REPRESENTATION AND PLANNING OF DEFORMABLE THIN OBJECT MANIPULATION

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ABSTRACT

A qualitative representation method and a rough planning method of thin object manipulation in the three-dimensional space are proposed. Firstly, contact states of a thin object with environmental surfaces are represented qualitatively as finite contact patterns and their combinations. Secondly, state transitions among contact states are defined. Possible sequences of state transitions can be then generated when the initial state and the objective state are given. Furthermore, by introducing five kinds of basic operations, only feasible sequences can be derived. Thirdly, the difficulty of state transition sequences is introduced. Then, state transition sequences with the small difficulty can be selected as manipulation plans. Finally, it is demonstrated that our proposed method can be applied to the planning of thin object manipulation when a required task is not predetermined in detail.

1 INTRODUCTION

The majority of manipulative tasks, including grasping and assembly, are performed through mechanical contact. As rigid object manipulation can be represented as transitions 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. We have proposed a qualitative representation method of thin object manipulation[3]. However, it is not practical because it assumes that the working space has only two dimension. In this paper, we propose a more practical representation method of thin object manipulation in the three-dimensional space and apply it to manipulation planning.

Firstly, contact states of a thin object with environmental surfaces are represented qualitatively. Secondly, state transitions among contact states are defined. Furthermore, by introducing five kinds of basic operations, only feasible sequences of state transitions can be generated. Thirdly, the difficulty of state transition sequences is introduced in order to select preferable sequences as manipulation plans. Finally, it is demonstrated that our proposed method can be applied to manipulation planning.

2 REPRESENTATION OF CONTACT STATE

Manipulation can be defined as to change the position or the direction of an object by contacting controllable objects like a manipulator with it and imposing forces and/or moments on it. Moreover, the object may contact with environmental objects like a table during manipulation. So, we can represent a manipulation process as contact states of a manipulated object with other objects and their transitions. However, it seems that contact states of deformable objects exist infinitely. Therefore, we propose a method to represent the contact of thin objects in the three-dimensional space as finite states.

First, Let us assume that some environmental surfaces, which are orthogonalized each other, exist in the three-dimensional working space. Moreover, we assume that a polygonal thin object to be manipulated is smaller than any environmental surface. This implies that the object can contact simultaneously with not more than three environmental surfaces.

Next, let us represent a polygonal thin object as a set of two kinds of elements ; vertices V_i $(i = 1, \cdots, n)$ and edges E_j $(j = 1, \cdots, n)$. Let us consider how this object can contact with environmental surface S_1.

In this study, we define that a vertex has three properties: (1) the contact state, that is, whether it contacts with the environmental surface or not, (2) the direction of contact, which means whether its obverse side, reverse side, or others contacts, and (3) how to overlap, which indicates whether its neighboring region covers another region or the region is covered by another region when the object contacts with folding. Let us describe a vertex as $\mathrm{V}_i(s, d, o)$ where s, d, and o represent the contact state, the direction of contact, and how to overlap, respectively. Table 1 shows the classification of vertices. As shown in this table, they are classified into ten types.

We also define that an edge has one property. Let us describe an edge as $\mathrm{E}_j(s)$ where s represents its contact state, that is, whether it contacts wholly, partially, or not at all. Note that this definition does not distinguish between the contact state of an edge illustrated in Fig.1(a) and that illustrated in Fig.1(b). Both of their contact states are identified as "partial contact". Table 2 shows the classification of edges.

If an edge adjoins to vertex $\mathrm{V}_i(0,0,0)$, its contact state must be 0 or 1. If a vertex adjoins to edge $\mathrm{E}_j(2)$, its contact state must be 1. Thus, possible combinations of vertices $\mathrm{V}_i(s, d, o)$ and edges $\mathrm{E}_j(s)$ are limited.

