Two- and Three-dimensional Caging-Based Grasping of Objects of Various Shapes with Circular Robots and Multi-Fingered Hands

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***Abstract*—This paper describes a geometrical method for grasping objects wherein an object is caged by rigid parts of a robot hand and simultaneously grasped by soft parts attached to said rigid parts. We term this process as caging-based grasping.**

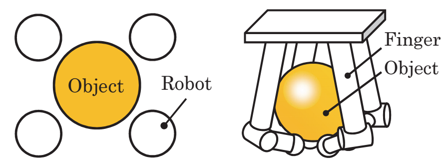
In this study, we derive concrete conditions for two- and three-dimensional caging-based grasping of objects of various shapes using circular robots and multi-fingered robot hands. Then, we validate the derived conditions by performing caging-based grasping experiments.

I. INTRODUCTION

Considering the applications of active robotics in a wide, ever-growing range of fields, high usability and robustness are expected of robots. One of the most important tasks performed by all types of robots is manipulation, and the most common method of constraining objects for manipulation is grasping. Grasping is useful for uniquely determining the position and posture of objects. However, grasping generally needs complex force control or mechanical analysis; thus, it is by no means an easy task for contemporary robots.

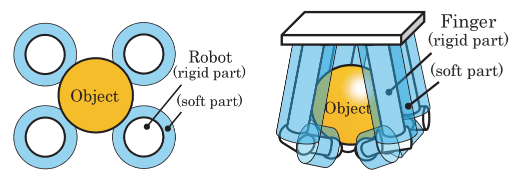
Caging is another method of constraining objects. In this method, an object is held such that it is inescapable from a cage composed of robot bodies [1] (Fig. 1). Position-controlled robots can cage and constrain objects based only on geometrical information. Therefore, caging is executed easily by contemporary robots. Many researchers have employed caging as a substitute for or as a complement to conventional grasping in robotic manipulation ([2]–[14]). However, caging cannot uniquely determine the position and posture of an object in a cage unless the region is a single point (i.e., form closure). Some reseachers proposed transition from caging to grasping [15], [16]. However, grasping by position-controlled robot hands may lead to excessive internal force.

In a previous study, we proposed a novel caging-based method called caging-based grasping, for grasping objects with a robot hand covered with soft parts [17]. In this method, an object is caged by the rigid parts of a hand, and grasping is achieved by soft parts attached to the rigid parts (Fig. 2). This method requires neither complicated force control nor mechanical analysis, and only geometrical information is necessary.



(a) 2D example (b) 3D example

Fig. 1: Caging



(a) 2D example (b) 3D example

Fig. 2: Caging-based grasping

Furthermore, the method allows for sensing error and control error to some extent. We formulated and realized caging-based grasping, but the result was limited to the grasping of circles by circular robots and spheres by articulated hands. In this paper, we describe two- and three-dimensional (2D and 3D) caging-based grasping of objects of various shapes using circular robots, articulated hands, and parallel-jaw grippers.

Some studies on grasping using position-controlled compliant fingers have been conducted in the past (for example, [18] and [19]). However, these studies require that the stability of a grasp be analyzed based on mechanical information for ensuring successful grasping. In contrast, our caging-based grasping scheme requires geometrical information only and does not require explicit mechanical analyses of grasping, which depends on contact friction and elasticity.

II. CAGING-BASED GRASPING

Here we describe the definition of our caging-based grasping briefly. See [17] for more details.

