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On Three Phases for Achieving Enveloping Grasps

— Inspired by Human Grasping —

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Abstract

A practical procedure for achieving an enveloping grasp is presented especially for cylindrical objects. It is composed of three phases, the approach phase, the lifting phase and the grasping phase. For the grasping phase, we introduce the natural computation mode in which a preset torque is commanded to each joint, so that both the equilibrium position and the contact forces may be determined automatically. A sufficient condition for achieving the enveloping grasps is shown for the given procedure. Experimental results are also shown to verify the effectiveness of the proposed grasping procedure.

Key words: *Enveloping Grasp, Approach Phase, Lifting Phase, Grasping Phase, Constant Torque Control.*

1 Introduction

Although there have been a number of works concerning multi-fingered robot hands, most of them address a finger tip grasp, where it is assumed that a part of inner link of finger never makes contact with the object. Enveloping grasp (or power grasp) provides another grasping style, where multiple contacts between one finger and the 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. While there are still many works discussing enveloping grasps, most of them deal with the grasping phase only, such as contact force analysis, robustness of grasping and contact position sensing. The goal of this work is to provide a practical strategy for finally achieving an enveloping grasp under the assumption that the object is initially placed on a table.

Suppose that human eventually achieves an enveloping grasp for an object placed on a table. Actually, such a situation is often observed in a practical environment, for example, 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. This is why we focus on cylindrical object as the first example, while the procedure is later extended to more general objects. When approaching an object on the table, human unconsciously makes a preshape of hand according to the shape and the size of object. Then, based on the initial contact between the finger and the object, human quickly envelops and lifts up the object by the finger. To cause the object to lose the contact with the support, human often utilizes the wedge effect, in which each finger is pushed between the object and the table, so that a lifting force can be generated. We are particularly interested in the utilization of such wedge effect for lifting phase, while there are, of course, many objects in which human directly envelops without utilizing the slipping motion between the finger and the object.

Although the series of human motion are so fast that we can not clearly decompose it into individual motions, for robot application, we separate the whole procedure into three phases, the approach phase, the lifting phase and the grasping phase, respectively. At the end of approach phase, we command the finger tip to insert into the space existing between the table and the bottom part of the object. Then, by forcing each finger between them, the finger tip can produce a lifting force on the bottom surface of the object and, as a result, the object is lifted from the table. During such a lifting phase, the freedom for the object motion is lost gradually by closing each finger. When the finger satisfies some constraint condition, we switch into the natural computation mode, where constant torque commands are simply sent to all joints. Such a natural computation mode releases us from computing the exact contact forces as well as the exact object's position, since they are naturally determined by the combination among the commanded torque, the object's weight and the geometrical relationship. Therefore, we can expect that the enveloping grasp can be easily achieved without any complicated motion planning. Assuming the friction coefficient between the finger and the object, we consider a sufficient condition for finally achieving an enveloping grasp. One emphasis is that the sufficient condition spans a large area which is desirable for a practical utilization. We show an optimum palm position, in which the finger can complete both the approach and the lifting phases for the largest range of diameter of objects. We also show a disirable region of joint torque command for achieving an enveloping grasp for various size of objects. Experimental results are also shown to verify the effectiveness of the proposed grasping procedure.

2 Related Work

Approach phase: Jeannerod[1] has studied human grasping intensively and has shown that during the approaching phase of grasping, the hand preshapes in order to prepare the shape matching with the object to be grasped. Bard and Troccaz[2] 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[3] proposed an active sensing method for localizing multiple contact points for an inner link based grasp.

Lifting phase: Trinkle and Paul[4, 5] proposed the concept of grasp liftability and derived the liftability regions of a frictionless planar object for use in manipulation planning.

