Method for Representing 3-D Virtual Origami

Takashi Terashima* Hiroshi Shimanuki* Jien Kato† Toyohide Watanabe†
Graduate School of Information Science, Nagoya University, Japan
*{takashi, simanuki}@watanabe.ss.is.nagoya-u.ac.jp †{jien, watanabe}@is.nagoya-u.ac.jp

Abstract

This paper proposes a method for representing overlapping-faces of 3-D virtual origami in order to support beholder's recognition of its conformation. Generally, an origami model is constructed by planar polygons corresponding to faces of origami. Therefore, when an origami model is displayed, multiple faces (polygons) on the same plane are probably recognized as one face. Our proposed method moves such overlapping-faces apart slightly by rotating polygons along a rotation axis determined from shapes and relationships of faces. As a consequence, beholders can recognize the conformation of origami correctly. This method can be applied to the user interface of a system we develop to recognize folding operations from origami drill books.

1. Introduction

Origami, one of the Japanese traditional cultures, is accepted worldwide as the art of paper folding which has the abundant potential globally. Traditionally, people play origami based on drill books or materials on web pages in which the folding processes consist of simple folding operations are illustrated by diagrams.

However, as origami works are complicated, it is usually the case that people give up following the instructions of illustrations because they are difficult to understand. In order to solve this problem, a system which recognizes folding operations from origami drill books and displays 3-D animation of folding processes has been proposed [1, 2]. In this system, several image-processing techniques are applied to origami illustration images in order to recognize how a sheet of paper is folded. However, the system may fail to recognize folding operations at some steps. Such failure is mainly due to ambiguity of images, and it is extremely difficult for the system to appreciate them. Consequently, an interface which allows users to input information about folding operations is required. In this case, the system has to help the users to input information about folding operations easily and correctly.

Generally, an origami model is constructed by planar polygons corresponding to faces of origami. Therefore, when an origami model is displayed, multiple faces on the same plane (i.e. overlapping-faces) probably seem to be one face. This incorrect perception occasionally obstructs users' inputs. Consequently, in this paper, we propose a method for representing overlapping-faces of 3-D virtual origami in order to support users' recognition of origami's conformation. As a result, users can input information about folding operations easily and correctly. As related work, a system that represents dialogical operations of origami in 3-D space has been introduced [3]. However, the representation of origami model in an easy-to-understand way is not considered in the system.

This paper first outlines the recognition system with the inclusion of above interface in Section 2. Then, Section 3 specifically describes our method for representing overlapping-faces of 3-D virtual origami for the user interface. Finally, we show the conclusions and future prospects in Section 4.

2. System for Recognition of Folding Process

This section outlines the system for recognition of folding process from origami drill books, and indicates the necessity for representing overlapping-faces of 3-D virtual origami.

2.1. Basic Framework

Figure 1 gives the framework of the system. The system firstly extracts crease information, both positions and types of the creases, from an origami illustration image which illustrates the state of origami and one folding operation to be performed [4] ("Extraction of Graphic Elements" step).

Then, the feasible (physically possible) folding operations are constructed based on the crease information. They are obtained by maintaining consistency of crease patterns

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under some geometrical constrains [5]. All the feasible candidates are simulated against the internal model, a data structure which maintains 3-D information about changes of origami states step by step. As a consequence, several different origami states are obtained from each candidate. Then, the ISGs, graphs generated by projecting each state of the internal model, are generated ("Generation of Folding Operations" step).

In order to determine the correct folding operation, each ISG is compared with the USG, a graph generated from the origami illustration of the next step. Furthermore, in order to get the position of the next crease, the ISG is matched with the USG ("Recognition of Folding Operations" step).

By this way, the system recognizes folding operations of each folding step.

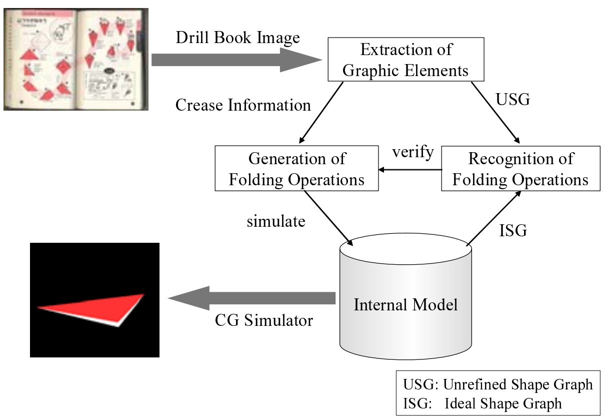


Figure 1. Basic framework of the recognition system for folding process.