Let us consider the grasping of an object by a robot hand with rigid and soft parts: the rigid parts, which are analogous to

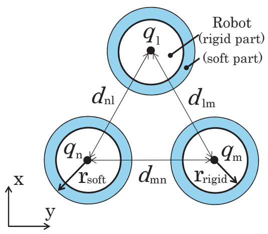


Fig. 3: Circular robots

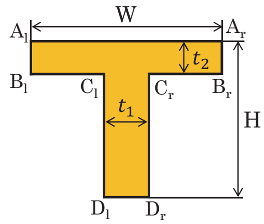
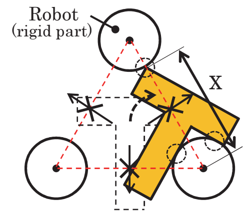
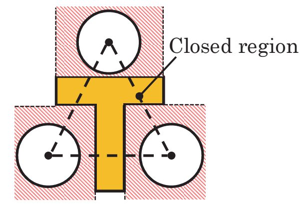


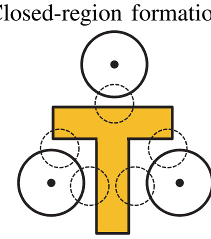
Fig. 4: T-shaped object



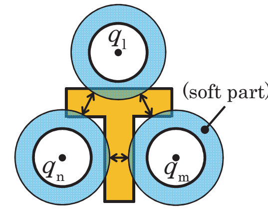
(a) Closed-region formation



(b) Object inside



(c) No interference



(d) Soft-part deformation

Fig. 5: Conditions for T-shaped object

"bones," are covered with the soft parts, which are analogous to "flesh." When the following conditions hold, we call the situation "caging-based grasping":

- Rigid-part caging condition: The object is caged in a closed region formed by the rigid parts of a robot hand.
- Soft-part deformation condition: Assuming that the soft parts of the robot hand become rigid, the closed region for caging in the configuration space of the object becomes empty.

From the rigid-part caging condition, the object is inescapable from a "cage" constructed by the rigid parts of a robot hand. This condition consists of the following three sub-conditions:

(a) Closed-region formation: A closed region through which the object cannot pass is formed by the rigid parts of a robot hand.
(b) Object inside: The object is within the closed region formed by the rigid parts of a robot hand.
(c) No interference: The rigid parts of the robot hand do not overlap with the object.

Namely, when the rigid-part caging condition holds, the object is in the closed area formed by the rigid parts of a robot hand. Furthermore, when the soft-part deformation condition holds, the soft parts of the robot hand are necessarily deformed in the closed region. Consequently, the object is caged by the rigid parts of the robot hand and grasped by reaction forces from the deformed soft parts. Note that both conditions can be tested geometrically, and an explicit mechanical analysis is not necessary.

III. 2D Caging-Based Grasping by Circular Robots

In this section, we consider 2D caging-based grasping by two or three circular robots. We use rectangles; triangles; ellipses; and cross-, H- , L-, T-, and square U-shaped objects. The following is a simple and sufficient condition of caging-based grasping of a T-shaped object by three circular robots (Fig. 3, 4) and the associated experimental results. Owing to page limitations, we have omitted the sufficient conditions for other objects. However, we present the experimental results of all objects.

A. Sufficient condition for caging-based grasping of T-shaped object by three circular robots

In this section, we describe the sufficient condition for the caging-based grasping of a T-shaped object.

• *Rigid-part caging condition*

(a) *Closed-region formation*

The following is a sufficient condition for preventing passage of a T-shaped object through the gaps between the circular robots:

$$\begin{cases} d_{ij} - 2r_{\text{rigid}} < \min\{W, H, X - r_{\text{rigid}}\} \quad (i, j = l, m, n) \\ X = \sqrt{\left\{\frac{1}{2}(W + t_1) + r_{\text{rigid}}\right\}^2 + (t_2 + r_{\text{rigid}})^2}, \end{cases} \tag{1}$$

where X is the distance shown in Fig. 5a when the T-shaped object is in contact with the circular robots at three points.

(b) *Object inside*

A sufficient object-inside condition is that the three robots exist in each of the three shaded areas around the T-shaped object, as shown in Fig. 5b.

(c) *No interference*

The robots' rigid parts and the T-shaped object must not overlap (Fig. 5c). This condition can be tested using a collision detection program such as V-COLLIDE [20].