Enveloping grasp or power grasp: Mirrza and Orin[6] applied a linear programming approach to formulate and solve the force distribution problem in power grasps, and showed a significant increase in the maximum weight handling capability for completely enveloping type power grasps. Trinkle[7] analyzed planning techniques for enveloping, and frictionless grasping. Salisbury[8, 9] has proposed the Whole-Arm Manipulation (WAM) capable of treating a big and heavy object by using one arm which allows multiple contacts with an object. Vassura and Bicchi[10] have proposed a dexterous hand using inner link elements to achieve robust power grasps and high manipulability. Melchiorri and Vassura[11] discussed mechanical and control issues for realizing such a dexterous hand. Bicchi[12] showed that internal forces in power grasps which allow inner link contacts can be decomposed into active and passive. Omata and Nagata[13] analyzed the indeterminate grasp force by fixing their eyes upon that contact sliding directions are constrained in power grasps. Zhang et. al.[14] evaluated the robustness of power grasp by utilizing the virtual work rate for all virtual displacements. Kumar[15] used WAM as an example to explain their minimum principle for the dynamic analysis of systems with frictional contacts.

Work combined with more than two phases: For a two-fingered hand whose opening is controlled by a single parameter, Rimon and Blake[16] discussed a preshaping problem combining with grasping phase. For an initial hand configuration, an object has some freedom to move but finally leads to the desired immobilizing grasp by simply closing the fingers. Kleinmann et.al.[17] showed a couple of approaches for finally achieving power grasp from finger tip grasp. In our previous work[18], we have shown that human chooses the grasp planning according to the scale of objects, even though they are geometrically similar (Scale-Dependent Grasp). Based on the observation of human grasping, we introduced three grasping strategies depending upon the size of objects for cylindrical objects placed on a table.

3 Grasping Procedure

3.1 Hand and grasp model

We assume a three-fingered robot hand as shown in Fig.1. While most of the developed hands have a swing

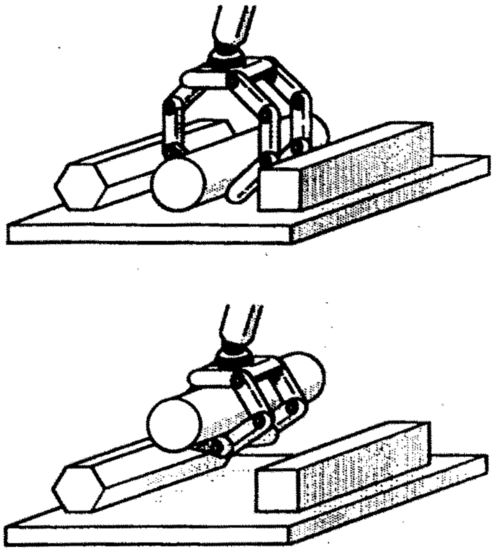

Fig.1 An example of emveloping grasp.

joint at the base of each finger, it is regarded that the swing joint is locked so that each finger can move only in 2D plane. The motion plane of finger is parallel in each other. Each joint has a joint position sensor and a joint torque sensor. The joint position sensor is indispensable for determining the finger posture and the joint torque sensor is conveniently utilized for detecting the contact between the finger and the table (or the object) and for realizing either torque control or compliance control. We assume that the object has cylindrical shape and it is placed on a flat table. We also assume that the object is placed at the center between the right and the left fingers. These assumptions allow us to discuss the grasping problem in 2D space. We further assume that the palm is already positioned close to the object and, therefore, do not discuss the approach phase of the robot arm itself. Also, the diameter of the object is roughly given by a visual sensor.

