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Robotic Grasp/Motion Planning for Efficient Packing Assuming Multiple Grippers

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Abstract

It is challenging for a robot to densely pack various types of objects into a box because the packing posture of an object depends on the grasp configuration of the gripper. In this study, assuming multiple grippers, we propose a method for automatically planning the motion of a robot that packs objects into a box, considering whether the grippers can grasp the objects and pack them in a box. The proposed method first determines the appropriate gripper candidates for grasping each object. The initial solution is then generated by arranging the objects in random order and placing them in the available space in order, considering the gripper for each object. To increase the filling rate of each container and reduce the final number of required containers, the system repeatedly exchanges and replaces the objects in each container. Finally, the grasping and placement postures using the appropriate gripper are obtained for each object position, based on which the packing motion is planned. Through simulation and experiments, we determine the container and the position where the object is to be inserted, and confirm that the object can be placed in a suboptimal position by planning the grasping motion of the robot without collision using a gripper that can grasp the object.

Keywords: 3D Bin Packing Problem; Grasp/Motion Planning; Gripper; Robot

Introduction

In recent years, attempts have been made to automate logistics processes using industrial robots. Among such processes, this study focuses on the packing of goods into containers, which is one of the most popular warehouse operations. In the packing process, it is often necessary to minimize the number of containers required to pack all the objects efficiently. However, because it is difficult to plan the motion of a robot to densely pack objects into a container, complete automation of the packing process has not yet been achieved.

Thus far, the robotic packing problem has been solved without considering the gripper used for grasping an object [1] or by assuming only a two-fingered gripper[2]. However, without sufficient types of grippers, a robot may not be able to realize the determined object packing configuration. This is because daily goods have various shapes, and even though a robotic gripper can stably grasp one object, the same gripper may not be able to grasp another type of object. Moreover, the same problem is encountered when a robot places an object in a container. Even if a

robotic gripper can stably place one of the objects into a container, it may not be able to place another object because a finger may collide with the surroundings. To solve such problems, we apply a motion planning approach to the object packing problem assuming multiple grippers. In the proposed method, we first assume that there is a suitable gripper for grasping each object. The objects are then arranged in random order, and the deepest-bottom-left(DBL) method[3] is used to determine the positions of all the objects in the available space, considering the grippers grasping each object. Further, the objects in each container are repeatedly exchanged and relocated to increase the boxing density and reduce the number of required containers. Finally, the grasping posture and placement posture of each object are obtained with the appropriate gripper, and grasping motion is planned based on each posture. Through simulation and experiment, it is confirmed that each object can be placed in the placement position by determining the container and the position where the object is inserted, and by planning the grasping motion of the robot without collision, using a gripper that can grasp the object.

The remainder of this paper is organized as follows. We introduce the related work on robotic packing planning using various methods, and adopt the best

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Figure 1 Overview of the Robotic Packing Problem

method for handling a wide variety of objects. Further, we describe the selection of the appropriate gripper for an object, the packing plan, the grasping motion plan, and the proposed method in which they are applied. We then present the conducted experiment and the results using the proposed method, and compare it with other methods. Finally, we discuss the conclusions and future work.

Related Works

We distinguish between two types of packing problems: online packing in which the once-determined position of objects cannot be changed and offline packing in which the once-determined position objects can be changed, and compare them with the method proposed in this study.

Online packing involves the sorting of all the objects based on various rules and determining the position of each object in the box in the sorted order. Once the position is determined, it cannot be changed. This packing problem is NP-hard[4] and approximate solutions are commonly used.

Y. Tanaka et al.[3] used the DBL method, which is an extension of the BL method to three dimensions, to solve the three-dimensional bin packing problem for objects sorted by volume with a computational complexity of $O(N^3 \log N)$. R. Verma et al.[5] developed a method for rapidly determining the position of each object through reinforcement learning. H. Zhao et al.[6] applied a method that uses deep learning to ensure that the object to be placed as well as the next object are always in a position where it is easy to place. Wang and K. Hauser [2] used the DBL method and other methods for packing problems with robots to achieve packing considering the stability of each object.

