Grasp Planning for Constricted Parts of Objects Approximated with Quadric Surfaces

Tokuo Tsuji, Soichiro Uto, Kensuke Harada, Ryo Kurazume, Tsutomu Hasegawa and Ken'ichi Morooka

Abstract— This paper presents a grasp planner which allows a robot to grasp the constricted parts of objects in our daily life. Even though constricted parts can be grasped more firmly than convex parts, previous planners have not sufficiently focused on grasping this part. We develop techniques for quadric surface approximation, grasp posture generation, and stability evaluation for grasping constricted parts. By modeling an object into multiple quadric surfaces, the planner generates a grasping posture by selecting one-sheet hyperbolic surfaces or two adjacent ellipsoids as constricted parts. When a grasping posture being generated, the grasp stability is evaluated based on the distribution of the stress applied to an object by the fingers. We perform several simulations and experiments to verify the effectiveness of our proposed method.

I. INTRODUCTION

Service robots are expected to pick up daily life objects and deliver them to persons. For robots to execute this task, a stable grasping posture of an object has to be planned to prevent the object from dropping off. To hold an object firmly, a human often places his/her fingers on a constricted part of the object. However, previous robot grasp planners have not sufficiently focused on the surfaces of an object. On the other hand, we propose a grasp planner which allows a robot to grasp a constricted part of an object. By using a parallel gripper whose fingers are covered with a soft material, we will show that our method is very effective in grasping an everyday object firmly.

Our proposed method first models an object using several quadric surfaces [1][2]. As shown in Fig.1, we can find two definitions of a constricted part of an object: one is defined as the constriction at the center of a one-sheet hyperbolic surface, and the other is defined as the constriction constituted by two adjacent quadric surfaces. Since a constricted part can be found by checking the quadric parameter of surfaces, our proposed grasp planner can realize a grasping posture where the fingers pinch the constricted part of an object.

The proposed grasp planner checks the grasp stability based on the six dimensional wrench applied to an object

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T. Tsuji, R. Kurazume and K. Morooka are with Faculty of Information Science and Electrical Engineering, Kyushu University, 744 Motooka, Nishi-Ku, Fukuoka, 819-0395, Japan. tsuji, kurazume, morooka@irvs.kyushu-u.ac.jp

S. Uto is a student of Information Science and Electrical Engineering, Kyushu University, 744 Motooka, Nishi-Ku, Fukuoka, 819-0395, Japan. uto@irvs.ait.kyushu-u.ac.jp

K. Harada is a research group leader of National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukiba-Shi, Ibaragi, 305-8568, Japan. kensuke.harada@aist.go.jp

T. Hasegawa is a principal of Kumamoto National College of Technology, Koshi-Shi, Kumamoto, 861-1102, Japan. hasegawa@kumamoto-nct.ac.jp



Fig. 1. Grasping constrictions.

by considering the shape information of a quadric surface around the contact point. For evaluating the grasp stability of two-fingered pinching, the frictional torque about the contact normal plays an important factor. So far, the stress distribution, which differs depending on the shapes of the contact surfaces, has not been reflected in the frictional torque when evaluating the grasp stability. On the other hand, our method estimates the stress distribution on the basis of the quadric surface approximation. Hence, the frictional torque changes depending on the shape of the surface around the contact point. In our proposed method, the grasp stability index is evaluated by using the frictional torque calculated from the stress distributions. We show that a grasping posture is very stable if fingers pinch a constricted part of an object.

We verify the effectiveness of grasping a constricted part using simulations and experiments with a robot. Several everyday objects and toys are tested in the simulations. We also show experimental results which show the difference of grasp between a convex part and a constricted part of an object.

This paper is organized as follows: In the section 2, related works are listed. The quadric surface approximation method is explained briefly in the section 3. The method for grasp posture generation is explained in the section 4. The proposed grasp stability index is explained in the section 5. This paper is concluded in the chapter 6.

