Tool Exchangeable Grasp/Assembly Planner

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Abstract. This paper proposes a novel assembly planner for a manipulator which can simultaneously plan assembly sequence, robot motion, grasping configuration, and exchange of grippers. Our assembly planner assumes multiple grippers and can automatically selects a feasible one to assemble a part. For a given AND/OR graph of an assembly task, we consider generating the assembly graph from which assembly motion of a robot can be planned. The edges of the assembly graph are composed of three kinds of paths, i.e., transfer/assembly paths, transit paths and tool exchange paths. In this paper, we first explain the proposed method for planning assembly motion sequence including the function of gripper exchange. Finally, the effectiveness of the proposed method is confirmed through some numerical examples and a physical experiment.

1 INTRODUCTION

In factory environments, industrial robots are expected to assemble a product. During a robotic assembly process, robotic grippers have to firmly grasp a variety of parts with a variety of physical parameters such as shape, weight and friction coefficient. However, even if we design a gripper to firmly grasp a part, it is not always possible for the same gripper to firmly grasp the other parts with different physical parameters. To cope with this problem, a robotic manipulator used to assemble a product usually equips a tool exchanger at the wrist. By using a tool exchanger, we can selectively use a gripper from multiple candidates. As shown in Fig. 1, we prepared two parallel grippers with different sized fingers. To assemble a toy airplane, a robot first grasps the body and places it on a table. Then, a robot grasps the wing and assembles it to the body. In this example, it is difficult for a robotic gripper to firmly grasp the wing by using the gripper used to grasp the body. Selection of a gripper is often more difficult and complex than this example since a robot has to select a suitable gripper from a set of two-fingered parallel jaw grippers, three-fingered grippers and suction grippers. So far, a gripper use to assemble a part has been selected based on the experience of human workers. On the other hand, this paper aims to construct a grasp/assembly planner which can automatically determine a gripper suitable for a given assembly task.

The robotic assembly is a classical topic of robotics extensively researched by many researchers such as [1–6]. However, in most of the previous researches on

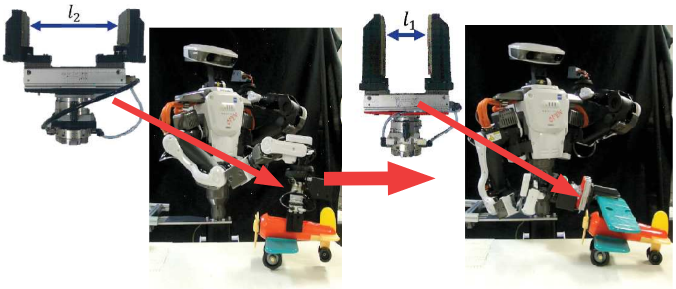


Fig. 1. Industrial robots with a tool changer where a gripper was selected depending on each task

assembly planners [3–5], grasping posture of a part was assumed to be known. While some researchers such as [9–12] have proposed manipulation planners combined with grasp planners, it is relatively recently where assembly planners combined with grasp planners have proposed [6–8]. Hereafter, we call such assembly planner as the grasp/assembly planner. However, in spite of the fact that the tool exchanging capability is needed for actual assembly tasks, there has been no research on grasp/assembly planner taking the tool exchanging capability into consideration. We believe that this is the first trial on adding a function of automatically selecting a gripper to a grasp/assembly planner. In our previous research, we have proposed a dynamic regrasp graph [8,12] for solving a grasp/manipulation and grasp/assembly planning problems. On the other hand, this research newly assumes multiple grippers for the grasp/assembly planner proposed so far [8]. We show that, by using our proposed grasp/assembly planner, it becomes possible for automatically selecting a gripper from multiple candidates to assemble a part.

The rest of the paper is organized as follows. After discussing previous works in Section 2, we show the definitions used in this research in Section 3. Section 4 formulates our proposed grasp/assembly planner. In Section 5, we confirm the effectiveness of our proposed method through a few numerical examples and a physical experiment where we assume two two-fingered grippers with different size. We show that, according to the shape and the size of a assembled part, our proposed planner can automatically select a feasible one and can complete an assembly task.

