape is extremely flat, and both β_1 and β_2 are smaller than $\pi/2$ [rad], while it can grasp an object if $\beta_1 > \pi/2$ [rad] and $\beta_2 > \pi/2$ [rad]. In other words, if the robot hand can not find any contact points which can produce upward force, it can not grasp the object firmly in the air.

B. Toward the Utilization of a New Robot Hand

Now, let us consider the same grasping task with a new hand. The functions do not change irrespective of the hardware of robot hands, while the motions have to be changed so that they may match with the hardware. Therefore, we can cope with this

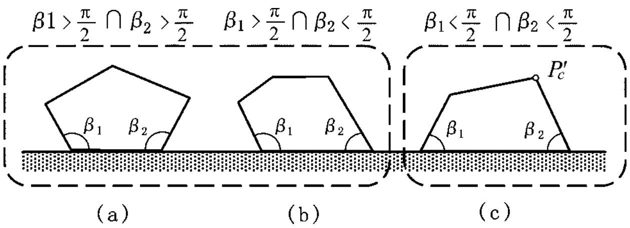

Fig. 18. Grouping of column objects whose cross sections are convex.

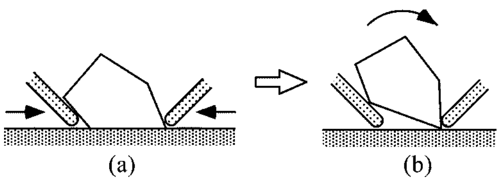

Fig. 19. Wedge-effect at one edge of the object.

issue easily by changing the software, so that we can achieve the basic functions obtained through the human observation.

C. Toward a New Task

As for a new task, the first thing to do is to extract the basic functions (tasks) from the human grasping and then we develop software so that it can achieve these functions instead of realizing the exactly same motions as human do.

D. Clue for Determining Torque Command

Under multiple contacts, it is generally difficult to find a set of torque commands sufficient for lifting up the object to the palm. This is because we have to solve a kind of inverse problem where we obtain a set of torque commands producing a stable motion of object toward the palm. To cope with this, we have proposed the *force-flow diagram* [25] where we can see how the object will move for a given set of torque. By utilizing this diagram, we can easily examine whether a given set of torque commands are sufficient for moving the object to the palm or not.

VI. Conclusion

Through human observation, we found that human changes the grasp pattern according to the scale, the shape of cross section and the contact friction of objects. We proposed five basic grasping strategies (*direct grasp, sliding-based grasp, rolling-based grasp, regrasping-based grasp, initial adjustment motion*) which are easily applicable for general multifingered robot hands. We proposed the guide-line-map for choosing an appropriate strategy among these strategies according to the size, the shape of cross section, and the contact friction of object. We also proposed the strategy flow diagram to explain how to switch grasping strategy from one to another when the robot hand fails in grasping the object. Finally, we tried to relax the assumptions, so that we can pursue the generality of the grasping strategy.

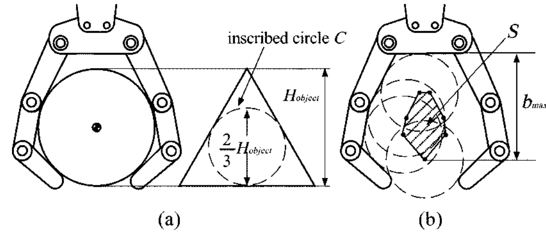

Fig. 20. Estimate that the area of $\boldsymbol{O}_{\rm object}$.

Appendix

The *success condition of enveloping grasp* is composed of three conditions concerning $G_{\rm tips}$, I_a and I_b. $G_{\rm tips}$ can be obtained by joint angular sensor only, while both I_a and I_b need $\boldsymbol{O}_{\rm object}$ to compute a_{ij} and b. Suppose that the shape of cross section is not given. Since the palm sensor is available by Assumption A-6, the robot hand can measure the object's height $H_{\rm object}$. However, since the robot does not know the shape of cross section of object, the candidate of $\boldsymbol{O}_{\rm object}$ generally forms an area S, as shown in Fig. 20(b). To obtain S, we define the circle C whose diameter is equal to that of the inscribed circle of the cross section. For example, Fig. 20(a) shows the relationship between $H_{\rm object}$ and the diameter of C for a triangular object. Since the finger link never reaches the inside of C, we can obtain the candidate of $\boldsymbol{O}_{\rm object}$, as shown in Fig. 20(b). Now, we consider the worst scenario in a sense of having the largest area of S. The worst scenario is expected when we assume triangular cross section, while we have the smallest area of S for a cylindrical object. For all possible $\boldsymbol{O}_{\rm object}$ in S, we obtain the largest $I_{a\_\max}$ and $I_{b\_\max}$, so that we can evaluate the worst case. If $I_{a\_\max}$ and $I_{b\_\max}$ satisfy the following success condition, we say that the enveloping grasp is completed

$$I_{a\_\max} \leq I_{ae} \ \cap \ I_{b\_\max} \leq I_{be} \ \cap \ G_{\rm tips} < H_{\rm object}. \quad (4)$$

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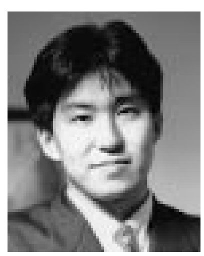

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