Strip creation for designing curved papercraft models adopting mesh subdivision scheme

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Abstract We propose a new method for creating smooth mesh models that consist of a set of smooth strips. The triangles in the strips created by our method are quite thin, so the strips can be treated as approximate unfoldable surfaces. This feature is useful for designing models for curved papercraft-toys. Firstly we unfold a low triangle mesh model and classify edges into two groups: inner edges and contour edges. We then subdivide the contour edges to create triangles in the thin strips. Edge-swap operation is also applied to make the model becomes smooth. With this method, the unfolded pattern for curved papercraft models can be generated by simple operations.

Keywords Triangle Mesh Model, Subdivision, Papercraft, Stripification

1. Introduction

Designing 3D figures on a computer is quite common these days. Although we can see and evaluate them by displaying them on a screen, we cannot touch them because they are just digital data. Realizing such 3D figures as physical objects is useful as a tool for engineering prototyping and for educational purposes. To achieve this, making papercraft from an unfolded pattern of the model is one of the simplest approaches. Nowadays there are some software for making unfolded patterns from 3D polygonal models [1], and a lot of people enjoy making papercraft models as a hobby.

Unfoldable surfaces are a subset of ruled surfaces, and other surfaces cannot be unfolded to a plane without any distortions. Even though arbitrary surface can be approximated by a dense triangle mesh, the pattern of such mesh becomes too complicated. Fig.1b shows an unfolded pattern of a mesh model that represents a rhinoceros using 4624 triangles shown in Fig.1a. Physically creating and assembling such a pattern is unrealistic. Although we can reduce the number of faces of original mesh model by mesh simplification methods [2] to relieve the load of creation, this reduces the accuracy of approximation and tends to make models angler (not smooth). As paper is flexible and can be bend, by bending paper we can make smooth and more sophisticated figures instead of simply representing them with a set of polygons.

(a)

(b)

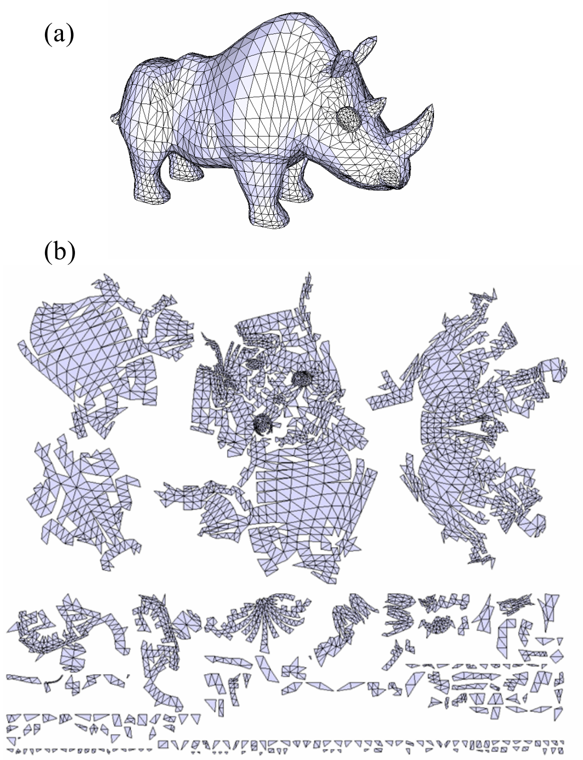


Figure 1. (a) A mesh model of a rhinoceros that has 4624 triangles. (b) The unfolded pattern of the model.

In this paper, we propose a new method for creating unfolded patterns for smooth papercraft models. We start from low triangle mesh model and then apply subdivision method to create smooth strips. After that, we apply edge-swap operation to smoothen the strips. This new approach is a natural way to design models because the creation of a smooth dense mesh model usually starts from a low resolution model.

2. Related works

2.1. Making strips

A triangle strip, a common concept in graphics APIs [3], is a sequence of triangles as illustrated by Fig.2a. Unfolding a polyhedron (or any closed set of faces) requires cutting, but a strip can easily be unfolded without cutting (see Fig.2b) as long as the unfolded triangles do not intersect in the plane. Normally, each edge of an unfolded pattern will be bent when the figure is crafted, but sometimes the two mesh triangles are almost coplanar and the edge remains no be bent, leaving a smooth surface in the crafted figure.

Elber's method approximates a parametric surface by a set of ruled surfaces such as part of a cone or a cylinder and then approximates these in turn by triangle strips [4].