2 Definitions

Let us consider a product composed of m parts $P = (P_1, \cdots, P_m)$ as shown in Fig. 2. Let $A = (A_1, \cdots, A_n)$ be the assembly of parts as shown in Fig. 3 where $n \leq \sum_{i=1}^{m} C_i^m$. For example, if the assembly A_i is composed of the parts P_u, P_v and P_w, it is defined as

$$A_i = \{(P_u, P_v, P_w), ({}^u\boldsymbol{T}_v, {}^u\boldsymbol{T}_w), ({}^u\boldsymbol{a}_v, {}^u\boldsymbol{a}_w)\} \tag{1}$$

where ${}^{u}\boldsymbol{T}_v$ denotes a 4×4 homogenous matrix expressing the pose of the part P_v relative to the part P_u, and ${}^{u}\boldsymbol{a}_v$ denotes a 3 dimensional unit vector expressing the approach direction of the part P_v relative to the part P_u. On the other hand, if the assembly A_i is composed only of the part P_i, it can be defined as follows:

$$A_i = \{(P_i), (), ()\}, \ i = 1, \cdots, m \tag{2}$$

A product assembly is composed of a sequence of individual assembly tasks. Possible assembly sequences can be expressed by using the AND/OR graph $G(A, E)$ [1] where it is composed of the assembly of parts A as the vertices and the edges E connecting them. An example of the AND/OR graph is shown in Fig. 3. Assembly sequence can be generated by searching for this graph.

Let us consider a case where a robot performs a sequence of assembly tasks on a horizontally flat table. Let us consider discretizing the horizontal area of the table. We impose the following assumptions:

A1: A robot assembles a product by using a single arm.
A2: A robot performs an assembly task by once placing an assembly of parts at one of the grid points hereafter called the assembly point.

Under these assumptions, a robotic gripper picks up an assembly of parts from the table and fit it to another assembly of parts placed at the assembly point.

According to the assumption **A1**, we further impose the following assumption:

A3: After finishing an individual assembly task, the assembly of parts is once moved to one of the grid points included in the escape area.

Let us consider preparing h multi-fingered grippers as $H = (H_1, \cdots, H_h)$. In this research, we consider using a grasp planner such as [13, 14] to calculate a grasping posture of a part. We can use any multi-fingered grippers as far as a grasping posture can be calculated. For each pair of a grasped object and a gripper, we consider preparing a database of stable grasping postures. When a robot tries to actually grasp an object, we consider searching for the database to find a stable grasping posture. Let $G_{ij} = (G_{ij1}, \cdots, G_{ijk})$ be a database of grasping postures of the part P_i grasped by the gripper H_j where each element is composed of the wrist's pose with respect to coordinate system fixed to the part P_i and joint angles of each finger.

We additionally impose the following two assumptions:

A4: The AND/OR graph is given in advance of planning the assembly motion of a robot.
A5: Once a part is assembled, the assembly of parts will not be broken.

As for the assumption **A4**, since there have been a number of researches on automatically generating the AND/OR graph such as [2, 3], we can follow their research if we want to automatically generate the AND/OR graph.

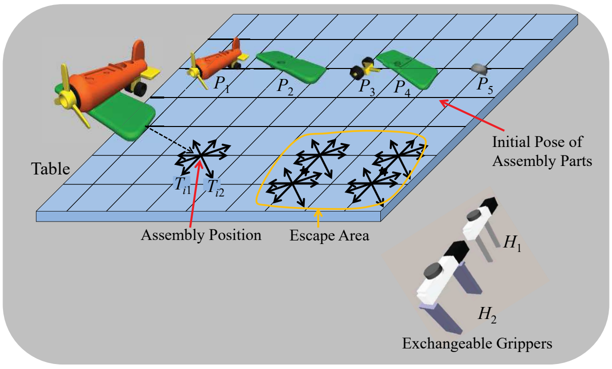


Fig. 2. Definition of working area performing product assembly

3 Assembly/Grasp Planner

This section details the grasp/assembly planner proposed in this research.

