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Representation of Deformable Thin Object Manipulation Based on Contact State

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A qualitative representation method of thin object manipulation in the two dimensional space is proposed. Firstly, contact states of a thin object with environmental surfaces are represented qualitatively as 23 contact patterns and their combination. Secondly, state transitions among contact patterns are defined by introducing some simple rules. Then, possible contact state transitions can be generated when the initial state and the objective state are given. Thirdly, the state changeable region with which a manipulator may change the state by contacting is introduced. If this region does not exist on a thin object, the contact state transition can not be realized even if it can be generated. Finally, that our proposed method can be useful for the manipulation planning is demonstrated.

INTRODUCTION

The majority of manipulative tasks, including grasping and assembly, are performed through mechanical contact. As rigid object manipulation can be represented as the transition of contact states, planning methods for it using contact state graphs have been studied. Hirai et al. had analysed manipulation process of rigid objects. He represented it as a network whose nodes correspond to contact states and whose arcs correspond to state transitions[1]. This method was applied to the planning of manipulation or assembly[2]. However, systematic approach to the planning of deformable object manipulation has not been established yet. In this paper, we represent manipulation of a thin object, a kind of deformable objects, as finite contact states and their transitions, and apply this representation method to the manipulation planning.

Firstly, a qualitative representation of the contact state of a thin object with one environmental surface in two dimensional space is proposed. Secondly, state transitions among those patterns are defined by introducing some basic rules. Furthermore, it is verified that this representation method can be also applied when there are several environmental surfaces. By use of this method, the manipulation process can be represented as the sequence of contact state transitions. Thirdly, state changeable regions with which a manipulator may change the state by contacting is introduced for considering feasibility of manipulation. Finally, that our proposed method can be useful for the manipulation planning is demonstrated.

REPRESENTATION OF MANIPULATION PROCESS

Definition of Contact Pattern

Manipulation can be defined as to change position or direction of an object by contacting controllable objects like manipulators with it and imposing forces/moments on it. So, we can represent manipulation process as contact states of a manipulated object with other objects and their transition. However, it seems that contact states of deformable objects exist infinitely. Therefore, we propose a method in order to represent contact of thin objects in two dimensional space as finite states.

First, let us represent a thin object in two dimensional space as a set of two kinds of elements ; vertices V_i $(i = 0, \cdots, N)$ and edges E_j $(j = 1, \cdots, N)$. We assume that there is one environmental surface S_1 like a table in the space. It can be either flat or curved. Then, we consider how a thin object can contact with this surface S_1. First, we classify vertices in three types. The vertex which contacts with an environmental surface S_1 is type I vertex, and the vertex which does not contact with it is type II vertex. These two type vertices can be touched by another object like a manipulator. Type III vertex can not be touched even if it contacts with the environmental surface S_1 or not. Furthermore, we classify edges in four types. In case of type I edge, We can bring another object into contact with both the front side and the reverse side of it. The only front side of type II-1 edge can contact with another object because the other side contacts with a surface S_1, and the only reverse side of type II-2 edge can contact with it. Nothing can contact with type III edge. We assume that same type edges can be identified with one edge if they adjoin each other. Fig.1 shows an example of the contact state of a thin object. The real shape of the object is illustrated in fig.1(a). Fig.1(b) shows the result of above classification. Then, this result can be simplified as shown in fig.1(c). Finally, we represent this contact state of the object graphically as shown in fig.1(d).

By the above definition, we can classify the contact state of a thin object in 23 types as shown in fig.2. One endpoint of the object, which is represented as a vertex, is painted grey in order to distinguish the other. Let us call them contact pattern P_1 through P_{23}, respectively. Note that each pattern as shown in fig.2 does not represent the real shape of the object.

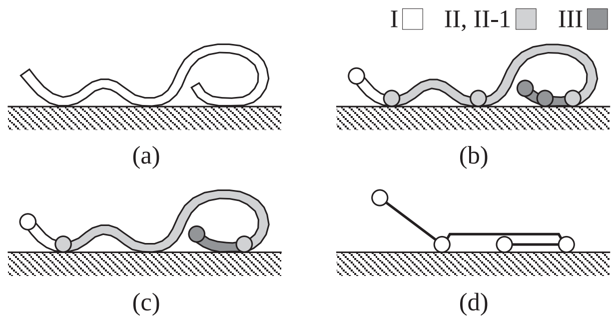

fig. 1 Example of contact state of thin object

Definition of Pattern Transition

Next, let us consider transition from one contact pattern to another. We assume that the pattern transition occurs when the type of one vertex changes, that is, when one vertex contacts or leaves. Then, not all contact patterns can change into any other patterns. We represent the possibility of the pattern transition as a matrix described in eq.(1). If $M^t_{mn} = 1$, We can change the state from contact pattern P_m to P_n. Let us call M^t the pattern transition matrix.