Previously we proposed a method that creates a set of strips from a target mesh model that has dozens of thousands of triangles [5]. This method has the advantage that no approximation by ruled surfaces is needed – it is purely a mesh method. One of the goals of this method is to approximate the triangulated mesh model by a set of 'smooth' triangle strips where many edges need not be cut when crafting. In this method, we firstly generate charts that correspond to the shape of a strip. The contours of the charts become cut-lines and the inner vertices are removed (Fig.3). The point of this method is that when the strips are smooth enough, we can treat them as approximate unfoldable surfaces. The method we propose in this paper is based on the same concept. We use a set of smooth strips to represent a 3D model. The difference between the method in [5] and ours is that our method starts from a low polygon and uses subdivision. Hence, it can be considered that ours is a reverse approach.

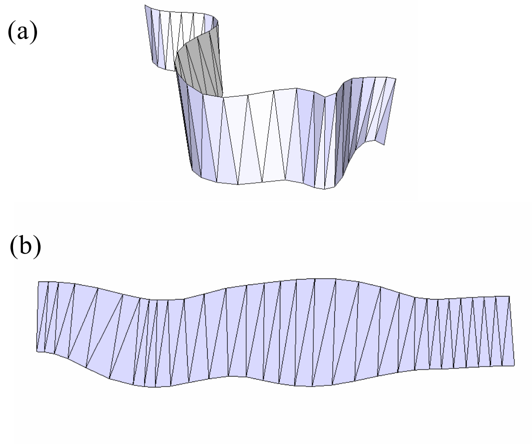


Figure 2. (a) A strip. (b) The unfolded pattern.

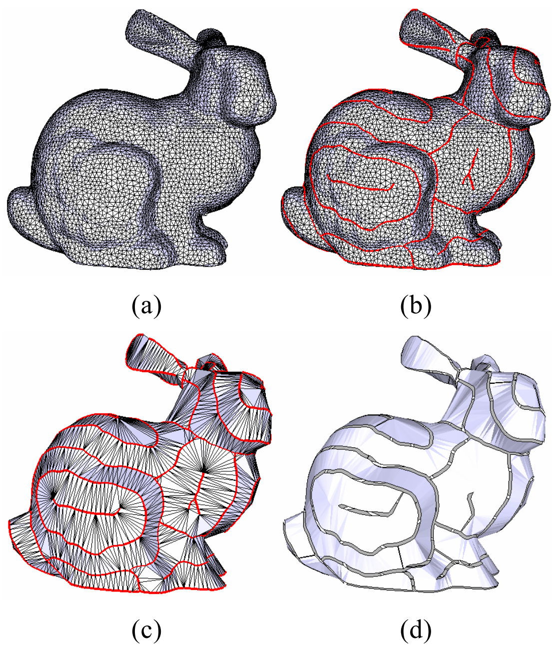


Figure 3. Overview of the method proposed in [5]. (a) An initial mesh model. (b) Cut-lines (colored in red). (c), (d) Generated strips by mesh simplification.

2.2. Subdivision methods

Subdivision method is a strategy in making smooth surfaces by repeatedly applying divide operation to a low polygonal model. The subdivision method is easily applied to a topologically complex model and does not require consideration of connectivity of patch boundaries. Subdivision method is commonly used for designing animations of character model [6].

There are some methods for generating subdivision surfaces and they are being summarized well in [7].

Generally a subdivision surface is defined as a result of applying infinity divisions, but the convergence to the surface is quite rapid. Sufficiently smooth approximate surfaces can be generated after applying several times of divide operations. Most of subdivision methods consist of two steps, namely the topological division (Fig.4) and the calculation of vertices' position [8].

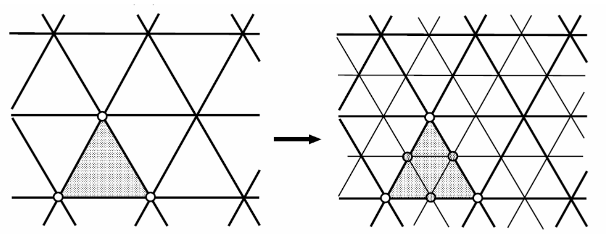


Figure 4. Topological division of face division.

The topological division step defines how to divide a mesh, while the calculation step defines the position of vertices by considering positions of connected vertices (1-ring vertices) and pre-defined weight masks.

