Measurement of Grasp Position by Human Hands and Grasp Criterion for Two Soft-Fingered Robot Hands

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Abstract—In this study, grasp positions of human hands are measured for planar objects for development of a reasonable grasp criterion for a two-soft-fingered robotic hand. We first propose a grasp criterion that yields the best grasping position for a robot hand with two soft fingers. To examine the properties of this criterion with respect to some weighting coefficients included in the criterion, a grasping experiment is performed by humans for planar objects with various sizes and shapes. Results show that many observed grasping positions used by humans correspond to a set of weighting coefficients that equally weigh all the factors in the criterion. A grasping experiment using a robot has also been conducted using a set of coefficients corresponding to the equal weight; the effectiveness of the criterion was confirmed.

I. INTRODUCTION

Grasping various objects using robotic hands is a fundamental operation that robots must perform. Many studies have been done to elucidate grasping[1]-[12]. We have also been examining the grasping of objects by robotic hands with soft fingers[13]-[17]. The problem of grasping an object with a robot hand can be divided into three subproblems: shape recognition of an object, determination of the grasping position, and a control algorithm for grasping operations. As described in this paper, we specifically examine the problem of determining the grasp position in the case of robot hands with two soft fingers.

Although research on the decision of the best grasping position on the object surface has a long history, there are cases in which the obtained grasping position differs from those that humans usually take as a result of intuitive judgment. For example, a human grasping a long and slender rectangle using two fingers might choose to grasp the object by the long direction or short direction depending on the rectangle’s size. Although various grasp criteria have been proposed for robot hands, there is apparently no criterion that explains such a difference of grasping position clearly yet. Ikeda et al.[18] measured pinching motions of human hands for quantification of pinching facility. Although they discussed the size of the object for easy pinching, they did not consider the effect of the object shape.

In this study, we investigate how humans decide the grasping position for contacting objects of various sizes and shapes using two fingers. Hereinafter, the grasp criterion to grasp the object (lamina that can be considered to be a two-dimensional shape) for two fingers is presented, and the relation between the grasping positions by humans and those given by the grasp criterion are examined. In addition, experimental results underscore the validity of the proposed criterion.

II. GRASP CRITERION

Using soft fingers has two merits. One is that a hand with only two soft fingers can grasp and manipulate an object in three-dimensional space. The other merit is that it can grasp an object not only at smooth surfaces but also at corners (edges or vertices) because they can envelop the corner through elastic deformation of the finger surface. However, these factors have not been described before in detail in the literature related to grasp optimization. The vertex contacts are discussed in [19] in the framework of grasping using fingers with rounded fingertips. However, the rounded fingertips are introduced mainly to guarantee the condition that the object is “well defined and continuous surface normal everywhere on its surface”.

Considering the merits of soft fingers described above, we propose the following grasp quality criterion for determining the optimal grasping position to minimize the criterion. Let a pair of candidate contact points on the object surface be \(c_1\) and \(c_2\). We define the criterion \(J\) as

\[
J(c_1, c_2) = k_p J_p(c_1, c_2) + k_\alpha J_\alpha(c_1, c_2)
\]

(1)

where \(J_p(c_1, c_2)\) is the term evaluating the global location of the contact points, \(J_\alpha(c_1, c_2)\) is the term evaluating the surface direction of the object at the contact points, and \(k_p\) and \(k_\alpha\) are weighting coefficients. We can think about the index of the distance and the index of the angle separately by defining it as shown below. Fig. 1 shows that \(d_\alpha\) is the distance between \(c_1\) and \(c_2\), \(d_b\) is the distance between the straight line from \(c_1\) to \(c_2\) and the center of gravity of the object, and \(\alpha_1\) and \(\alpha_2\) respectively signify the angle between the straight line from \(c_1\) to \(c_2\) and the direction of normal
vector on the surface in \( c_1 \) and \( c_2 \). \( J_p(c_1, c_2) \) and \( J_\alpha(c_1, c_2) \) are given by the following equations.

\[
J_p(c_1, c_2) = k_a \frac{d_a}{a_{max}} + k_b \frac{d_b}{b_{max}} \tag{2}
\]

\[
J_\alpha(c_1, c_2) = \frac{\max(|\alpha_1|, |\alpha_2|)}{\pi} \tag{3}
\]

Therein, \( a_{max} \) is the maximum size of a side of the object, and \( b_{max} \) is the maximum value in distances between the center of gravity and all vertexes of the object. Each paragraph is regularized from 0–1. Moreover, \( k_a \) and \( k_b \) are weighting coefficients.