• *Soft-part deformation condition*

A sufficient condition for soft-part deformation is that the gap between the soft parts be shorter than the width of the T-shaped object being grasped (Fig. 5d). This can be expressed as follows:

$$\begin{cases} \max\{d_{lm}, d_{nl}\} - 2r_{\text{soft}} < t_2 \\ d_{mn} - 2r_{\text{soft}} < t_1. \end{cases} \tag{2}$$

B. Experiment

To validate the derived conditions for caging-based grasping, we used two or three circular robots. Three iRobot Create units were used as the rigid parts, and urethane foam was employed for the soft parts.

In an experiment involving the caging-based grasping of a T-shaped object by three circular robots, we located the robots

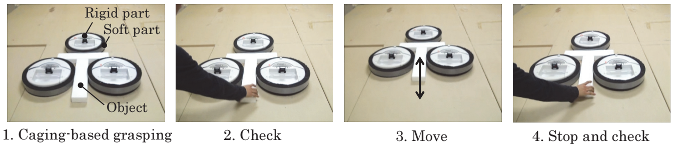
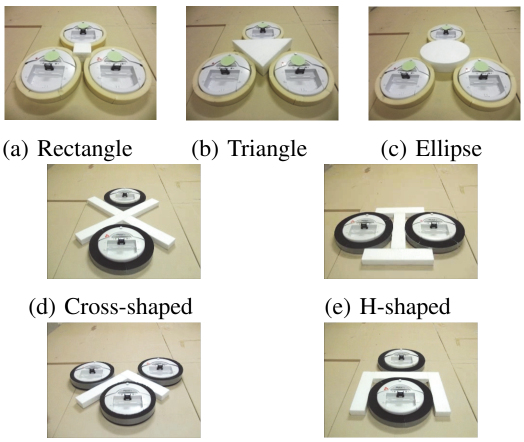


Fig. 6: 2D caging-based grasping of T-shaped object



(a) Rectangle (b) Triangle (c) Ellipse

(d) Cross-shaped (e) H-shaped

(f) L-shaped (g) Square U-shaped

Fig. 7: 2D caging-based grasping of objects of various shapes

and the object at the positions at which all derived conditions were satisfied. Then, we controlled the three robots to translate while maintaining their formation (Fig. 6). Here we simply sent the same motion commands to the robots and did not use position feedback for motion synchronization. Due to the margins of caging-based grasping and limited travel distance, the object was successfully grasped and manipulated without jamming.

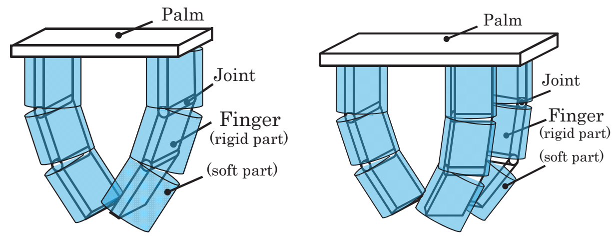
Similarly, we conducted experiments of caging-based grasping on other objects under the respective sets of derived conditions (Fig. 7). Thus, the relative positions of the object and the robots were maintained throughout the manipulation, which is difficult in conventional caging.

IV. 3D Caging-Based Grasping by Articulated Hands

We consider caging-based grasping using two- or three-fingered articulated hands with the following features (Fig. 8):

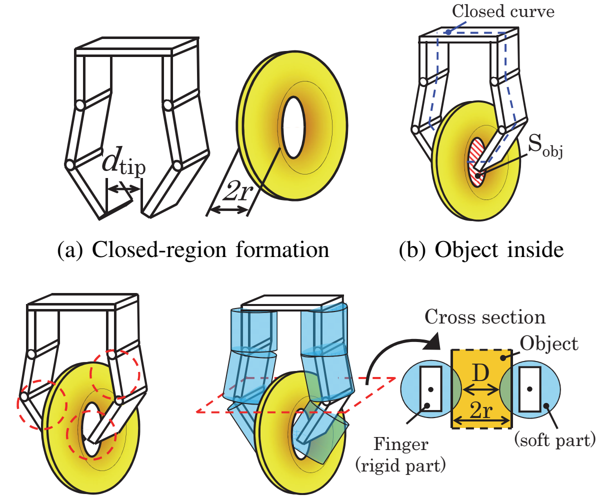
- The hand consists of a flat palm and two or three fingers.
- Each finger has three cuboid links as its rigid parts, is covered with cylindrical soft parts, and connected by two rotary joints.
- All fingers are attached to the palm with circular symmetry.
- All angles of the first joints of the fingers are identical. Simultaneously, all angles of the second joints of the fingers are identical.

