

# A Grasp Planning for Picking up an Unknown Object for a Mobile Manipulator

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**Abstract**—This paper describes a grasp planning for a mobile manipulator which works in real environment. Mobile robot studies up to now that manipulate an object in real world practically use ID tag on an object or an object model which is given to the robot in advance. The authors aim to develop a mobile manipulator that can acquire an object model through video images and can manipulate the object. In this approach, the robot can manipulate an unknown object autonomously. A grasp planning proposed in this paper can find a stable grasp pose from the automatically generated model which contains redundant data and the shape error of the object. Experiments show the effectiveness of the proposed method.

## I. INTRODUCTION

A mobile manipulator working in office or home environments is an important issue in robotics. Carrying an object is a fundamental and common task for mobile manipulators. To manipulate an object, the robot needs to sense the environment and to acquire the object information. Many issues which deal with mobile manipulator utilize predefined object models[5], or ID tags which makes it easy to identify the object by the mobile manipulator or the robot[3][10]. When a new object to be manipulated is found, we must add new information for object shape, desired grasp location of the object, or desired motion of the manipulator. However it becomes difficult to give information for all each of the objects in advance, if there were so many objects to be manipulated in real environment. Therefore, the authors prefer to take such an approach that the robot acquires an object shape on the spot and manipulates the object autonomously.

We aim at developing the object picking and carrying task by a robot system even if there are no tags nor object information in advance. To accomplish this aim, it is necessary to provide the robot system with functions of object model acquisition and grasp planning by automatic means. Grasp planning must find necessary grasping position on the object and grasping pose of a robot hand by using on-the-spot object model. The object model which is acquired by external sensing on the spot is very different from the artificially generated model such as the one used in CAD. Therefore, a novel grasp planning method must be developed taking account of the characteristics of the "measured" model. This paper proposes a grasp planning method based on object model that the robot acquires on the spot, and demonstrates how to use this method in solving practical problems in object manipulation.



Fig. 1. Mobile manipulator

The object grasping will be achieved with two steps as follows: acquiring a 3D object model from a camera mounted on the robot, and grasp planning from the model. The method of 3D modeling is based on SFM (Structure from motion) approach using image streams[11]. In this paper, "3D model" means an object surface model which is represented by dense 3D points. SFM method is incorporated into acquisition of the model without any marks or knowledge in advance. Grasp planning finds a grasp position on the object based on the automatically generated model.

There are two major problems in using such 3D models for grasp planning. The first problem is that a 3D model has a large amount of data. We cope with this problem by utilizing voxelized model for grasp planning. The second problem is shape error. We cope with this problem by reducing the raw model data with averaging the shape error. In grasp planning, stable grasp position is detected based on several criteria such as contact area between the hand and the object, a moment balance of the grasp pose and manipulability of the manipulator system.

This paper is described as follows: In the next section, related works are described. Section III presents a scheme of this study and problem definition. The outline of grasp planning based on 3D object model is described in Section

IV. Section V provides experimental results with grasping to demonstrate the effectiveness of our proposed method. Section VII concludes this paper.

## II. RELATED WORKS

### A. Mobile manipulation

Miura et al.[5] developed a service robot which was applied to the task of fetching a can from a remote refrigerator. They gave the robot a can model by image in advance. Petersson et al.[8] developed a mobile manipulator system in real world. The robot was able to achieve a series of task of recognizing, picking and conveying an object. In their study, the simple shape object is assumed and its model is given in advance. Compared to these systems, the authors aim at a robot system in which the robot can grasp an object based on the object model which is automatically acquired by itself without any restriction for the object shapes.

### B. Grasp planning

Bin-picking task was achieved based on an object model such as CAD model. To find a target object, the object recognition process matches the object with its model and estimates the object pose[9]. Because of a limited variety of objects for a task in industry, this technology to provide the object model in advance is often utilized for industrial situation. In other applications, there are grasp planning methods which are based on various shape models[4][1]. In these approaches, grasp planning necessary takes accurate and precise object models which are given in advance. In contract, we allow inaccurate object model in the proposed grasp planning algorithm in this paper.