When the contact point \( i \) is a corner of the object, we define the angle \( \alpha_i \) as follows. We first define two angles \( \alpha_{ir} \) and \( \alpha_{il} \), where \( \alpha_{ir} \) is the angle from the normal vector on the right side surface of the corner to the grasp force direction, and where \( \alpha_{il} \) is the angle from the normal vector on the left side surface of the corner to the grasp force direction. The angle is taken to be positive in a counterclockwise direction. Then we define \( \alpha_i \) as the minimum absolute value in the interval \([\alpha_{ir}, \alpha_{il}]\). For instance, regarding Fig. 2(a), the value of \( \alpha_1 \) is 0. In the case of Fig. 2(b), \( \alpha_1 \) is given as \( |\alpha_{il}| \). This corresponds to the fact that it is easy to grasp in case (a), but it is not easy to grasp in case (b).

### III. Calculated Optimal Positions

We examine how the grasping positions will change when the weighting coefficients of Eq. (1) are changed. We made an optimization program that calculates the optimal grasping positions minimizing the grasp criterion when the vertex coordinates of the object and the weighting coefficients are given. The search resolution is 10 points for each side of the object.

#### A. Isosceles Triangles

We mainly discuss an isosceles triangle with a base-to-height ratio of 1 : 2 for demonstrating the relation between the weighting coefficients and the grasping positions. We have selected the weighting coefficient values presented in TABLE I. Fig. 3 portrays the calculated optimal grasping positions corresponding to these weighting coefficients. The features of each case are described in the following.

Fig. 3(a) depicts the most basic result for the case in which the weighting coefficients are set with equal weight. The three components in the criterion are balanced. They are close to the center of gravity. The distance between the two grasping points is small. Furthermore, the direction of the grasping is near the direction of the normal vector at the grasping position. In this case, the grasping position comes in the nearest position to the gravity point on the isosceles side of the triangle.

Fig. 3(b) shows the grasping position when \( k_a \) for the weighting coefficient for the angle is large. In fact, \( J_\alpha(c_1, c_2) \) is minimized easily when the foot of the perpendicular from the gravity point is grasped or when the vertex of the object is grasped. Both of these positions are portrayed in this example.

Fig. 3(c) shows the grasping position when \( k_a \) is large, and shows \( k_a \) for large grasping distances. That is, the grasping position is set far from the center of gravity and the criterion for the angle is minimized. In this example, results show that the two isosceles feet are the best places to grasp.

Fig. 3(d) portrays the grasping position when \( k_a \) for the distance between grasplings is large, and the criteria for both the distance and the angle are equal. In this case, the grasping position for which the term for angle is not minimized compared with Fig. 3(c) is selected. The position near the vertex of the two isosceles sides is grasped in this example.

Fig. 3(e) and Fig. 3(f) show the grasping position when the weighting coefficient for the angle is small and the weighting coefficient for the distance is large. In these cases, very difficult positions to grasp are found. Fig. 3(f) shows a particular illustration of the positions in this example, which cannot be readily grasped.

Therefore, results show that a large variety of grasping positions are obtainable by changing the weighting coefficients of the proposed grasp criterion.

#### B. Other Shapes

Fig. 4 shows the optimal grasping positions for some other shapes when the weighting coefficient is adjusted to the basic case of \( k_p : k_d = 1 : 1 \) and \( k_a : k_b = 0.5 : 0.5 \). As might be readily apparent from Fig. 4(a), the top and
TABLE II

MAXIMUM GRASPABLE ANGLE WITH SUBJECTS

<table>
<thead>
<tr>
<th>subjects</th>
<th>position</th>
<th>sex</th>
<th>results</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>graduate student</td>
<td>man</td>
<td>50 [deg]</td>
</tr>
<tr>
<td>B</td>
<td>graduate student</td>
<td>man</td>
<td>35 [deg]</td>
</tr>
<tr>
<td>C</td>
<td>young teacher</td>
<td>man</td>
<td>55 [deg]</td>
</tr>
<tr>
<td>D</td>
<td>graduate student</td>
<td>man</td>
<td>60 [deg]</td>
</tr>
<tr>
<td>E</td>
<td>faculty student</td>
<td>woman</td>
<td>35 [deg]</td>
</tr>
<tr>
<td>F</td>
<td>faculty student</td>
<td>man</td>
<td>55 [deg]</td>
</tr>
<tr>
<td>G</td>
<td>graduate student</td>
<td>man</td>
<td>55 [deg]</td>
</tr>
<tr>
<td>H</td>
<td>graduate student</td>
<td>man</td>
<td>50 [deg]</td>
</tr>
<tr>
<td>I</td>
<td>graduate student</td>
<td>man</td>
<td>55 [deg]</td>
</tr>
<tr>
<td>J</td>
<td>graduate student</td>
<td>man</td>
<td>50 [deg]</td>
</tr>
</tbody>
</table>

