Clothing skirt designed on conical truss model

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Abstract Several applications of Origami have been
tested in industrial area. However, Origami based design is
found only in lamp shade and wrapping in design area, and
has not been practically applied especially in clothing. In
this paper, the conical truss model is applied in the clothing
skirt, and the simulation software from 2D to 3D is
developed by parametric Origami module (POM). Finally,
the pattern is copied on felt clothing, and the scaled model
of skirt on the basis of conical reverse truss model design is
made.

1 Introduction

Origami engineering conical truss core panel has been
applied to the absorption member and truss panel has been
applied to floor structure for automobile. Origami based
design is not popular in the clothing field. Miyake [1]
designed clothing and bag on the basis of Origami folding,
as shown in Fig. 1. Figure 1a shows the changes from flat
to 3D while spiral rotation. Figure 1b is designated BAO-
BAO which is popular among comparatively elderly ladies
in Japan. Figure 1c is created by cutting complete form and
folding into flat. It can save storage space, hence it is useful
in travelling. In this paper, various kinds of conical truss
model [1] are generated and applied to clothing model for

skirt, and simulation software is developed on the basis of
parametric Origami module (POM) [2]. Furthermore, the
fabricated samples designed on different conical truss
models are made of felt clothing and compared considering
the functions of skirt.

2 Conical truss model

2.1 Way of drawing conical truss model

It has already been proved by Nojima that the pattern where
reverse spiral structured conical is folded into flat by rotating
in 360° is drawn in Fig. 2a [3, 4]. Firstly, the condition that the
elements constitute the Fig. 2a is represented as Eq. (1). Here,
N is the number of triangle that stands in the circle, and Θ is the
center angle of pattern. An angle of β can be arbitrary but to be
folded flat since it has the restriction related with the angle of
α. The fun shaped pattern is found to be drawn in curving lines,
however all lines constituting each triangle are straight in
Fig. 2b. Therefore, the way of drawing whole of the pattern is
firstly drawing both the diagonal lines which divide equally
the arch of fun shaped pattern and parallel lines with arch ones.
Secondly, all adjacent points are connected with straight lines.
Figure 2(c) is completed by drawing step by step which is
composed of triangles and have the same rate of agreement in
the direction of cent orderly in this way. Conical reverse spiral
structure can be drawn in several patterns according to α, β, γ
in Fig. 2a–c. The developable and foldable condition is
dependent on the angles α and β. When α and β are both 30°,
Figs. 2a, b and d can be applied to skirt design. Therefore, we
try to fold 3 kinds of patterns for skirt design in this paper.

$$\alpha = (2\pi - \Theta)/2N. \tag{1}$$

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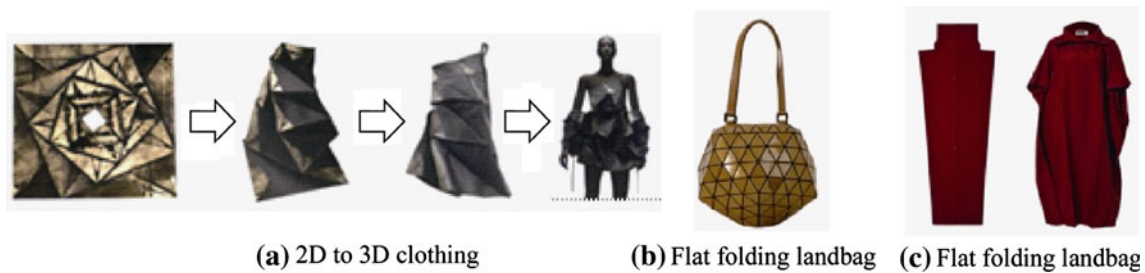e-mail: tz12007@meiji.ac.jp

(a) 2D to 3D clothing   **(b)** Flat folding landbag   **(c)** Flat folding landbag

Fig. 1 Origami based fashion designed by Miyake [1]

