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Scale-Dependent Grasp

– A case study –

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Abstract

This paper discusses scale-dependent grasp. Human beings unconsciously change their grasp strategy according to the size of objects, even though those objects have similar geometry. We first observe the grasping strategy of the human hand in wrapping around a cylindrical object placed on a table. We show that the human grasp planning can be roughly classified into three patterns according to the object's size. For a large cylindrical object, the human hand wraps around it directly without any regrasping process. As the diameter of the object decreases, a human begins to slip the object along the finger, so that the object can finally make contact with the palm. For a further smaller diameter, a human first picks it up by his/her finger tips and then makes a transition from a finger tip to a wrapping grasp. We also extract the essential motions of human grasping so that we can implement them in multi-fingered robot hands.

I Introduction

There have been a number of works concerning multi-fingered robot hands. Most of them address a particular type of grasp only, such as a finger tip grasp, power grasp, or wrapping grasp. Suppose that a human eventually achieves a wrapping grasp for an object placed on a table. 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 objects in this paper. For a cylindrical object having a sufficiently large diameter, a human hand wraps around it directly without any regrasping process, since the table causes no interference with the finger links. For an object having a small diameter, however, the hand can not wrap around it directly since the table interferes with fingers. In such a case, a person first picks it up by his/her finger tips and then achieves the target grasp through the phase transition from the finger tip to the wrapping grasp. More complicated transition phases may be observed depending on the diameter of the cylinder and on the person-dependent choice of grasp strategy. These examples suggest that a human being chooses the grasp strategy according to the scale of objects, even though they are geometrically similar. We call this grasp method the scale-dependent grasp. This paper discusses why such a scale-dependent grasp occurs, at what parameter the grasp process is switched from one to another method, and just how human grasp strategies can be incorporated into a multi-fingered robot hand.

If a robot hand has exactly the same configuration, degrees-of-freedom (d.o.f), and surface material to those of a human, it will be able to achieve a similar grasp by applying a proper master-slave operation in which all position data during the grasping process are automatically sent from a human hand to the robot one. However, since all robot hands so far developed have their own configurations, d.o.f, and surface material, and are still mostly far different from those of humans, the master-slave operation by simply sending the signal from the human hand does not seem to work appropriately and the robot hand will eventually fail to achieve the target grasp. We do not apply the exact same human motions to a robot hand. Instead, our goal is to extract a couple of essential motions of the human grasp strategy and to simplify them, so that we may apply them to as many robot hands as possible, irrespective of their mechanical configurations. Thus, determining the essential motions of human grasping is another important issue in this paper.

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We begin by observing the scale-dependent grasp of human beings, especially in achieving a wrapping grasp for various sizes of cylindrical objects whose cross sections are of similar shape to each other. We show that the strategies used in the grasping can be roughly separated into three patterns according to the scale of the object. We also show that the grasp transition made by humans appears to be based on the object's non-dimensional diameter which is normalized by the reference length of the human hand. For each pattern, we introduce a simple grasp strategy that can be easily applicable for most robot hands.

II Related Works

In view of the potentially large number of alternative strategies, a human can make an unconscious choice of one of them based on heuristic criteria derived from experience. This is due to redundant skeletal degrees of freedom, the large number of available muscles, and the adaptability of the human nervous system. Such human grasping often provides a good example when we set about achieving the stable grasp of an object by a robotic hand. In robotic hands, there have been a number of papers written concerning human behaviors [1]–[7]. Cutkosky and Wright [1], [2] have analyzed manufacturing grips and correlation with the design of robotic hands by examining grasps used by humans working with tools and metal parts. Based of Napier's work [8], they classified the human grasps into two major categories, one emphasizing stability and security (power grasps) and the other dexterity and sensitivity (precision grasps). They classified the two groups into further sub-groups according to the level of power, the dexterity, and the object size. Bekey et.al. viewed the ability of human beings to grasp objects with infinitely variable shapes as proof that it is possible to translate target geometry and task information into grasping modes (i.e., hand opening, hand posture, selection of fingers used) and grasp location on the object. Postulating that this process relies on a knowledge base built up from a myriad of experiences, which relate grasp mode to target geometry and task, they presented a knowledge-based control of grasping in robot hands using heuristics from human motor skills [3]. They discuss how to achieve the mapping

$$(p(i), T) \Rightarrow (G', c) \tag{1}$$

where $p(i)$ denotes one of the geometric primitives and an element of P given by