Contact Pattern with Respect to Multi-Surfaces

If there are some environmental surfaces, we can represent the contact state of a thin object as the combination of contact patterns with respect to each surface. Then, not all combination of patterns is possible. Now we assume that there are two environmental surfaces. Then, for example, a thin object which has contact pattern P_{22} with respect to surface S_1 can not have contact pattern P_2 with respect to surface S_2 as shown in fig.3. We can represent the possibility of the pattern combination as a matrix.

If the number of environmental surfaces is more than three, we identify two surfaces S_1 and S_2 with one surface S'_1 after determining the contact pattern with respect to each surface. Then, a new contact pattern with respect to surface S'_1 can be generated. Next, we consider the possibility of the combination of the contact

$$M^t = \begin{pmatrix}
0&1&1&0&0&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
1&0&0&1&1&0&0&0&0&1&1&1&1&0&0&0&0&0&0&0&0&0&0\\
1&0&0&1&1&0&0&1&1&0&0&0&0&1&1&0&0&0&0&0&0&0&0\\
0&1&1&0&0&0&0&1&0&1&0&1&0&1&0&0&0&0&0&0&0&0&0\\
0&1&1&0&0&0&0&0&1&0&1&0&1&0&1&0&0&0&0&0&0&0&0\\
1&0&0&0&0&0&0&1&0&1&0&0&1&0&1&1&0&1&1&1&1&0&1\\
1&0&0&0&0&0&0&0&1&0&1&1&0&1&0&0&1&1&1&1&1&1&0\\
0&0&1&1&0&1&0&0&0&0&0&0&1&1&0&1&0&1&1&0&0&0&1\\
0&0&1&0&1&0&1&0&0&0&0&1&0&0&1&0&1&1&1&0&0&1&0\\
0&1&0&1&0&1&0&0&0&0&0&1&0&0&1&1&0&0&0&1&1&0&1\\
0&1&0&0&1&0&1&0&0&0&0&0&1&1&0&0&1&0&0&1&1&1&0\\
0&1&0&1&0&0&1&0&1&1&0&0&0&0&0&0&1&1&1&0&0&1&0\\
0&1&0&0&1&1&0&1&0&0&1&0&0&0&0&1&0&1&1&0&0&0&1\\
0&0&1&1&0&0&1&1&0&0&1&0&0&0&0&0&1&0&0&1&1&1&0\\
0&0&1&0&1&1&0&0&1&1&0&0&0&0&0&1&0&0&0&1&1&0&1\\
0&0&0&0&0&1&0&1&0&1&0&0&1&0&1&0&0&1&1&1&1&0&1\\
0&0&0&0&0&0&1&0&1&0&1&1&0&1&0&0&0&1&1&1&1&1&0\\
0&0&0&0&0&1&1&1&1&0&0&1&1&0&0&1&1&0&1&0&0&1&1\\
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0&0&0&0&0&1&1&0&0&1&1&0&0&1&1&1&1&0&0&1&0&1&1\\
0&0&0&0&0&0&1&0&1&0&1&1&0&1&0&0&1&1&1&1&1&0&0\\
0&0&0&0&0&1&0&1&0&1&0&0&1&0&1&1&0&1&1&1&1&0&0
\end{pmatrix} \quad (1)$$

pattern with respect to surface S'_1 and that with respect to surface S_3. By the repeat of this operation, we can represent the contact state of a thin object even if there are some environmental surfaces. Now, we introduce a pattern combination matrix M^c described in eq.(2). M^c_{mn} represents the possibility of combination of pattern P_m and pattern P_n. If $M^c_{mn} = 0$, such a combination is impossible. Otherwise, it is possible and its number represents a new contact pattern when P_m and P_n are merged. Fig.4 shows an example of the contact state with four environmental surfaces. This state is represented as contact patterns P_8–P_{15}–P_6–P_{16}.

If environmental surfaces do not adjoin each other, we can also define another pattern combination matrix.