By the above definitions, we can classify contact states of a thin object into finite patterns which are represented as sets of elements $\mathrm{V}_i(s, d, o)$ and $\mathrm{E}_j(s)$. For example, contact state C_0 of a triangular thin object shown in Fig.2 can be described as follows:

$$\mathrm{C}_0 = \{\mathrm{V}_1^1(0,0,0), \mathrm{E}_1^1(1), \mathrm{V}_2^1(1,1,0), \mathrm{E}_2^1(2), \mathrm{V}_3^1(1,1,0), \mathrm{E}_3^1(1)\} \tag{1}$$

where superscript 1 of each element indicates that its properties are determined with respect to environmental surface S_1.

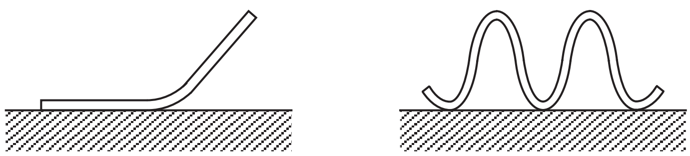
Contact states of a thin object with several environmental surfaces can be represented as the combination of contact patterns with respect to each surface. For example, the contact state illustrated in Fig.3 can be described as follows:

$$\mathrm{C}_0 = \left\{ \begin{array}{l} \mathrm{V}_1^1(0,0,0), \mathrm{E}_1^1(1), \mathrm{V}_2^1(1,1,0), \mathrm{E}_2^1(2), \mathrm{V}_3^1(1,1,0), \mathrm{E}_3^1(1), \\ \mathrm{V}_1^2(1,1,0), \mathrm{E}_1^2(1), \mathrm{V}_2^2(0,0,0), \mathrm{E}_2^2(0), \mathrm{V}_3^2(0,0,0), \mathrm{E}_3^2(1), \\ \mathrm{V}_1^3(0,0,0), \mathrm{E}_1^3(0), \mathrm{V}_2^3(0,0,0), \mathrm{E}_2^3(0), \mathrm{V}_3^3(1,0,0), \mathrm{E}_3^3(0) \end{array} \right\}. \qquad (2)$$

Thus, contact states of a thin object with environmental surfaces can be represented qualitatively as finite contact patterns and their combinations.

Table 1 Classification of vertices

contact state	s	direction of contact	d	how to overlap	o
contact	1	obverse side	1	cover	1
				covered	-1
				not fold	0
		reverse side	-1	cover	1
				covered	-1
				not fold	0
		others	0	cover	1
				covered	-1
				not fold	0
not contact	0	—	0	—	0



(a) (b)

Fig.1 Identifiable contact states of edge

Table 2 Classification of edges

contact state	s
not contact	0
partial contact	1
whole contact	2

3 REPRESENTATION OF STATE TRANSITION

In the previous section, we defined contact states of a thin object. Let us consider state transitions among contact states in this section.

When a thin object is manipulated, its contact state may change. This implies that the contact state of at least one element, a vertex or an edge, changes. Therefore, we can describe the contact state transition as $\mathrm{E}_1^1(1) \rightarrow \mathrm{E}_1^1(2)$, for example.