Fig. 5. Triangles for Measurement of the Maximum Graspable Angle

bottom of the object are grasped when the object height is low. In addition, from Fig. 3(a), the center of the short distance side of the object is grasped when the object height is high. Using a similar idea to that described above, the grasping position of the rectangle is determined as shown in Fig. 4(b). Furthermore, the grasping position of the hexagon is determined as shown in Fig. 4(d).

IV. GRASP EXPERIMENTS WITH HUMANS

Results show that the best grasping position changes according to change in the weighting coefficient of Eq. (1). However, it is necessary to discuss further what value of the weighting coefficient should be selected. As the first step of the discussion, we investigate what position humans usually take for grasping various objects.

A. Subjects

Subjects are ten people, as shown in TABLE II. Subject C is a young teacher. The other subjects are faculty or graduate students working at positions in the author’s laboratory. Subject E is the only woman.

B. Preliminary Experiment

It is expected for grasping experiments that the size and the friction condition of each subject’s finger differ. Consequently, we investigated the friction characteristic of each subject’s finger using the seven triangles shown in Fig. 5 after subjects washed their fingers with soap. These triangles have angles from 15[deg] to 75[deg] at intervals of 5[deg]. Using these triangles, we can measure how many degrees subjects are unable to grasp. Fig. 6(a) shows that we directed the subjects to grasp the object directly from above using the thumb and the forefinger. Moreover, we directed the subjects to rotate the object on the table until it reached a position that they could grasp it most easily. Afterwards, we directed the subjects to grasp the object. Table II presents the maximum angle which each subject was able to grasp.

C. Experiment Method

We directed the subjects to grasp the 29 objects shown in Fig. 7. These objects’ characteristics are as follows. 5 pieces of the similar figure of isosceles triangles exist. 2 pieces of the isosceles triangles have different angles. 3 pieces are similar figures of right-angled isosceles triangles. 3 pieces are similar equilateral triangles. 4 pieces of rectangles have different lengths. 4 pieces are similar figures of rectangles. 3 pieces are similar figures of squares. and 5 pieces are similar figures of hexagons. All objects have thickness of 9[mm].

The grasping style is the same as the preliminary experiment (Fig. 6(a)). That is, we directed the subjects to grasp the object after rotating it to an orientation at which they were able to grasp the object most easily. Here, we took pictures using a digital camera, which has six million pixels and a macro mode, from the other side of the hand (bottom of the object) as shown in Fig. 6(b) to record the grasping position accurately. We read these pixel values of the pictures and showed the object and the grasping positions in the figure, as in Fig. 6(c). The point at the center of the finger was determined to be a grasping position. This experiment ended for each subject after about ten minutes.

D. Experimental Results

Fig. 8 shows the experiment results. For convenience, if multiple subjects grasp almost identical positions, the data of a representative one is displayed. The letters displayed under the figures of objects show which subjects grasped them. Two letters connected with a dash, e.g. A–C, represent successive subjects, e.g. from A through C. The numerical values on the right of the object names show the base and height in the case of the triangle and show widths and heights in other cases.

The two ○ of each object show grasping positions used by subjects. For displaying many figures within the allowed
space of this paper, the objects of the same shape but with different sizes are displayed with almost identical area with reduced constant scales in this figure. Therefore, the size of \( \bigcirc \) and the line thickness differ for each object. If \( \bigcirc \) is small and the line of the object is thin, the object is actually large.

### E. Discussion

We observed the grasping positions for the similar type objects portrayed in Figs. 8(1)–(5), Figs. 8(8)–(10), etc. When the objects are small relative to the finger size, the subjects can grasp the objects with various positions. In contrast, the difference decreases for large objects; most subjects grasp at very similar positions. Additionally, we found that all subjects grasp at the same position in Fig. 8(10), etc.