Pattern Transition with Respect to Multi-Surfaces

The pattern transition when there are some environmental surfaces is defined as to change only the contact pattern with respect to one environmental surface. By referring the pattern transition matrix M^t, we can know which pattern the current pattern with respect to one environmental surface can be changed into. If a new pattern can be combined with patterns with respect to any other environmental surfaces, such pattern transition is possible. For example, if the current state is illustrated in fig.5(a), which is represented as contact patterns P_{10}–P_3, it is found that this state can be changed to P_2–P_3, P_4–P_3, P_6–P_3, P_{16}–P_3, P_{20}–P_3, P_{21}–P_3, P_{10}–

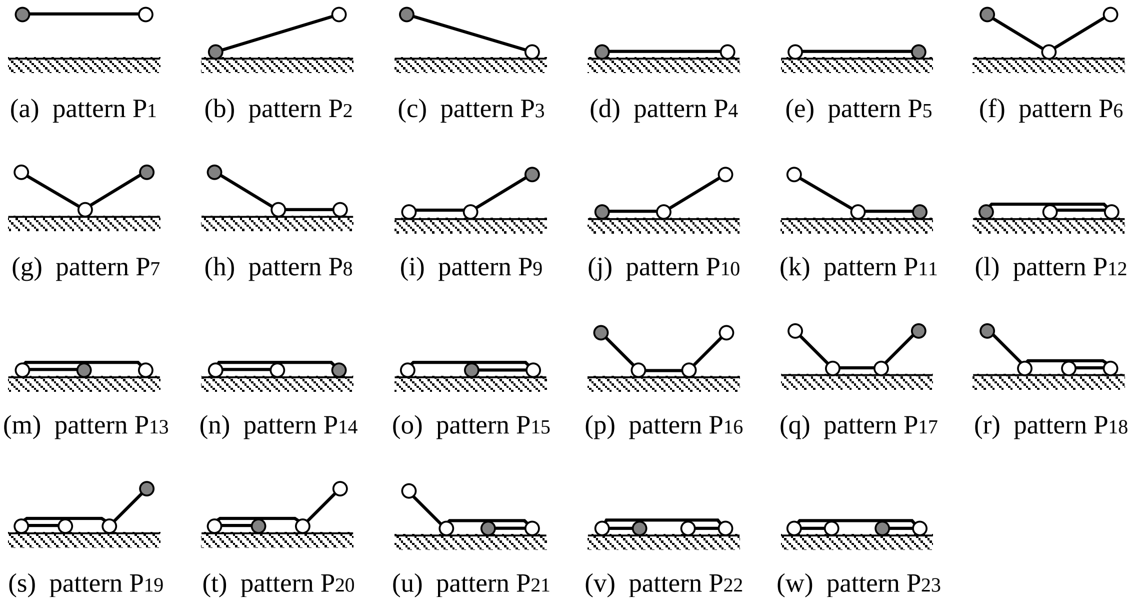

fig. 2 Contact patterns of thin object

$$M^c = \begin{pmatrix}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 & 18 & 19 & 20 & 21 & 22 & 23 \\
2 & 2 & 4 & 4 & 0 & 10 & 12 & 4 & 12 & 10 & 0 & 12 & 0 & 0 & 0 & 10 & 12 & 12 & 12 & 0 & 0 & 0 & 0 \\
3 & 5 & 3 & 0 & 5 & 15 & 9 & 0 & 9 & 15 & 5 & 0 & 0 & 0 & 15 & 15 & 9 & 0 & 0 & 15 & 15 & 0 & 0 \\
4 & 0 & 4 & 0 & 0 & 0 & 12 & 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 \\
5 & 5 & 0 & 0 & 0 & 15 & 0 & 0 & 0 & 15 & 0 & 0 & 0 & 0 & 0 & 15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
6 & 13 & 8 & 0 & 13 & 16 \text{ or } 23 & 18 \text{ or } 19 & 8 & 18 & 23 & 13 & 0 & 13 & 0 & 15 & 16 \text{ or } 23 & 18 \text{ or } 19 & 18 & 18 & 23 & 23 & 0 & 23 \\
7 & 11 & 14 & 14 & 0 & 20 \text{ or } 21 & 17 \text{ or } 22 & 14 & 22 & 20 & 11 & 22 & 0 & 14 & 0 & 20 \text{ or } 21 & 17 \text{ or } 22 & 22 & 22 & 21 & 21 & 22 & 0 \\
8 & 13 & 8 & 0 & 13 & 23 & 19 & 0 & 19 & 23 & 13 & 0 & 0 & 0 & 23 & 23 & 19 & 0 & 0 & 23 & 23 & 0 & 0 \\
9 & 5 & 0 & 0 & 0 & 15 & 9 & 0 & 0 & 15 & 5 & 0 & 0 & 0 & 0 & 15 & 9 & 0 & 0 & 15 & 15 & 0 & 0 \\
10 & 0 & 4 & 0 & 0 & 10 & 12 & 4 & 12 & 0 & 0 & 0 & 0 & 0 & 0 & 10 & 12 & 12 & 12 & 0 & 0 & 0 & 0 \\