On the other hand, there is an approach in which an unknown object is subject to grasp planning[7]. Morales et al.[6] performed a grasp planning on planer object. Utilizing the contour information which is extracted from an image, squeezing or expansion grasp is realized. However, it is difficult to apply Morales's approach to variety of objects which can not be regarded as planer. In this paper, the object model is acquired in 3D from a series of images without any knowledge on the object. Grasp planning is also be performed in 3D space.

## III. PROBLEM DEFINITION AND SCHEME

### A. Object grasping by a mobile manipulator

As a compact and light weight hand has an advantage for a mobile manipulator, Jaw Gripper Hand is utilized in this study. We assume that the finger tips will contact with the object with some area and not with at a point. Also they assume that the object model obtained from a series of images in this paper is not perfectly accurate. Therefore, the area contact will save the planning algorithm from the difference of the model shape and real shape of the object.

Object carrying by our mobile manipulator is performed according to the following procedure.

- 1) The object is put on the desk and approximate object position is given to the robot manually.

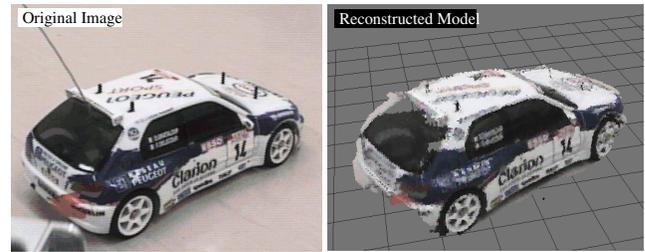


Fig. 2. Image based 3D modeling[11]

- 2) Create 3D object model using a camera mounted on the robot and do grasp planning.
- 3) Pick up the object by the manipulator based on the grasp planning result.
- 4) Convey the object and put it on another place.

The object is assumed to have equivalent size that human can grasp it by one hand. No constraint on its shape is assumed. The item 3. is a main topic in this paper (See Section IV).

### B. 3D model acquisition

To acquire 3D model, SFM (structure from motion) method[11] is utilized. The 3D model means an object surface model which is represented by dense 3D points (Fig.2).

This model is acquired with a procedure as follows: first, many "feature points" are extracted from a small area which has strong intensity in image by using particular image processing operator. Then they are tracked between images. From these points, object sparse model and camera poses are acquired by means of SFM. Next, the object dense shape is reconstructed from a close pair of images. The reconstruction process calculates 3D location of each triangular patch whose three vertices are adjoining and are common feature points in the pair of the images. This process is applied to all the pairs of images and all the results for 3D locations of the triangular patches are integrated to obtain the 3D dense object model.

The method in [11] achieves at most 5mm error in reconstructed shape of an object of 10cm to 15cm size. This error arises from mistracking of feature points or linear approximation in reconstruction algorithm.

### C. Approach

The purpose of grasp planning in this paper is to find reasonable grasping pose in manipulatable space of the manipulator with making use of the reconstructed dense 3D model on the spot.

Grasp planning in this study has two major issues: (1)how to plan a grasp pose efficiently from the 3D model, and (2)how to find a stable grasp from the 3D model, even though the 3D model has redundant data and errors in shape. We propose grasp planning to answer the above two issues.

An approach in this paper is as follows:

- Voxelized model is applied to reduce the redundant data and the shape error.

- Best grasp pose to pick up the object is obtained through criteria as follows:

- 1) Contact area is enough between the hand and the object model.
- 2) A gravity balance is stable which depends on grasp position on the object.
- 3) Manipulatable space is large enough for moving the object after grasping.
- 4) Motion cost of the mobile robot is low when the robot moves from start to grasping pose.

In this approach, after reducing search space, grasp pose searching is performed efficiently. A voxel in this paper means a small cubic bin, and an object model (voxelized model) is represented by a group of voxels.