$$P = \{p(1), p(2), p(3), p(4), p(5)\} \tag{2}$$

where $p(1)$:cone, $p(2)$:cylinder, $p(3)$:box, $p(4)$:torus, and $p(5)$:sphere. T represents the task description, c is the center of the grasping zone. G' is a subset of grasp modes G given by

$$G = \{g(1), g(2), g(3), g(4), g(5), g(6)\} \tag{3}$$

where $g(1)$:wrapping grasp or power grasp, $g(2)$:tip grasp, $g(3)$:snap grasp, $g(4)$:pulp pinch, $g(5)$:spherical grasp, and $g(6)$:lateral grasp. The mapping eq.(1) is one-to-many, since many grasp modes may be available as the solution of the grasping problem. They determined the mapping operator with the help of the knowledged-based systems. They also showed that four types of knowledge can be used to effectively design a task-oriented grasp planner. Stansfield also discussed the robotic grasping based on knowledge from a different viewpoint[5]. These works [1]–[5], and [7] focus on either the final grasp mode or finding an appropriate grasp posture under a set of grasp modes, target geometric characteristics and task description, while our paper focuses on the change of grasping strategy according to the size of objects that have similar geometry. There is other literature based on experimental research on pure human grasping [8]–[10], which do not deal with robotic hands. Within our knowledge, this is the first paper to discuss scale-dependent grasp.

III Observation of human behavior

The main purpose here is to observe the change of grasp pattern made by human beings according to the size of an object. In eq.(1), G', c, $p(i)$, and T, respectively, correspond to the following:

G'	:	$g(1)$ (wrapping grasp).
c	:	Geometrical center of the object.
$p(2)$	:	Cylinder.
T	:	Approach an object on the table and grasp it with the grasp mode $g(1)$.

Every element in eq.(1) is given. Through simple experiments, we first show that we have to include scale-dependent parameter in eq.(1), so that we can uniquely determine the mapping operator.

A. Experiments

A subject sitting on a chair is commanded in such a way that he/she grasps a cylindrical object placed on a table, finally holding it in a wrapping style. Each one of thirty-two subjects with various size of his/her

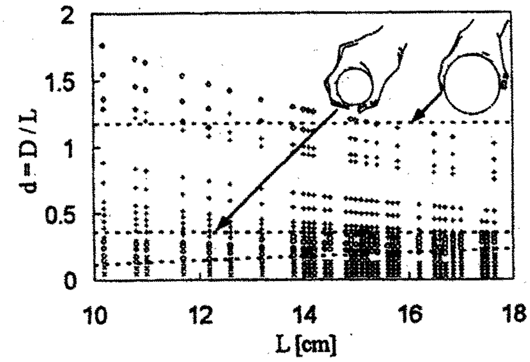

Fig.1: Modified grasp strategy classification map.

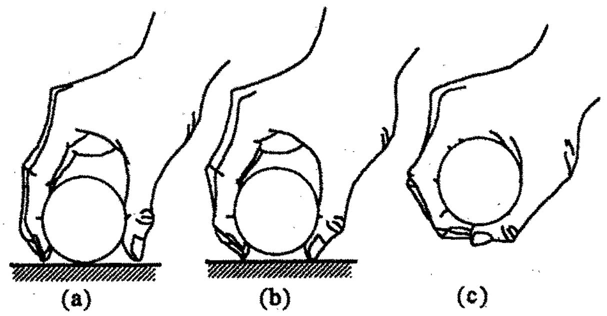

Fig.2: Two-VFs-based transition grasp.

hand executes eighteen trials for various cylindrical objects with eighteen different diameters and each trial is recorded through a video camera so that we may analyze it later in detail.

B. Results

Figure 1 shows the change of grasp strategy according to the diameter of cylinder. In order to suppress the scale effect brought about by the hand size, we define and choose the normalized diameter d given by

$$d = D/L \tag{4}$$

as parameter, where D and L are the diameter of cylinder and the length measured along the hand surface from the tip of the thumb to the tip of the index finger. $\diamond$ denotes that a subject cannot grasp the object due to its large diameter, $+$ denotes that the person's hand wraps around it directly without any regrasping process, $\bigcirc$ denotes that the person first utilizes the wedge effect to lift up the object from the table as shown in Fig.2(b), and then closes each finger around the object to achieve the target grasp (Fig.2(c)), and $\times$ denotes that the subject first picks up the object