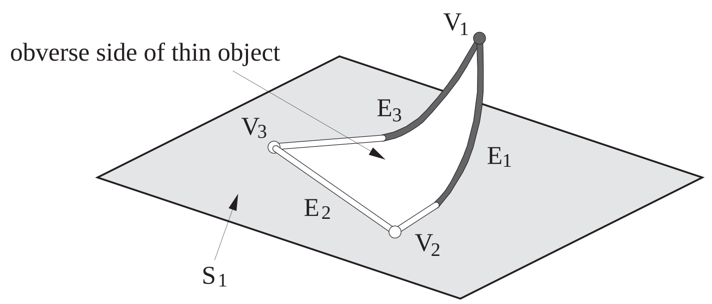


Fig.2 Example of contact state with respect to single environmental surface

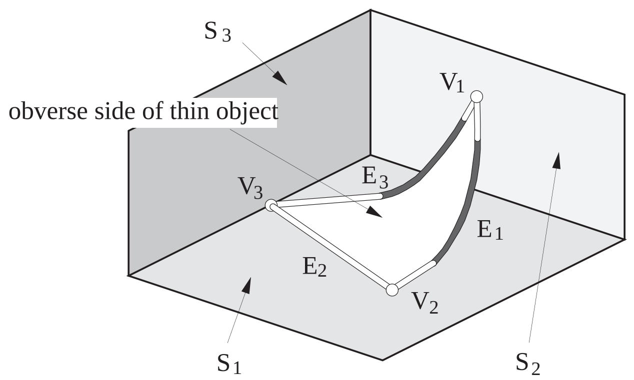


Fig.3 Example of contact state with respect to multiple environmental surfaces

Furthermore, we can represent a manipulation process as a sequence of state transitions. However, a great amount of state transition sequences can be generated. In this study, not feasible sequences are excluded by considering operations of a manipulator, which cause state transitions.

Let us introduce five basic operations: "push", "pull", "pick up", "put down", and "rotate". "Push", "pull", and "rotate" operation cause parallel motion to an environmental surface. It is assumed that these operations can act on only elements which contact with the surface wholly. Especially, a thin object can be "rotated" only when its all elements contact wholly. "Pick up" and "put down" operation cause perpendicular motion to the surface. As the force imposed on a thin object by manipulators is unidirectional, manipulators must contact on the downside of the object in order to "pick up" it. Therefore, only elements which contact with the surface partially or not at all can be "picked up".

In Fig.2, V_2, V_3, and E_2 can be "pushed" or "pulled". V_1, E_1, and E_3 can be "picked up" or "put down". However, the contact state illustrated in this figure is never changed by "push" or "pull" operation. By "pick up" operation, the contact state of E_1 and/or E_3 may be changed. The next feasible contact states are then described as follows:

$$C_1 = \{V_1^1(0,0,0), E_1^1(0), V_2^1(1,1,0), E_2^1(2), V_3^1(1,1,0), E_3^1(1)\}, \tag{3}$$

$$C_2 = \{V_1^1(0,0,0), E_1^1(1), V_2^1(1,1,0), E_2^1(2), V_3^1(1,1,0), E_3^1(0)\}, \tag{4}$$

$$C_3 = \{V_1^1(0,0,0), E_1^1(0), V_2^1(1,1,0), E_2^1(2), V_3^1(1,1,0), E_3^1(0)\}. \tag{5}$$

Let us describe a state transition from contact state C_i to C_j as follows:

$$T_j^i = O_{operation}^n(element) \tag{6}$$

where n, *operation*, and *element* denote a referred environmental surface in order to determine an operation, the kind of operations for this transition, and a controlled element, respectively. In this case, the state transition can be described as follows:

$$T_1^0 = T_2^0 = T_3^0 = O_{\text{pickup}}^1(V_1). \tag{7}$$

"Put down" operation may also make the contact state of V_1, E_1, and/or E_3 change. Then, 19 contact states are derived as the next states. Thus, by considering the current contact state and operations which can be done in the current state in order to change the state, only feasible state transitions can be generated.

From the above discussion, manipulation process of a deformable thin object can be represented as a network whose nodes correspond to contact states and whose arcs correspond to state transitions. Each node has properties of all elements with respect to each environmental surface as described by eq.(2). Each arc has information about the state transition described by eq.(6). Note that multiple arcs can be generated between one node and another node because multiple operations and multiple controlled elements can exist for the same state transition. Moreover, identical arcs, which have the same operation and the same controlled element, can point to different nodes each other.

When the initial state and the objective state of a thin object are given, we can generate sequences of feasible contact state transitions, that is, manipulation processes, by applying this qualitative representation method.

4 EVALUATION OF STATE TRANSITION SEQUENCE

In the previous section, we explained a method for generation of feasible state transition sequences. However, the number of them can be still large. In this section, we introduce some criteria for evaluation of state transition sequences.

First, let us consider the number of state transitions; D_t. A sequence in which the contact state reaches to the objective one through less intermediate states is preferable. Therefore, a state transition sequence with smaller D_t should be selected as a manipulation plan.

