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Experimental Approach on Enveloping Grasp for Column Objects

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Abstract: A grasping strategy for enveloping column objects is presented. In enveloping a cylindrical object placed on a table, a multifingered robot hand can conveniently utilize the wedge effect, in which the object can be automatically lifted up through the slipping motion caused when each finger pushes the bottom part of the object[1],[2]. This paper further extends the strategy to general column objects whose cross sections are polygon. One difficult situation appears when applying the strategy for triangular or rectangular objects, because the wedge effect cannot be expected any more or becomes weak. To cope with this problem, our alternative strategy includes two additional phases before lifting the object, (1)rotating the object and (2)inserting a finger tip into the gap produced by the rotating motion. We precisely discuss how to detect the pushing point for generating the rotating motion. We also show experimental results to verify the idea proposed in the paper.

Key words: Enveloping Grasp, Power Grasp, Active Sensing, Constant Torque Control.

1. Introduction

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 the sensing and grasping strategy for finally achieving an enveloping grasp for general column objects whose cross sections are polygon, where the object is assumed to be placed on a table.

Lifting up the object is the initial task for finally achieving an enveloping grasp. In order to realize the task, a multifingered robot hand can conveniently utilize the wedge effect, in which the object can be automatically lifted up through the slipping motion caused when each finger pushes the bottom part of the object. In case of either cylindrical objects or the object whose cross section is close to circle, the wedge effect can be easily produced through a simple pushing motion by the finger tip[1, 2]. In case that the object's cross section is triangular, however, no lifting motion is expected by such a pushing motion, because the resultant force will push the object toward the table and does not produce any lifting component. This implies that we are obliged to prepare an alternative grasping strategy for such objects. For preparing the new strategy, a couple of questions coming up are (1)how can the robot detect the failure in lifting up the object by a pushing motion in the horizontal direction, (2)what kind of sensing and grasping strategies are needed for lifting up the object, and (3)how can the robot achieve the target grasp after the object is away from the table.

We first discuss how to detect the failure in lifting up the object by a pushing motion. Once the robot recognizes such a failure, we execute two additional phases before lifting the object, namely, rotating the object around one side of the support polygon, and inserting a finger tip into the gap produced by the rotating motion. In order to obtain a reasonable pushing point for rotation, we introduce an active sensing technique to detect the local shape of object. One emphasis of our work is that we do not assume any tactile sensor except both joint position and joint torque sensors. Generally, when we implement a number of sophisticated tactile sensors over the finger surface, we can easily obtain contact information. At the same time, we have to expect a couple of troubles, such as the damage of sensors due to the direct contact with the object, broken wires due to many signal and power lines, and so forth. On the other hand, an active motion often provides us with new information that can not be obtained without any active motion. We try to make the most advantage of such an active sensing in this work. We utilize the active sensing for obtaining the local shape of object and for finally providing a pushing point for making the object rotate around one side of the support polygon. By rotating the object around an edge, we can produce an enough space to insert one finger tip. The insertion of one finger between the object and the table is the starting point to isolate the object from the table. Once the isolation is completed, a similar grasping strategy as that taken for a cylindrical object is applied for finally achieving an enveloping grasp.

In this paper, both the active sensing and the grasping strategies are precisely discussed. We also verify the proposed grasping strategy experimentally.

2. Related Work

Trinkle and Paul[3] proposed the concept of grasp liftability and derived the liftability regions of a frictionless planar object for use in manipulation planning. Mirrza and Orin[4] 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. Salisbury[5, 6] 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. Bicchi[7] showed that internal forces in power grasps which allow inner link contacts can be decomposed into active and passive. Omata and Nagata[8] also analyzed the indeterminate

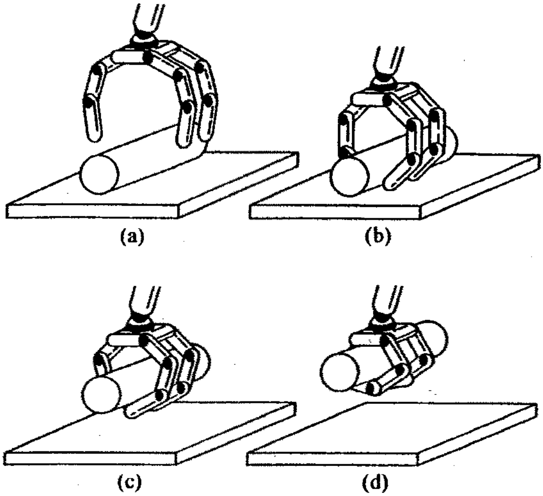


Fig.1 An example of enveloping grasp.