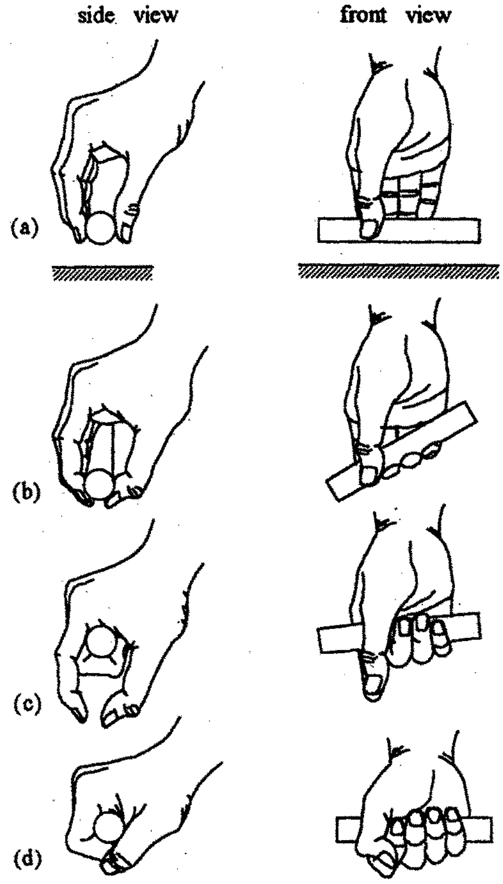

Fig.3: Three-VFs-based transition grasp.

between his/her index finger and thumb, and then the remaining fingers hook the object and squeeze it until the finger tip grasp is broken and the object contacts the palm as shown in Fig.3. Both the second and the last grasps are accompanied by grasp transition, such as that from finger tip to wrapping grasps. In both the first and the second grasps, the remaining fingers except the thumb are replaced by a virtual finger(VF) since they act as if they were just one finger. In the last grasp, the fingers other than the index finger and thumb can be regarded as a VF. Although there are, of course, some subjects utilizing exceptional grasp strategies, most of them exhibit a similar tendency to change the grasp strategy according to the size of the object. If we remove the ungraspable region from Fig.1, the grasp strategies can be roughly classified according to the diameter of the cylinders into three groups: direct-grasp, Two-VFs-based transition grasp, and Three-VFs-based transition grasp.

An interesting observation is that each switching line which separates the changing from one strategy to another becomes almost constant with respect to the hand scale L, which means that the subject automatically changes his/her grasp strategy based on the non-dimensional parameter d alone. For example, the person cannot grasp a cylinder whose non-dimensional diameter d is more than 1.2. This condition can be rewritten by $L > 1.2D$. $1.2D$ approximately corresponds to 40% of the circumference of a cylinder. Normally a person feels it difficult to wrap his/her hand around a cylinder when the hand length L cannot cover half of the circumference. This result is reasonable and matches our intuition. According to Fig.1, without any regrasping process, the human subject wraps a cylinder directly under $0.35 \leq d \leq 1.20$. The lower bound can be explained in the following. As D decreases, the table may cause interference with the finger tips when applying a direct-grasp strategy. To avoid such interference, the person is obliged to change the grasp strategy from the direct-grasp to another under the condition of $\pi D \leq L$. This critical condition is given by $d = 1/\pi = 0.32$ which also makes a nice coincidence with the lower bound $d = 0.35$. There is another switching line around $d = 0.20$, while this line is not as clear as the last two lines. Humans utilize Two-VFs-based transition grasp for achieving the target grasp under $0.20 \leq d \leq 0.35$, and they achieve it through Three-VFs-based transition grasp under $d \leq 0.20$. Actually, both grasp strategies are physically feasible under $d \leq 0.35$. Now, let us consider a couple of possible reasons why human beings switch their grasp strategy from Two-VFs-based transition grasp to Three-VFs-based transition grasp according to the diameter of a cylinder. As the diameter of the object decreases, the wedge effect between the finger tip and the object is weakened since each finger tip can not reach the bottom part of the object any more. This makes it more difficult to change the contact condition into slipping phase at the point of contact. Furthermore, the Two-VFs-based transition grasp is not efficient from the viewpoint of the quick achievement of the task especially when the diameter becomes small. This is because the object has to move a long distance while keeping contact with the fingers until it finally makes contact with the palm. Due to these disadvantages, a human automatically changes the grasp strategy from Two-VFs-based to Three-VFs-based transition grasps.