#### IV. GRASP PLANNING

This section describes a grasp planning method using a 3D object model which is built by SFM. The method allows the model data redundancy and the shape error on the model.

##### A. Formulation

The authors define "stable grasp" by the lowest sum total of four functions as follows:

$$F = w_1 F_1(P_1, \xi) + w_2 F_2(P_1, \xi) + w_3 F_3(P_1, \eta, \xi) + w_4 F_4(\eta, map), \quad (1)$$

where  $P_1$  is a center point of finger plane on the hand. This is a point contacts with object.  $\xi$  is a hand pose (6-DOF),  $\eta$  is a position of a mobile robot and  $map$  is a map of environment where the robot works.  $w_i$  is a weight.

The value  $F$  is good for grasping when it is small.  $F_1(\cdot)$  represents the function of contact area between the hand and the object. The evaluation value become smaller if the hand pose has more contact area.  $F_2(\cdot)$  represents the function of a gravity balance of the object. The evaluation value become small if a moment of the object is small.  $F_3(\cdot)$  represents the function of the grasping pose. The evaluation value becomes small if manipulatable range is large against the direction in which the robot wants to move the object.  $F_4(\cdot)$  represents the function of a motion cost of the robot. The evaluation value becomes small if the amount of robot motion is small. The policy of grasp planning is to find  $P_1$ ,  $\eta$  and  $\xi$  which minimize the function of  $F$ . This paper covers mainly how to find reasonable  $P_1$  and  $\xi$ .

##### B. Model representation for grasp planning

Before  $F_i (i = 1, \dots, 4)$  in eq.(1) are defined, model representation is illustrated in this section.

Object models in our use are automatically generated using a camera mounted on the robot. Our object models are suitable to represent various shapes since they are defined as an aggregation of dense 3D points. However the object model has redundant data and shape errors accumulated through the SFM process. The problem is how to calculate the eq.(1) from this model. The authors utilize "oriented points" to cope with this problem.

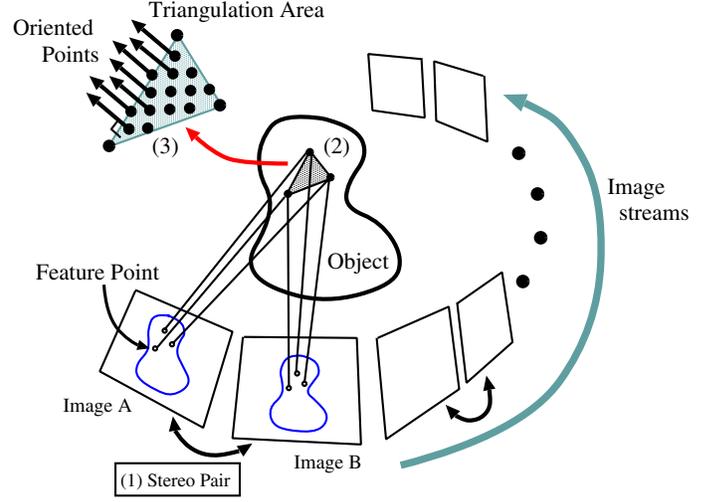


Fig. 3. Surface model reconstruction

1) *Oriented points*: "Oriented point" means the 3D point which has a normal vector standing on the object surface. Oriented points is similar to the "needle diagram" proposed by Ikeuchi et al.[2]. This representation is used as data registration or detection of object orientation. The oriented point or needle diagram can easily be obtained from 3D surface model which can be acquired by LRF scans or image based modeling.

The flow of acquiring the oriented points from image streams here is as follows (Fig.3):

(1) pick a pair of images with an image and next image in the image streams (Fig.3(1)),

(2) make triangle patch which consists of three neighbor feature points which are common in the pair images (Fig.3(2)),

(3)select a pixel inside of the triangle in one image of the pair, and calculate a corresponding 3D position of the pixel by linear interpolation (Fig.3 (3)). A normal orientation is added to the each calculated pixel. Same procedure is performed all possible patches in the image and also in the other images.

