Title:
Surface Segmentation based on Concave Region and Flattenability

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Introduction:

Surface segmentation is widely applied in digital modeling, 3D model construction and identification. In garment industry, a 3D-2D-3D process is commonly used to segment a 3D human body surface into 2D patterns for cutting the material into patches before reshaping the patches into the 3D body shape. Accuracy is essential to unfold a 3D surface into 2D patches that will be formed back to the 3D shape. Based on the computational geometry, only developable surfaces such as cylindrical and cone can be unfolded into a 2D plane without deformation and distortion. As most 3D free-form surfaces are non-developable, it is a challenge to unfold non-developable 3D surfaces into 2D patches with less deformation and distortion. Some cutting lines can be added on the original non-developable 3D surface to reduce deformation and distortion. Thus, the problem of non-developable 3D surface unfolding becomes the selection of a suitable position to add cutting lines.

Flattenability can be used to measure the surface ability to be unfolded into 2D patterns. This paper combines the concave region and flattenability to propose a surface segmentation method based on the extraction of surface features that include the vertex-level concave region, triangle-level concave region, curvature-level concave region and flattenability. Cutting lines are then fitted based on feature vertices by curve fitting.

Main Idea:

The proposed method of the surface segmentation is described in Fig. 1. The input is a triangular mesh surface model. Surface features are first extracted. Feature vertices that satisfy all the features are used to form segmentation regions. A curve fitting method is then applied to design cutting lines to divide the surface into several parts using a least-squares fitting method. After then, the 3D surface is segmented into several segments to be unfolded into 2D patterns with less deformation and distortion.

Implementation

The topology structure of a mesh surface M is defined as a set $\{V, E, F\}$ including vertices, edges and triangles. $V = \{v_i \mid v_i \in R^3, 1 \le i \le m\}$ is a vertex set with m vertices. $E = \{e_{ij} = (v_i, v_j) \mid v_i, v_j \in V, i \ne j\}$ is an edge set, $F = \{f_{ijk} = (v_i, v_j, v_k) \mid v_i, v_j, v_k \in V, i \ne j, j \ne k, i \ne k\}$ is a triangle set. N^i is the set of one-ring neighborhood vertices of v_i. Surface features including concave regions and flattenability are selected to search segmented regions for cutting lines. Three regions include vertices-level concave region, triangle-level concave region and curvature-level concave region.

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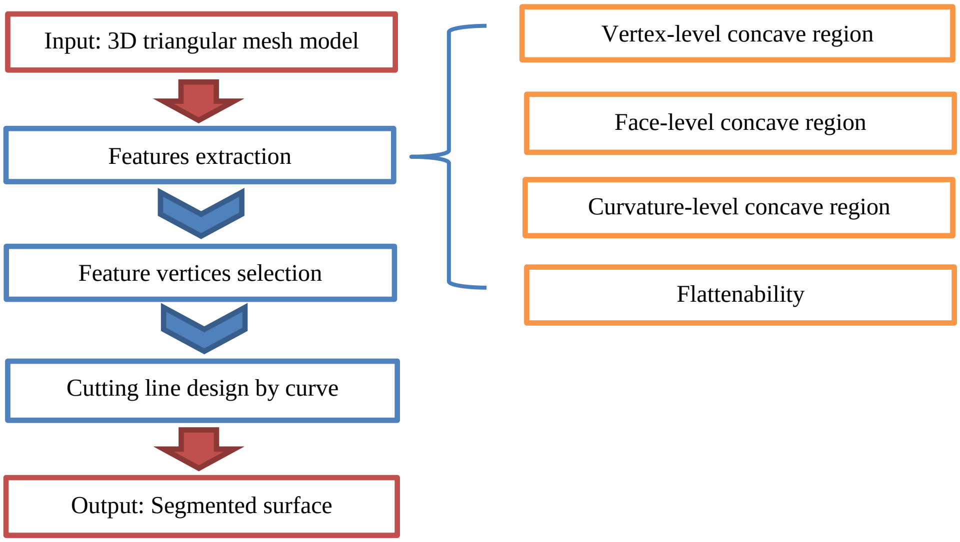

Fig. 1: Flowchart of the proposed surface segmentation method.