II. RELATED WORKS

Generally, grasp planning explores feasible grasp postures in the configuration space of a robot hand. To efficiently find a good quality grasp, object shape approximation methods using shape primitives have been proposed. Miller [3] proposed a method that uses spheres, cylinders, cones and boxes as shape primitives. Yamanobe et al. [4] proposed a method that uses various primitive shapes such as spheres, cylinders, cones, boxes, tubular boxes, and tubular cylinders. Harada et al. [5] proposed a method where objects are approximated using a plane. These primitives are difficult to represent a constriction. Goldfeder et al. [6] proposed a method that approximates an object using multiple super quadric surfaces. In general, a super quadric surface can express a wider variety of shapes than a quadric surface. However, this method uses closed super ellipsoids and does not use opened super quadric surfaces. For example, an unbounded hyperboloid cannot be expressed as a closed surface. Therefore a bounded approximated surface is suitable for representing various shapes.

We divide an object into several bounded quadric surfaces [2]. These surfaces can express concave surfaces including constrictions. In addition, a bounded quadric surface fits local features more suitably than a closed quadric surface.

As a technique for evaluating grasps, several methods are proposed based on force closure [7]-[9]. Force closure is a concept that was originally introduced in kinematics [7] and was later introduced in the field of robot hands [9]. Ferrari and Canny [11] proposed an index for grasp stability evaluation using a grasp wrench space. Nguyen [10] discussed a force closure constitution method for robot hands.

Some researchers have already considered contact stability problem depending on the curvature by assuming the contact between a rigid body and rigid fingers. Montana [12][13] proposed a contact stability evaluation method that considers the curvatures of both a hand and an object. Rimon and Burdick [14] proposed a mobility index that considered the curvatures at contact points. Funahashi [15] also analyzed grasp stability considering the curvatures at contact points. These methods can only apply to the point contact between a finger and an object. Also, these methods do not consider the frictional torque of a surface contact model. Ciocarlie et al. [16] proposed a force closure index that considers the frictional torque for surface contact between objects and soft fingers. Here, they just consider the case where the contact area has an ellipsoidal shape. As far as we know, there has been no research on grasp planning to grasp a constricted part of an object. Also, there has been no research on grasp stability which can evaluate the difference in the frictional torque between a constricted shape and a convex shape.

III. QUADRIC SURFACE APPROXIMATION

In this section, techniques of quadric surface approximation of objects are described. Wu [20] proposed surface recovery using quadric elements. Yan [21] proposed quadric segmentation method considering surface shape and normal. Our method [1][2] divides an object with bounded surfaces which is approximated by quadric surfaces with consideration of the approximation error of the shapes. We assume that the polygon model is given for each object. The quadric surface equation is classified into types such as an ellipsoid, a cylinder, and a hyperboloid. The detail of our approximation is described in [2].



Fig. 2. Procedures of face clustering: (a)Total procedures for a cup, (b)Two merging steps for a duck.

A. Least square fitting of quadric surface

We describe a method for delivering a quadric surface equation which approximates polygon meshes. Let f(x, y, z) = 0 be an implicit function of a quadric surface defined as:

$$f(x, y, z) = \mathbf{a} \cdot \mathbf{p}$$
(1)
where
$$\mathbf{a} = [a_0 \ a_1 \ a_2 \ a_3 \ a_4 \ a_5 \ a_6 \ a_7 \ a_8 \ a_9]^T$$
$$\mathbf{p} = [x^2 \ y^2 \ z^2 \ xy \ yz \ zx \ x \ y \ z \ 1]^T$$

A least square fitting method acquires the parameter a to minimize the distance between the quadric surface f(x, y, z) = 0 and original meshes. The constraint matrix proposed by Taubin [17] is used for this fitting.

B. Face clustering using a quadric approximation

Garland et al. [19] proposed a method for decomposing a surface into connected triangles called "face clusters." The same clustering method is used for dividing an object into quadric surfaces. Examples of the process are shown in Fig.2. In the initial state, each cluster has a triangle and all of the triangles for the object are included in distinct clusters. Then, an adjacent pair of clusters is regarded as a cluster and approximated using a quadric surface. The pair with the least approximation error in all pairs is merged and replaced with a new cluster. By repeating this procedure iteratively, clusters grow. If the approximation error exceeds a threshold, the merging procedure stops. Then clusters with an approximation error less than the threshold are generated. The threshold is set so that the average distance between clusters and quadric surfaces is less than 10 [mm]. The generated clusters are used for grasp postures generation. In addition, our planner continues merging process as shown in Fig.2(b) and generated clusters with the larger approximation error are also used for grasp postures generation. Then our planner generates various grasp postures for a object.