However, although the computational load of online packing is relatively low, the density of the container

is also low, and the solution varies considerably depending on the placement order. Therefore, it is not practical, and the packing ratio must be improved.

On the other hand, offline packing is a method of finding the optimal packing configuration offline. In contrast to online packing, the offline packing method incrementally improves the solution by changing the object position. Y. Tanaka et al.[7] converted the packing problem into a linear programming problem and applied the greedy method after relaxing the constraints to obtain the optimal solution. Stakic et al.[8] used the greedy randomized adaptive search procedure (GRASP) to find the optimal solution for several types of objects. Hifi et al. [9] adapted two-dimensional cutting problems and employed a day-climbing strategy achieving good results in terms of the computation time and solution quality. N. Kobatake et al.[10] reduced the computation time of a computationally expensive three-dimensional packing problem by representing the positions of all the objects in a three-dimensional slice tree. A. Mikkil et al.[11] constructed a linear program from the object- type and position information to determine the positions of all the objects in order to pack as many complex figures as possible into a container. To solve the one-dimensional bin packing problem, T. Yakawa et al. [1] sorted the objects by length and inserted them into bins in order. Subsequently, they used the genetic algorithm to reduce the number of required bins by increasing the density of each bin as much as possible. Y. Wu et al.[12] used the genetic algorithm to solve a three-dimensional bin-packing problem, considering the orientation of each object to determine the position of each container. Wang and K. Hauser [13] proposed a method for inserting irregular three-dimensional objects into containers, independent of the arrival order. A. Yasuda et al.[14] applied the particle swarm optimization method to determine the position of each object offline and used a robot to perform the packing, while V. Chekanin[15] and R. Sridhar[16] showed

that the genetic algorithm, which guarantees the speed and packing rate to a certain extent, is optimal for the packing problem.

However, only a few conventional packing methods consider the grasping posture of an object. When the density is increased, there is a high possibility of collision between a finger and the container or other objects. Moreover, a packing algorithm that considers the exchange among multiple grippers has not yet been presented. In this study, we propose an algorithm that imitates the genetic algorithm by considering the grippers that grasp each object in advance and combine this algorithm with grasp/motion planning.

Proposed method

In this section, we describe the proposed motion-planning method for bin packing. We first define the problem and outline the proposed method. We then present a simple method for determining the gripper for grasping each object, and then describe a method for generating the initial solution for the bin packing problem considering the grippers, using the DBL method [3]. Further, we explain a method for determining the object placement position, considering the gripper for an object. Finally, to realize the determined placement position using a robot, grasp/motion planning is performed.

Problem statement and overview of the proposed method

In this study, we consider the problem of arranging objects, placed randomly on a table, in a container, while minimizing the number of required containers. In the proposed method, we consider the gripper for each object, as shown in Figure 1. The three-dimensional-shape model of the object is assumed to be known. The grasping posture of an object grasped by a gripper and the orientation of the object placed in the container are

(a) Suction gripper (b) Two-fingered gripper

Figure 3 Grippers used in this study

calculated in advance for executing the packing planner. The outline of the proposed method is shown in Fig 2. First, given the length, width, and height of each object, we select the gripper to be used for the object and generate an initial solution considering the gripper. The planner then repeatedly repositions the objects in the container, exchanges objects between containers, and determines the position of each object offline. Next, the objects are sorted in the order of placement using the grasp/motion planner. The grasping and placement postures are determined for each object in the sorted order considering the inverse kinematics (IK) and collisions with the other objects. This is performed online for all the objects, and the objects are packed into containers.

Selection of a gripper

As shown in Fig 3, we select an appropriate gripper from two-fingered gripper and suction gripper.