For searching the vertices-level concave region, vertex v_i is considered as a concave vertex if at least one adjacent vertex $v_j \in N^i$ satisfies Eqn. (1) [1].

$$\left\langle \frac{v_i - v_j}{\| v_i - v_j \|}, N(v_j) - N(v_i) \right\rangle > \varepsilon_1 \tag{1}$$

where $N(v_i)$ and $N(v_j)$ are the unit normal vectors of v_i and v_j, respectively.

The triangle-level concave region is searched as follows. For triangle f_i and its adjacent triangle f_j, vertices on common edges of f_i and f_j are concave vertices if the relation of f_i and f_j satisfies Eqn. (2).

$$\frac{\cos\alpha_i + \cos\alpha_j}{2} > \varepsilon_2 \tag{2}$$

where α_i is the angle between the normal vector of triangle f_i and the line connecting centroids of f_i and f_j. α_j is the angle between the normal vector of triangle f_j and their centroids as shown in Fig. 2. [2]. $\cos\alpha_i$ is calculated as follows.

$$\cos\alpha_i = \frac{\langle N(f_i), (c_i - c_j) \rangle}{\| N(f_i) \| \cdot \| c_i - c_j \|} \tag{3}$$

where, c_i and c_j are centroids of f_i and f_j, respectively. $N(f_i)$ is normal vectors of f_i [2].

For searching the curvature-level concave region, vertex v_i is a concave vertex if the mean curvature in vertex v_i satisfies Eqn. (4). v_i is decided by Eqn. (5).

$$H(v_i) > \varepsilon_3 \tag{4}$$

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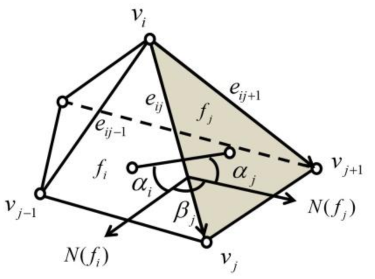

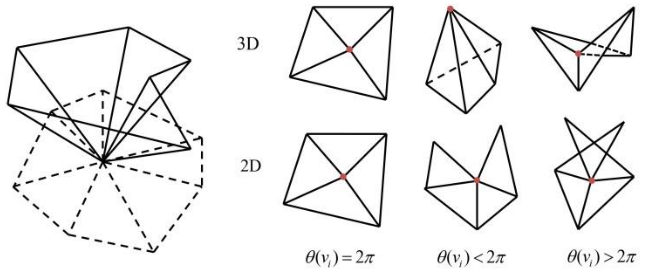

Fig. 2: Schematic diagram for mesh surface. Fig. 3: $\theta(v_i)$ for surface with different inner angles [4].

$$H(v_i)=\frac{1}{4}\sum_{j=1}^{n}\| e_{ij} \| \beta_j \tag{5}$$

where β_j is a dihedral angle for triangles f_i and f_j, and $\| e_{ij} \|$ is the length of an edge as shown in Fig. 2.

Flattenability at v_i is defined in Eqn. (6). A lower value of $\varpi(v_i)$ means that when unfolding a 3D shape into 2D patterns, the unfolded 2D patterns have less distortion and deformation. Thus, if $\varpi(v_i)$ satisfies Eqn. (7), v_i is a feature vertex.

$$\varpi(v_i)=\left|\theta(v_i)-2\pi\right| \tag{6}$$

$$\varpi(v_i)>\varepsilon_4 \tag{7}$$

where $\theta(v_i)=\sum_j \theta_j$ is the summed inner angle in vertex v_i, as shown in Fig. 3. If $\theta(v_i)=2\pi$, one-ring neighborhood triangles of v_i can be unfolded into a 2D plane without distortion and deformation. If $\theta(v_i)<2\pi$ unfolding one-ring neighborhood of triangles of v_i will cause gaps. If $\theta(v_i)>2\pi$, unfolding one-ring neighborhood triangles of v_i will cause overlaps.