Next, let us consider the number of changing times of a controlled element; D_c. If a controlled element is changed during manipulation, the position and/or the direction of an element to be controlled next must be estimated for the detailed planning. Therefore, A sequence in which a grasping point is not changed frequently is preferable.

Finally, let us consider the distance from a controlled point to near environmental surfaces. When a thin object is located near a concave region as shown in Fig.4, a manipulator may interfere with environmental surface S_2 of S_3 if it grasps and controls element V_1, E_1, V_2, E_2, or V_3 of the object. Grasping and controlling E_3, V_4, or E_4 has lower risk of interference. Therefore, we regard manipulation of elements which are more far from environmental surfaces as be preferable. Let D_d be the value corresponding to the reciprocal of the minimum distance from a controlled element to the nearest environmental surface.

In this study, we define the difficulty D_k of k-th state transition sequence as weighted summation of D_{tk}, D_{ck}, and D_{dk}. By introduction of this difficulty, we can select a sequence of contact state transitions with smaller difficulty as one of valid manipulation plans. Thus, rough planning of thin object manipulation and evaluation of generated plans can be done in the qualitative analytical phase by using our proposed method.

A qualitative analysis is also needed in order to verify the realizability of manipulation processes derived from the above qualitative analysis. We have developed an analytical method to model the shape of a deformable thin object[4]. In this method, the shape of a thin object can be computed by minimizing its potential energy under geometric constraints imposed on it. Geometric constraints can be estimated by considering the contact state of each element and the kind of basic operation. Then, the actual shape of a thin object can be computed if its properties such as Young's modulus, modulus of rigidity, Poisson's ratio, and so on are given. Therefore, we can eliminate sequences of state transitions including a contact state which can not be realized physically. Furthermore, by considering some criteria, for example, the maximum potential energy of a thin object during its manipulation, it is expected that the optimal manipulation plan can be determined.

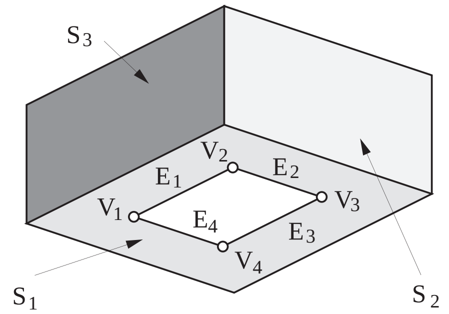


Fig.4 Evaluation with respect to distance from environmental surface

5 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.5 shows a required task. There are a square thin object and three environmental surfaces. The initial state of the object is described by eq.(8) and in the objective state, all elements of the object do not contact with any environmental surface.

$$\mathrm{C}_0 = \left\{ \begin{array}{l} \mathrm{V}_1^1(1,1,0), \mathrm{E}_1^1(2), \mathrm{V}_2^1(1,1,0), \mathrm{E}_2^1(2), \mathrm{V}_3^1(1,1,0), \mathrm{E}_3^1(2), \mathrm{V}_4^1(1,1,0), \mathrm{E}_4^1(2), \\ \mathrm{V}_1^2(0,0,0), \mathrm{E}_1^2(0), \mathrm{V}_2^2(0,0,0), \mathrm{E}_2^2(0), \mathrm{V}_3^2(0,0,0), \mathrm{E}_3^2(0), \mathrm{V}_4^2(0,0,0), \mathrm{E}_4^2(0), \\ \mathrm{V}_1^3(0,0,0), \mathrm{E}_1^3(0), \mathrm{V}_2^3(0,0,0), \mathrm{E}_2^3(0), \mathrm{V}_3^3(0,0,0), \mathrm{E}_3^3(0), \mathrm{V}_4^3(0,0,0), \mathrm{E}_4^3(0) \end{array} \right\}. \tag{8}$$

The effect of gravity is negligible. Let us assume that the contact state must reach to the objective one within four state transitions. Then, 318 state transition sequences are generated by our developed system. When only the contact state is considered, These sequences can be classified into four groups as shown in Fig.6. If the number of state transitions D_t is emphasized, it turns out that sequence group type-I is preferable to any other group. This group includes 30 state transition sequences which have a different basic operation and a different controlled element each other in each contact state. Furthermore, by considering D_c and D_d, state transition sequences described by eqs.(9) through (12) can be selected as adequate manipulation plans.