3.1 Placing Pose

To obtain a set of stable placing postures of the assembly A_i, we first calculate its convex hull. We consider drawing a line including the assembly A_i's CoG and perpendicular to one of the convex hull's facet. If this line passes through the facet,

Let T_{ik} be the homogenous matrix expressing the k-th pose of the assembly A_i stably placed on the table. To determine the homogenous matrix T_{ik}, we need the information on 1) the grid point at which the assembly A_i is placed, 2) the facet of the convex hull contacting the table, and 3) rotation of A_i about the table normal. According to these information, we consider multiple candidates of the assembly A_i's placing pose when planning the assembly motion of a robot.

3.2 Grasping Posture Set

Let us consider a situation where the assembly A_i is stably placed at one of the grid points. Let us also consider grasping the assembly A_i by using the gripper H_j. If the assembly A_i is composed of the parts $P_u, P_v, \cdots, P_w$, a set of grasping postures grasped by the gripper H_j are composed of the elements of the database $G_{uj}, G_{vj}, \cdots, G_{wj}$. For each grasping posture, we consider solving the IK and checking the collision between the robot and the environment. We can obtain a set of IK solvable and collision free database of grasping postures $\hat{G}_{ijk} = (\hat{G}_{ijk1}, \cdots, \hat{G}_{ijkl})$ of the assembly A_i grasped by the gripper H_j where the assembly A_i is stably placed at one of the grid points on the table.

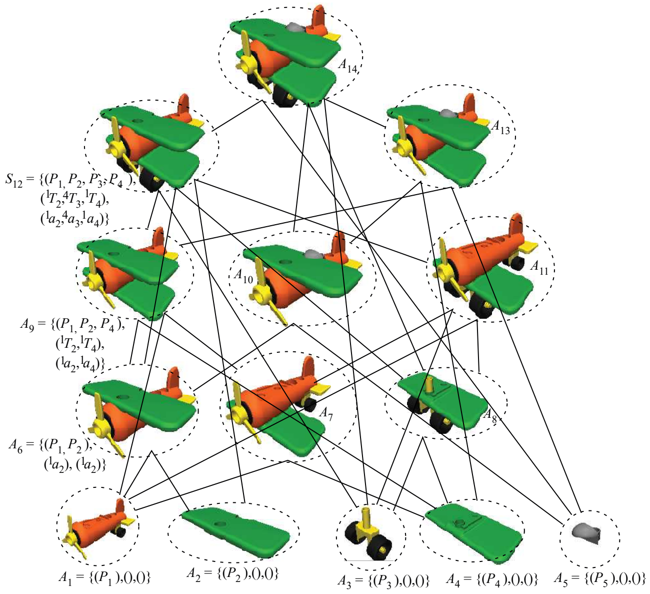

A_{14}
A_{13}
$S_{12} = \{(P_1, P_2, P_3, P_4), ({}^1T_2, {}^4T_3, {}^1T_4), ({}^1a_2, {}^4a_3, {}^1a_4)\}$
A_{10}
A_{11}
$A_9 = \{(P_1, P_2, P_4), ({}^1T_2, {}^1T_4), ({}^1a_2, {}^1a_4)\}$
A_7
A_8
$A_6 = \{(P_1, P_2), ({}^1a_2), ({}^1a_2)\}$
$A_1 = \{(P_1),(),()\}$
$A_2 = \{(P_2),(),()\}$
$A_3 = \{(P_3),(),()\}$
$A_4 = \{(P_4),(),()\}$
$A_5 = \{(P_5),(),()\}$

Fig. 3. A part of AND/OR graph of a toy airplane

3.3 Assembly Graph Search

To plan the motion of a robot to assemble a product, we first search for the AND/OR graph. Then, by using the solution path of the AND/OR graph, we consider constructing the assembly graph where, by searching for the assembly graph, we can generate the motion of a robot to assemble a product. If we failed to find a path of the assembly graph, then we try to find another solution path of the AND/OR graph.

It would be easier for us to understand the structure of the assembly graph if we visualize it by drawing a circle for each $\hat{G}_{ijk}$ and plot the dots on the edge of the circle corresponding to $\hat{G}_{ijk1}, \cdots, \hat{G}_{ijkl}$ (Fig. 4).