As shown in Fig 3, between the two-fingered gripper and suction gripper, we select the appropriate gripper for each object. As the suction gripper picks up the object from the top, it is less likely to collide with other objects or containers. On the other hand, the

two-fingered gripper has a high possibility of collision with other objects or containers when opening and closing the hand; however, it can grasp a wide variety of objects. Therefore, it is possible to increase the success rate of packing motion planning by selecting an appropriate gripper for each object.

The method for calculating the grasping posture using the suction gripper is as follows. We divide the surface of the object-shape model into regions that can be approximated by a plane. Then, as shown in Fig 4(a), we select a plane with a certain area and a normal direction pointing vertically upward, and determine the gripping posture of the gripper to hold this surface. The method for determining the grasping posture of the two-fingered gripper is as follows. We divide the surface of the object model into regions that can be approximated by a plane and select two regions whose normals are opposite to each other, as shown in Figure 4(b). The grasping posture of the two-fingered gripper is determined such that each finger contacts with one of the planes.

Placement position

Figure 5 presents an overview of the algorithm for determining the placement position in a container.

To establish the initial placement position of each object in a container, we use the DBL method[3], which is a method for solving the cramming problem for a rectangular object, to cram the object into a container. Next, we relocate the objects in a container with probability p , and exchange objects between containers with probability $1 - p$. This operation is repeated N times to determine the number of containers needed to place the objects and the positions of the objects in these containers. The method is detailed as follows:

Initial solution generation

Figure 7 depicts an overview of the algorithm for generating the initial solution. As shown in Figure 6(a),

a reference coordinate system is defined at the bottom of the container. We first determine the gripper used for each object. We then randomly establish the insertion order of the objects and place the first object at placement point $point(x, y, z) = (0, 0, 0)$ according to the generated order. Next, as indicated by the black dots in Figure 6(b), we define a set of candidates $cand(x, y, z)$ for the next placement position. Here, from the generated candidates, we exclude the points in which placement is not possible, and set the position shown in Figure 6(c) as the next candidate $cand(x, y, z)$. We further find the set of candidates $cand2(x, y, z)$ with the smallest z among the current candidates $cand(x, y, z)$, for the two subsequent objects. Similarly, we find $cand3(x, y, z)$, which is the set of candidates with the smallest y among the current candidates $cand2(x, y, z)$. Finally, we find the point with the smallest x among the current candidates $cand3(x, y, z)$, and determine the placement point $point(x, y, z)$. However, when using a two-fingered gripper, we consider the possibility of collision of the gripper with the surroundings. We exclude the candidate placement position that can cause collision with the surroundings. When using a suction gripper, such collisions need not be considered; therefore, insertion can be performed without restrictions. The objects are placed in order. However, if the objects cannot be placed in the available space because of collisions with the container or with other objects, they are inserted into the next container.

Exchange of objects between containers

To increase the density of each container, we exchange objects between containers in the initial solution generated using the DBL method. Let C_i and C_j be containers with large and small densities, respectively. The adopted algorithm is as follows:

Step1. Select two containers randomly.

Step2. Sort the objects in C_j in the order of their volume, and set $O_k^j (k=1, 2, \dots)$, $k=1$, in the increasing order of the volume.

Step3. To check whether O_k^j can be inserted into C_i , perform a raster scan of C_i to find the placement position where O_k^j can be placed. If it is possible to obtain the placement position, proceed to Step 4. If not, set $k \leftarrow k + 1$ and repeat Step 3. If it is impossible to place all the objects in C_j , go to Step 5.

Step4. Insert the object O_k^j into C_i and complete the exchange of objects.

Step5. Find object O_{min}^i with the least volume in C_i . find all the objects in C_j whose volume is greater than O_{min}^i , and sort them in the order of volume, in order to set $O_k^j (k=1, 2, \dots)$, $k=1$.