Existing subdivision methods are mainly classified using the following 4 terms:

- The type of topological division: face division or vertex division.
- The type of generated mesh: triangle mesh or square mesh.
- The way of defining vertices position: interpolation or approximation.
- The connectivity of limit surfaces: C^1 or C^2, etc.

The interpolate subdivision is a method that only moves vertices which are inserted during the topological division step. On the other hand, approximate subdivision moves both inserted vertices and vertices existed before topological subdivision. Generally, the latter generates smoother surfaces than the former. As the approximate subdivision treats the initial mesh vertices as control points of surfaces, it has a drawback that the subdivided surfaces shrink compare to the initial mesh. Here, we use the approximate subdivision method proposed by Hoppe, *et al*[9]. The details are described in Sec.3.2.

3. Method

The flow of our method is as follow:

(1) Prepare a low triangle mesh model (Fig.5a).

(2) Unfold the model on a plane (Fig.5b).

(3) Edit the unfolded pattern according to users' preference (Fig.5c).

(4) Subdivide contour edges in the 3D model (Fig.5d, e and f).

(5) Execute edge-swap operation so that the model becomes smoother (Fig.5g).

(6) Unfold the modified model onto a plane (Fig.5h and i).

The details of our method are described in the following subsections.

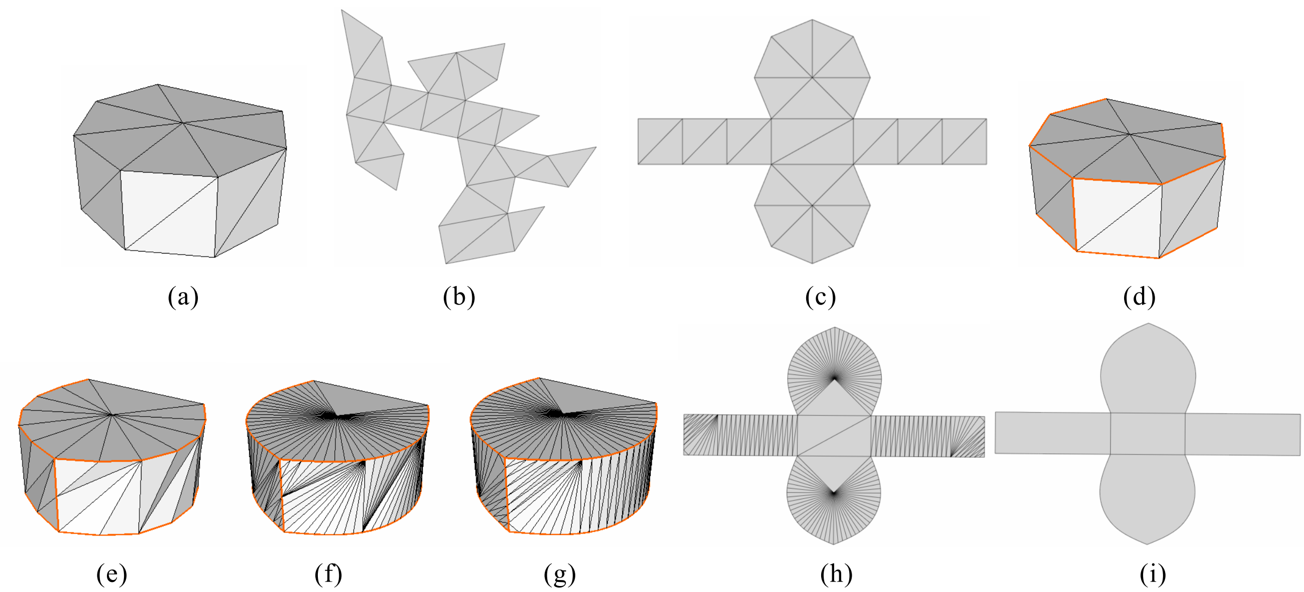


Figure5. Flow of our method. (a) The initial low polygon. (b) The unfolded pattern. (c) The edited pattern. (d) Contour edges of the pattern are colored with Orange. (e, f) Subdivision operations are applied. (g) Edge-swap operations are applied. (h, i) The unfolded pattern of (g).

3.1. Unfolding a low triangle mesh model

We start from a low triangle mesh model. Unfolding a triangle mesh model is straightforward. Firstly, one of the triangles in the model is placed on the plane whereby recursively triangles are added, connected to existing triangles on the plane. If and when they intersect, they are divided into two parts. If we are not satisfied with the pattern, we can rearrange the pattern by splitting or connecting parts manually. It is not difficult in this case because the target model does not have a lot of faces.