By extending the transit/transfer paths which have been introduced in manipulation planners such as [9], we define the following three kinds of edges included in the assembly graph:

*Transit Path***:**
Connect two nodes having the same object placing pose and having the same gripper but having different grasping pose.

*Transfer/assembly Path***:**
Connect two nodes having the same gripper and having the same grasping pose but having different object placing pose.

*Tool Exchange Path***:**
Connect two nodes having different gripper.

This visualization method is outlined in the upper side of Fig. 4. The transit paths can be expressed as edges connecting two nodes included in the same circle. The transfer/assembly path can be expressed as edges connecting two nodes included in the different circle but having the same gripper. The tool exchange path can be expressed by edges connecting two nodes included in the different circle, and having different grippers.

Here, we consider the simplified assembly graph as shown in the lower side of Fig. 4. In this expression, each circle of the original manipulation graph is expressed as a single dot. Multiple transfer/assembly paths between two circles are merged into a single bold line. Multiple tool exchange paths between two circles are also merged into a single bold line. This simplified assembly graph does not explicitly include the transit paths.

Next, we consider constructing the assembly graph. Since we imposed the assumptions **A1**, **A2** and **A3**, we consider introducing the following four kinds of nodes included in the assembly graph:

Base Node:
An assembly of parts is placed at the assembly point.

Assembly Node:
An assembly of parts is fit to another assembly of parts placed at the assembly point.

Escape Node:
An assembly of parts is moved to one of the grid points included in the escape area.

Initial Node:
A part is placed at the initial position.

Here, for an assembly of parts placed at one of the grid points, we can assume multiple nodes of the assembly graph depending on the rotation of the assembly about the table normal, multiple grasping configurations of the assembly, and multiple grippers grasping the assembly of parts.

To construct the assembly graph from the AND/OR graph, the nodes of the AND/OR graph is replaced by a set of nodes of the assembly graph by the following rules:

- The root node of the AND/OR graph is replaced by a set of base and assembly nodes (Fig. 5) where one of the base nodes and one of the assembly nodes are connected by using the transfer/assembly path.
- The leaf nodes of the AND/OR graph are replaced by the initial and a set of the escape nodes where one of the initial nodes and one of the escape nodes are connected by using a transfer/assembly path and where the escape nodes are connected each other by using a transit and transfer paths.
- The nodes except for the root and the leaves are replaced by a set of base, assembly and escape nodes where one of the assembly nodes and one of the escape nodes are connected by using a transfer/assembly path, and where the escape nodes are connected each other by using a transit and transfer paths.

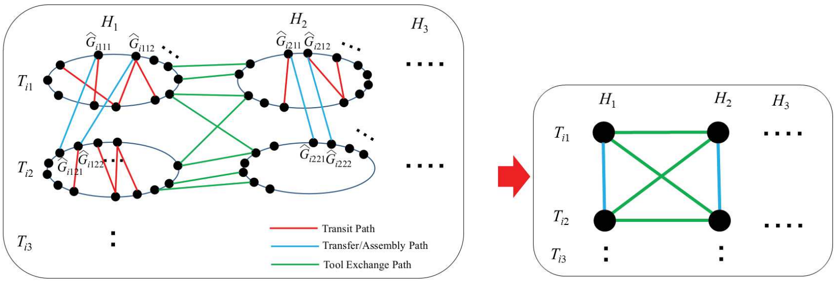
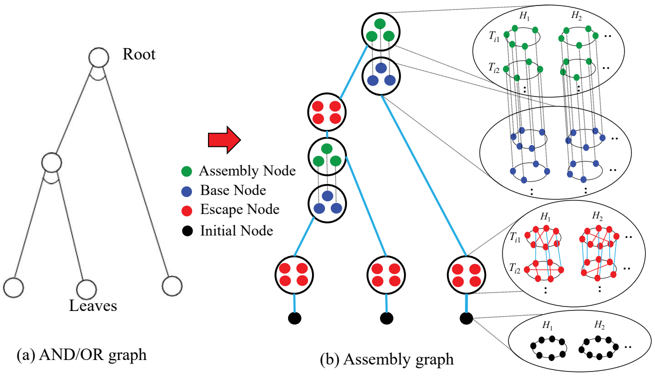