IV Introduction of the Scale Factor

Now, let us again consider the mapping equation. Based on the above results, we modify the mapping equation, so that we may assign a unique grasping strategy as a mapping operator.

$$(p(i), s, T) \Rightarrow (G', c) \tag{5}$$

where s is a non-dimensional scale factor which designates the relative size of an object compared with that of the robot hand. s is defined by $s = S/L$, where S is a reference length of the object to be grasped. In this paper, we are choosing d instead of s.

V Scale-Dependent Grasps by Multi-Fingered Robot Hands

We focus on a cylindrical object for simplifying the discussion. As mentioned earlier, there are three grasp strategies depending on the diameter of the object. Since the direct-grasp can be easily realized if a robot hand can satisfy the geometrical conditions, we do not discuss this strategy here. Instead, focusing on the two other grasp strategies, we extract essential motions which are applicable for a robot hand. Also, to simplify the discussion, we assume a three-fingered robot hand with three d.o.f for each finger. We also assume that each link and the palm are of equal length and never cause interference, and that the robot knows the object shape and its position in advance.

A. Two-VFs-based transition grasp

As the diameter of the cylinder decreases, there exists a critical switching point where the direct wrapping can not be realized any more since the table causes interference with the fingers. Such an interference starts with $\pi D \leq L$, namely, $d \leq 0.32$. Under $d \leq 0.32$, based on human behaviors, we decompose the grasp strategy into individual motions as shown in Fig.4. Each finger tip first rests on the table as shown in Fig.4(a). In the next step, each finger tip is closed around the base of the object so that it may be lifted up from the table surface as shown in Fig.4(b). As long as the object has a sufficiently large diameter compared with that of the finger tip, the object will automatically be lifted up from the table due to the wedge effect between the object and the table. This is the first stage, in which the object is isolated from the table and no more interference is expected. The next issue is how the robot hand can perfectly wrap the object using its inner links and palm. Figure 4(c) shows the finger postures for the next step, where each finger link is preshaped so that it may come in contact with the maximum circle. After preshaping, the

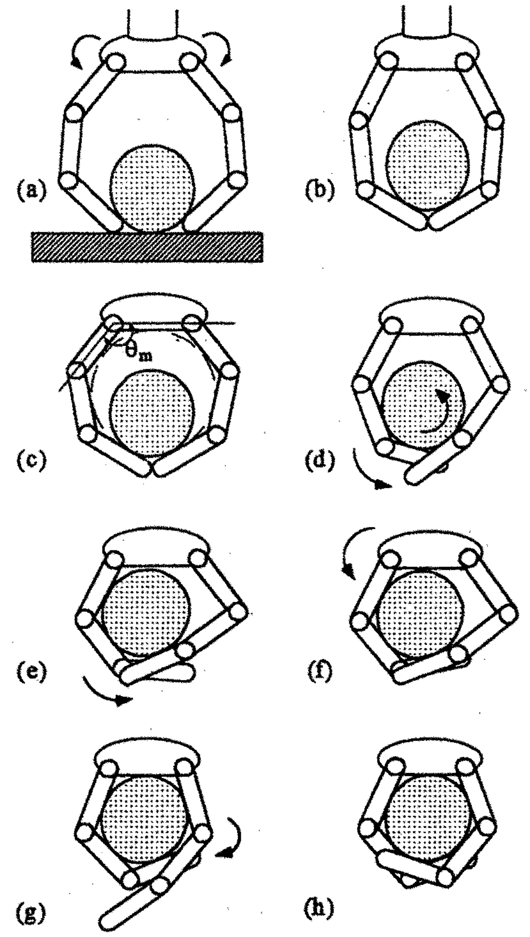

Fig.4: Two-VFs-based transition grasp

internal angle of the polygon formed by both the finger link and the palm is equal to $\theta_m = 5\pi/7$. This preshaping is convenient for achieving the wrapping grasp, in which every link and the palm make constant contact with the object. In the next step, the right finger pushes the object toward the left until the object makes contact with the second link of the left finger. By using a simple geometrical relationship, we can easily prove that under $\pi D \leq L$ the second link always makes contact with the object in advance of either the first link or the palm. Note that during this motion, the object can keep rolling contact with the third link of left finger, while slip happens between the object and the right finger link. In the next step, the third joint of the left finger is rotated in the counter clockwise (CCW) direction until the joint angle comes to the predetermined value α which is computed from the final posture of the finger. Then the second joint of the left finger is rotated in the CCW direction until the angle results in α. Since $\theta_m \geq \alpha$, the first link makes contact with the object earlier than the palm. During this motion, the right finger continuously supports the object, so that it may prevent its falling away from the fingers. A simple torque or force control may work for this purpose. Then, the first joint of the left finger is rotated in the CCW direction until the object makes contact with the palm, as shown in Fig.4(f). Finally, the right finger completely finishes wrapping around the object as shown in Fig.4(g) and (h). Of course, we may swap the role assignment between the right and the left fingers.