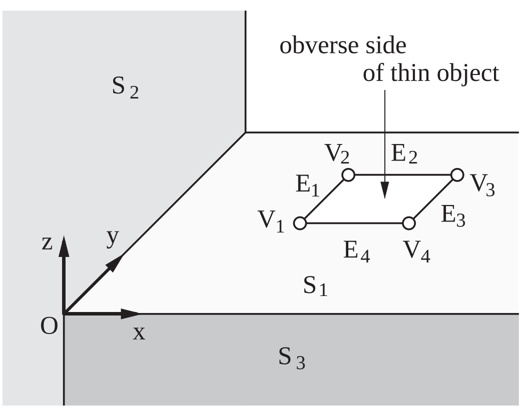
$$\mathrm{T}_1^0 = \mathrm{O}^1_{\text{push}}(\mathrm{E}_2),\ \ \mathrm{T}_3^1 = \mathrm{O}^1_{\text{push}}(\mathrm{E}_2),\ \ \mathrm{T}_8^3 = \mathrm{O}^1_{\text{pickup}}(\mathrm{E}_1). \tag{9}$$

$$\mathrm{T}_1^0 = \mathrm{O}^1_{\text{push}}(\mathrm{E}_2),\ \ \mathrm{T}_3^1 = \mathrm{O}^1_{\text{push}}(\mathrm{E}_2),\ \ \mathrm{T}_8^3 = \mathrm{O}^1_{\text{pickup}}(\mathrm{E}_3). \tag{10}$$

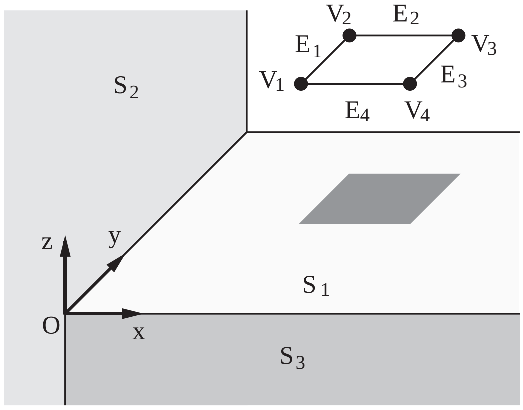
$$\mathrm{T}_1^0 = \mathrm{O}^1_{\text{push}}(\mathrm{V}_3),\ \ \mathrm{T}_3^1 = \mathrm{O}^1_{\text{push}}(\mathrm{V}_3),\ \ \mathrm{T}_8^3 = \mathrm{O}^1_{\text{pickup}}(\mathrm{E}_1). \tag{11}$$

$$\mathrm{T}_1^0 = \mathrm{O}^1_{\text{push}}(\mathrm{V}_3),\ \ \mathrm{T}_3^1 = \mathrm{O}^1_{\text{push}}(\mathrm{V}_3),\ \ \mathrm{T}_8^3 = \mathrm{O}^1_{\text{pickup}}(\mathrm{E}_3). \tag{12}$$

Thus, by applying our proposed method, we can plan thin object manipulation roughly even if a required task is not predetermined in detail.