3 Development of 2D to 3D simulation software

3.1 Real transformation from 2D to 3D

The final purpose is to develop 2D to 3D simulation software. In this paper, the conical truss model is focused on as the first step for 2D to 3D simulation. Before developing system, this model is folded with paper and its real gradual motion is confirmed, as shown in Fig. 3. This model is non rigid Origami, hence every folding line is not kept straight during being folded. Figure 3a is the flat form, and gradually transformed into 3D completion, as shown in Fig. 3c.
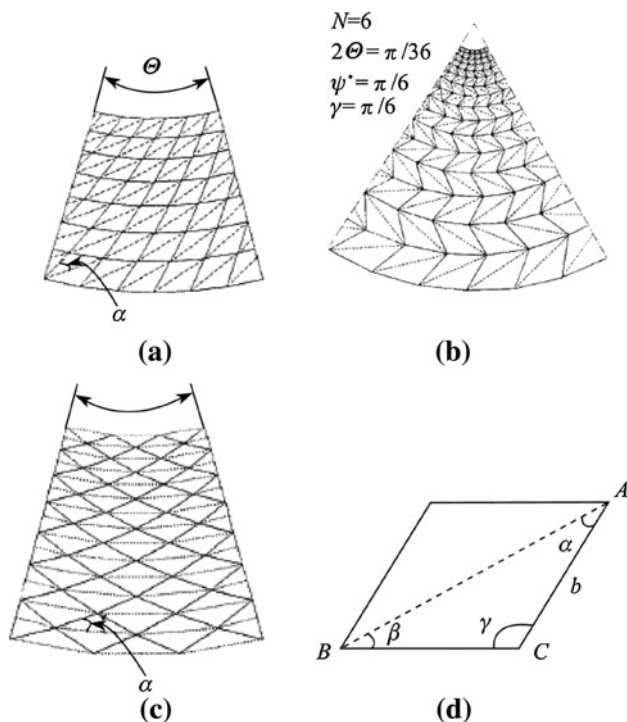

Fig. 2 a–c Pattern of foldable conical shell, d one element of development

3.2 Prior Origami related software

The software which creates pattern and shows complete form has already been developed by Mitani. He publishes the editor for flat Origami "ORIPA [5]" in his website, as shown in Fig. 4a for free [7]. However, the function of this editor is limited to drawing fold lines on the screen referring to the marked lines on paper and displaying the estimated completion. In this process, the correctness of folding lines drawn on ORIPA can be confirmed. It means that ORIPA is just the editor based on the existing pattern and not the software which can realize all folding process including the completion. Mitani also developed the software called ORI-REVO [6, 7], which is limited only for the shapes based on the surface of revolution, as shown in Fig. 4b. The shapes generated by ORI-REVO are based on the surface of revolution. Actually, the software not depending on shapes has not been completed by any researchers because of complex properties of Origami. While there is software called "Freeform Origami [8]" dealing with only rigid Origami, as shown in Fig. 4c. By using Freeform Origami, the simulation from 2D to 3D of conical truss model is tried to be failed. The reason is that each side of this model is bent during being folded. Considering these research results, the system functioned with editor and simulation is aimed to be developed.

