Interactive Feature Extraction on 3D Meshes

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ABSTRACT

Feature lines, curves on a surface along which the surface bends sharply, convey specific 3D shapes. In this paper, we present an interactive method for extracting feature lines on 3D meshes. Our method first estimates the principal curvatures and principal directions on local neighborhoods. Then we compute an initial approximation of the feature lines on the global meshes by using a threshold. The threshold controls the number of feature points to keep the most important shapes for the global surface. To capture the interesting features accurately, we finally use an interactive method based on regional meshes. Some examples are presented to illustrate the usefulness of our method. Compared with other automatic methods, our method possesses the advantage of convenience to capture the feature points.

Keywords: principal curvature, feature lines, interactive extraction, 3D meshes.
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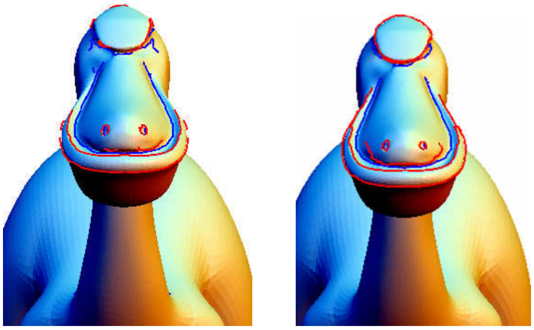

Fig. 1: Comparison of our interactive method with the global method. Left: a global method based on the global threshold often gets some spurious feature lines or incomplete feature lines. Right: our interactive method can effectively modify the feature lines fragments that a global method lost. Ridge lines are marked red and ravine lines are marked blue.

1 INTRODUCTION

Feature lines, curves on a surface along which the surface bends sharply, are powerful shape descriptors. Mathematically the sharply bended curves of the surface are described via extrema of the surface principal curvatures along their corresponding lines of curvature. From human perception, Features are usually defined as entities of an object that are considered important by a human for an accurate description of the object. Forrester Cole [2] pointed out that lines draw by artists largely overlapped one another and correlated strongly with predictions made by the definition of feature lines in computer graphics. Feature lines have numerous applications in object registration[3], growth simulation [4], surface segmentation [5] and non-photorealistic rendering [6, 7].

We have witnessed significant advances in the extraction of feature lines on polygonal data, volume data and point-sampled surfaces over the last decade [8-14]. The existing methods mainly use a threshold, e.g. top 10-30% points with high principal curvatures (absolute value), to extract the feature automatically. However, a purely automatic method may not necessarily be a good method for feature detection algorithm because some features that can help us to infer shape easily may not be of global importance, but of regional importance. Furthermore, noise and irregularities of the triangulation make the method only based on the global threshold often get some spurious feature lines or incomplete feature lines. As an example, the feature lines extracted by the global threshold are shown in the left of Fig. 1, where the resulting feature lines are incomplete and inaccurate.

In this paper, we propose an interactive system for quick and accurate generation of feature lines from 3D meshes. Our method firstly extracts the feature lines on global meshes by threshold. The features extracted on this phase are globally important and some features of less global importance may be lost, so the feature lines on this phase is probably incomplete. On the next phase, we use an interactive method to re-compute the feature lines of regional importance in a selected region. The right of Fig. 1 shows that our interactive method can effectively find out the feature lines that an automatic and global method loses.

The next section reviews the related work in the field of feature lines detection. In Section 3, we describe necessary background of differential geometry. In Section 4, we firstly discuss the detection of feature lines on global meshes, and then we integrate the interactive method with the automatic method to detect the feature lines accurately. Section 5 shows various experimental results and finally, Section 6 concludes this paper.

2 RELATED WORK

For the past decade or so, a wide variety of techniques have been proposed in the field of feature extraction on 3D meshes. Mathematically, feature lines on a surface are the loci of points where the maximal principal curvature takes a positive maximum along its curvature line, or the loci of points where the minimal principal curvature attains a negative minimum along its curvature line. Prior to the extraction of feature lines, we need to calculate their principal curvatures and directions. Then, we evaluate whether a point is a feature point or not.