11 & 11 & 14 & 14 & 0 & 20 & 22 & 14 & 22 & 21 & 0 & 22 & 0 & 0 & 0 & 20 & 22 & 22 & 22 & 0 & 0 & 0 & 0 \\
12 & 0 & 0 & 0 & 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 12 & 0 & 0 & 0 & 0 & 0 & 0 \\
13 & 13 & 0 & 0 & 0 & 23 & 0 & 0 & 0 & 23 & 0 & 0 & 0 & 0 & 0 & 22 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
14 & 0 & 14 & 0 & 0 & 0 & 22 & 0 & 22 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 22 & 0 & 0 & 0 & 0 & 0 & 0 \\
15 & 0 & 0 & 0 & 0 & 15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 15 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
16 & 13 & 8 & 0 & 13 & 16 \text{ or } 23 & 18 \text{ or } 19 & 8 & 18 & 23 & 13 & 0 & 13 & 0 & 23 & 16 \text{ or } 23 & 18 \text{ or } 19 & 18 & 18 & 23 & 23 & 0 & 23 \\
17 & 11 & 14 & 14 & 0 & 20 \text{ or } 21 & 17 \text{ or } 22 & 14 & 22 & 21 & 11 & 22 & 0 & 22 & 0 & 20 \text{ or } 21 & 17 \text{ or } 22 & 22 & 22 & 21 & 21 & 22 & 0 \\
18 & 13 & 0 & 0 & 0 & 23 & 19 & 0 & 0 & 23 & 13 & 0 & 0 & 0 & 0 & 23 & 19 & 0 & 0 & 23 & 23 & 0 & 0 \\
19 & 13 & 0 & 0 & 0 & 23 & 19 & 0 & 0 & 23 & 13 & 0 & 0 & 0 & 0 & 23 & 19 & 0 & 0 & 23 & 23 & 0 & 0 \\
20 & 0 & 14 & 0 & 0 & 20 & 22 & 14 & 22 & 0 & 0 & 0 & 0 & 0 & 0 & 20 & 22 & 22 & 22 & 0 & 0 & 0 & 0 \\
21 & 0 & 14 & 0 & 0 & 20 & 22 & 14 & 22 & 0 & 0 & 0 & 0 & 0 & 0 & 20 & 22 & 22 & 22 & 0 & 0 & 0 & 0 \\
22 & 0 & 0 & 0 & 0 & 0 & 22 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 22 & 0 & 0 & 0 & 0 & 0 & 0 \\
23 & 0 & 0 & 0 & 0 & 23 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 23 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix} \quad (2)$$

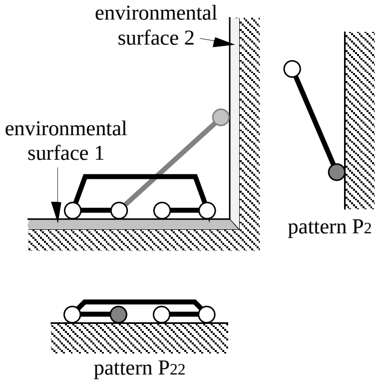

fig. 3 Example of no combinable contact patterns

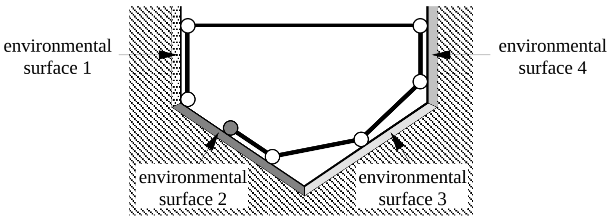

fig. 4 Contact pattern with respect to four environmental surfaces

P_1, P_{10}–P_8, and P_{10}–P_9 as shown in fig.5(b) through fig.5(j).