Fig. 4. Path definitions of assembly graph and its simplified expression



(a) AND/OR graph

(b) Assembly graph

Fig. 5. Transformation from AND/OR graph to assembly graph

Here, the assembly nodes are automatically determined by the corresponding base nodes since assembly of parts defined in an assembly node includes the assembly of parts defined in the base node (shown in the dotted line in Fig. 5).

Then, we show a method for searching the assembly graph. In our method, we first search for a solution path of the simplified assembly graph. There are multiple root nodes included in the simplified assembly graph. From each root node, we consider searching for a solution path of the simplified assembly graph by using Dikstra method. Then, we consider selecting a root node where the path cost becomes minimum.

For a solution path of the simplified assembly graph, we consider obtaining a sequence of assembly as will be explained in the next subsection.

For a sequence of assembly tasks, we consider determining the grasping configuration. We first disregard the transit path and try to find grasping configurations with maximum grasping stability index [16]. Our grasp stability index proposed in [16] evaluates the contact area and can be applied for the soft-finger contact model. Thus, the gripper having fingers with large contact area tends to be selected.

After obtaining a sequence of assembly, we check whether or not each edge included in the sequence is a feasible one by using the RRT (Rapidly-exploring Random Tree) algorithm. If RRT algorithm does not find a solution, we consider cutting the corresponding edge and try to find the grasping configuration again.

3.4 Assembly Sequence

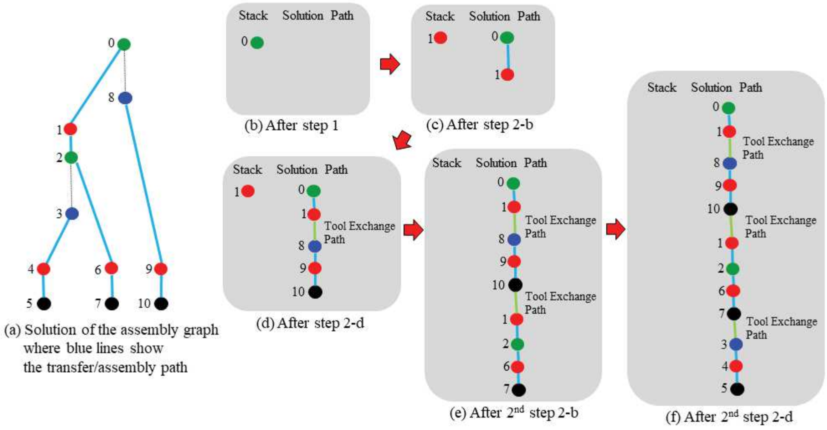
To perform an product assembly under the assumptions **A1**, **A2** and **A3**, an assembly of parts has to be first placed at the assembly point before it is fit to another assembly of parts. Let us consider the case where a robot assembles the assembly A_u to the assembly A_v. After a robot places the assembly A_u to the assembly point, a robot may first exchange the gripper, then picks the assembly A_v, and finally assembles it to the assembly A_u. However, the solution of the assembly graph obtained in the previous subsection does not include such information. In this subsection, we consider generating an assembly sequence taking the exchange of grippers into consideration. From the assembly graph constructed in the previous subsection, a sequence of assembly is generated by using the following method:

1. Push the root node of the assembly graph to the stack.
2. Iterate the following steps until the stack becomes empty
   (a) Pop the stacked nodes. Connect the path including an assembly node between the stacked node and either an initial or an escape node to the solution path by using the tool exchange path.
   (b) If the last node of the solution path is an escape node, push the escape node to the stack.
   (c) Connect the path between the corresponding base node and either an initial or an escape node to the solution path by using the tool exchange path.
   (d) If the last node of the solution path is an escape node, push the escape node to the stack.