grasp force by fixing their eyes upon that contact sliding directions are constrained in power grasps. Zhang et. al.[9] evaluated the robustness of power grasp by utilizing the virtual work rate for all virtual displacements. Kumar[10] used WAM as an example to explain their minimum principle for the dynamic analysis of systems with frictional contacts. Kleinmann et. al.[11] showed a couple of approaches for finally achieving power grasp from finger tip grasp. In our previous work[1, 2] we have shown the grasping strategy for achieving enveloping grasp for cylindrical objects.

3. Sensing and Grasping Procedures

3.1. Hand and Grasp Model

We assume the three-fingered robot hand as shown in Fig.1. While most of the developed hands has a swing 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 and 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 column objects whose cross sections are polygon and they are initially placed on a flat table. 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, it is assumed that the size of the object is roughly given by a visual sensor.

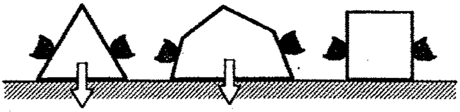


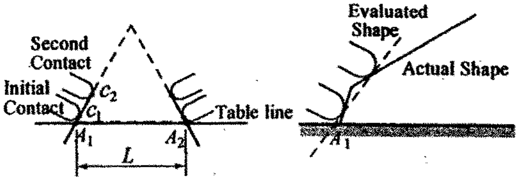
Fig.2 Examples of objects where the upward force is not expected by a simple pushing motion in the horizontal direction.

3.2. Grasping Procedure for Cylindrical Object

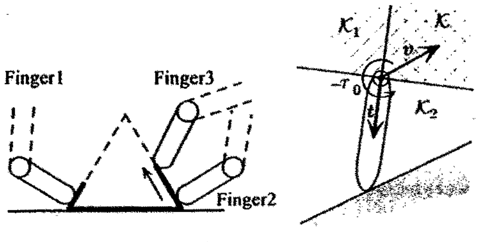
Fig.1 explains three phases for grasping a cylindrical object where (a)–(b), (b)–(d), and (d) are the approach phase, the lifting phase, and the grasping phase, respectively. In the approach phase, each finger first takes the designated initial posture (see Fig.1(a)) and then the first link is rotated 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 the table (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 (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 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). At this moment, the outputs from joint torque sensors abruptly increase, because the degree of freedom of finger 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 second links. Whether the object really reaches the palm or not and how firmly grasp the object, strongly depend on how much torque command is imparted to each joint.

3.3. Failure Mode in Wedge-Effect Based Grasping

For a cylindrical object, there usually exists an enough space to insert a finger tip between the bottom part of the object and the table, unless the object's diameter is smaller than that of finger tip. As a result, the finger tip can easily produce the upward force. For a general column object, however, depending upon the object's shape, the finger tip forces may balance within the object or they may produce the downward force. Under such situations, the lifting force is not produced, even though we increase the contact force. For example, such situations will be observed for the objects shown in Fig.2. Especially, when the object's cross section has a triangular shape, the vertical force caused by a pushing motion in the horizontal direction always results in the downward, while this is not always the case for the object having quadratic shape. For the objects shown in Fig.3, the wedge effect can not be expected any more. This



(a) L and m sensing (b) An example of error



(c) Local shape sensing (d) An example of $\mathcal{K}$

(e) Pushing point sensing (f) Rotating motion

Fig.3 Sensing procedure

situation can be easily detected by the joint torque sensor, because their outputs will sharply increase during a pushing motion in the horizontal direction.

3.4. Human Behavior in Grasping Objects with Triangular Cross Section

Suppose that we achieve an enveloping grasp for a triangular column object placed on the table. Also suppose that the room is dark enough not to be able to utilize our vision. Under such a situation, we try to utilize our tactile information as much as possible by moving our finger over the object. This active motion is for obtaining the information on the object's shape. After we estimate the rough shape of object, we try to grasp the object in an appropriate manner. For a column object having a triangular cross section, however, grasping it from the table may be not always an easy task. Human often tries to produce a space between the table and the object by rotating the object around one side of the support polygon, such that we may insert our fingers into the space. Inserting our fingers into the space produced contribute to easily detaching the object from the table and to lifting it by our fingers. We apply such a procedure to a multi-fingered robot hand.