3.3 POM

The fundamental structure shown in Fig. 5 is called POM. POM can be extracted as many different types from complex 3D origami structure. POM with the fewest number of nodes which is suitable for 3D origami structure use has been investigated. As a result, in the cases of one mountain line, one valley line, two mountain lines, one valley line, there will have an unstable curved surface and cannot be applied as POM for 3D origami structure. While in the case of three mountain lines and one valley line shown in Fig. 5, there are straight lines between nodes which make each facet become stable plane.
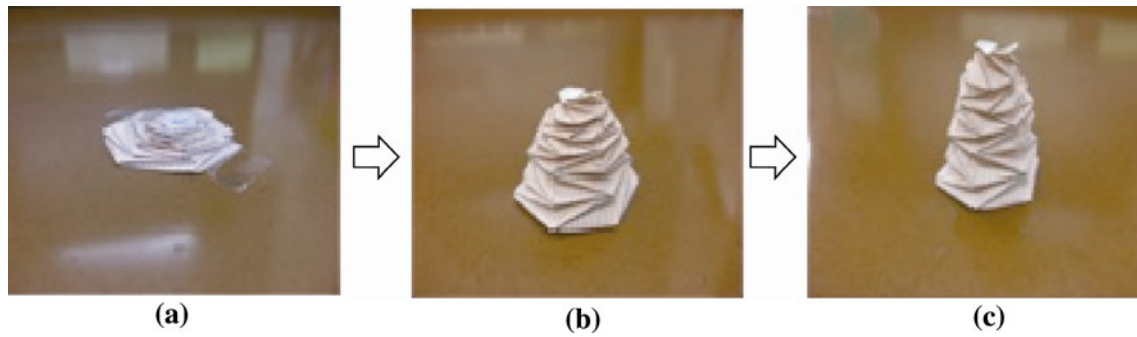
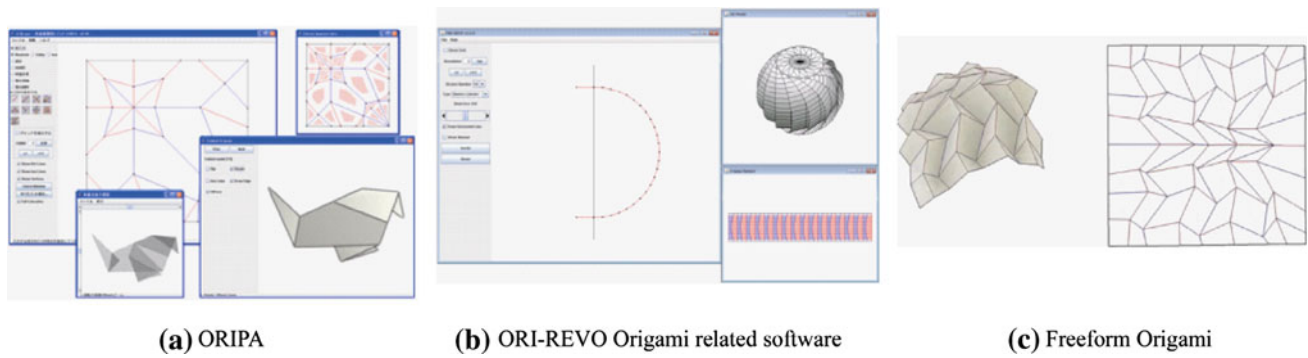**Fig. 3** Real transformation from 2D to 3D of conical truss form

(a) ORIPA   (b) ORI-REVO Origami related software   (c) Freeform Origami

Fig. 4 Origami related software

T and G are defined as follows for general 3D origami structure (T is the abbreviation for topologic parameter and G is the abbreviation for geometric parameter)

$$
T = \begin{Bmatrix}
1 & P_1^{(1)} & P_2^{(1)} & P_3^{(1)} & P_4^{(1)} \\
2 & P_1^{(2)} & P_2^{(2)} & P_3^{(2)} & P_4^{(2)} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
i & P_1^{(i)} & P_2^{(i)} & P_3^{(i)} & P_4^{(i)} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
n & P_1^{(n)} & P_2^{(n)} & P_3^{(n)} & P_4^{(n)}
\end{Bmatrix},
$$

$$
G = \begin{Bmatrix}
1 & x_1 & y_1 & z_1 \\
2 & x_2 & y_2 & z_2 \\
\vdots & \vdots & \vdots & \vdots \\
i & x_i & y_i & z_i \\
\vdots & \vdots & \vdots & \vdots \\
n & x_n & y_n & z_n
\end{Bmatrix},
$$

(2)

where n is the node sequence number of 3D origami structure; $P_1^{(i)}, P_2^{(i)}, P_3^{(i)}, P_4^{(i)}$ are number of the node which node i connect with, and node i is regarded as center node of element i. χ_i, y_i, z_i ($i = 1, 2, \cdots, n$) are the node coordinates. The composition of T of in Eq. (1) is explained as follows
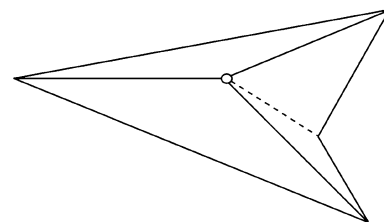

Fig. 5 POM

(i) The node number of node i connected with is 4 or 3. When it equals to 3, the 4th element $P_4^{(i)}$ is set 0.