C. Classification of type of quadric surfaces

A quadric surface is defined as the general form of an implicit equation:

$$q_x x^2 + q_y y^2 + q_z z^2 = 1 (2)$$

TABLE I CLASSIFICATION OF QUADRIC SURFACES

type	condition
Ellipsoid	$q_x > 0, q_y > 0, q_z > 0$
Elliptic cylinder	$q_x > 0, q_y > 0, q_z \simeq 0$
	$q_x > 0, q_y \simeq 0, q_z > 0$
	$q_x \simeq 0, q_y > 0, q_z > 0$
One-Sheet Hyperboloid	$q_x > 0, q_y > 0, q_z < 0$
	$q_x > 0, q_y < 0, q_z > 0$
	$q_x < 0, q_y > 0, q_z > 0$



Fig. 3. Exclusion cases of grasp postures because of undesirable collisions. The red lines indicate target surfaces.

Table.I lists the relation of the surface types and the conditions of q_x , q_y and q_z . Ellipsoids, cylinders and one-sheet hyperboloids are selected from the quadric surfaces.

IV. GENERATION OF GRASP POSTURES

This section describes a process for generating a grasp posture for a soft-finger parallel gripper. To show the effectiveness of our method, grasp postures for convex shapes are also generated[2]. Several posture candidates for an ellipsoid, an elliptic cylinder, a one-sheet hyperboloid, and a constriction constituted by quadric surfaces are generated. In this process, the postures which have an undesirable collision between a finger and a quadric surface that is not a target surface are excluded as shown in Fig.3.

A. Ellipsoid

Quadric surfaces whose parameters q_x , q_y and q_z are positive are selected from the quadric surfaces. For the selected ellipsoids, three principal axes r_1 , r_2 , and r_3 are calculated. The six directions r_1 , r_2 , r_3 , $-r_1$, $-r_2$, and $-r_3$ are used as the hand-approaching direction and the gripperclosing direction as shown in Fig.4(a). The approaching direction for each approaching direction can vary in four directions, which do not include the approaching direction and the negative one. Thus, the ellipsoid has 24 candidates for grasp postures.

B. Elliptic cylinder

Elliptic cylinders are selected by checking quadric surfaces parameters q_x , q_y , and q_z . For the elliptic cylinders, two principal axes r_1 , and r_2 of the ellipses of the end faces are calculated. The approaching direction can vary in four directions and the gripper closing direction can vary in two directions. As shown in Fig.4(b), the upper, middle, and the lower points of the elliptic cylinder are set as grasping points. Let l be the length between the end faces of the cylinder. The



Fig. 4. Postures for grasping (a) ellipsoid, (b) elliptic cylinder and (c) one-sheet hyperboloid.



Fig. 5. Common cutting plane.

upper and lower points are set at positions that are moved +l/4 and -l/4 from the middle point, respectively. Thus, the cylinder has 24 candidates for grasping postures.

C. One-sheet hyperboloid

A "constriction" is defined as an area that is thinner than the neighboring areas in a certain direction. A one-sheet hyperboloid is selected by checking parameters q_x , q_y , and q_z . Vectors r_1 and r_2 are defined as the two principal axes of an ellipse with the smallest sectional area. The one-sheet hyperboloid has eight candidates. Fig.4(c) shows an example that a hand approaches along r_2 and the gripper closes along r_1 .

D. Constriction between quadric surfaces

Previous grasp planners have generated grasp postures for only one primitive. We generate grasp postures for constrictions constituted by two adjacent quadric surfaces. The boundary of two adjacent clusters is used for a grasp posture parameter. The generation process has four steps as follows:

- (1) Derive the common cutting plane.
- (2) Check whether the boundary shape is an ellipse.
- (3) Check whether the boundary is a constriction.
- (4) Generate grasping postures.