3.5. Active Sensing by Robot Fingers

When torque sensor outputs sharply increase at the beginning of the lifting phase, the lifting phase is stopped and we start the active sensing phase to detect the local shape of object. One feature in our active sensing is that we do not assume any other sensors except joint position and torque sensors. By imparting an active motion to each finger, we can obtain the tactile information as if there were tactile sensor over each finger tip. We produce such a virtual finger tip tactile sensor by active motion. We believe that this is one of most advantages of active sensing. The information which we intend to detect by active sensing is the geometrical parameters necessary for the robot to rotate the object. Such geometrical parameters are explained step by step based on the sensing procedure as shown in Fig.3.

(a) Base length L:
This parameter is indispensable when we determine how much angle should be rotated to ensure the finger tip insertion. In order to evaluate L, we make each finger tip contact with the object with a different height, as shown in Fig.3(a). Since the robot has any tactile sensor at the finger tip, the exact contact point is not provided by each trial. By utilizing two finger postures, however, we can obtain one straight line in contact with both fingers. This line is a candidate for the object surface. We extend this line until it passes through the table line which is already known. (The table line becomes known when each finger tip detects the table.) The intersection, for example, A_1, is a candidate for one side of the polygonal object. Thus, we can evaluate L by simply measuring the distance between both intersections as shown in Fig.3(a). Although this may not provide with the accurate L if two contact points lie on two different lines, respectively as shown in Fig.3(b), we can obtain L accurately enough by achieving the initial contact as close as possible to the table.

(b)Slope of the bottom part of the object m:
In order to determine the pushing point, we have to know the partial shape of object to confirm whether the finger tip can really impart an enough moment for rotating the object around one side of the base or not. However, since the robot has no precise knowledge on object's shape, it is difficult to start a tracing motion along the object's surface. To cope with this, we need to know the local slope of the object at the starting point for partial shape sensing. Such a local shape can be obtained simultaneously when we evaluate L. Because the slope information is indispensable for computing the intersection between the table line and the common tangential line. However, as mentioned earlier, the slope obtained is just a candidate. The coincidence between the computed and actual slopes is not guaranteed until we confirm that one finger makes contact with the same tangential line with an arbitrary point between two detected points, C_1 and C_2.

(c) Pushing point P:
The goal of the series of sensing is to find the pushing point for rotating the object around one side of the support polygon. For this purpose, we apply an active sensing for detecting the object's shape by utilizing a finger. One difficulty for tactile based active sensing is how to make a motion planning to avoid a large interaction force between the robot and the environment to be sensed. By always assigning at least one compliant (or constant torque) joint for the finger during sensing motion, we can avoid such a large interaction force. Another remark is that pulling a finger tip lying on object's surface can be easily achieved, while pushing it is more difficult due to stick-slip or blocking up by the irregularity existing on the surface. To cope with the difficulty of

pushing motion on frictional surface, the sensing algorithm is based on pulling motion of finger tip as shown in Fig.3(c), where the finger 3 is chosen as a probe finger. For more general discussion, we first define $\mathcal{K}_1$ and $\mathcal{K}_2$.

[Definition] *Define $\mathcal{K}_1$ as an assemble of $\boldsymbol{v}$ satisfying $f_1(\boldsymbol{v}) = sgn(\boldsymbol{v}^{\mathrm{T}}\boldsymbol{t}) < 0$, where $\boldsymbol{v}$ and $\boldsymbol{t}$ are vectors expressing the moving direction, and the longitudinal direction of the finger tip, respectively. Also, define $\mathcal{K}_2$ as an assemble of $\boldsymbol{v}$ satisfying $f_2(\boldsymbol{v}) = sgn\{\boldsymbol{t} \otimes \boldsymbol{v}\} > 0$, where $\otimes$ denotes a scalar operator performing $\boldsymbol{x} \otimes \boldsymbol{y} = x_1y_2 - x_2y_1$ for two vectors $\boldsymbol{x} = (x_1, x_2)^{\mathrm{T}}$ and $\boldsymbol{y} = (y_1, y_2)^{\mathrm{T}}$.*

A sufficient condition for keeping the pulling condition is given by the following theorem.