2.2. User Interface

In "Extraction of Graphic Elements" step and "Recognition of Folding Operations" step, several image-processing techniques are applied. However, the system may fail to recognize folding operations at some steps.

One of the countermeasures is building a user interface which allows users to input information about folding operations. When the system can not extract graphic elements, it requires the users' input about position of folding line (see left of Figure 2). Additionally, when the system can not determine the correct folding operation among several candidates of operations, it requires the users' selection of correct (i.e. represented in drill books) operation (see right of Figure 2). This interface plays a supplementary role of the system.

Users input these informations on the basis of drill books. Therefore, origami on the entry display must look just like origami in drill books for users. This will enable users to present information about folding operations in accordance with illustrations in drill books.

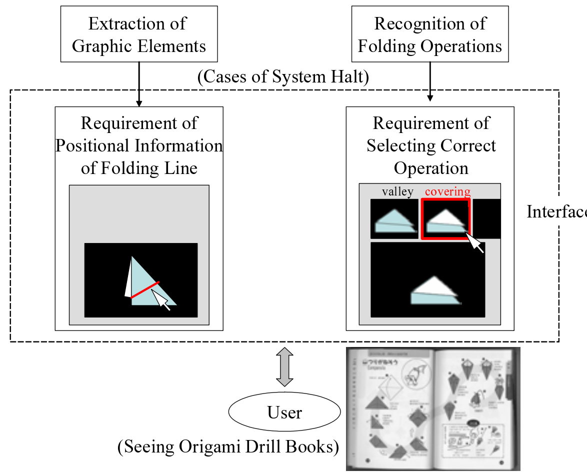


Figure 2. User Interface.

2.3. Overlapping-faces

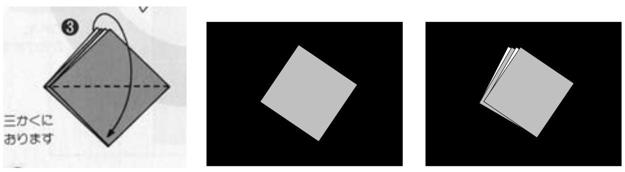
When an origami model is displayed, the key is to bridge the gaps between the representation on drill books and that on a computer display. In drill books, overlapping-faces are drawn in order to be understood without trouble by moving overlapping-vertices slightly, as Figure 3(a). On the other hand, as discussed previously, an origami model is constructed by planar polygons. Therefore, there is a gap between the representation on drill books and that on a computer display (see Figure 3(b)). If the system can not present an origami model 3-dimensionally, users who want to input the position of a folding line may feel confusion. Namely, they may not be able to determine which vertices are terminal nodes of the folding line that is needed to be specified. Consequently, we consider the method for representing virtual origami so that it is close to the illustration on the drill book, as Figure 3(c).

3. Method for Representing Origami Model

This section specifically describes our method for representing overlapping-faces of 3-D virtual origami for the user interface.

3.1. Our Approach

In order to represent virtual origami 3-dimensionally, we consider the extended (i.e. ideal) representation as the reconfiguration of a 3-D origami model. Specifically,



(a) Illustration on drill books. (b) Semplice representation. (c) Ideal representation.

Figure 3. Representations of overlapping-faces.

overlapping-faces are moved apart slightly by rotating polygons along a rotation axis determined from figurations and relationships of faces. Because of the reconfiguration in 3-D space before 3-D rendering, this method has the advantage that an origami model can be seen from all viewpoints without any renewed reconfigurations if once it is reconfigured. Namely, the reconfiguration depends not on users' viewpoints, but on the origami model.

The elementary transformation is a movement (i.e. rotation) targeted at two faces which are adjoining each other. Order and portions of movement are based on figurations and relationships of overlapping-faces. We discuss which faces should be moved, which portions of the faces should be rotated, and what order they should be rotated in.

3.2. Free-portion

We define a "free-portion" (part of a face) as the portion that is not restrained by the adjoining face and can move freely. Such free-portions should be moved (i.e. rotated). In order to find out a free-portion, firstly, we define a "free-edge" as follows.

Free-edge. Given two faces (F_1 and F_2) that are on the same plane and are adjoining each other, an edge E of F_2 is a "free-edge" to F_1 if following conditions are all satisfied:

- E is not an edge of F_1, but an edge of F_2.
- E and F_2 are not covered by other faces.