(1) Common cutting plane: The plane that approximates the boundary of two adjacent quadric surfaces is called the "Common Cutting Plane (CCP)." The derivation method for the CCP is shown in Fig.5. The boundaries shared by two clusters are approximated by a plane, which is called the CCP (Fig.5(a),(b)). The coordinates of the *i*-th(= 1, ..., n) boundary point is denoted as (x_i, y_i, z_i) . A normal vector of the plane is provided as the eigenvector ν of the smallest



Fig. 6. Check of constriction.

eigenvalue in the covariance matrix $\mathbf{R} \in \mathbb{R}^{3 \times 3}$ of boundary points. Let u be the center of the boundary points. The equation of the common cutting pane is expressed as follows:

$$(x, y, z)\boldsymbol{\nu} = \boldsymbol{u}^{\mathrm{T}}\boldsymbol{\nu} \tag{3}$$

(2) Ellipse check: The equation of the intersection line between the CCP and the quadric surface is calculated using (2)-(3) as follows:

$$q'_x x^2 + q'_y y^2 = 1. (4)$$

The planner checks whether the intersection line between CCP and the quadric surface is an ellipse. If q'_x and q'_y are positive, the line is an ellipse. Two intersection lines for the two quadric surfaces are checked.

(3) Constriction check: Let s_1 and s_2 be the areas of the ellipses generated in the previous step. CCP' is generated by moving the CCP half a finger width to the quadric surface center in the direction ν as shown in Fig.6. The area inside the intersection line between the CCP' and the quadric surfaces is defined as s'_1 and s'_2 , If the conditions $s_1 < s'_1$ and $s_2 < s'_2$ are satisfied, there is a constriction.

(4) Generation of grasping postures: Let r_1 and r_2 be the axes of the ellipse. One axis is used as the approaching direction and the other is used as the gripper closing direction. Since there are two quadric surfaces and eight candidates per quadric surface, 16 grasping posture candidates are generated for a constriction.

V. EVALUATION OF GRASP STABILITY

We use a gripper whose surface is made of a soft material. The gripper affects an object with a frictional torque, which is a moment in the normal direction at the contact surface. Frictional torque is an important factor for grasp stability. When frictional torque is small, a grasped object may rotate and slip off. Ciocarlie et al. [16] proposed a force closure index using a frictional torque for a surface contact model. A Hertzian contact and Winkler elastic foundation are used as the stress distribution model. The stress distribution is expressed as shown in Fig.7(a). We use different models of stress distribution depending on a shape of contact regions, as shown in Fig.7(b).



Fig. 7. Difference of the shapes of contact surfaces.

A. Force closure index on surface contact

The relation between the tangential force and the frictional torque is expressed in the following form:

$$f_t^2 + \frac{{\tau_n}^2}{{e_n}^2} {\le} \mu^2 p^2 \tag{5}$$

where f_t is the magnitude of the tangential contact force, p is the magnitude of a total load, μ is the frictional coefficient, and τ_n is the magnitude of a frictional moment. e_n is referred to as the eccentricity parameter and is calculated using the following equation:

$$e_n = \frac{max(\tau_n)}{max(f_t)} \tag{6}$$

 e_n is calculated at each contact point. The stability index is calculated using the values of e_n .

B. Calculation of the maximum static frictional torque

We show the calculation method for the maximum static frictional torque $max(\tau_n)$ in (6). $max(\tau_n)$ is derived by integrating the static frictional moment over the contact surface. $max(\tau_n)$ is shown in the following equations:

$$max(\tau_n) = \int \int_D \sqrt{x^2 + y^2} \mu s(x, y) dx dy \quad (7)$$
$$max(f_t) = \int \int_D \mu s(x, y) dx dy \quad (8)$$

where s(x, y) is the stress distribution, which depends on the shape of the grasped object. The integral range D is determined by a condition s(x, y) > 0 and the width of the finger. As shown in (7)(8), when a high stress is generated far from the center of the contact surface, e_n becomes high.