Principal Curvature Estimation Principal Curvature estimation has become a basic step in many computer graphics algorithms because of the rapid development of 3D scanning and acquisition technology. There are three principal curvature estimation methods outlined below [15]. The first is the normal curvature approximation method [1, 16]. The tensor of curvature of surface at the each mesh point was estimated. The principal curvatures values and directions were obtained as eigenvalues and eigenvectors of a symmetric matrix. The second is the surface approximation method [17, 18]. To achieve a fast and accurate estimation of the principal curvatures a bivariate polynomial was fitted locally to the neighborhood of each mesh vertex. The third is the Finite volume method [19]. The method incorporates the Laplace-Beltrami operator and Gauss-bonnet theorem to derive the mean curvature and the Guassian curvature. The principal curvatures at the vertex can be consequently computed. Here, the computation of curvature in continuous case is extended to discrete meshes by computing spatial averages on surface patches of the 1-ring neighborhood (so-called finite volume in the Mechanics literature).

Features Extraction There are many developing methods for the shape description and various rules have been proposed. The contours (silhouettes) are locations at which the surface normal is perpendicular to the view direction. Suggestive contours are contours would firstly appear with a minimal change in viewpoint [9]. Apparent ridges are the loci of points at which the surface normal is changing at a locally maximal rate with respect to the viewing plane [6]. Ridge and valley lines are local maxima of principal curvature magnitude in a principal direction [11], which are also called feature lines because they can capture important surface shapes. Currently, the extraction of feature lines is a subject of intensive research in computer graphics. Burns et al. [12] created line drawings from volumetric datasets by extracting linear features such as contours and suggestive contours. Pauly et al. [14] present a feature lines extraction method on point-sampled geometry, feature lines are extracted by using a minimum spanning graph, which is modeled by a set of snakes for subsequent smoothing. Ohtake et al. [11] proposed a simple and effective method for detecting ridge-valley lines by combining multi-level implicit surface fitting and finite difference approximations. Stylianou and Farin [5] presented a reliable, automatic method for extracting crest lines from triangulated meshes. The algorithm identified every crest point, and then joined them using region growing and skeletonization. Yu-Kun Lai et al. [13] presented a robust feature extraction and classification algorithm which was used for feature-specific editing operations. Juddy et al. [6] found that view-dependent lines could better convey smooth surfaces, and they defined view-dependent feature lines to render line drawings of 3D meshes. All these methods mainly focus on the salient features that depict the apparent shape of a surface. In general, global methods do a better job in estimating the globally salient features. On the other hand, some features of regional importance may not be with high principal curvatures, but they are also important for depicting the surface shape. Specially computing of the feature lines involves estimation of high-order surface derivatives, so these surface features are very sensitive to noise. For the reasons mentioned above, the resulting feature lines only based on the global threshold are often incomplete or unclear. The interactive method provide flexibility to the users in that they can interactively choose a region to accurately recomputed the incomplete part of the feature line.

3 DIFFERENTIAL GEOMETRY BACKGROUND

Consider the local behavior of a surface $\mathbf{S}$ at a single point $\mathbf{p}$ with a given local parameterization (u,v). The unit normal $\mathbf{N}$ of a surface $\mathbf{S}$ at $\mathbf{p}$ is the vector perpendicular to $\mathbf{S}$, e.g. the tangent plane of $\mathbf{S}$, at $\mathbf{p}$. With the given non-degenerate parameterization, $\mathbf{N}$ can be calculated by $\boldsymbol{N} = \frac{\boldsymbol{S}_u \times \boldsymbol{S}_v}{\left\|\boldsymbol{S}_u \times \boldsymbol{S}_v\right\|}$. The curvature of a surface $\mathbf{S}$ at a point $\mathbf{p}$ is defined by the rate that $\mathbf{N}$ rotates in response to a unit tangential displacement as in Fig. 2. That is, $-\mathbf{T}\cdot\mathbf{N_T}$.