From the above discussion, we can represent the manipulation process of a thin object in two dimensional space as finite contact patterns and their transition.

Fig.6 shows an example of required operation. There are three environmental surfaces in this case. The initial state can be represented as contact patterns P_4–P_1–P_1 and the objective state can be represented as P_1–P_1–P_1. If it is assumed that the state must reach to the objective one within three state transitions, 10 state transition paths can be generated as shown in fig.7. Such paths can be also generated even if not only the initial and the objective state but also some intermediate states are given.

Next, let us consider the feasibility of manipulation processes represented as the sequence of state transitions.

FEASIBILITY CONSIDERATION OF MANIPULATION PROCESS

The contact state of a thin object can be changed when another objects like manipulators contacts with the object and imposes forces/moments on it at the contact region. We consider regions which a controllable object can change the contact state with respect to one environmental surface by contacting with. These

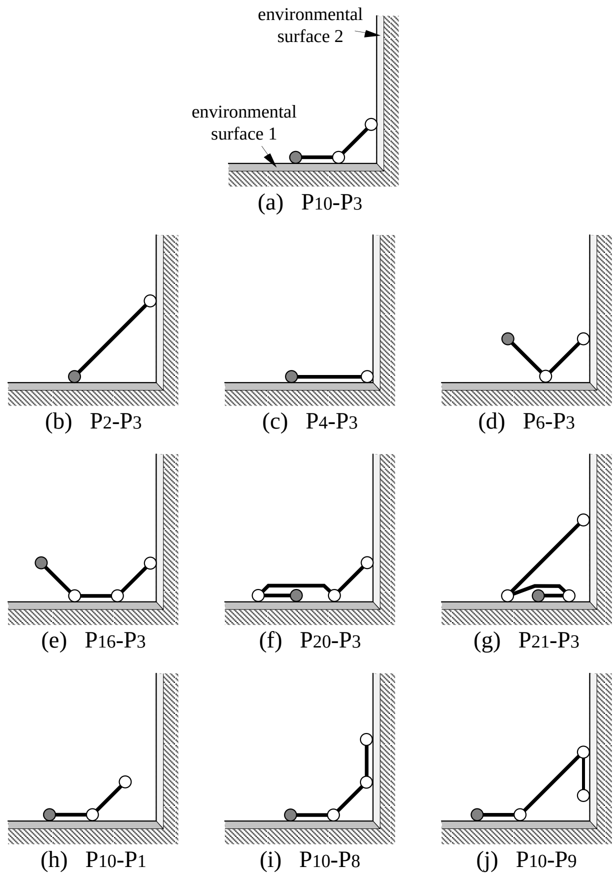

fig. 5 Pattern transition with respect to two environmental surfaces

regions are defined as the vertex V_i^c whose contact state changes through the state transition, the front/reverse side of edges E_j^a which adjoin the vertex V_i^c and which can be touched through the state transition, and Type I vertices V_i^a which adjoin edges E_j^a. Let us call them state changeable regions. If any state changeable regions do not exist on the object, such a state transition can not be realized. Fig.8 shows an example of the state transition. The grey region in fig.8(a) represents the state changeable region from contact pattern P_8 as shown in fig.8(a) to contact pattern P_3 as shown in fig.8(b). Note that the reverse side of edge E_2 is not selected for the state changeable region because it can not be touched by manipulators in the initial state.