Flattenablility value (FLV) is applied to measure the flattenablility of the surface [3].

$$\mathrm{FLV}=10\times 0.5^{\sum_{i=1}^{m}\left|\theta(v_i)-2\pi\right|} \tag{8}$$

Feature vertices are vertices that satisfy Eqns. (1, 2, 4, and 7) simultaneously. ε_1 to ε_4 in Eqns. (1, 2, 4, and 7) are the thresholds defined based on the shape of the model to generate enough feature vertices. After generating feature vertices, a curve fitting method is applied to segment the surface into several parts based on feature vertices. The 3D surface is first projected into a 2D plane. Cutting lines between two segments' boundaries are easy to put together into a whole surface. Thus, a polynomial function is applied as cutting lines between two adjacent segments as follows.

$$v^y = f(v^x)=a_1 v_x^n + a_2 v_x^{n-1}+\cdots+a_n v_x + a_{n+1} \tag{9}$$

The least-squares fitting method calculates the function of cutting lines by minimizing the objective function as follows. After generating cutting lines, the surface is segmented into several segments.

$$\min \sum_{i=1}^{N}[f(v^x;a_1,a_2,\cdots a_{n+1})-v^y]^2 \tag{10}$$

where N is the number of feature vertices.

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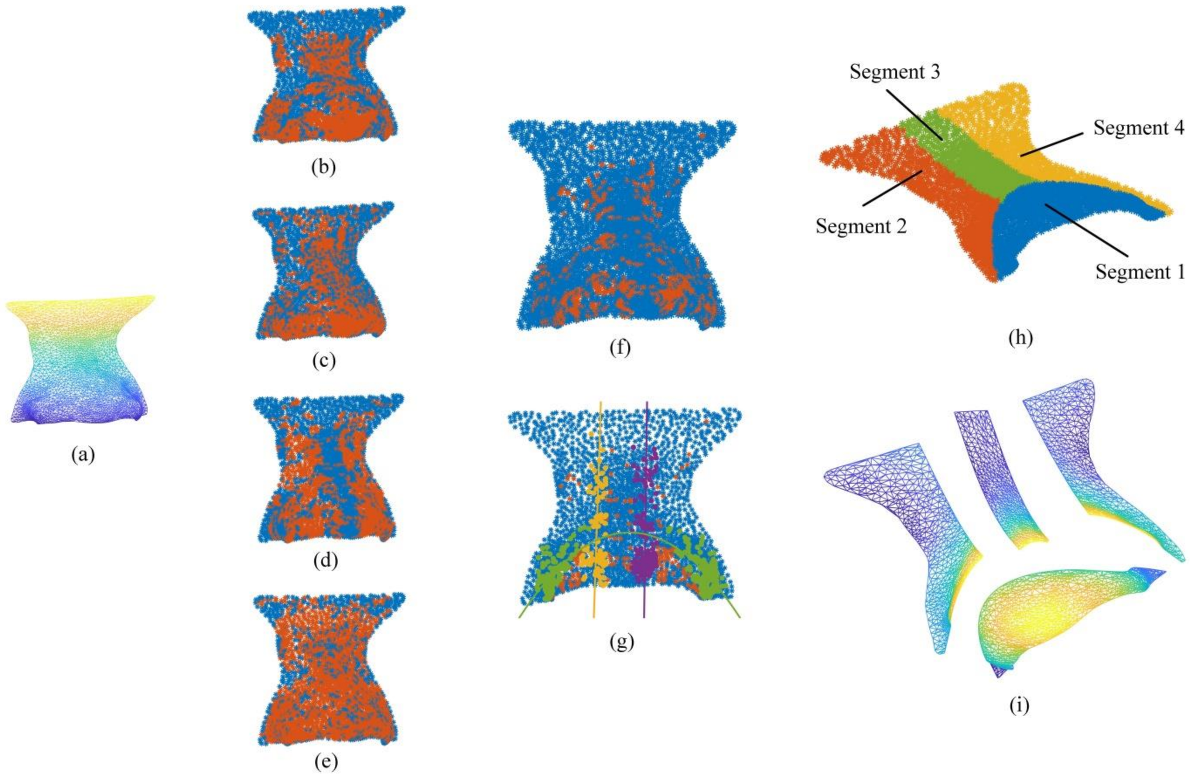

Fig. 4: Segmentation of the nose model.