$$-\mathbf{T}\cdot\mathbf{N_T} = \begin{bmatrix}\partial \mathrm{u} & \partial \mathrm{v}\end{bmatrix}\begin{bmatrix}\mathbf{S}_\mathrm{u}\\ \mathbf{S}_\mathrm{v}\end{bmatrix}\cdot\begin{bmatrix}-\mathbf{N}_\mathrm{u} & -\mathbf{N}_\mathrm{v}\end{bmatrix}\begin{bmatrix}\partial \mathrm{u}\\ \partial \mathrm{v}\end{bmatrix} = \begin{bmatrix}\partial \mathrm{u} & \partial \mathrm{v}\end{bmatrix}\mathbf{II}_\mathrm{s}\begin{bmatrix}\partial \mathrm{u}\\ \partial \mathrm{v}\end{bmatrix} \quad (2)$$

Where $\mathbf{II}_\mathrm{s}$ is the second fundamental form which describes curvature information. The curvature function has maximum and minimum values that occur at directions that are orthogonal to each other. The eigenvalues of $\mathbf{II}_\mathrm{s}$ are the principle curvature values $k_{\max}$, $k_{\min}$. The eigenvectors of $\mathbf{II}_\mathrm{s}$ are the corresponding principal directions $\mathbf{t}_{\max}$, $\mathbf{t}_{\min}$. A point is called a ridge (ravine) point if $k_{\max}$ ($k_{\min}$) has a maximum (minimum). In short, we call them feature points. Feature points witness extrema of principal curvatures and their definition involves derivatives of curvatures, or third order differential quantities. Moreover, the classification of feature points as ridges or ravines involves fourth order differential quantities. Therefore, the calculation of feature points from dense triangle meshes approximating a smooth surface is not easy.

4 INTERACTIVE FEATURE EXTRACTION

Well-drawn feature lines typically contain a small number of curved lines and yet effectively convey the identifying characteristics of the surface, so that they can quickly recognize and appreciate the subject without being distracted by redundant or unimportant information. Developing methods for fast and accurate detection of feature lines on mesh or other 3D data are currently a subject of intensive research.

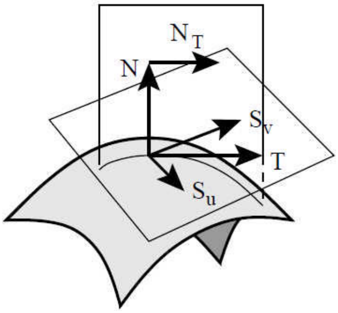

Fig.2: Normal section of S. The curvature of the normal section curve is the curvature of S in the direction T.

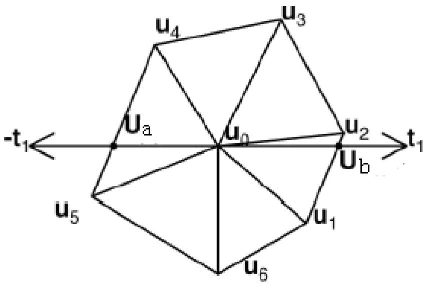

Fig.3: Feature points classification [5].

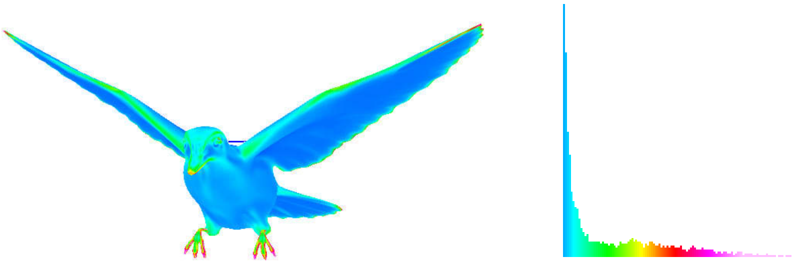

Fig.4: Left: visualize the principal curvature (maximum value) of each mesh vertex with color; Right: Corresponding histograms. Warm color represents global feature points, such as the claws, the wingtips and the back fringes of the wings. The front fringes of the wings are cool color, which are not global feature points, but they are very important to depict the shapes of the wings.

4.1 Global Feature Extraction

Practical extraction of the feature lines on meshes involves estimation of high-order surface derivatives and, therefore, is not a simple task. Prior to the feature point detection, we calculate the principal curvatures and their directions by using the normal curvature approximation method[1]. Then, we follow Stylianou's feature point classification method [5] to decide whether $k_{\max}$ ($k_{\min}$) attains maximum (minimum) along its line of curvature (see Fig.3).