(a) Grasp planning for the suction gripper

(b) Grasp planning for the two-fingered gripper

Figure 4 Overview of the proposed grasp planner

Figure 5 Diagram of the packing algorithm

Figure 6 State transition using the DBL algorithm

Step6. Find the position where O_{min}^i can be placed in C_j without O_k^j using the raster operation, and if possible, find the position where O_k^j can be placed in C_i without O_{min}^i using the raster operation. If it is possible to find the position, proceed to Step 7. If not, repeat Step 6 with $k \leftarrow k + 1$. If it is impossible to establish the positions of all the objects O_k^j , terminate the exchange.

Step7. Insert O_k^j into C_i at the position determined by the user, and insert O_{min}^i into C_j to complete the exchange.

Figures 8 and 9 depict an overview of the proposed method. Exchange between containers is performed because increasing the density within a container eventually reduces the number of required containers.

Object Relocation within a container

To further increase the density of each container, we relocate objects in the container using the following steps.

Step1. Select one container at random, sort the objects in the container by volume, and let $O_k (k=1,2,...)$ be the order of increasing volume.

Step2. Relocate the objects in the container in volume-order using the DBL method considering the grippers, which is the same method used to generate the initial solution.

Step3. If relocation succeeds for all the objects, the process is terminated; if not, the position before relocation is maintained.

Figure 10 depicts the flow of the relocation method.

After execution, we output the seven-dimensional vector for each object composed of the number of inserted containers, the object position in the container, and its size (length, width, and height).

Placement order

The objects with seven-dimensional vectors are not necessarily sorted in the order of placement. Therefore, for each object's seven-dimensional vector, we find a

Figure 7 Algorithm for initial solution creation

Figure 8 Exchange of objects using the proposed algorithm1

set of candidates $point2(x, y, z)$ with the smallest container number and the smallest z among the placement positions $point(x, y, z)$. We then find a set of candidates $point3(x, y, z)$ with the smallest y among the current candidates $point2(x, y, z)$. Finally, we find the candidate point $pointsort(x, y, z)$ with the smallest x among the current candidates $point3(x, y, z)$. Further, $pointsort(x, y, z)$ is iteratively determined in order. After obtaining the placement order, grasp/motion planning is performed, and the objects are placed in the container. If grasp/motion planning fails, we solve the problem again using the described method and execute grasp/motion planning for objects other than those inserted in the containers after packing.

Grasp/Motion Planning

To realize the placement order using a robot, we execute grasp/motion planning where the grasping pose of an object and the object motion are simultaneously planned. Grasp/motion planning is based on our previous research[17]. In offline grasp planning, the can-

didates for a stable grasping posture and stable placement posture of an object are determined in advance [18, 19]. To select the gripper, we cluster the three-dimensional shape model of the object into a set of planar areas. When calculating the placement posture, we check the gravitational equilibrium of the object.

The outline of grasp/motion planning for realizing the pick-and-place motion of a robot is shown in Figure 11. We first assume a grasping posture and an object placement posture that places the object at the desired position and generate a series of key poses through which the robot moves the object from the initial to target posture. At each key pose, we check the inverse kinematics (IK) and collision of the robot. If the IK is solved and there is no collision, trajectory planning is performed between every two key poses. If the IK is unsolvable or collision occurs, the process is repeated assuming the next grasping and placement posture.

Experiments

Experimental environment

Figure 9 Exchange of objects using the proposed algorithm2

Figure 10 Overview of Object Relocation

Table 1 Object information

Object	quantity	size
Plastic bottle	5	$0.07 \times 0.07 \times 0.1(\text{m})$
Box L	5	$0.06 \times 0.06 \times 0.06(\text{m})$
Box M	5	$0.05 \times 0.05 \times 0.05(\text{m})$
Box S	5	$0.04 \times 0.04 \times 0.04(\text{m})$
container		$0.22 \times 0.29 \times 0.1(\text{m})$

In order to verify the proposed method, we simulated the method on software platform graspPlugin for Choreonoid[20] and conducted an experiment using a dual-arm industrial robot, Nextage. A suction gripper was attached to the right-hand of the robot and a two-fingered gripper was attached to the left. The proposed method was employed for packing PET bottles and large-(BoxL), medium-(BoxM), and small(BoxS)-sized boxes. The object and container details are depicted in Table 1. We set $pandN$ to $p = 1/3$ and $N = 1000$, respectively, as defined in our proposed method.