C. Quadratic approximation of stress distribution

We use a quadratic approximation for the stress distributions, similar to Winkler's elastic foundation. We categorize the stress distributions into the following models: a paraboloid of revolution, a parabolic cylinder and a hyperbolic paraboloid. The stress distribution models are shown in Fig.8 The stress distributions are classified depending on the target of quadric surfaces, as listed in Table.II.

(1) **Paraboloid of revolution:** An ellipsoid grasp belongs this category. The stress model of Winkler is shown in Fig.8(a), and the stress distribution s(x, y) is shown as a following equation:

$$s(x,y) = p_{max} \left(1 - \left(\frac{x}{a_r}\right)^2 - \left(\frac{y}{b_r}\right)^2 \right) \tag{9}$$

 CLASSIFICATION OF STRESS DISTRIBUTION.

 Stress distribution
 Grasped quadric surface

 Paraboloid of revolution
 Ellipsoid

 Parabolic cylinder
 Elliptic cylinder

 Hyperbolic paraboloid
 One-sheet hyperboloid

 Constriction constituted by quadric surfaces

TABLE II



Fig. 8. Stress distribution models.

where each of a_r and b_r is two radiuses of elliptic contact surface and p_{max} is the maximum stress. e_n derived by (9) is shown as approximate expression [22]:

$$e_n = \frac{8}{15\pi}\sqrt{4(a_r - b_r)^2 + \pi^2 a_r b_r}$$
(10)

(2) Parabolic cylinder: An elliptic cylinder grasp belongs this category. The stress model is shown in Fig.8(b), and the stress distribution s(x, y) is shown as a following equation:

$$s(x,y) = p_{max} \left(1 - \left(\frac{x}{a_c}\right)^2 \right) \tag{11}$$

where a_c is the half region length in parallel to the generatrix of the cylinder, and b_c is the half length in the other direction on the contact surface. e_n is derived using (11) and is shown



Fig. 9. Considering for e_n .

in a following equation:

$$e_n = \frac{1}{80a_c^3 b_c} \left(a_c b_c (22a_c^2 - 3b_c^2) \sqrt{a_c^2 + b_c^2} + 8a_c^2 \log \frac{b_c + \sqrt{a_c^2 + b_c^2}}{a_c} + b_c^3 (20a_c^2 + 3b_c^2) \log \frac{a_c + \sqrt{a_c^2 + b_c^2}}{b_c} \right)$$
(12)

(3) Hyperbolic paraboloid: A one-sheet hyperbolic and a constriction constituted by two quadric surfaces belongs this category. The stress model is shown in Fig.8(c)(d). When the number of contact regions is one as shown in Fig.8(c), the condition is called "Contact Condition 1 (CC1)", and when the number of contact surface is two as shown in Fig.8(d), the condition is called "Contact Condition 2 (CC2)". The stress distribution of the hyperbolic paraboloid is shown in the following equation:

$$s(x,y) = p_{min} - p_{max} \left(\frac{x}{a_h}\right)^2 + \left(p_{max} - p_{min}\right) \left(\frac{y}{b_h}\right)^2 \tag{13}$$

where p_{\min} is the maximum stress at the constriction. If $p_{\min} > 0$, the condition is CC1. If $p_{\min} < 0$, the condition is CC2. a_h is parallel to the generatrix of the hyperboloid, and b_h is perpendicular to a_h on the contact surface. The resulting e_n using (13) is too lengthy to be shown in this paper.

D. Discussion

In the following, we discuss e_n to confirm the validity of the evaluation equation. For the e_n of a paraboloid of revolution, Ciocarlie et al. [16] also derived e_n using Winkler's elastic foundation. They derived the following equation:

$$e_n = \frac{8}{15}\sqrt{a_r b_r}$$

 $a_r b_r$ is proportional to the area of the ellipse, and e_n is proportional to the square root of the $a_r b_r$. If the shape of the contact surface is a circle, this method and our method output the same value for e_n . In our method, e_n can be calculated accurately in a case where the shape of the contact surface is an ellipse. The difference is shown in Fig.9(b) where $a_r b_r$ is fixed at 1 and the ratio between a_r and b_r is changed as $(a_r, b_r) = \{(1, 1), (\sqrt{2}, 1/\sqrt{2}), (2, 1/2), (\sqrt{8}, 1/\sqrt{8})\}$. When the contact region is narrow as a line contact, the



Fig. 10. Result of grasp planning.

previous method returns a small value, whereas our method returns the frictional torque that is proportional to the length of line.