3.2 The grasping procedure

Fig.2 explains three phases for grasping a cylindrical object where (a)–(c), (d), (e) and (f) are the approach phase, the lifting phase, the grasping phase and the coordinate system, respectively. In the approach phase, each finger first takes the designated initial posture (see Fig.2(a)) and then the first link is rotated until the finger tip detects the table. By monitoring a torque sensor output in each joint, we can detect any contact between the finger and table as shown in Fig.2(b) (table detection). After the table detection, the finger tip is commanded to move along the table until it makes contact with a part of the object as shown in Fig.2(c). (object detection). The approach phase is composed of these two sub-steps. Since the finger tip is commanded to follow the table, it is most probable for the finger tip to make contact with the bottom part of the object. In the lifting phase, the finger tip is further commanded to

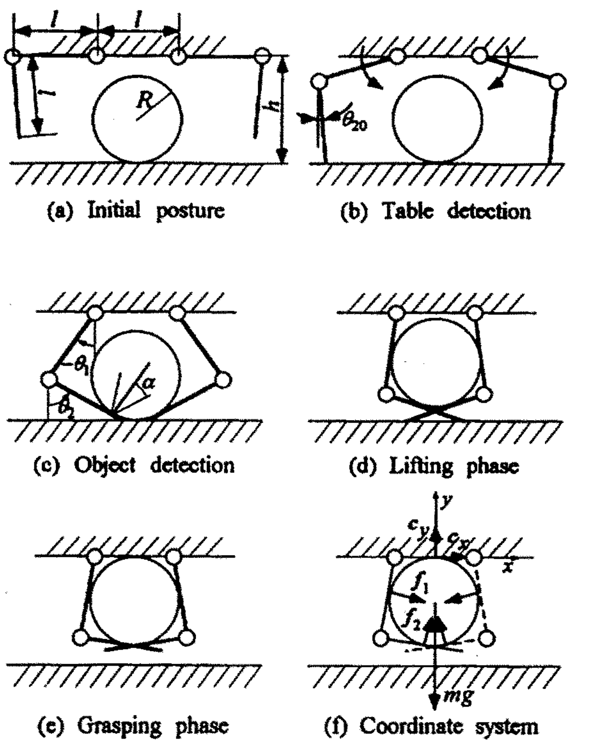

Fig.2 The procedure for achieving an enveloping grasp.

move along the table to make the most use of the wedge effect. Therefore, there is no real switching point between the approach and the lifting phases. The object height during the lifting phase varies according to the finger tip position, and finally both the first and the second links will make contact with the object (two-points-contact mode), as shown in Fig.2(d). At this moment, the outputs from joint torque sensors abruptly increase, because the degree of freedom for the finger tip to move along the table surface is no more available under such multiple contacts. By utilizing a large joint torque as a trigger signal, we switch from the lifting phase to the grasping phase. The grasping phase is realized by the natural computation mode, in which a constant torque is commanded in each joint for finally making the object contact with the palm in addition to both the first and the secoond links as shown in Fig.2(e). Whether the object really reaches the palm or not and how firmly the hand grasps the object, strongly depend on how much torque command is imparted to each joint.

4 A Sufficient Condition

4.1 Some definitions

Define the vector, $u = (R/l,\ h/l)^t$, where R, h and l are the radius of cylinder, the height between the palm and the table and the link length, respectively. The area $\mathcal{F}$ is defined, such that $u \in \mathcal{F}$ can ensure that the tip reaches the table and the second link makes contact with the object before the other part of the finger link makes contact with the object. The area $\mathcal{V}$ is defined such that $u \in \mathcal{V}$ can ensure that the object is lifted until the two-points-contact mode is achieved. We stop the lifting phase if the two-point-contact mode is not achieved before the finger link results in the straight-lined posture. Define the vector $v = (\tau_{1c}, \tau_{2c})^t$, where τ_{1c} and τ_{2c} are the command torque for the first and the second joint, respectively. The area $\mathcal{T}$ is defined, such that $v \in \mathcal{T}$ can ensure that the finger completely envelops the object until the object finally reaches the palm.

4.2 Problem formulation

Problem 1:
Find two areas $u \in \mathcal{V} \cap \mathcal{F}$ *and* $v \in \mathcal{T}$.