In order to determine whether the latter condition is satisfied, cross-sections of origami are generated by cutting origami perpendicular to E. Figure 4 gives examples of free-edge and not-free-edge. At State C, both sides of $F2$ are covered by other faces, and these faces are joined on the same side of E. Namely, E and F_2 are not covered by other faces, and E is a not-free-edge. This definition is used to determine free-portion as follows.

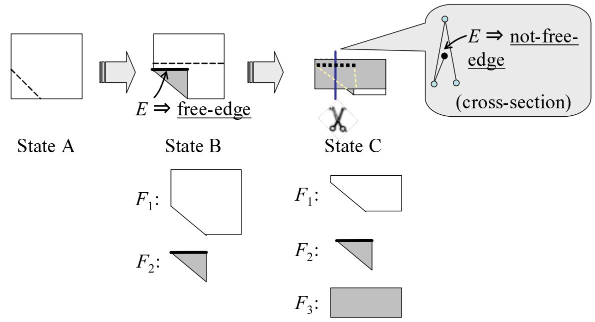


Figure 4. Examples of free-edge and not-free-edge.

Free-portion. A free-portion of a face F_2 to the adjoining face $F1$ is determined by following steps.

1. Determine whether each edge of F_2 is a free-edge to F_1.
2. Draw a line L that connects two points between free-edge and not-free-edge.
3. Define the polygonal area enclosed by the free-edges and L as a free-portion.

This line L becomes the rotation axis when the free-portion is rotated. Figure 5 show examples of determining free-portion. In the case of F_1, the free-portion is the triangular shape (i.e. half of F_1). On the other hand, in the case of F_2, the free-portion is the whole face F_2. More specifically, F_2 is unrestrained in moving by F_3. In addition to these examples, there are cases where no free-portions of some faces exist since polygonal area can not be formed in step 3.

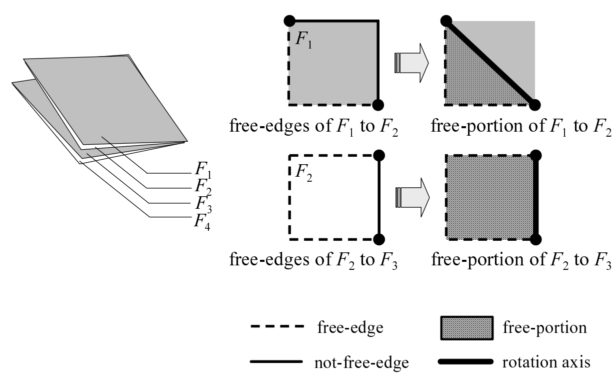


Figure 5. Examples of determining free-portion.

3.3. Grouping of Faces

In Figure 5, the free-portion of F_3 to F_4 is the triangular shape like that of F_1 to F_2. If the free-portion of F_3 is rotated before the rotation of F_2 (whole area is the free-portion), the free-portion of F_3 collides against F_2 and the reference plane of the rotation of F_2 gets fuzzy.

To solve this problem, we propose a method that groups overlapping-faces based on dependency relation about their movements. Namely, if a face can move independently of another face, the two faces are classified into different groups. Otherwise, they are classified into the same group. This grouping of faces determines the order of face's movements. The procedure for grouping overlapping-faces is described as follows.

Procedure for Grouping.

1. Make the order list of overlapping-faces.
2. Determine free-portion of each face to the adjoining face behind it (beginning at the bottom).
3. Let the faces that whole area is the free-portion be chief faces of their groups. Let the undermost face also be chief face.
4. Crassify each not-chief face into the group the nearest behind chief face belongs to.

Figure 6 gives an example of grouping faces. In this case, F_2 and F_4 are chief faces of Group 2 and Group 1, respectively. Obviously, the number of chief faces is equivalent to the number of groups. F_1 and F_3 are not chief faces, and are classified with Group 2 and Group 1, respectively.

This grouping solves the problem described above. More specifically, no faces collide against other faces by moving all faces which belong to the same group before the rotation of each free-portion. Each rotation angle can be decided in consideration of angular difference between anteroposterior groups.

3.4. Rotation

Let e be a located vector in 3-D space. Additionally, let $R(\theta)$ be a matrix which rotates a coordinate point e along a rotation axis, where θ is the rotation angle. All coordinate points of polygones which form the free-portions are rotated by R. At this time, rotation angle is decided according to whether rotated face is a chief face or not.

Rotation.