In the experiences of us, typical average of the thickness around the real surface of the object is about 10mm. This arises from the fact that oriented points are obtained by the interpolation, and that the triangle patches are "approximated" surface formed by sparsely distributed feature points on the object.

2) *Elimination of redundant data*: Oriented points described in Section II.B.1) is redundant data representation for grasp planning. Transforming from this points to voxelized model utilizes to reduce redundancy. Moreover, this process has effects of reducing a shape error of the object model. The size of voxel is set with 5mm or 10mm based on an allowable shape error in the grasp planning.

A new oriented points are acquired as "thin" model according to the following procedure. At first, 3D-space is squared up fine cubic voxels (the voxel size is 5mm or 10mm). Voxels are deleted except special voxels which include several oriented points in it. Next, orientation component is averaged in each

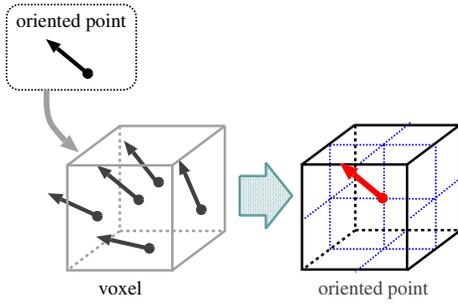


Fig. 4. Make Oriented Points

voxel. Finally, oriented points is acquired as the position is the center of each voxel and the orientation is an average value (Fig.4).

As it is necessary to yield the moment of inertia of the object, the model must be volumetric. For this purpose, once a voxel space including all the part of the model is defined. Then, the voxels of outside of the object are pruned away. The reminder of the voxels is the volumetric model of the object. It is utilized for calculation of the moment of inertia.

### C. Evaluation of contact area

To calculate the function  $F_1(P_1, \xi)$  in eq.(1), contact area between the hand and the object is considered.  $F_1(P_1, \xi)$  is defined as follows:

$$F_1(P_1, \xi) = \begin{cases} 1 & (\text{if } S(P_1, \xi) \geq S_0) \\ \exp(S_0/S(P_1, \xi)) & (\text{if } S(P_1, \xi) < S_0) \\ \infty & (\text{if } S(P_1, \xi) = 0) \end{cases} \quad (2)$$

where  $S(P_1, \xi)$  is the size of contact area. This area is counted from the number of the voxels that are covered by the finger tips of the hand.  $S_0$  is a threshold.

The size of contact area is approximately estimated by counting the object voxels in the vicinity of the fingers. The advantage of this way is that we can merely accomplish the estimation in spite of complexity of the object shape.

The steps to evaluate the contact area are as follows: (i) Assume that the hand is maximally open, choose one contact point  $P_1$  which is a voxel on the surface of the model. Consider the condition that the center of the one finger touches at  $P_1$  and the contact place of the one finger is perpendicular to the normal at  $P_1$ . The contact area is the number of voxels which are adjacent  $P_1$  with the finger tips. (ii) Assume that the hand is closed and the other finger is touched with the counter side of the object. Count the number of voxels which are touched with the other finger plane.

The grasping does not possible if any of following contact conditions applies.

- Contact area is too small for either one or both of fingers,
- the width between the finger exceeds the limit,
- the normal with the contacting voxel is not perpendicular to the finger plane.

Change the posture  $\xi$  by rotating the hand around the normal at  $P_1$  with certain step angles, above evaluation(i)(ii) is performed.

### D. Evaluation of gravity balance at grasping

To calculate the function  $F_2(P_1, \xi)$  in eq.(1), a moment caused by a gravity in the grasping pose  $\xi$  is considered.

The moment can be acquired easily because it can be calculated from the position of voxels which occupies in the volume of the object model.

The object model is divided into two volumes by a plane which is parallel to the direction of gravitation. If the two volumes give equivalent moment, good evaluation is obtained:

$$F_2(P_1, \xi) = \begin{cases} m(u)/m(w) & m(u) \geq m(w) \\ m(w)/m(u) & m(u) < m(w) \\ \infty & m(u) = 0 \text{ or } m(w) = 0 \end{cases} \quad (3)$$

where  $m(x)$  is moment of volume  $x$  arising from gravitation.