We consider cuboids, ellipsoids, tori, hollow and solid cylinders, and dumbbell- and bulb-shaped objects. As an example,



(a) Two-fingered hand (b) Three-fingered hand

Fig. 8: Multi-fingered articulated hands



(a) Closed-region formation (b) Object inside

(c) No interference (d) Soft-part deformation

Fig. 9: Conditions for caging-based grasping of torus

the following is a simple, sufficient condition of caging-based grasping for tori. Owing to page limitations, we have omitted sufficient conditions for the other objects. However, experimental results are presented for all objects.

A. Sufficient condition for caging-based grasping of torus by two-fingered articulated hand

In the following, we describe a sufficient condition for the caging-based grasping of a torus with major and minor radii of R and r, respectively.

- *Rigid-part caging condition*

(a) *Closed-region formation*

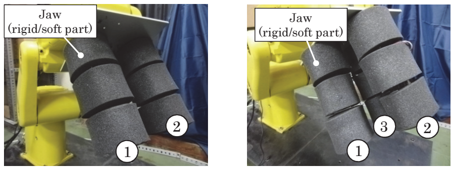
The following is a sufficient condition for preventing a torus from passing through gaps between the fingertips:

$$d_{\text{tip}} \le 2r, \tag{3}$$

where d_{tip} is the distance between the fingertips (Fig. 9a).

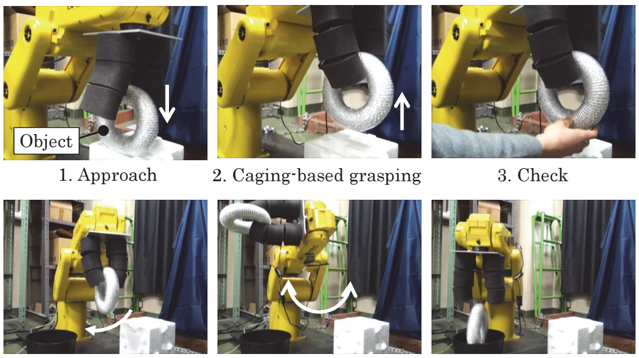
(b) *Object inside*

A sufficient object-inside condition is that the closed curve linking the frameworks of the robot hand and the fingertips, which has no self-intersection, crosses a planar closed region S_{obj} of the torus hole an odd number of times (Fig. 9b).



(a) Two-fingered hand (b) Three-fingered hand

Fig. 10: Multi-fingered articulated hand



1. Approach 2. Caging-based grasping 3. Check

4. Carry 5. Swing and check 6. Release

Fig. 11: 3D caging-based grasping of torus

(c) *No interference*

The rigid parts of the robots and the torus must not overlap (Fig. 9c). This condition can be tested using a collision detection program.