Fig. 6 shows how the algorithm shown in the example of Fig. 5 works. As shown in this figure, the base node is scheduled before the assembly node and whole assembly sequence can be performed where an adequate gripper is selected according to the assembly of parts.

4 Results

In this section, we show some numerical examples to show the effectiveness of our proposed method. We prepared two two-fingered parallel grippers used to assemble a product. One of the grippers has relatively small contact area where it would be suitable for assembling a small object. On the other hand, the other gripper has relatively large contact area where it would be suitable for assembling a large object.



(a) Solution of the assembly graph where blue lines show the transfer/assembly path

(b) After step 1

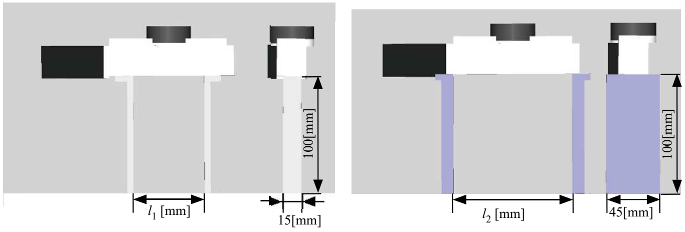
(c) After step 2-b

(d) After step 2-d

(e) After 2^{nd} step 2-b

(f) After 2^{nd} step 2-d

Fig. 6. Searching algorithm of assembly sequence



(a) Dimension of the gripper H_1

(b) Dimension of the gripper H_2

Fig. 7. Two fingered parallel grippers used in numerical examples

In the first example, the robot tries to assemble a product made of three blocks as shown in Fig. 8. In this example, the width l_1 and l_2 of the gripper shown in Fig. 7 is set as $0 \leq l_1 \leq 0.06$[m] and $0 \leq l_2 \leq 0.1$[m], respectively. The simplified assembly graph is shown in Fig.9 where the solution path is expressed by the red transfer paths and blue tool-exchange paths. We used a grasp planner proposed in [13] to calculate the grasping posture. The number of grasping posture included in the database is $\dim(G_{11}) = 347$, $\dim(G_{12}) = 443$, $\dim(G_{21}) = 1221$, $\dim(G_{22}) = 2162$, $\dim(G_{31}) = 12$, and $\dim(G_{32}) = 18$. Some examples of grasping postures are shown in Fig. 10. It took about 2 [min] to calculate the solution path by using the 3.4[GHz] Quad-core PC. Some examples of grasping posture are shown in Fig. 10. The motion of the robot is shown in Fig. 11 where the robot first used the hand H_2 to stably pick the part P_3. Then, the robot used the hand H_1 to pick the part P_1 and assembled it to the part P_3. Here, it is impossible to use the large hand H_2 to assemble P_1 to the concaved part of P_3. Finally, the robot used again the hand H_2 to assemble the part P_2.

In the second example, we consider the assembly of a toy airplane where its AND/OR graph is shown in Fig. 3. In this example, we consider the assembly