Although it is naturally strict to consider another balance requirement such as force-closure, the authors rather take  $F_2(\cdot)$  for moment balance criterion according to the following reasons. The one reason is that it is difficult to evaluate the amount of the friction force between the hand and grasped object, because there are no knowledge about the material or mass of the object. The second reason is that a grasping pose which is finally fixed on the basis of evaluation with eq.(4) can be expected to maintain the gravity balance of the object. It can be assumed that the grasping can be successfully achieved unless the grasp position is shifted in very wrong balance, because the Jaw Gripper Hand in this paper has enough grasping force. This means that the finally obtained grasp pose by the method proposed here maintains force-closure grasp.

### E. Evaluation of manipulator pose

The function  $F_3(P_1, \eta, \xi)$  in eq.(1) is calculated from manipulability[12].

A measure of manipulability is calculated under the condition that the object will be picked up to vertical direction. In this evaluation, the position of mobile manipulator is considered because manipulator can change its position by mobile-base motion.

$$F_3(P_1, \eta, \xi) = \begin{cases} 1/\sqrt{\det(\mathbf{J}(\mathbf{q})\mathbf{J}^T(\mathbf{q}))} & \mathbf{q} \text{ is solved} \\ \infty & \text{otherwise,} \end{cases} \quad (4)$$

where  $\mathbf{J}$  is Jacobian matrix of the mobile manipulator,  $\mathbf{q}$  is parameter vector of joints and it is solved by inverse kinematics with respect to relative location of the object and the manipulator  $f(\eta, map)$  and grasping pose  $h(P_1, \xi)$ . The evaluation  $F_3(P_1, \eta, \xi)$  becomes large if the mobile manipulator moves largely to take a grasping pose  $\xi$ . On the other hand,  $F_3(P_1, \eta, \xi)$  is set to  $\infty$  when the inverse kinematics can not be solved to obtain  $\mathbf{q}$ .

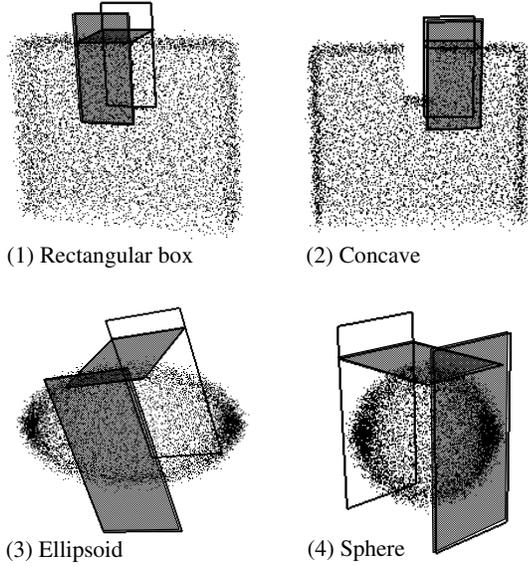


Fig. 5. Grasp planning with some series of shape

#### F. Evaluation of the amount of robot motion

The function  $F_4(\eta, map)$  in eq.(1) is calculated from the amount of robot motion. There is a possibility that the evaluation of the function  $F_3(P_1, \eta, \xi)$  yields good if the robot moves.

The motion cost is calculated from initial robot position to target position. The robot has a map of its environment. If the distance of the motion is large or obstacles give some influence to the motion path, the evaluation becomes large and worse.

### V. EXPERIMENTS

#### A. A robot system

Experiments are performed with a fixed manipulator 'KatanaII(HD-6M)' which is made by Neuronics Inc. KatanaII has 5 joint arms and Jaw Gripper. The 5 degrees of freedom is not enough for grasping in full 3D space. In our experiment, if the inverse kinematics has approximate solution for required real pose, this solution is applied. In this experiment, grasp planning is performed on a PC Pentium4 at 2.8GHz CPU.