• *Soft-part deformation condition*

If the soft parts are larger than a threshold at the cross section of the hand, which is parallel to the palm shown in Fig. 9d, the torus cannot exist inside the "cage" without deformation of the soft parts. This can be written as follows:

$$D < 2r, \tag{4}$$

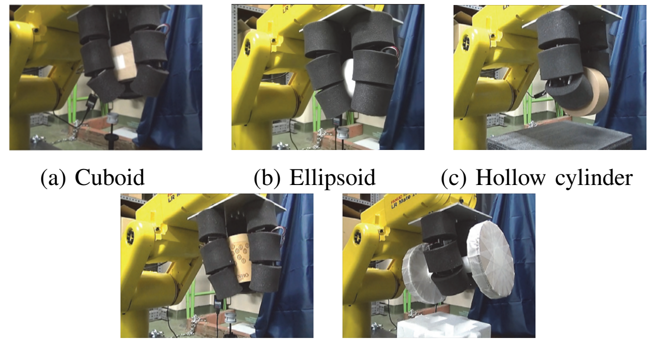
where D is the distance between the soft parts. This is a sufficient condition for soft-part deformation.

B. Experiment

To validate the derived conditions for caging-based grasping, we fabricated two- and three-fingered articulated robot hands. Each finger comprised two servomotors (Futaba RS405CB). The hands were attached to a manipulator, Fanuc LR-Mate 200iA. For caging-based grasping, urethane foam was attached to each finger link in the hand for forming cylindrical soft parts (Fig. 10).

In the caging-based grasping experiment of a torus by a two-fingered articulated robot hand (Fig. 11), we controlled the robot hand to satisfy the derived conditions and to pick up the torus by caging-based grasping. Then, the hand carried the torus to a destination and released it successfully.

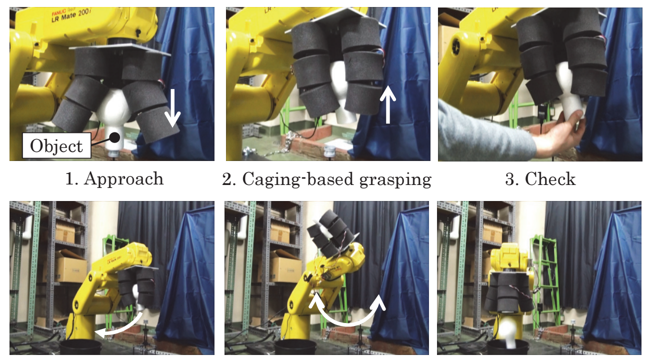
Similarly, we performed caging-based grasping of other objects using the respective sets of derived sufficient conditions (Fig. 12). As a result, the relative positions of the objects and the robots were maintained throughout the manipulation, which is difficult to achieve with conventional caging.



(a) Cuboid (b) Ellipsoid (c) Hollow cylinder

(d) Solid cylinder (e) Dumbbell-shaped

Fig. 12: 3D caging-based grasping of various objects



1. Approach 2. Caging-based grasping 3. Check

4. Carry 5. Swing and check 6. Release

Fig. 13: 3D caging-based grasping of combination object

C. 3D Caging-Based Grasping of Combination Object

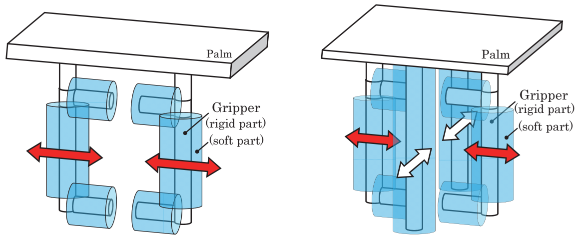
Here, we show an experiment conducted for the caging-based grasping of a bulb-shaped object, which can be regarded as a combination of a sphere and a solid cylinder. We can apply concrete conditions for the caging-based grasping of spheres and solid cylinders to the spherical and the solid cylindrical parts of this object, respectively.

In the experiment shown in Fig. 13, we focused on the spherical part because the concrete condition for spheres is easier to satisfy. The hand picked up the combination object by caging-based grasping, carried it to a destination, and placed it successfully.