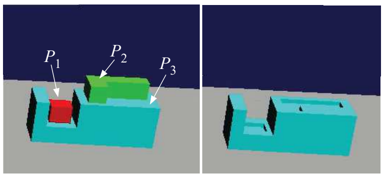


Fig. 8. Assembled product used in Example 1

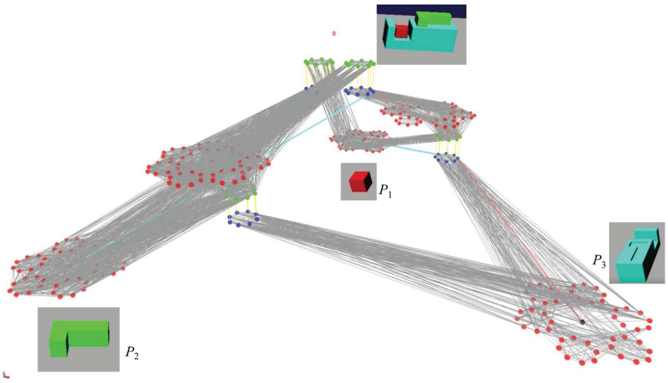


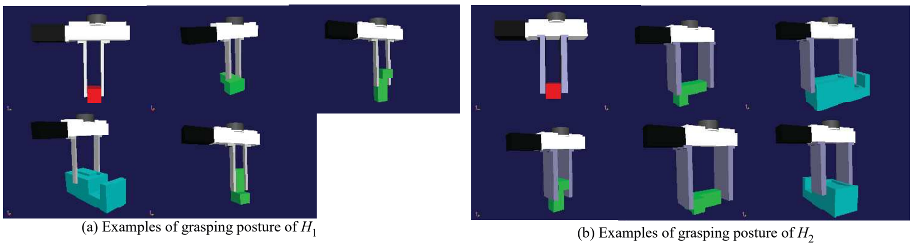
Fig. 9. Assembly graph generated in Example 1

problem of three parts: A_2, A_5 and A_{11}. The width l_1 and l_2 of the gripper shown in Fig. 7 is set as $0 \leq l_1 \leq 0.06$[m] and $0.4 \leq l_2 \leq 0.1$[m], respectively. In this example, the gripper H_1 is suitable for grasping a thin object while the gripper H_2 is suitable for grasping a thick one. The number of grasping posture included in the database is $\dim(G_{11}) = 49$, $\dim(G_{12}) = 58$, $\dim(G_{21}) = 4$, $\dim(G_{22}) = 24$, $\dim(G_{31}) = 0$, and $\dim(G_{32}) = 263$. Some examples of grasping postures are shown in Fig. 12. It took 28[sec] to plan the robot motion. The motion of the robot is shown in Fig. 13 where the robot first used the hand H_2 to stably pick the thick A_{11}. Then, the robot used the hand H_1 to pick the part A_2 and A_5. Since the same hand is used two individual assembly tasks sequentially connected, the robot does not exchange the gripper.

Finally, we performed experiment on the toy airplane assembly. In this experiment, we used two kinds of parallel jaw gripper as shown in Fig. 14 corresponding to the simulation result of toy airplane assembly. Fig. 15 shows experimental result where a robot stably grasps each parts and successfully conducted the assembly task.

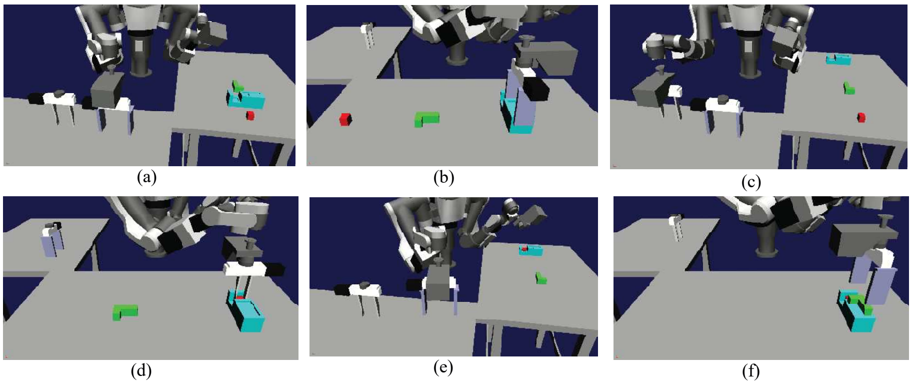
5 Conclusion

In this paper, we proposed a grasp/assembly planner for a manipulator which can simultaneously plan assembly sequence, robot motion, grasping configuration,


(a) Examples of grasping posture of H_1

(b) Examples of grasping posture of H_2

Fig. 10. Grasping posture used in Example 1


(a)

(b)

(c)

(d)

(e)

(f)

Fig. 11. Snapshot of assembly motion of Example 1

and exchange of grippers. For a given AND/OR graph of an assembly task, we generated the assembly graph where its edges are composed of three kinds of paths, i.e., the transfer/assembly path, the transit path and the tool exchange path. We showed numerical examples assuming two kinds of two-fingered parallel grippers where one of the grippers is suitable for grasping a small part and the other is suitable for grasping a large part.

For a future research, we consider conducting a real world experiment. Motion optimization is also considered to be our future research topic.