#### B. Simulation

The effectiveness of our grasp planning is proved by means of simulation. The hand is 60mm in length and 30mm in width, the limit of width between two fingers is 80mm. The model is placed on the front of 200mm for the robot. A shape error which follows a normal distribution is added to the model. The position error is 5mm when  $2.5\sigma=5\text{mm}$  and the orientation error is  $2.5\sigma=10\text{deg}$ . Errors over  $2.5\sigma$  is omitted.  $F_1$  and  $F_2$  are evaluated as they appear in eqs (2) and (3) in evaluation  $F$ .  $F_3$  is only considered whether the approximately inverse kinematics solution exists or not. and  $F_4$  is not considered in this simulation.

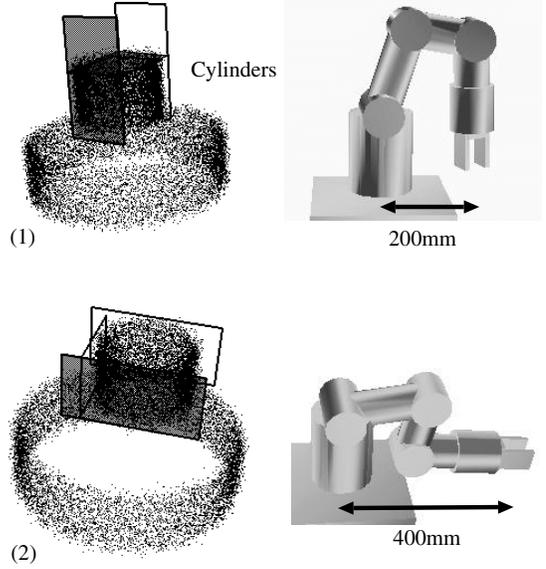


Fig. 6. Grasp planning with different object position

TABLE I  
COMPUTATION TIME

	Box	Ellipse	Sphere	Cylinders
Oriented points	8400	10000	10000	21600
Voxels	515	107	77	264
time[s]	1.99	0.73	0.66	1.46

Fig.5(1) illustrates a planning result for a rectangular object. The object size is 120x30x60mm, and the number of oriented points is 8400 in this model. Fig.5(2) shows the same as Fig.5(1) but a center of this model has a hollow which is 25mm in height and 20mm in width. Fig.5(3) and (4) are the results for ellipsoidal and spherical objects respectively. Solutions for these objects are obtained successfully and properly.

Table.I shows the computation time statistics for the number of oriented points and voxels in grasp planning. By our method, the size of voxel is determined from the permissible errors of robot hand. For this reason, the complexity of an object shape does not affect the processing time in our grasp planning so much because the processing time depends on the number of voxels. Fig.6 shows examples in case that the object position relative to the base of the manipulator is changed. Different grasp pose can be found according to the object position.

Fig.7 and Fig.8 show relations graph between  $y$  displacement of the object model and evaluation  $F$  in the grasp planning for Fig.5. In this figure, grasping poses which are approached only perpendicular direction are shown. When a grasping is performed from the top at the rectangular object, a center of rectangle should be most stable(Fig.5(1)). On the other hand, about the object for Fig.5(2) shows stable grasp at the next of the hollow. The simulation is performed at the both situation that the model has the shape error or not, the