Results

The proposed method was used for obtaining the packing solution. As the initial solution, we repeatedly inserted the objects in the following order: PET bottles, BoxL, BoxM, and BoxS. Five containers were required according to the initial solution, and the number of inserted objects was five containers in which four objects (PET bottle, BoxL, BoxM, and BoxS) were inserted. After relocation and exchange, two containers were required, and the position of the objects to be inserted into each container was determined. Figure 13 shows the results after exchange and relocation.

Using the proposed method, we inserted randomly-placed objects into containers. After filling container-1 with the objects to be packed, the container was removed once, and other objects were added at that time. Figure 12 shows the progress of the experiment from initial state-1. In initial state 1, the objects were inserted in the following order: PET bottle → box L → box L → PET bottle → PET bottle → box L → box L → box L → PET bottle → box M → box M. The course of the experiment from initial state-2 is shown in Figure 14. In initial state-2, the objects were inserted in the following order: PET bottle → box M → box M → box M → box S → box S → box S → box S → box S. The experimental results are presented in Fig. 15.

Discussion

In Fig. 15, the objects are not packed tightly because gaps are created considering the insertion width of the gripper.

To demonstrate the effectiveness of our method, we compared it with the conventional packing method

Figure 12 Experiment on container-1 **Figure 13** Result of exchange and relocation

grasp/motion planning. As the gripper used for each object was not considered in this method, collisions with other objects occurred during grasp/motion planning. The proposed method succeeded in planning the grasp/motion for all the objects, as shown in Figures 12 and 14. Even if grasp/motion planning fails once, the total execution time increases considerably because it is necessary to redetermine the position of the object and execute it again. This demonstrates the advantage of the proposed method.

Moreover, we analyzed the values of p, n used in the packing algorithm. For the same experimental environment, we calculated the value of n up to convergence for various values of p . If the state of all the containers was the same for 300 consecutive times, convergence was considered to have occurred. One hundred runs were performed to obtain the average convergence

that applies the genetic algorithm [21] without considering the gripper. Using the placement position generated by the genetic algorithm, we performed

Figure 14 Experiment on container-2

(a) container-1

(b) container-2

Figure 15 Packing result

Figure 16 Analysis of p, n

value. The experimental results are shown in Figure 16. Convergence is fastest when $p = 0.20$. Thus, it is optimal to execute relocation and exchange at a 1:4 ratio.

Conclusion and Future works

In this study, we proposed a method for packing-motion planning that considers the selection of an appropriate gripper for grasping an object. Unlike conventional methods, the proposed method could determine suitable object placement, considering the appropriate gripper. In addition, we analyzed the optimal values of the probability of relocation and replacement and the number of trials, and succeeded in improving the speed of the packing algorithm.

However, the initial solution generated by the proposed method often varies depending on the insertion

order of the objects. Moreover, gaps as wide as the width of the gripper exist between the arranged objects in a container. In future, to achieve gap-free placement, we intend to minimize the number of containers required for various insertion orders, and incorporate robotic manipulation of objects in our method to achieve dense packing.

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Authors' contributions

Mr. Kazuki Iwao developed the theory and performed the simulation and experiment. Prof. Keisuke Koyama provided advice on performing the experiment. Prof. Weiwei Wan developed the grasp/motion planner and advised the first author. Prof. Kensuke Harada suggested that the first author could work on the packing problem considering multiple grippers and provided advice. ...

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