The answer for the Problem 1 provides a sufficient condition for finally achieving an enveloping grasp. A larger area is of course desirable, because we can easily find h, τ_{1c} and τ_{2c} without any complicated process. Our second goal is to find h that can succeed in enveloping various size of objects. Mathematically, this is formulated as follows:

Problem 2:
Find h_o *maximizing* R_o, *where* $R_o = R_{max} - R_{min}$, $R_{max} = \max\{(1,\ 0)u\}$, $R_{min} = \min\{(1,\ 0)u\}$ *and* $u = (R,\ h_o)^t \in \mathcal{V} \cap \mathcal{F}$.

The answer for the Problem 2 is conveniently utilized for practical application. Because we can simply set h_o irrespective of the size of object for completing both the approach and the lifting phases, if $R_{min} \le R \le R_{min}$.

4.3 The approach phase: $\mathcal{F}$

Although there are many possible postures during the approach phase, for simplicity, we assume that the second joint is controlled so that it always keeps a certain angle θ_{20} with respect to the absolute coordinate system as shown in Fig.2(a) and (b). As described before, the approach phase is composed of two sub-steps (table detection and object detection). For each step, we now consider a couple of conditions for obtaining $\mathcal{F}$.

Step 1 (table detection):
(a) To avoid for the object to penetrate the palm, h must be larger than $2R (h \ge 2R)$.
(b) The tip must contact with the floor. This condition varies according to how much θ_{20} is imparted to the second link, where the subscript "0" denotes the initial value.
(c) The first link should not make contact with the object before detecting the table. In other words, the link posture should not have any intersection between the link and the object when the finger detects the table.

Step 2 (object detection):
(d) The first link should not make contact with the object before the second link contacts the object, while the finger tip is moved along the table.

$\mathcal{F}$ is given by the common area satisfying all conditions (a), (b), (c) and (d).

4.4 The lifting phase

(e) The contact point should always keep the sliding condition, which is given by $\theta_2 > \alpha$, where 2α denotes the top angle of the friction cone at the point of contact as shown in Fig.2(c). Although θ_2 varies according to the link posture, we utilize the minimum θ_2 during the approach and the lifting phases. The sliding motion is always guaranteed if the minimum $\theta_2 > \alpha$ is satisfied. Because the contact force finally comes out from the friction cone under the condition, when the grasping force is increased.
(f) Two-points-contact mode should be completed before the finger posture results in the straight-lined posture.
(g) Two-points-contact mode should be completed before the object makes contact with the palm.

Both constraints (f) and (g) come from the grasping procedure explained in 3.2. $\mathcal{V}$ is given by the common area satisfying all conditions (e), (f) and (g).

4.5 The grasping phase

Under two-points-contact mode, the link posture is uniquely determined when the position of object is given. Assuming the contact position $\boldsymbol{p}_i = (p_{ix}, p_{iy})^t$ for i-th link (i=1 or 2), we can express the relationship between the contact force $\boldsymbol{f}_i = (f_{ix}, f_{iy})^t$ and the joint torque τ_i as follows:

$$\tau_1 = \boldsymbol{p}_1 \otimes \boldsymbol{f}_1 + \boldsymbol{p}_2 \otimes \boldsymbol{f}_2 \quad (1)$$
$$\tau_2 = (\boldsymbol{p}_2 - \boldsymbol{e}_1) \otimes \boldsymbol{f}_2 \quad (2)$$

where $\boldsymbol{e}_i = (e_{ix}, e_{iy})^t$ is the vector indicating i-th link tip, and $\otimes$ denotes a scalar operator performing $w_{1x}w_{2y} - w_{2x}w_{1y}$ for two vectors $\boldsymbol{w}_1 = (w_{1x}, w_{y1})^t$ and $\boldsymbol{w}_2 = (w_{2x}, w_{2y})^t$. The contact force is decomposed into two components and is described by using the normal and tangential unit vectors, $\boldsymbol{n}_i$ and $\boldsymbol{t}_i$.