V. 3D Caging-Based Grasping by Parallel Jaw Grippers

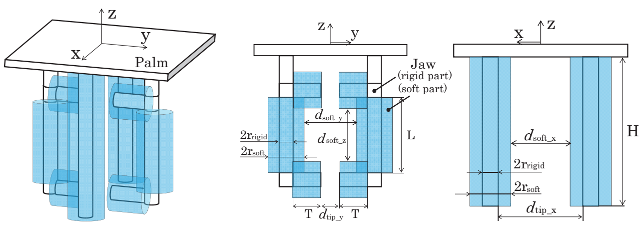
In our study, we use not only articulated hands, as described in section IV, but also two- and four-jaw parallel grippers for 3D caging-based grasping. These grippers have the following features (Fig. 14):

- They consist of a flat palm and two or four jaws.
- Each jaw has cylindrical links as its rigid parts, and these links are covered with cylindrical soft parts.



(a) Two-jaw parallel gripper (b) Four-jaw parallel gripper

Fig. 14: Multi-jaw grippers



(a) Exterior (b) yz section (c) zx section

Fig. 15: Parameters of four-jaw gripper

- All jaws are attached to the palm.
- The two-jaw gripper consists of a pair of inverted F-shaped jaws.
- The four-jaw gripper consists of a pair of inverted F-shaped jaws and a pair of cylindrical jaws.

Given their lower degrees of freedom than the articulated hands, the grippers offer advantages in terms of cost and control effort.

We considered spheres, cuboids, tori, hollow and solid cylinders, bottomed hollow cylinders, and dumbbell- and bulb-shaped objects. As an example, the following is a sufficient condition for the caging-based grasping of spheres. Owing to page limitations, we have omitted the sufficient conditions for the other objects. However, we present the experimental results of all objects.

A. *Sufficient condition of caging-based grasping of sphere by four-jaw gripper*

In the following, we describe a sufficient condition for the caging-based grasping of a sphere of radius R.

• *Rigid-part caging condition*

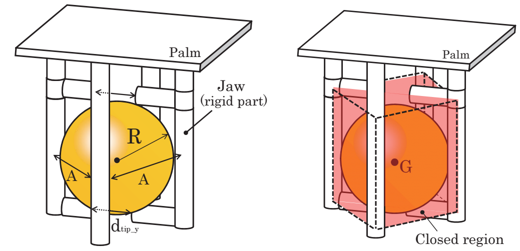
(a) *Closed-region formation*

A sufficient condition for preventing the sphere from passing through the hand is that the gaps between adjacent jaws and fingertips along the y axis be smaller than the diameter of the sphere (Fig. 16a). This can be written as follows:

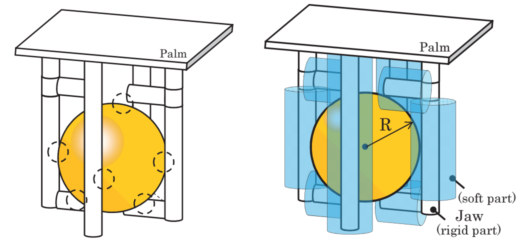
$$\max\{A, d_{\text{tip\_y}}\} < 2R. \tag{5}$$

(b) *Object inside*

A sufficient condition for object-inside is that the center of the sphere is in the prismatic region formed by the rigid parts of the hand (Fig. 16b).

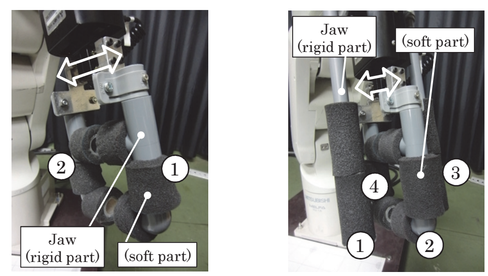


(a) Closed-region formation (b) Object inside



(c) No interference (d) Soft-part deformation

Fig. 16: Conditions for caging-based grasping of sphere



(a) Two-jaw gripper (b) Four-jaw gripper

Fig. 17: Multi-jaw grippers

(c) *No interference*

The rigid parts of the hand and the sphere must not overlap (Fig. 16c). This condition can be tested using a collision detection program.