- $e' = eR(\theta)$ (If rotated face is a chief face)

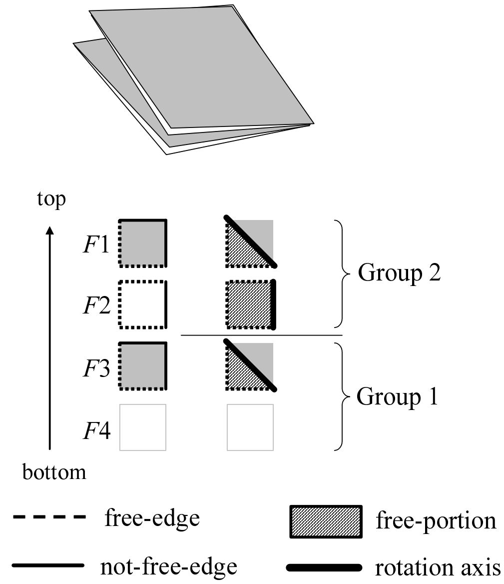


Figure 6. Examples of grouping faces.

- $e' = eR(\theta(e))$ (Otherwise)

If rotated face is a chief face, rotation angle is constant. Namely, rotated face becomes a flat surface after rotation. On the other hand, rotation angle is the function of each coordinate point when rotated face is not-chief face. Obviously, rotated face becomes a curved surface after rotation.

3.5. Representation Algorithm

Our proposed method for representing 3-D virtual origami is summarized as follows.

Representation Algorithm.

1. Make the order list of overlapping-faces.
2. Determine free-portion of each face to the adjoining face behind it (beginning at the bottom).
3. Determine chief faces and classify other faces with appropriate groups.
4. Rotate set of faces in each group collectively along the chief's axis (i.e. chief face of the group and faces which belong to the group). Rotation angle is constant.
5. Rotate free-portions of overlapping-faces in sequence along respective axes. Rotation angle is the function of each coordinate point.

Figure 7 shows example of representing 3-D origami based on this algorithm. In this case, four chief faces and four groups are formed. Subsequently, sets of faces in group 2, group 3, and group 4 are rotated along their chiefs' axes. Finally, the free-portion of F_5, only not-chief face which can move, is rotated along own axis.

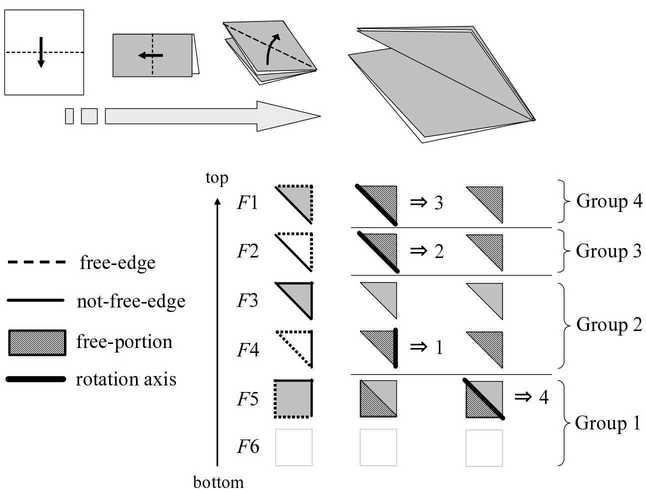


Figure 7. Examples of grouping faces.

4. Conclusions

This paper describes a method for representing overlapping-faces of 3-D virtual origami in order to support beholder's recognition of its conformation. Our proposed method can reduce the difficulty in understanding origami model which have multiple faces on the same plane. The advantage of this method is depending not on users' viewpoints, but only on the origami model. Consequently, an origami model can be seen from all angles without any renewed reconfigurations if once it is configured. By our method, the system for recognition of folding process from origami drill books will be suitable for practical use.

Furthermore, we are convinced that this method can be applied to other systems. By way of example, we have an interactive support system for origami creation in view. This system supports the origami creators who have created origami factures using tangible papers thorough trial and error processes. Using this system, they may be able to create factures more comfortably in 3-D virtual space. The system receives information about folding operations from users at each step. Under such circumstances (i.e. without any drill books), it is more important to represent an origami model in order to be understood easily. By the repetition of these processes, the system can understand a sequence of folding operations required to create a certain origami facture, and represent them in the form of 3-D animation or 2-D illustrations. In order to represent these original works, our proposed method will make a significant contribution.

As our future work, we must evaluate proposed method in accurate detail. Especially, we should apply this to more complicated models. Furthermore, applying to other useful systems must be considered.

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