$$\boldsymbol{f}_i = f_{in}\boldsymbol{n}_i + f_{it}\boldsymbol{t}_i \quad (3)$$
$$-\mu f_{in} < f_{it} < \mu f_{in} \quad (4)$$

where μ is the frictional coefficient at the point of contact, and f_{in} and f_{it} are the normal and the tangential force components at the contact point in the i-th link, respectively. The vertical component of the force is given by

$$f_v = \boldsymbol{c}_y^t(\boldsymbol{f}_1 + \boldsymbol{f}_2) \quad (5)$$

where $\boldsymbol{c}_y$ denotes the y-directional unit vector as shown in Fig.2(f). Under eqs.(1), (2), (3) and ineq.(4), let us now consider the linear programming problem to maximize f_v. Let f_v^+ and f_v^- be the maximum and the minimum values, respectively. If both $2f_v^+ - mg$ and $2f_v^- - mg$ are positive for all possible heights, the object moves upward until it finally reaches the palm, where $2f_v^+$ (or $2f_v^-$) denotes the vertical force by two fingers. If both are negative, the object moves downward and the hand will finally fail in enveloping the object.

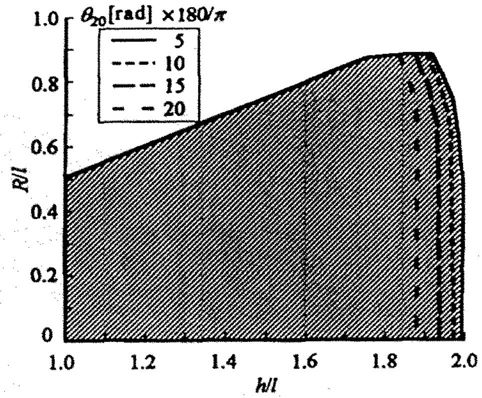

Fig.3 $\mathcal{F}$ in the approach phase.

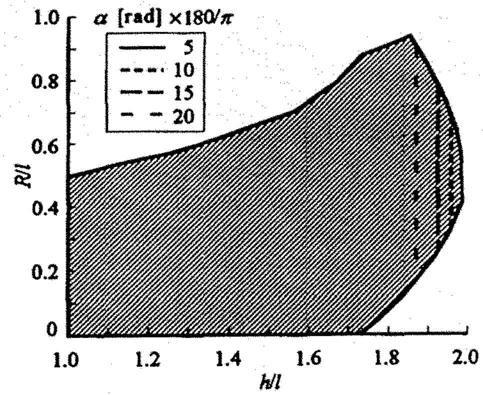

Fig.4 $\mathcal{V}$ in the lifting phase.

4.6 Simulation for $\mathcal{F}$, $\mathcal{V}$ and $\mathcal{T}$

Fig.3 and Fig.4 show $\mathcal{F}$ and $\mathcal{V}$, respectively, computed for the hand shown in Fig.2, where θ_{20} and α are chosen as parameters. As θ_{20} increases in Fig.3, the area of $\mathcal{F}$ reduces. Similarly, as α increases in Fig.4, the area of $\mathcal{V}$ reduces. Note that we can still obtain a large area $\mathcal{V}$ under a relatively large α. Since we do not know the friction coefficient in advance, this result is desirable. Fig.5 shows the intersection between $\mathcal{F}$ and $\mathcal{V}$, where α=$\pi/36$ and θ_{20}=$\pi/36$. One important remark is that $\mathcal{F} \cap \mathcal{V}$ still keeps a large area and if h/l=1.75 is chosen, the procedure ensures to complete both the approach and lifting phases for an object whose diameter is in the range of $0.02 < R/l < 0.87$. In other words, an object ($0.02 < R/l < 0.87$) on the table finally results in the two-points-contact mode by simply choosing h/l=1.75. This result is very noticeable from the viewpoint of actual application. Because as far as h/l=1.75 is selected, the exact size of object is not necessary, while most of the grasping procedures need the exact information of object size. The answer for the Problem 2 is h_o=1.75 with $0.02 < R < 0.87$, for this particular example. One remark is that we can keep h_o=1.75 with $0.02 < R < 0.87$, even though the frictional angle increases up to α=$7\pi/45$. Fig.6 shows $\mathcal{T}$ computed for the hand shown in Fig.2, where the area