1. Find the intersection between the principal direction $\mathbf{t}_1(-\mathbf{t}_1)$ and 1-ring neighborhood of u_0. Let the intersection consist of two points U_a and U_b. Get the two vertices, the endpoints of each intersecting edge, for example, point U_b belongs to the edge $u_1 u_2$.
2. Get the largest curvature $k_{\max}^{U_a}, k_{\max}^{U_b}$ of intersection points U_a and U_b, respectively, by interpolating along $(k_{\max}^{u_4}, k_{\max}^{u_5})$ and $(k_{\max}^{u_1}, k_{\max}^{u_2})$.
3. If $(k_{\max}^{u_0})^2 - (k_{\max}^{U_a})^2 > 0$, $(k_{\max}^{u_0})^2 - (k_{\max}^{U_b})^2 > 0$, then u_0 is a feature point.

Like other global methods, this method produces many insignificant feature points because of defects in the triangulated surface, e.g. a piecewise linear approximation for surface. In order to reduce the number of undesirable vertices, one way is to apply a mesh smoothing procedure before the detection procedure, a major disadvantage of this method is that smoothing may change positions of feature lines. Thresholding the result can also help. We can modify the step 3 as:

3a. If $(k_{\max}^{u_0})^2 - (k_{\max}^{U_a})^2 > e$, $(k_{\max}^{u_0})^2 - (k_{\max}^{U_b})^2 > e$, then u_0 is a feature point, where $e > 0$ is a threshold

We use a global threshold e to remove unessential feature points and guarantee that the selected feature points are globally salient points. Stylianou suggested that a good value for e was $e = 0.01$. Threshold can control the level of maximality and make the selected feature points keep the most important shape of the surface. But the global threshold parameter also filters out the regional features and makes the feature lines be fragmented and incomplete (See Fig. 1).

4.2 Interactive Feature Extraction

The existing global methods mainly focus on the globally salient feature points. However, regional feature points may not be on the most salient features. But they are also very important for depicting the surface shape. Specially, noise and irregularities of the triangulation make the resulting feature lines only based on the global threshold often incomplete and inaccuracy. In Fig. 4, we visualize the principal curvature (maximum value) of each mesh vertex with color. People can find that the claws, the wingtips and the back fringes of the wings are the most salient feature points on the model. The front fringes of the wings are regional saliency points, and they are also very important to depict the shapes of the wings. In this paper, we propose an interactive method based on the local meshes to improve the accuracy of the global extraction method. First we extract the globally salient feature points by using the global method mentioned in section 4.1. Then, we extract the regional feature points by using an interactive method to modify the incomplete or inaccuracy feature lines. There is one key change in our interactive method: we extract the feature lines in a local region instead of the global threshold parameters.

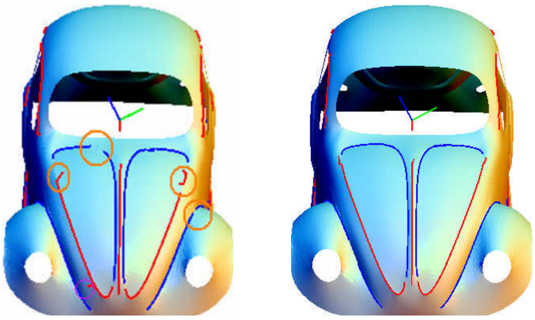

Fig.5: The extraction of feature lines on "beetle car" model. We introduce an interactive method on the right that can improve the defective parts of the feature lines on the left

Interactive feature extraction algorithm:

- Detect the most salient feature points by the global extraction method as it was showed in section 4.1. Then for each of the feature points,
  1. Label it as ridge point if its maximal principal curvature takes a positive maximum along its curvature line.
  2. Label it as ravine point if its minimal principal curvature attains a negative minimum along its curvature line.
- Interactive region selection tools are provided to click the neighborhood of defective part of the feature line to modify the defective feature line fragments. For the ridge feature line:
  1. Delete the labels of the ridge points in clicked region.
  2. Detect the regional feature points in clicked region. Sort the order by the principal curvature in the clicked region, relabel the top 20-40% points as ridge points if these points are not labeled ravine points.