3.2. Subdivision of contour edges

After creating an unfolded pattern, each part corresponds to a strip that does not have any inner-vertices. The edges in the unfolded pattern are categorized to two groups, namely the inner-edges and the contour-edges. Because a strip is not allowed have any inner-vertices, we adopt a subdivision method only to contour-edges.

The usual subdivision method inserts vertices on every edge and divides 1 triangle into 4. But the subdivision method we propose is different. We only insert new vertices on edges which are contours of the unfolded pattern. Fig.6 shows the difference of topological subdivision applied to the initial mesh (Fig.6a) between the usual 1-to-4 division and ours. The grayed points in the figure show the newly inserted vertices. Fig.6d and (e) show the results of both subdivision methods. Fig.6e shows that the resulted mesh has thin triangles and they are arranged in the figure of a strip.

After the topological subdivision step, we adjust vertices to smoothen the strip. To achieve this, we use a subdivision mask proposed by Hoppe, *et al.* [9]. Although some masks are proposed in their work, we only adopt the mask for 'regular crease edge' and 'regular crease vertex' to the contour edges. The masks introduced by Hoppe, *et al.* and the masks we use are shown in Fig.7.

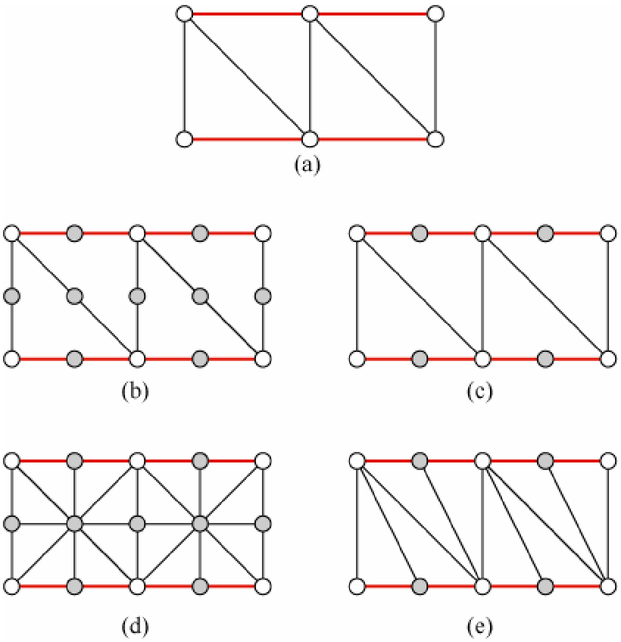
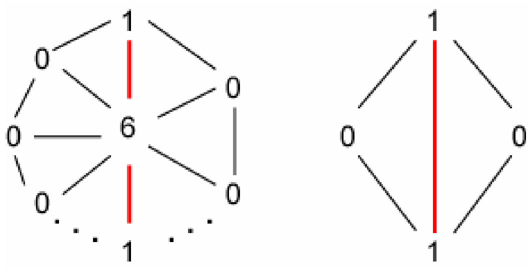


Figure 6. Comparison of the usual subdivision method ((b) and (d)) and ours ((c) and (e)). (a) is the initial mesh.



(a) (b)

Figure 7. Vertex and edge subdivision masks. (a) is for regular crease vertices and (b) is for regular crease edges.

3.3. Edge-swap for smoothing

After the subdivision step, we use an edge-swap operation to smoothen the strips. The edge-swap (Fig.8) is only applied to edges that are not contour edges and only if the angle (second order difference) becomes smaller by applying it. This operation is repeated until the number of edges that should be swapped becomes zero or the swaps are done predefined number of times.

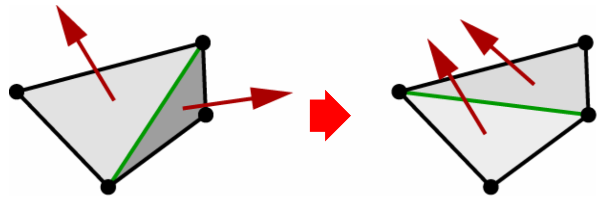


Figure 8. Edge-swap operation.

3.4. Unfolding a modified model

Lastly, we unfold the subdivided and edge-swapped mesh model to the plane. The inner edges are adjusted to be connected in the pattern as much as possible, while the contour edges remain on the contour so that the figure of every part does not change extremely compared to those of a low triangle mesh model.