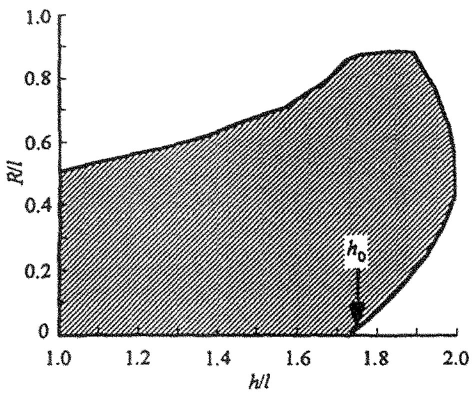

Fig.5 Intersection between $\mathcal{F}$ and $\mathcal{V}$ ($\alpha=\pi/36$, $\theta_{20}=\pi/36$).

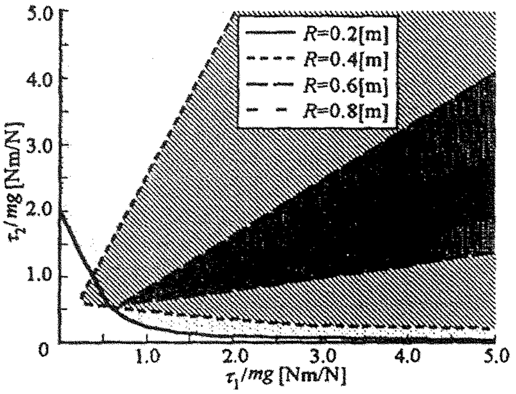

Fig.6 $\mathcal{T}$ in the grasping phase ($\alpha=\pi/36$).

of $\mathcal{T}$ is denoted by the hatched line and mg is chosen by $mg = 1.0$. From Fig.6, we can again see a large area, while the area varies rather strongly depending upon the radius of the object. This radius dependency, however, does not make much problem. Because the robot hand can roughly estimate the size of object by utilizing the link posture when the two-points-contact is achieved. Therefore, we can choose the pair of τ_{1c} and τ_{2c} for the object whose radius is roughly given. As a general tendency, for a small cylinder, the sufficient condition for achieving an enveloping grasp is easily satisfied if we choose large and similar joint torque for both joints, while for a large cylinder, the possible area reduces. One desirable feature of $\mathcal{T}$ is that if we choose the pair of τ_{1c} and τ_{2c} within $\mathcal{T}_{R=0.8}$, it can cover the object whose radius is less than R=0.8 and greater than R=0.2.

5 Experiments

5.1 Mechanical description of Hiroshima-Hand

The Hiroshima-Hand is composed of three finger units, where each finger unit has completely same configuration. Each finger unit has three joints and the joint assignment is same as that of human finger except the

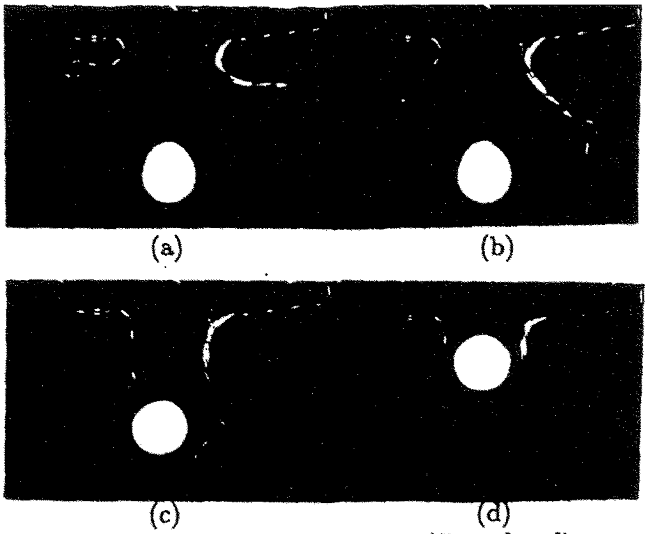

Fig.7 A grasping experiment (R=15[mm]).