(ii) Connection relationship of nodes is contained in element of i row. The end of valley line is regarded as the first element $P_1^{(i)}$ as usual, and elements $P_2^{(i)}, P_3^{(i)}, P_4^{(i)}$ by mountain line end in anti-clockwise order are set up. Thus it can be shown as in the way: valley line end $i - P_1^{(i)}$, mountain line end $i - P_2^{(i)}$, mountain line end $i - P_3^{(i)}$, mountain line end $i - P_4^{(i)}$.

(iii) There is a case that valley end does not exist on all the edge nodes. This time the node f first element $P_1^{(i)}$ can be selected freely. However, the remaining elements should follow anti-clockwise order.
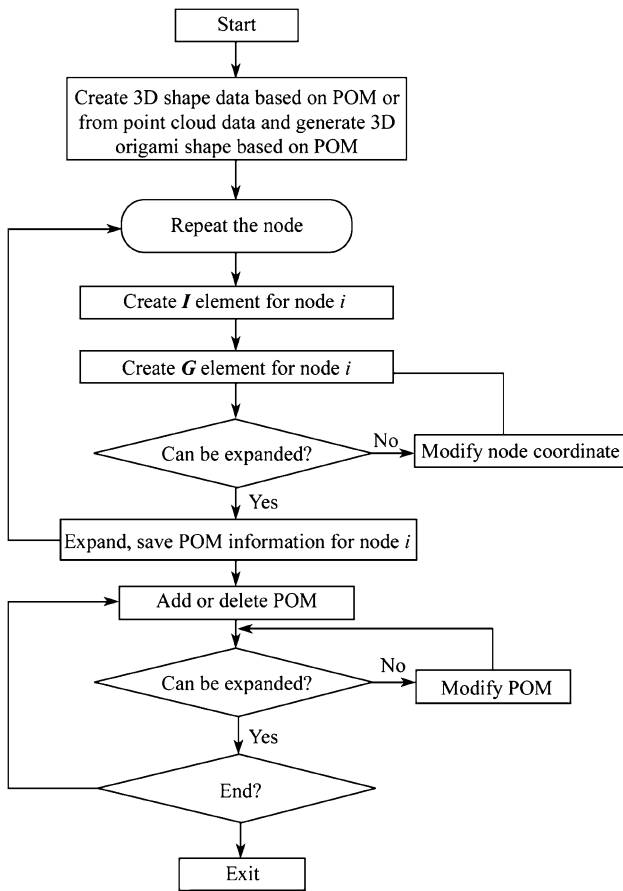
Fig. 6 Flowchart of 2D–3D simulation

Fig. 7 Decision movement by POM method

carried out for completing the design of 3D Origami structure.

3.4 Algorithm of newly developed 2D to 3D software by POM

The algorithm for 2D to 3D simulation using POM is illustrated in Fig. 6. The procedure is divided into 3 following working blocks

(i) 3D Origami structure is created from 3D form and point cloud data. This part corresponds to the architectural design, where basic structure and shape are decided.
(ii) The POM information about each node is created according to the given shape data. Specifically, T and G are recreated automatically inside system, then GP condition is checked and modified to satisfy the development condition of each POM. This part is the main of POM based Origami design.
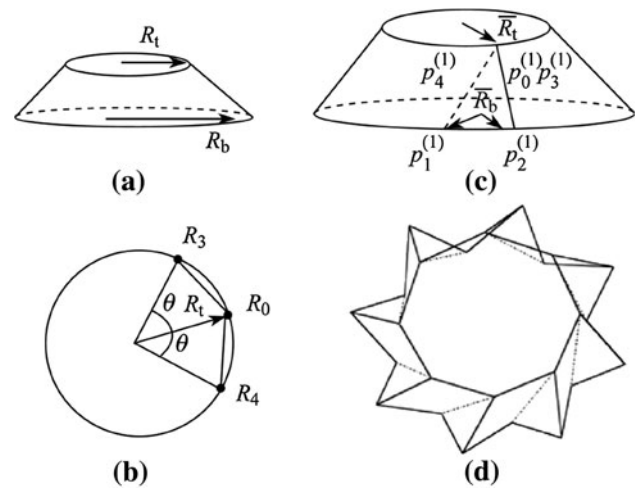(iii) If necessary, POM is added or deleted. This part corresponds to finishing where little arrangement is