[Theorem] *Let $\mathcal{K}$ be the area where the last joint can be moved without generating pushing motion. A sufficient condition for achieving a pulling motion based tracing is as follows:*
$\mathcal{K} = \mathcal{K}_1 \cap \mathcal{K}_2$ and $\tau = sgn(\boldsymbol{v} \otimes \boldsymbol{t})\tau_0$
where τ_0 is the reference torque and the positive direction for torque is chosen in the clockwise direction.

Proof :(Omitted)

The moving direction of the last joint is chosen to satisfy the condition of $\mathcal{K} = \mathcal{K}_1 \cap \mathcal{K}_2$ and the direction of torque applied is determined based on the sign function $sgn(\boldsymbol{v}\otimes\boldsymbol{t})$. The region of $\mathcal{K}$ and the direction of τ are, for example, shown in Fig.3(d).

Now, let us discuss how to detect the pushing point. Suppose an extreme case, where the friction between the finger tip and the object is zero. In order to produce a rotating moment around one side of the support polygon, we have to impart a pushing force at the upper point than P_c, where P_c is the intersection between the object surface and the normal line from the supporting edge, as shown in Fig.3(e). A sufficient condition capable of imparting a rotating moment, even under a small frictional condition, is to apply the pushing force at the upper point than P_c. However, P_c does not always exist over the object surface and whether P_c exists on the object surface or not strongly depends on the object's geometry. In case of the object with triangle cross section, P_c never exists for the object whose top angle is greater than 90 degrees. When P_c is not detected during the active sensing, the robot anyway tries to impart a rotating moment at the point in which the finger tip can apply the largest moment under a constant pushing force.. This approach can work under a significant friction, while it may not under frictionless condition.

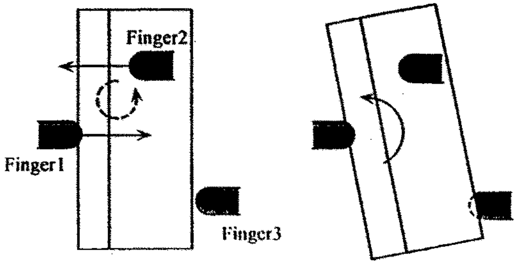
(d) Rotation angle α:

The rotation angle α is determined according to an approximate vertical displacement $L\alpha$ produced by the rotation. A sufficient condition for inserting a finger tip into the gap produced by the rotating motion is given by the following inequality.

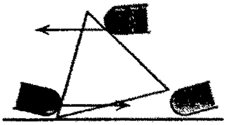
$$L\alpha > d \tag{1}$$

where d is the diameter of a finger tip or an equivalent diameter if the cross section is not exactly circle. An example satisfying the sufficient condition is shown in Fig.3(f).

The sensing procedure explained in this subsection can be applied for objects not only with triangular cross section but also with quadratic or other cross sections if they need the sensing phase.



(a) Top view (b) Top view



(c) Side view

Fig.4 Finger Inserting Phase

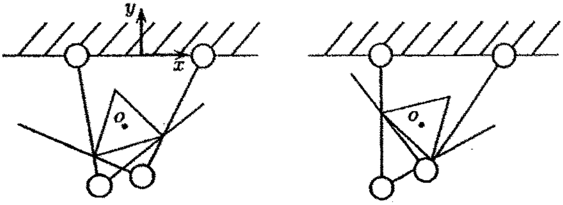


Fig.5 Triangle object enveloped by two jointed fingers

3.6. Finger Inserting Phase

After a sufficient gap is produced, one finger is removed away from the object's surface to be inserted into the gap, as shown in Fig.4(a),(c). At this instant, the contact line between the object and the table has to support the clockwise moment produced by two fingers. If the contact line fails in supporting the moment, the object will rotate around the tip of finger 1, as shown in Fig.4(b). In this work, we assume that the coefficient friction between the object and the table is large enough to avoid such a rotation due to slip.

3.7. Lifting and Grasping Phase

After the finger tip is sufficiently inserted into the gap between the object and the table, we apply the same grasping mode as that taken for a cylindrical object[2]. However, the condition for the object to reach the palm is not as simple as that for a cylindrical object. Because, for a general column object, contact points between the object and finger links change according to the orientation of object, even though the center of gravity of object does not change. This is a big difference between a cylindrical object and a general column one. If the resultant force acted by each contact force is greater than

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