3. Connect ridge points together to get the feature lines.

- Do the same procedure for ravine feature lines.

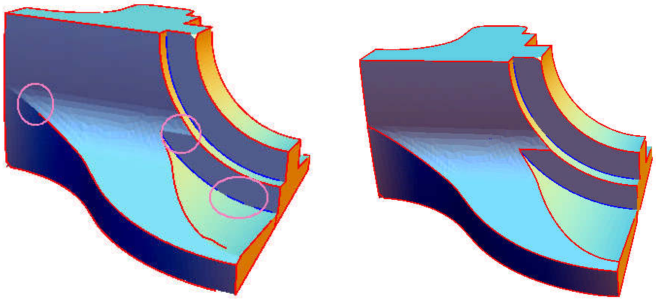

Fig.6: Feature lines extraction on Fandisk model. The piecewise smooth CAD-like model usually has large flat regions, long sharp edges and distinct corners. The representation of flat regions is often coarse. Left: Extraction by global threshold parameter. Right: Modified by our interactive method

4.3 Connecting Feature Points

Once the feature points have been detected, we need to connect them together. We follow the procedure proposed in [20] with an addition which can reduce the fragmentation of the feature lines:

1) Flag the top 80% feature points with high principal curvatures as feature points set M_1. Flag the other feature points as weak feature points set M_2. Define k-neighbor of a point $\mathbf{p}$ as $N(\mathbf{p}, k)$.
2) For a feature point $\mathbf{p}$, examine the point $\mathbf{q}$ in $N(\mathbf{p},1)$. If only one point $\mathbf{q} \in M_1$, connect it to $\mathbf{p}$.
3) If two or more points $\mathbf{q}_i \in M_1, i = 1,\ldots,n$ and $n \geq 2$, then we connected $\mathbf{p}$ to one of them by following the vertex $\mathbf{q}_i$ corresponding to the smaller dihedral with the orientation of the principal curvature.
4) No any point in M_1, but at least one point $\mathbf{q} \in M_2$. If having $k \in N(q,1)$ *and* $k \in M_1$ and $k \notin N(p,1)$, then connect $\mathbf{p}$ to $\mathbf{q}$ similarly following the rule in step 2 and step 3.
5) Repeat step 2 to step 4.

Although our scheme is not an automotive method, it extracts the points on the regional meshes and can detect the regional importance on the surface. It leads to highly effective feature lines extraction procedure which improves the detection result based on the global threshold on the first phase. Fig. 5 compares the set of feature lines extracted on 3D meshes via the global threshold method (on the left) and our interactive method (on the right).

Computing of the feature lines involves estimation of high-order surface derivatives, these surface features are very sensitive to noise, so the extraction procedure may generate some feature fragments. Ohtake[11] measures the strength of a feature line and ignores those feature lines for which the length is less than a user-specified value of threshold T. But the user-specified parameter may filter out small sharp features. In this paper, we use an interactive procedure to click and delete the unwanted feature lines (see the pink circle on the left of Fig. 5).

5 RESULTS

We have presented an interactive method for robustly extracting salient curvature extreme on surfaces approximated by dense triangle meshes in this paper. In this section, we verify the accuracy of the interactive method by comparing the results with the global threshold parameter method.

Typical result of test in Fig. 1 demonstrates how well our interactive feature lines extraction method works.

Red ridges and blue ravines are extracted on the dinosaur head model. The global threshold method can extract globally important feature points automatically, but usually gets incomplete and inaccurate feature lines fragments because of noise and irregularities of the triangulation. Note the area of the dinosaur's lips and noses in the left of Fig. 1. Our interactive method works in a local region and extracts the regional importance on the surface. Our method can modify the defective parts of the feature lines that extracted by using a global threshold as shown in the right of Fig. 1.

Fig. 4 visualizes the principal curvature (maximum value) of a dove model with color. Warm color corresponds to the sharp features and cool color corresponds to the flat regions.