3.5 Application of POM to conical truss model

The procedure to create POM model from skirt form is shown in Fig. 7. Firstly a cylinder is made, and partial structure by two POMs is generated, as shown in Fig. 7b. Secondly, the structures in the direction of peripheral direction are duplicated. Thirdly, each POM and chine line are studied and explored. Finally, based on the result of Fig. 7c, the node number of POM is adjusted, and the final structure is obtained, as shown in Fig. 7d. The way that pattern is transformed into flat form is shown in Fig. 8.

Step 1 Calculate the feature center for the crease pattern. Concerning the skirt pattern, the circle composed of POMs is a common center.

Step 2 Calculate the corresponding radius for the crease pattern.
Search connected size are the same POMs until end, sum of length are.
Then, by value L, the same type POM can be known.
The same type POM is supposed to move as the same around the central axis of the structure.

$$L = \sum \text{POM}_{\text{distance}},$$

where

$$\text{POM}_{\text{distance}} = \sqrt{\left(\text{POM\_CenterNode\_}x - \text{POM}_J\_\text{CenterNode\_}x\right)^2 + \left(\text{POM}_i\_\text{CenterNode\_}y - \text{POM}_J\_\text{CenterNode\_}y\right)^2}$$
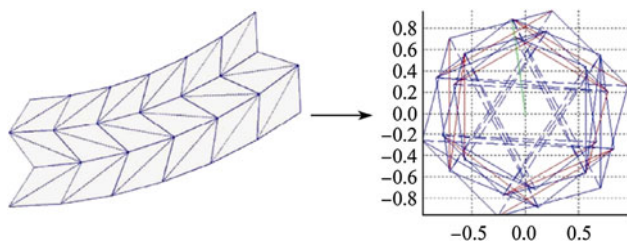
Fig. 8 Simulation from pattern to flat form

Step 3   Calculate flat state with max energy.
          Referring to POM, evaluation function for the
          minimum energy state (see Fig. 9c) is defined as

$$E_{POM} = \sum \theta_{dihedral\_angles_i},$$

where $\theta_{dihedral\_angles}$ represents close to facets
intersection angle of POM. When the value became
minimal, the POM reached the maximum energy
state. Suppose the normal vector of each facet is v_1
and v_2, then dihedral angles can be calculate as

$$\theta_{dihedral\_angle} = \pi - \frac{\arccos(v_1 \cdot v_2)}{|v_1||v_2|}.$$

Thus, for the conical type crease pattern, the
maximum energy state (see Fig. 9a) for all the
POM is calculated, and then flat state is obtained for
the object.

Follow Step 1–Step 3, the flat state can be obtained by
using the parameter of the reference conical structure.

4 Fabricated sample

4.1 Material and sewing way

The application in clothing is to be considered in this
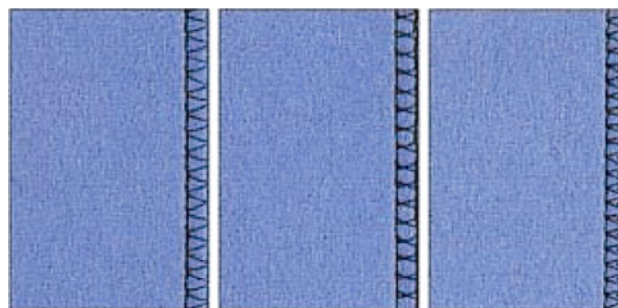section. The serious problem is that how to keep vertical

Fig. 10 Three kinds of overhand stitch

shape that is affected easily by gravity. Concerning this
problem, the approach from 2 viewpoints as material and
sewing is applied. Thick and hard clothing is appropriate
for the skirt designed on conical truss model from the
material viewpoint. At this time, the felt clothing is tried to
be used and overhand stitch illustrated in Fig. 10 is applied
regarding sawing viewpoint. This stitch is usually used for
preventing raveling, and as another property it can stick
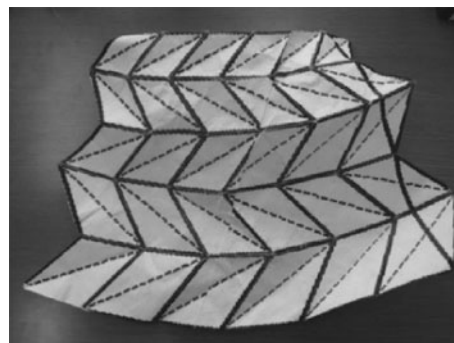each side together. By turning the sewing side according to