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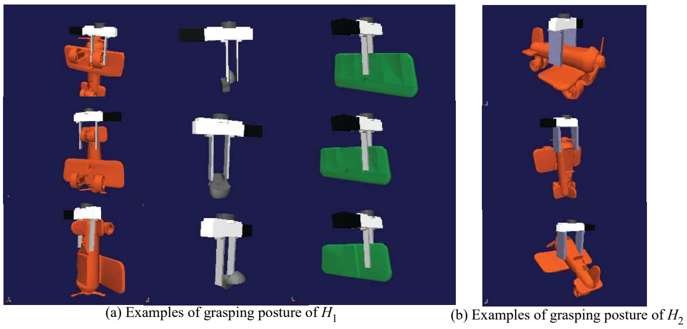
(a) Examples of grasping posture of H_1 (b) Examples of grasping posture of H_2

Fig. 12. Grasping posture used in Example 2

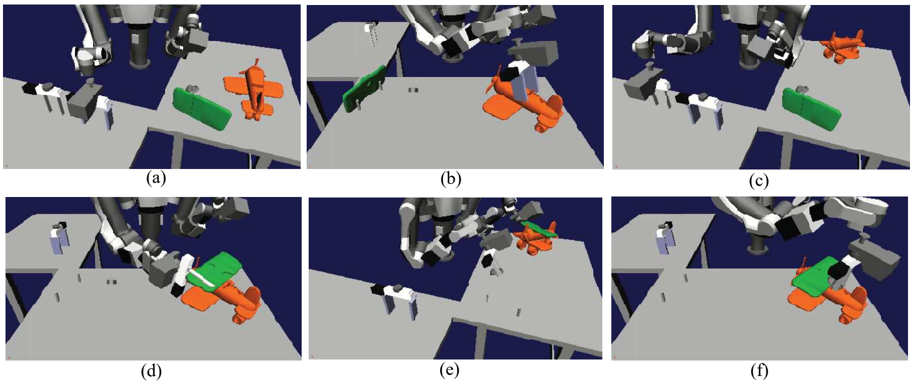
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Fig. 13. Snapshot of assembly motion of Example 2

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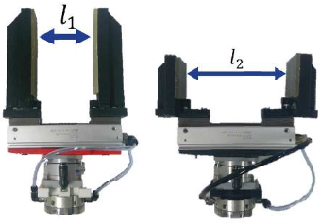
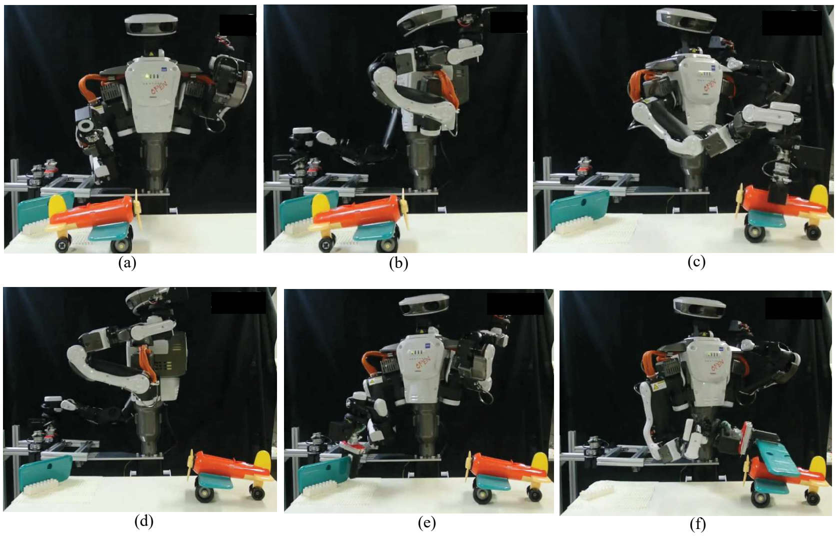


Fig. 14. Grippers used for experiment


(a) (b) (c)

(d) (e) (f)

Fig. 15. Snapshot of experiment

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