4. Result

We implement a system using VC++ on a PC.

Fig.10 shows the result of our method applied to a model of Japanese Daruma. This shows the difference between the two different cutting fashions. One is unfolded by cutting vertically ((a), (b) and (c)), while the other is unfolded by cutting horizontally ((d), (e) and (f)). (a) and (d) are the initial models whereby the cut lines are specified by red lines. (b) and (e) are the subdivided models. (c) and (f) are the unfolded patterns. It is clear that a single model can be represented as a smooth model by different ways according to the location of cut lines.

Fig.11 shows the results applied to a horse model. (a) and (c) are the initial models. The lines highlighted as orange color are cut lines. The subdivided model is (b). (c) and (d) are zoomed head of the horse of (a) and (b) respectively. (e) is the pattern generated from the initial model, while (f) is the resulted pattern after 3 subdivisions.

5. Conclusion

We proposed a new method for creating smooth models that consist of a set of smooth strips. We confirmed that the created model can be unfolded easily. The operation is quite simple and users can easily control the way of smoothing. This method is useful for designing curved papercraft models.

6. Future works

The density of triangles in a strip is decided by the number of times of subdivision and the size of the initial triangle. In future we want to control the number of times of subdivisions for each triangle so that the resulted strips possess almost the same density. We will have to control the edge-swap operation without disturbing the texture mapping for target model having UV coordinates.

7. Acknowledgements

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B), 17700131, 2005.

References

[1] Tama Software Ltd. "Pepakura Designer", http://www.tamasoft.co.jp/pepakura-en/ , 2004

[2] Cohen, J. D. "Concepts and Algorithms for Polygonal Simplification", SIGGRAPH 99 Course Tutorial #20, C1-C34. 1999.

[3] Neider, J., Davis, T., and Woo, M. "OpenGL Programming Guide. Addison-Wesley, 1993.

[4] Elber, "Model Fabrication using Surface Layout Projection". CAD 27, 4, 283-291, 1995.

[5] Jun Mitani and Hiromasa Suzuki. "Making Papercraft Toys from Meshes using Strip-based Approximate Unfolding", ACM Transactions on Graphics, 23, 3, 259-263, 2004.

[6] Tony DeRose, Michael Kass, and Tien Truong. "Subdivision surface in character animation". In Computer Graphics(Proc. SIGGRAPH 98), 85-94, 1998.

[7] Shingo Takeuchi, "Free form modeling using subdivision surface fitting", Master's thesis, Univ. of Tokyo, 1999.

[8] Schr¨oder and Denis Zorin et al. "Subdivision for modeling and animation", In Computer Graphics(Proc. SIGGRAPH 98 Course Notes), (36), 1998.

[9] Hugues Hoppe, Tony DeRose, Tom Duchamp, Mark Halstead, Hubert Jin, John McDonald, Jean Schweitzer, and Werner Stuetzle. "Piecewise smooth surface reconstruction". In Computer Graphics(Proc. SIGGRAPH 94), pages 295-302, 1994.

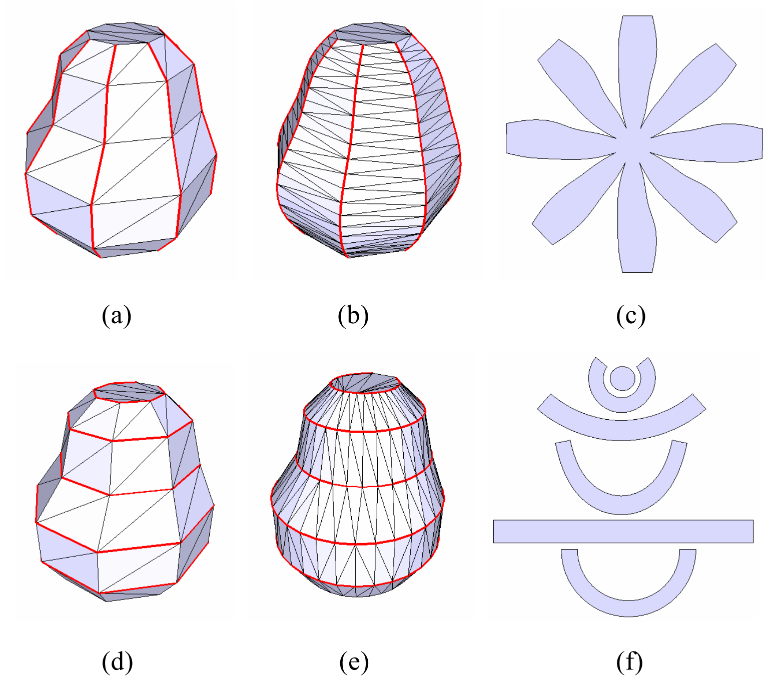


Figure 10. Initial model with cut-lines ((a) and (d)). Subdivision and edge-swap operations are applied twice ((b) and (e)). The unfolded patterns ((c) and (f)).