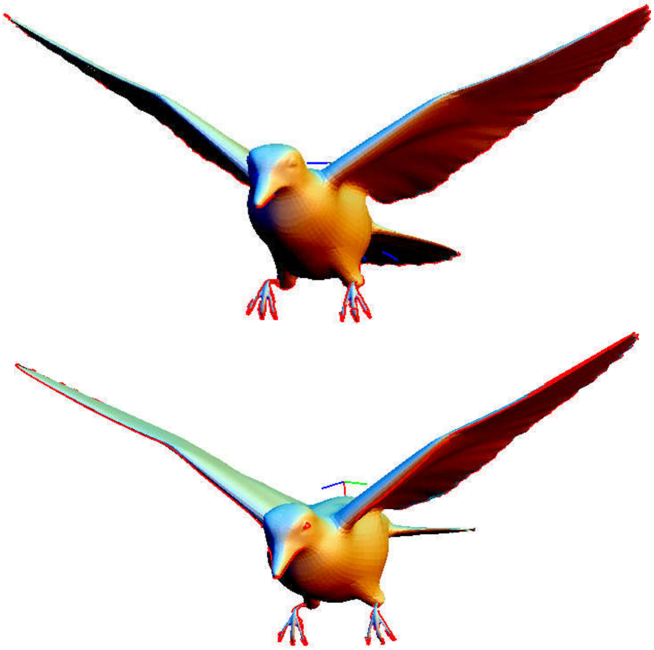

Fig.7: Comparison of our interactive method with the global threshold parameter method. The front fringes of the wings are regional saliency points, which are very important to depict the shapes of the wings. Upper: Extraction by global threshold parameter. Bottom: Modified by our interactive method.

Mathematically the sharply bended curves of the surface are described via extrema of the surface principal curvatures along their corresponding lines of curvature. The front fringes of the wings are in cool color, which are not global feature points. But they are very important to depict the shapes of the wings. In global method, we often give a threshold, e.g. top 30% points with high principal curvatures, to extract the salient features. The histogram in the right of Fig. 4 indicates the global threshold method maybe lose the regional importance.

In Fig. 5, Fig. 6 and Fig. 7, we give some comparative results.

Polygonal surface models usually can be roughly divided in two classes. The first class objects contain many visually meaningful fine details, and require very fine meshes to represent them well. See Fig. 5 and Fig. 7. The second class objects are piecewise smooth CAD-like models usually have large flat regions. See Fig. 6.

Fig. 5 gives the result of feature lines extraction on "beetle car" model. Notice the areas circled by yellow. They are the defective feature lines fragments and can be modified by our interactive method. We also use an interactive procedure to click and delete the unwanted feature lines (see the pink circle on the left of Fig. 5).

Fig. 6 is the comparison of a CAD-like model. The global method often failed in the joint of feature lines as shown in magenta circle in the left. Our interactive detection method can modify these defective lines fragments.

Fig. 7 compares our method with global threshold method by the dove model. From Fig. 4, we can find that the front fringes of the wings are of regional importance, but they are also important for depicting the surface shape. The global method lost these regional importance points and our method can find these regional importance points effectively.

6 SUMMARY AND CONCLUSION

Most feature lines extraction methods are based on the global threshold, which can detect the globally salient shape. However, a global threshold method is not a robust method because it usually loses some features that may not be a high principal curvature point on the surface, but regional importance. Furthermore, noise and irregularities of the triangulation often make the global method get some wrong results. In this paper, we have presented an interactive method for extracting feature lines on surfaces approximated by dense triangle meshes robustly. On the first phase, we use a global method to extract the feature lines that may be incomplete and inaccurate. On the second phase, we use an interactive method to click the neighborhood of the defective part of the feature line to modify the detected feature line.

Our interactive method is capable of achieving high quality results to compare with schemes based on the global threshold. It can modify the defective feature lines fragments effectively. Especially, our method is based on the local meshes, it can detect the regional importance that are also important to depict the surface shape, as demonstrated in Fig. 7. Our filtering scheme for removing unessential feature lines is also based on the interactive operation. Thus, small sharp features can be preserved, as shown in Fig. 6. Test results demonstrated its effectiveness. Since a fully automatic mechanism is always desirable, a future challenge is to find the defective parts of the detected feature lines and deduce the optimal neighborhood region to modify the inaccurate feature lines.

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