No significant relation was observed among grasping positions and the maximum graspable angle of each subject measured in the preliminary experiment. For instance, subject B and subject E of 35[deg] maximum graspable angle might have an object at the same grasping position in Figs. 8(1), (4), (7), (9)–(13), (22), (25), (27)–(29). However, they occasionally have an object at a different grasping position in Figs. 8(2), (3), (5), (6), (8), (14)–(21), (23), (24), (26). In addition, comparison shows that the grasping positions between subject D of 60[deg] in the maximum graspable angle resemble those of the other subjects.

Moreover, the grasping positions for which only female subject E is different were about 30%. However, the number of subjects is insufficient to infer that gender explains
this difference. Furthermore, all subjects work in the same laboratory. Therefore, the possibility of bias exists in these experimental results. An additional experiment should be conducted in the future to determine whether the result differs depending on subjects’ characteristics.

After the experiment, we asked the subjects why they selected their grasping position. Some answers were “It had a position which did not slip easily”, or, “It had a position that was convenient for looking at the object after grasping” etc. However, many subjects responded that “No other good mode of grasping exists” when the objects are large.

F. Correlation with Grasping Criterion

We compared Fig. 8(1) and Fig. 3. Both figures fit extremely well. Consequently, we considered that the grasping positions of Fig. 8(1) can be expressed using the weighting coefficients of Eq. (1). That is true because Fig. 3 was made by the change in the weight coefficient of Eq. (1). As for Figs. 8(2)–(5), it is similar. Moreover, from the discussion about the foregoing paragraph, we can understand many subjects such as the grasping position for the isosceles triangle on the leftmost of Fig. 8(1) for larger objects. In this case, the weighting coefficients in the grasping criterion are most evenly distributed. That is, the weighting coefficients are $k_p : k_d = 1 : 1$ and $k_a : k_b = 0.5 : 0.5$.

V. Grasp Experiment by Robot

Even if a robot has soft fingers, it functions under different conditions from those confronted by humans. Moreover, error occurs without fail in the shape recognition that is done using a robot camera. Therefore, it is necessary to verify whether the weighting coefficients to obtain an average human grasping position can be applied to the robot as it is. For that reason, we performed a grasping experiment using a robot hand with two soft fingers for an isosceles triangle (base:height= 1 : 2). Eq. (1) was applied using weighting coefficients $k_p : k_d = 1 : 1$ and $k_a : k_b = 0.5 : 0.5$. 

Fig. 14. Experiment of Grasping a Triangular Pillar
A. System Configuration

Fig. 9 portrays an outline of the experiment system. It consists of a robotic hand with two soft fingers (Fig. 10), an omnidirectional camera attached to the robotic hand (central interior of Fig. 10), a robot arm (Fig. 11), and two computers: one for control and data processing of the fingers and camera and the other for controlling the arm. The two computers are connected by Ethernet.

B. Shape Recognition

For recognizing the shape of the unknown object, we move the camera attached to the hand around the object horizontally while keeping the height of the camera constant and taking images of the object from different viewpoints (Fig. 12). Then by application of a two-dimensional version of the volume intersection method, we obtain the visual hull in the horizontal plane, which corresponds to a polygon circumscribing the horizontal cross section of the object (Fig. 13). Detailed procedures are described elsewhere [16] and [17].

C. Experiment Result

We performed an experiment of grasping an isosceles triangular pillar using a robot hand. The result is shown in Fig. 14. It consists of three operations. First, Figs. 14(1)–(6) show the appearance in which the shape of the object is recognized from images of the object taken using an omnidirectional camera while moving around the object, and using Volume Intersection Method. Second, Fig. 14(7) shows the robot aligning the fingers to the calculated best grasping position. Third, Figs. 14(8)–(10) show the motion of the robot grasping the isosceles triangular pillar.

After shape recognition was done, the robot successfully grasped the object at the same position as that shown in Fig. 3(a) using the proposed evaluation criterion. Some problems remain. One is that the direction of the object surface is not completely identical to the direction of the two robot fingers. Another is that the shape of the object obtained using the Volume Intersection Method differed slightly from the real shape. However, the robot was able to grasp the object without trouble because the robot has soft fingers.

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

We proposed a grasp criterion that gives the best grasping position for a robot hand with two soft fingers. To examine the properties of this criterion with respect to some weighting coefficients included in the criterion, grasping experiments with humans were done for planar objects with various sizes and shapes. Results show that many observed grasping positions by humans correspond to a set of weighting coefficients that equally weigh all the factors in the criterion. The grasping experiment was conducted for the robot using the coefficients obtained from the grasping experiments with humans. The effectiveness was confirmed.

B. Future Works

A grasping experiment that uses objects with the same shape but with different friction and weight will be examined in the future.

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REFERENCES