(a) Initial state

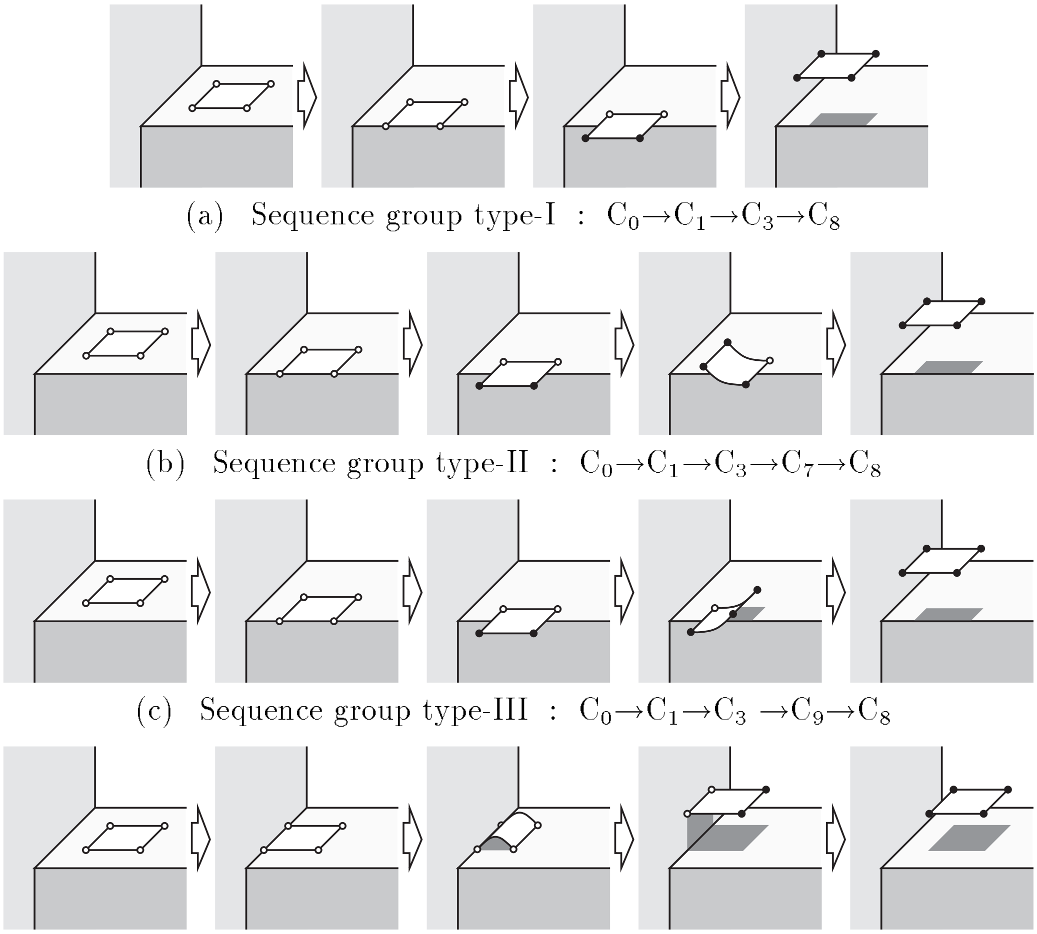


(b) Objective state

Fig.5 Result of state transition sequence generation

6 CONCLUSIONS

In this paper, a qualitative representation method and a rough planning method of thin object manipulation in the three-dimensional space were proposed. Firstly, contact states of a thin object with environmental surfaces were represented by combining properties of vertices and edges with respect to each environmental surface. Secondly, by introducing five kinds of basic operations, feasible state transitions among contact states were defined. Then, sequences of contact state transitions, that is, manipulation processes can be generated when the initial state and the objective state are given. Thirdly, the difficulty of state transition sequences was introduced in order to evaluate generated manipulation processes. By considering this difficulty, preferable manipulation plans can be derived in the qualitative analytical phase. Finally, it was demonstrated that our proposed method can be applied to rough planning of thin object manipulation. It is expected that this method will be useful for the establishment of systematic approach to the planning of deformable object manipulation.



(a) Sequence group type-I : $C_0 \rightarrow C_1 \rightarrow C_3 \rightarrow C_8$

(b) Sequence group type-II : $C_0 \rightarrow C_1 \rightarrow C_3 \rightarrow C_7 \rightarrow C_8$

(c) Sequence group type-III : $C_0 \rightarrow C_1 \rightarrow C_3 \rightarrow C_9 \rightarrow C_8$

(d) Sequence group type-IV : $C_0 \rightarrow C_2 \rightarrow C_5 \rightarrow C_{18} \rightarrow C_8$

Fig.6 Result of state transition sequence generation

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