We next consider the relationship between the stress distribution and e_n . For this consideration, we use the value of e_n calculated using s(x, y) for several stress distributions. A graph comparing the value of e_n where a is fixed at 0.01 m and b is changed is shown in Fig.9(a). The e_n of a hyperbolic paraboloid has the highest value because the stress is high at the points that are far from the center of the contact surface. In other words, the static frictional torque of grasping constriction shapes is higher than that when grasping convex shapes. Therefore, a constriction grasp is more stable than a convex grasp.

VI. SIMULATIONS AND EXPERIMENTS

We confirm the effectiveness of our grasp planning for constriction parts in simulation. We verify the feasibility of our method using experiments with a robot.

A. Simulation of the grasp planning

As a robot hand, we use a model with a two-finger parallel gripper on the tip of PA10 (7 DOF arm). The model of actual everyday objects and toys are used in simulation. The friction coefficient μ is set to 0.5. Results of nine objects are shown in Fig.10. In these objects, a Tokkuri (sake decanter) and a Tea pod are Japanese style. The gripper closes its fingers to 2 mm depth from the surface of the target object.

The models with color coding applied to each of the quadric surfaces are shown at left side in Fig.10. Each quadric surface has a different color. We only show a clustering result with an approximation error for each object. Grasping postures are also generated for clusters with the different approximation error in the process of cluster merging.

Two grasping postures for an object are shown in at the right side in Fig.10. The contact area and the stability index are shown under each image of a grasping posture. If a grasping posture has contact condition 2, two contact areas



(a) Grasping Tokkuri

Fig. 11. Results of grasping a tokkuri and a pet bottle.

(b) Grasping PET bottle

are shown. The type of quadric surfaces is shown on the top of each image of grasping posture. The type of "Ellipsoids" means a constriction constituted by two ellipsoids. Hyperboloid and Ellipsoids for grasping constrictions are indicated by red characters.

When the stability index is 0.03, the maximum frictional torque is approximately $3[cm \cdot N]$ with 1[N] contact force. The stability index is higher, the gripper needs less force for fixing a object.

One of the PET bottles has a side approximated by an elliptic cylinder, and the other has a side approximated by a one-sheet hyperboloid. We can confirm that the grasp of a PET bottle constriction is more stable. The grasp stability index of grasping a constriction is confirmed to be generally higher in spite of the contact area is small.

Calculation time is measured using a PC (CPU: Intel (R) Core (TM) i7-2600 3.4GHz, Memory: 4.00GB). Surface approximation costs approximately 4[s] with 10000 triangular faces. Grasp stability evaluation costs less than 0.2[ms]. Hand position optimization for fitting the fingers to the object surface costs approximately 5[s].

B. Experiment using an actual robot

We compare grasping a constricted shape and a convex shape. The object position is assumed to be known in advance. The planner selects a grasping posture by considering collisions and joint limitations.

The result of grasping a tokkuri (268 [g]) is shown in Fig.11(a). The gripper grasps the constriction of the tokkuri firmly where the stability index is 0.050. The gripper can not grasp a convex part of a tokkuri because of joint limitation of the gripper. When the gripper grasps a cap of the PET bottle (350 [g]), the bottle slips where the stability index is 0.032. When an object moves in a hand, it is difficult to be placed securely. The conditions such as friction coefficient, and relative positions of gravity center are different in these experiments. The tokkuri can be held firmly, regardless of a smaller contact area, a smaller friction coefficient compared with the ones of the PET bottle.

VII. CONCLUSION

In this paper, we proposed a grasp planning method for a constricted shape. The planner approximates a target object using quadric surfaces. One-sheet hyperboloids, or constrictions constituted by two quadric surfaces are selected, and several grasp postures are generated. We also proposed an evaluation method for grasp stability, that reflects the stress distribution.

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