swing motion. Because of simplification of the mechanism and limited research purpose, the swing degree of freedom (d.o.f) is not included on purpose. If we really need this d.o.f, however, we can impart it to the connection part between the finger unit and the base. The finger size is almost same as that of human and the length of each link segment is chosen with 40[mm], 25[mm] and 25[mm], respectively. The power is transmitted from an actuator to each joint through tendon-pulley driving system. The compliance coming from the tendon often produces undesirable behaviors, such as control instability and a large positional error. Three actuators are, therefore, placed just close to the base joint, so that the tendon length may become as short as possible. Each joint has a tension-differential type joint torque sensor[19]. Each joint angle is measured by the encoder directly connected to the rotor shaft of the actuator. For our particular experiments, we utilize three finger units, where two are fixed in the right side and one is in the left side. Since each finger has three links, we can keep a large and constant θ_{30} during the approach phase, which provides a larger $\mathcal{V}$ compared with that of two-link model.

5.2 Grasp experiments

Fig.7 shows continuous photos for an experiment, where the radius of the object is R=15[mm]. The hand can complete the task very quickly. For example, the executing time for finally enveloping the object by the fingers was just 2.8 [sec]. Fig.8 shows the map for judging the success or the failure (R=22.5[mm]) obtained by experiments when we change the command torque for each joint, where + and × denote failure for enveloping grasp, and ○ denotes the success. To avoid the complicated display, $\tau_{3c} = \tau_{2c}$ is imparted to the third joint. In experiments, there are basically two failure modes. One is that the command torques are not big enough to finally lift up the object to the palm, which is shown by +. The other is that the command torque for the first joint is too big compared with that of the other

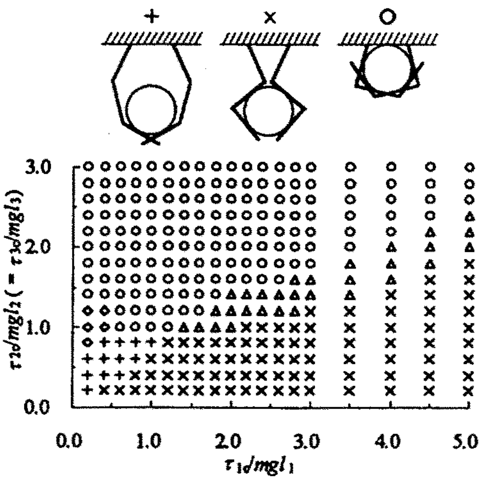

Fig.8 Map for judging the success or the failure (R=22.5[mm]).

joints and, as a result, the first link closes earlier than the remaining links envelop the object. The second case is shown by ×. In the second case, the object can not reach the palm. The second failure mode mainly comes from the redundancy of the system, while it is more difficult for the two-link finger to have the similar configuration after a two-points-contact mode. Of course, there are some ambiguous region between the success and the failure regions. This result is shown by Δ. From Fig.8, we note that there exists a large number of combinations for achieving the target grasp. Through the whole experiments, the success rate was almost 100% if we choose the torque commands from the region with ○.

6 Conclusions

We proposed a grasping procedure for finally achieving an enveloping grasp for an object placed on the table. The approach and the lifting phases were also included as well as the grasping phase. We showed that if the height between the palm and the table is selected by h=1.75, the finger can cover the most various size of cylindrical objects. We also showed that the determination of joint command torque during the natural computation mode has much choice. We confirmed that the proposed procedure works effectively by utilizing the Hiroshima Hand. It was shown that by inserting the additional phase, the proposed procedure can be easily extended to more general column objects whose cross sections are polygon. Finally, we would like to express our sincere gratitude to Mr. Thaiprasert for his cooperation in the experiment.

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