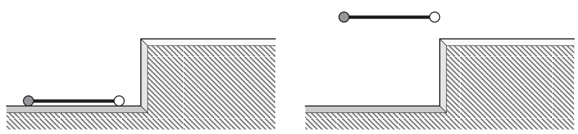

fig. 6 Example of required operation for state transition network generation

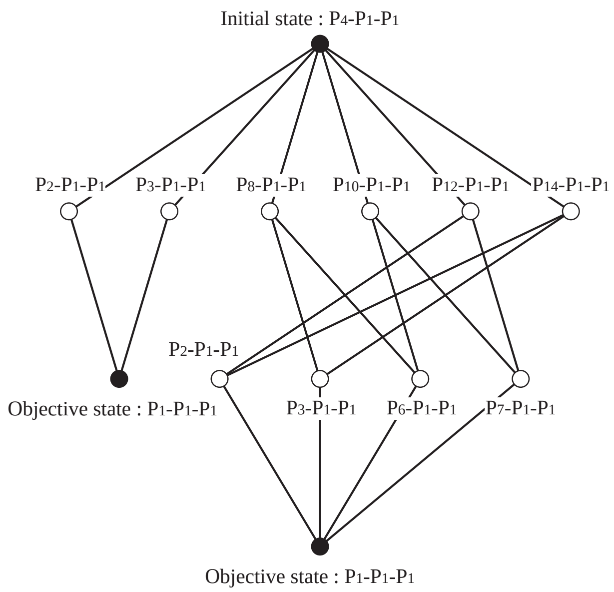

fig. 7 Result of state transition network generation

We can define it even if there are some environmental surfaces.

When one state transition path is selected from state transition network as shown in fig.7, its feasibility can be checked by considering whether state changeable regions exist or not in each state. The feasibility of manipulation should be more discussed, however, it seems that we can plan thin object manipulation roughly by consideration of state changeable regions.

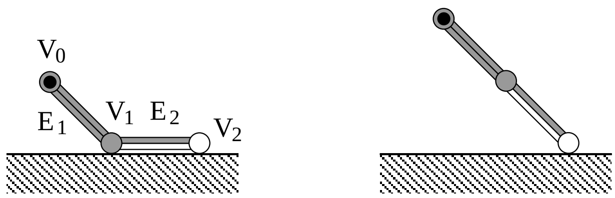

fig. 8 Example of state changeable region

CASE STUDY

In this section, we demonstrate the effectiveness of our developed manipulation process generation system using a qualitative representation method proposed in this paper. Fig.9 shows a required operation. There are three environmental surfaces. The initial state is represented as contact patterns P_4–P_1–P_1 and the objective state is represented as P_1–P_1–P_5. This operation means that a thin object on the lower floor is picked up, turned over, and put on the upper floor. We assume that the contact state must reach to the objective one within seven state transitions. Then, 15,154 state transition paths are generated by the system. Now, let us pick up some of them and consider their feasibility of manipulation.

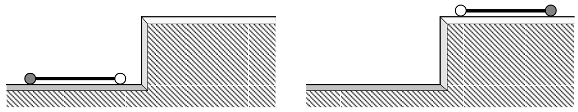

fig. 9 Example of required operation for manipulation feasibility consideration

Case 1 In this case, the left endpoint of the object is selected as the state changeable region through all states as shown in fig.10. Therefore, we can manipulate the object by grasping only this point in order to achieve the objective.

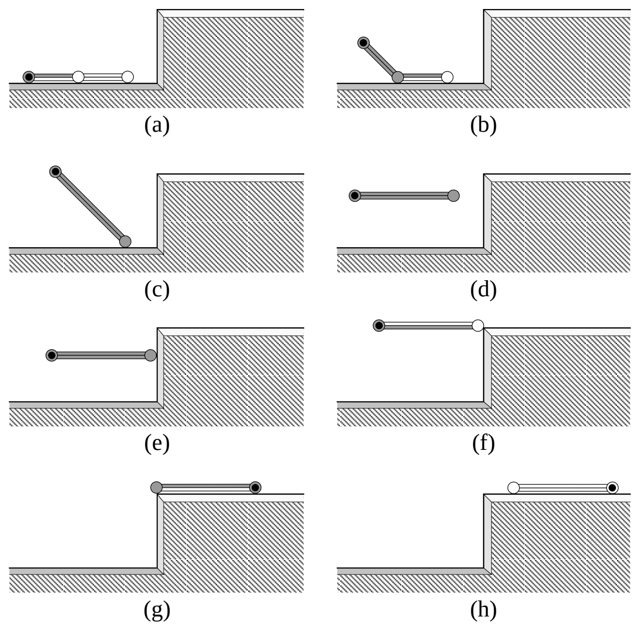

fig. 10 State transition path in case 1

Case 2 In case 2, the state changeable region in the first state as shown in fig.11(a) are completely different from that in the second state as shown in fig.11(b). Therefore, in order to realize this manipulation process, we have to change the contact point from the left endpoint to the right endpoint in the second state or two manipulators have to be prepared in advance.

Case 3 Case 3 is an example that the state transition is possible but any state changeable regions do not exist as shown in fig.12(c). Therefore, this manipulation process can not be realized.