Human nose model		*No. vertices*	*No. edges*	*No. triangles*	$\sum\varpi$	*FLV*
Whole model		3039	17883	8999	12.3425	0.0019
Segmented model	*Segment 1*	1248	3512	2265	6.0692	0.1489
	Segment 2	900	2487	1588	1.6734	3.1350
	Segment 3	695	1872	1178	0.9884	5.0404
	Segment 4	942	2611	1670	3.6115	0.8181

Tab. 1: Segmentation results of the human nose model.

Car shell model		*No. vertices*	*No. edges*	*No. triangles*	$\sum\varpi$	*FLV*
Whole model		3775	10981	7200	46.6140	9.3×10^{-14}
Segmented model	*Segment 1*	1506	4266	2753	21.4210	3.6×10^{-6}
	Segment 2	901	2505	1605	10.4642	0.0071
	Segment 3	1018	2797	1779	5.5552	0.2127
	Segment 4	908	2461	1556	9.0105	0.0194

Tab. 2: Segmentation results of the car shell model.

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Case study

A human nose model and a car shell model are segmented in this study to reduce deformation when unfolding them into 2D planes. Both of them are non-developable surfaces.

The nose model contains 3039 vertices, 17883 edges and 8999 triangles as shown in Fig. 4(a). The value of $\sum\varpi$ for the model is 12.3425. Red areas in Fig. 4(b) are regions with the large value of ϖ. Red areas in Figs. 4(c) (d) and (e) are the vertex-level concave region, triangle-level concave region, and curvature-level concave region, respectively. Red areas in Fig. 4(f) are feature vertices selected from vertices in red areas in Figs. 4(b) (c) (d) and (e). Curve fitting is applied to generate cutting lines for segmenting the nose model as shown in Fig. 4(g). The segmented result of the model is shown in Fig. 4(h) and Tab. 1. FLV is applied to measure flattenability of the model, where a larger value of FLV means the surface is more developable. Tab. 1 lists the number of vertices, number of edges and number of triangles for the whole surface and segmented results. Values of $\sum\varpi$ decrease and values of FLV increase after the segmentation. FLV of the whole model is 0.0019. The model is segmented into 4 pieces with FLV 0.1489, 3.1350, 5.0404 and 0.8181, respectively. The segmented results of the nose model are shown in Fig. 4(i).

The car shell model contains 3775 vertices, 10981 edges and 7200 triangles. The value of $\sum\varpi$ for the model is 46.6140. The segmented result of the car shell model is listed in Tab. 2. After the segmentation, values of $\sum\varpi$ decrease and values of FLV increase. FLV of the whole model is 9.3×10^{-14}. The model is segmented into 4 pieces with FLV 3.6×10^{-6}, 0.0071, 0.2127 and 0.0194, respectively.

For both human nose and car shell models, values of FLV for each segment increase significantly compared to the model without segmentations, which shows that segmented surfaces can be unfolded into 2D patterns with less deformation and can also maintain accuracy when 2D patches are formed back to the 3D shape.

Conclusions:

This paper proposed a model segmentation method by combining the concave region and flattenability to generate segments from a 3D surface to 2D patterns with less deformation and distortion. Vertex-level, triangle-level and curvature-level concave regions, and flattenability are features for selecting segmenting regions. Vertices in these concave regions with the large value of ϖ are selected as feature vertices. Curve fitting is applied to find cutting lines for the final segmented result. Two case studies validated performance of the proposed method. The FLV of surfaces is increased significantly after the segmentation.

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