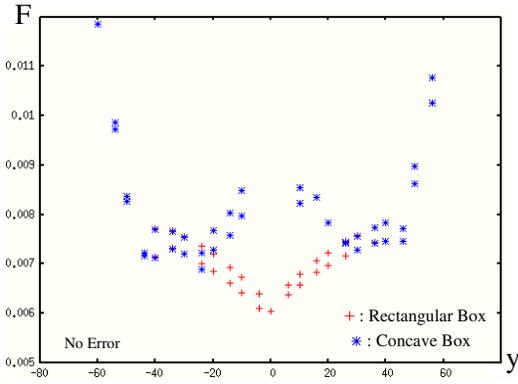


Fig. 7. Simulation result

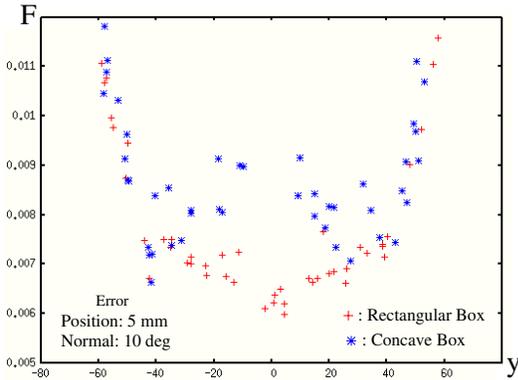


Fig. 8. Simulation result

result shows a similar result despite the shape error.

### C. Grasp planning with automatic generated model of real object

A realistic grasp experiment is performed at the model which is automatically generated from real images. The target object is plastic bottle whose height is 90mm and maximum diameter is 40mm (Fig.9(1)). A Modeling process is performed in offline and the number of oriented points are about 4000 (Fig.9(2)). Fig.9(3) shows examples of several grasp candidates which are judged as almost stable grasp from the contact area and the moment balance. Various grasp pose can be found by our grasp planning. Fig.9(4) shows the best grasp when the object is set the 200mm front of the manipulator. Fig.10 left shows the grasping motion. In Fig.10 right, different grasp pose can be found when the object is placed at another position. Fig.11 and Table.I show other examples by our grasp planning.

## VI. CONCLUSION

In this paper, we proposed a grasp planning algorithm for an unknown object which will be picked up by a mobile manipulator. The proposed planning method can find a stable grasp pose from the automatically generated 3D model from images including redundant data and the shape error. Experimental

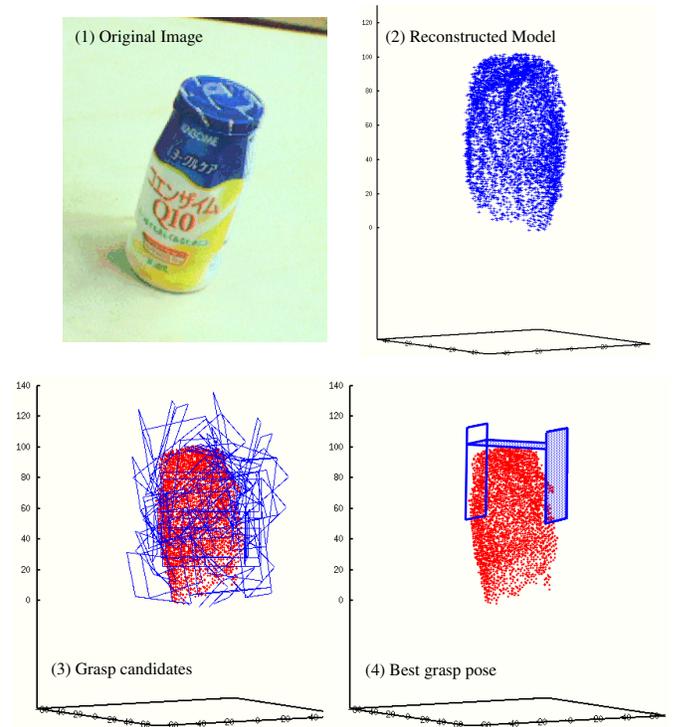


Fig. 9. Grasp planning with real object

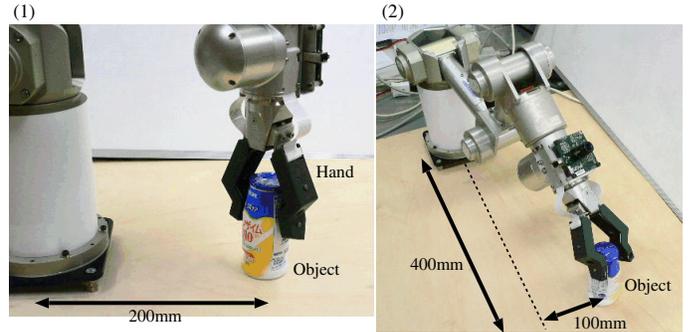


Fig. 10. Pick up the bottle

results are demonstrated and prove the effectiveness of our method.