• *Soft-part deformation condition*

If the distances between the soft parts along the x, y, or z axis are smaller than the sphere diameter, the sphere cannot exist in the "cage" without deformation of the soft parts. This can be expressed as follows:

$$\min\{d_{\text{soft\_x}}, d_{\text{soft\_y}}, d_{\text{soft\_z}}\} < 2R. \tag{6}$$

B. *Experiment*

To validate the derived caging-based grasping conditions in an actual environment, we fabricated two- and four-jaw parallel grippers (Fig. 17). These grippers consisted of U-shaped or cylindrical jaws, urethane foam, and an electrical gripper (MITSUBISHI 1A-HM01), and they were attached to a manipulator (MITSUBISHI RV-1A).

In the caging-based grasping experiment of a sphere by a four-jaw parallel gripper (Fig. 18), we controlled the robot

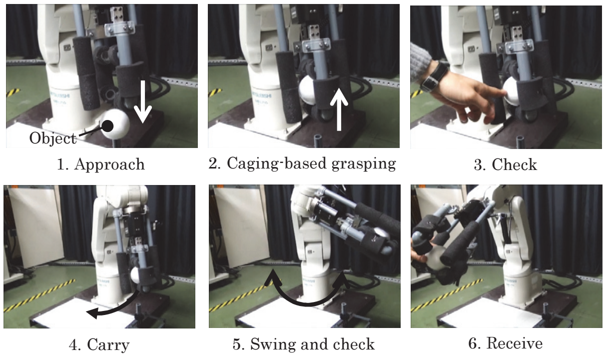
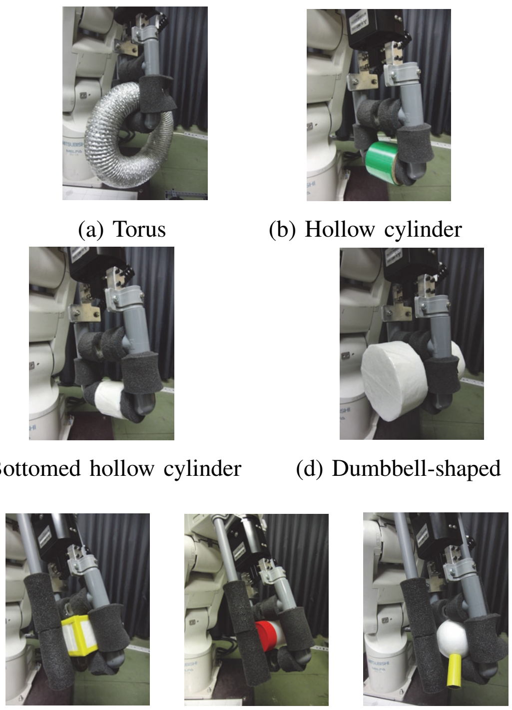


Fig. 18: 3D caging-based grasping of sphere



(a) Torus (b) Hollow cylinder

(c) Bottomed hollow cylinder (d) Dumbbell-shaped

(e) Cuboid (f) Solid cylinder (g) Bulb-shaped

Fig. 19: 3D caging-based grasping of various objects

hand to satisfy the derived conditions and to pick up the sphere by caging-based grasping. Then, the hand carried the sphere to a destination, where a human operator received it successfully.

Similarly, we conducted caging-based grasping experiments with other objects using derived the respective sets of sufficient conditions (Fig. 19). As a result, the relative positions of the object and the robots were maintained throughout the manipulation, which is difficult with conventional caging.

VI. Conclusion

In this study, we derived concrete conditions for the caging-based grasping of objects of various shapes by circular robots, articulated hands, and parallel jaw grippers. In addition, we present experimental results of caging-based grasping.

Many issues pertaining to caging-based grasping remain to be addressed, which include grasping and releasing objects, selecting appropriate softness for the soft parts, deriving concrete conditions for caging-based grasping by various types of robot hands, and the application of said conditions to various tasks.

Acknowledgements

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