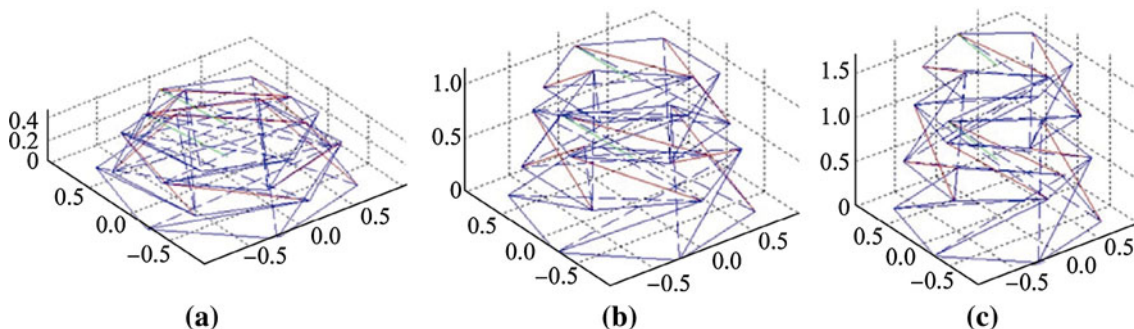**Fig. 11** Pattern of conical reverse truss model

Fig. 9 Simulation of application of reverse spiral conical structure to skirt

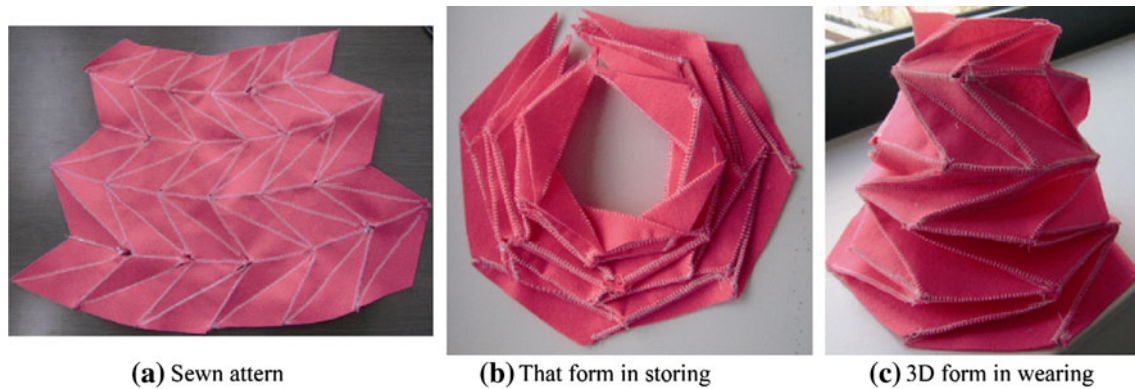**(a)** Sewn attern   **(b)** That form in storing   **(c)** 3D form in wearing

Fig. 12 Fabricated sample

the mountain line and valley line, the sewing line which makes stable form can be created.

4.2 Skirt sample made of felt clothing designed by conical reverse truss model

Figure 11 is the pattern of conical reverse truss model. This is copied on the prepared felt clothing with charcoal pencil, and cut one part by one part The adjacent sides are sewn by overhand stitch, as shown in Fig. 12a. The flat folded form is shown in Fig. 12b, and the 3D form is shown in Fig. 12c.

This sample is the scaled model of real skirt clothing. Hence it is necessary to make the skirt in real size and have a few models try on. The morphological stability of sides and folding lines is to be examined under the tried condition. It is assumed that the heavier the total gravity, the lower morphological stability will get.

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