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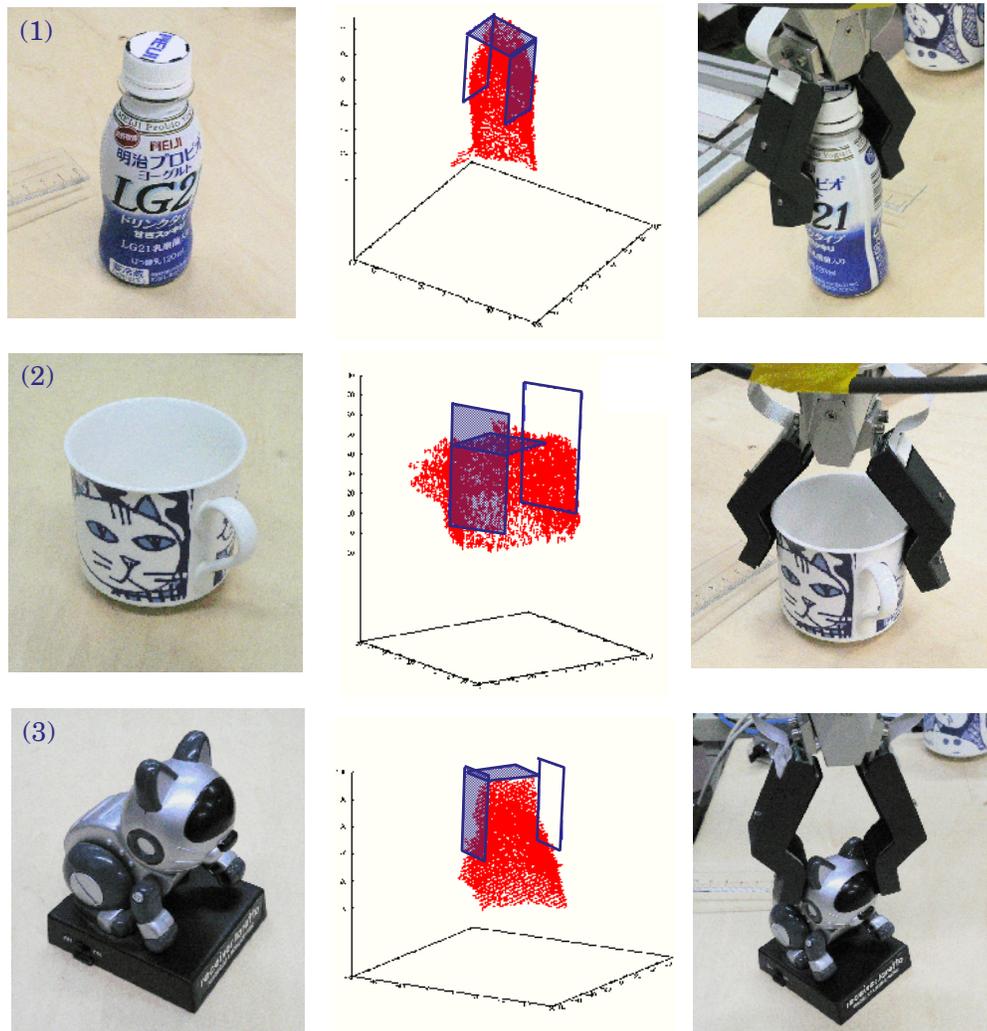


Fig. 11. Other examples

TABLE II  
COMPUTATION TIME

	Object in Fig.9	PET bottle	Cup	Ornament
Oriented points	4201	7587	6850	11774
Voxels	179	193	198	261
time[s]	0.71	0.81	0.72	0.99

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