Thus, our proposed method can be applied to the rough planning of thin object manipulation. It is not

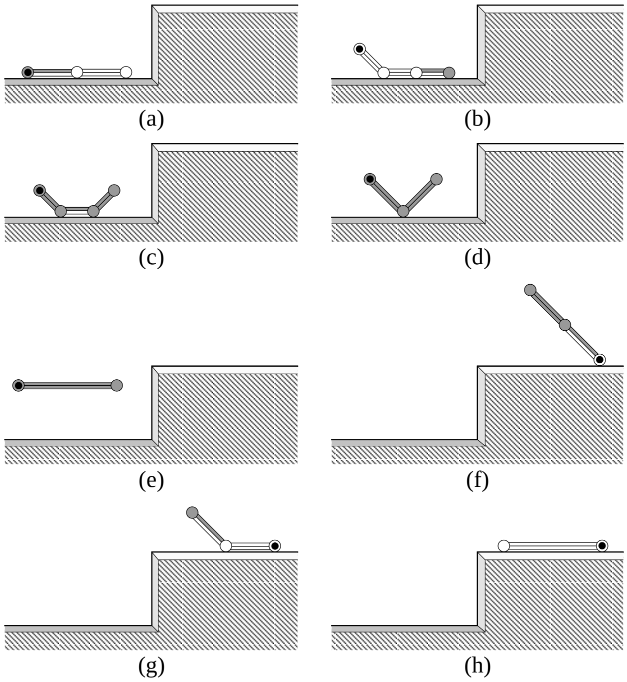

fig. 11 State transition path in case 2

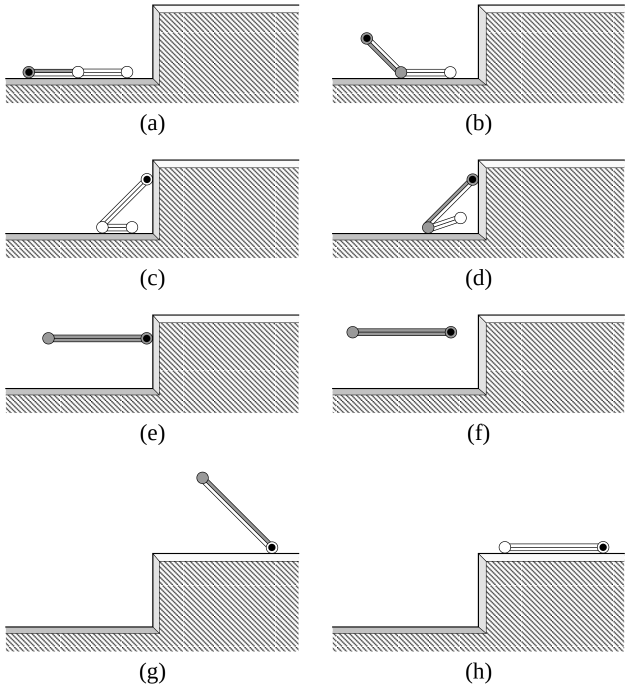

fig. 12 State transition path in case 3

enough to determine grasping points of manipulators or their trajectories in detail. However, we had also analysed the static deformation of thin objects in two dimensional space[3]. The geometrical shape of a thin object can be computed when various forces/moments are imposed on it. Therefore, it seems that the manipulation strategy can be derived automatically by combining a qualitative representation proposed in this paper with such a quantitative analysis.

CONCLUSION

In this paper, a qualitative representation method of thin object manipulation in the two dimensional space was proposed toward its general manipulation planning.

Firstly, a representation method of the contact state of a thin object with one environmental surface in two dimensional space was proposed. It can be represented as 23 contact patterns. Secondly, state transitions among those patterns were defined by the pattern transition matrix. This representation method can be also applied when there are several environmental surfaces by introduction of pattern combination matrices. Therefore, we can generate possible contact state transitions when the initial state and the objective state are given. Thirdly, the state changeable region was introduced. We can realize state transitions by contacting manipulators with this region and imposing forces/moments on it. Therefore, We can check the feasibility of state transitions, which mean manipulation processes, by considering existence of state changeable regions. Finally, that our proposed method can be applied to the rough planning of thin object manipulation was demonstrated. It is expected that this method will be useful for the establishment of systematic approach to the planning of deformable object manipulation.

ACKNOWLEDGEMENT

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