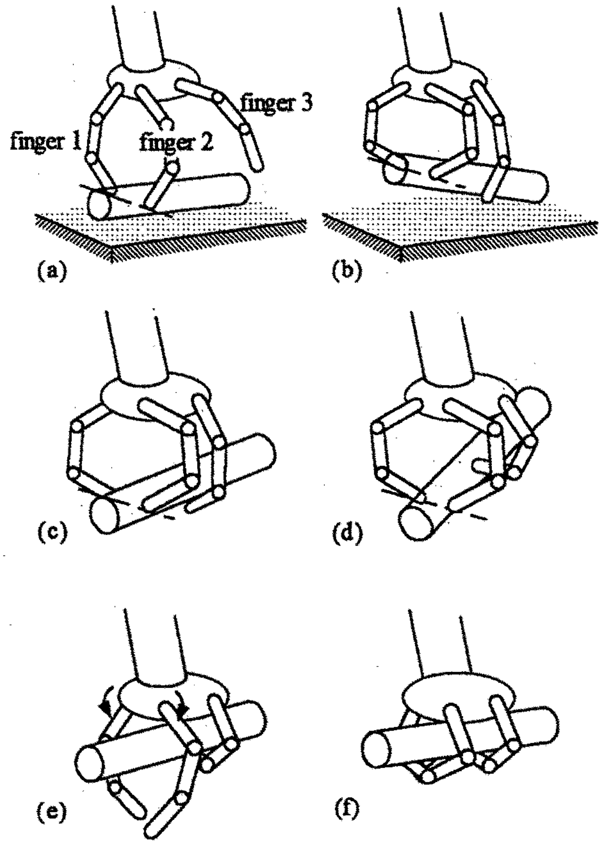

Fig.5: Three-VFs-based transition grasp

B. Three-VFs-based transition grasp

The Three-VFs-based transition grasp can be decomposed into two basic motions. One is the motion for picking up the object by using the index finger(finger 1) and thumb (finger 3) as shown in Fig.5(b), and the other is a series of motions for achieving the target grasp by using the last finger dexterously as shown in Fig.5(c)–(f). The first motion plays an important role in allowing no interference from the table, and can be easily realized if the object shape and location are perfectly given to the robot hand. In the following series of motions, the tip of finger 2 first hooks the object and draws it toward the palm. By this finger motion, the object will rotate around the grasp axis formed by the fingers 1 and 3 until a part of it makes contact with the palm as shown in Fig.5(d), unless the contact distance between finger 2 and finger 3 (or finger 1) is too small. In order to realize the rotating slip, we can apply the existing approaches [11]–[14]. After a part of the object dose make contact with the palm, we can regard the contact point between the palm and the object as a support point for a lever. Therefore, on increasing the drawing force, the finger tip grasping by the fingers 1 and 3 will eventually be broken by a large drawing force imparted by finger 2(Fig.5(e)). By utilizing the inertia effect after breaking contact, finger 2 can hold down the object against the palm. After that, both fingers 1 and 3 wrap the object quickly. This motion planning is simple enough so that we may be able to implement it to a multi-fingered robot hand, even though human beings exhibit more complicated motion planning for such an object.

VI Conclusions

We discussed the scale-dependent grasp for a cylindrical object as a case study. We first observed the human behavior for grasping an object when the object size is changed. Through experiments, we found that a human switches his (or her) grasp strategy according to the size of an object, even though the objects have similar geometry. We also found that there are three regions: direct-grasp, Two-VFs-based transition grasp, and Three-VFs-based transition grasp. The switching line between the direct-grasp and the Two-VFs-based transition grasp could be easily obtained from the geometrical limitation. The switching line between Two-VFs-based transition grasp and Three-VFs-based transition grasp seemed to be determined by more heuristic and empirical factors in human grasping. But we could provide a couple of physical reasons for the switching. We also extracted essential motions for each scale-dependent grasp, and simplified them in an easily applicable way. Although we only focused on cylinders in this paper, we are intending also to discuss the scale-dependent grasp for more general objects. This work is supported by the Ministry of Education, "Research on Emergent Mechanism of Machine Intelligence (grant number 07245103)".

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