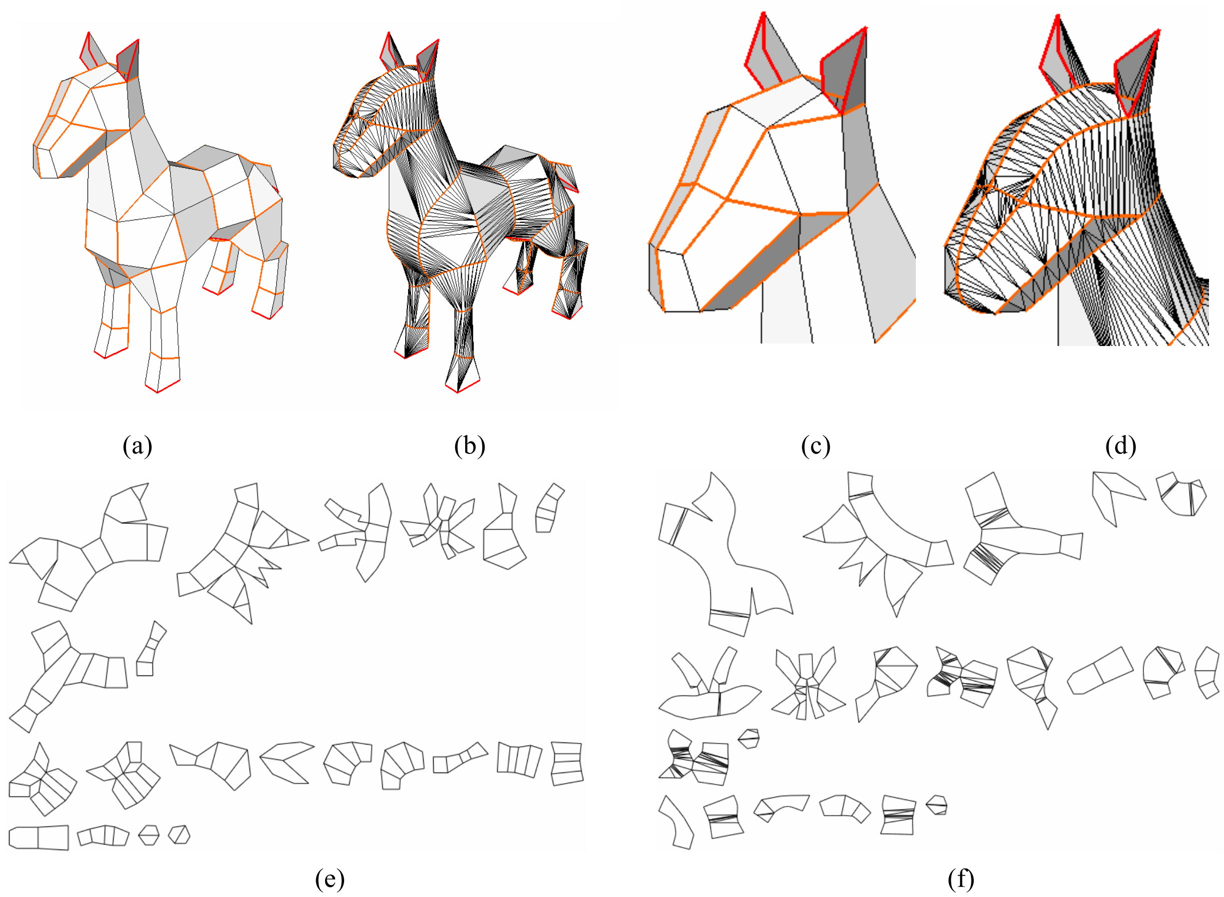


Figure 11. (a) Initial model with cut-lines. (b) Subdivision are applied three times and the edge-swap operation is applied. (c), (d) The zoomed head of (a) and (b). (e), (f) Unfolded pattern of (a) and (b).