Line Drawing Approach Based on Visual Curvature Estimation

Jun Liu, Mingquan Zhou, Guohua Geng, Feng Xiao, Defa Hu

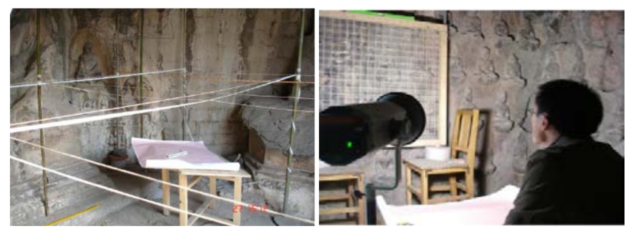
***Abstract*—**In order to effectively extract the feature lines of the three-dimensional model of the surface with noise, the reasons for the loss of texture details in the preprocessing stage are discussed and a new method of line drawing based on visual curvature estimation of the cultural relics is proposed. First, estimate the discrete curvature on triangular mesh vertex and divide the cultural relic model into the flat region and the non-flat region according to the curvature distribution; then, conduct the sharpening filter on the vertex of the non-flat region to calculate the new mesh vertex coordinates; finally, basing on the visual curvature, extract the curved contour line to achieve automatic line drawing of cultural relics of the triangular mesh model. The experimental results show that the non-flat contour lines based on the visual curvature remain the details of the surface texture of the 3D model and avoid the (?)uneven drawing lines by using the directed ridge line and valley line drawing.

***Keywords*—**cultural relics, line drawing, feature contour line,3D model, visual curvature.

I. INTRODUCTION

THE line drawing is a fundamental work in the preservation of cultural relics. In the archeological exploration, archaeologists should draw the line drawings for the fragment of cultural relics and depict its size, shape, structure, pattern and texture. A high-quality line drawing of cultural relics can be taken as the illustration in evacuation reports, dissertations, monographs and textbooks, as well as exhibition charts, and can be used for archive storage, auxiliary repairs and preservation of cultural relics, archaeological researches and cultural publishing [1]. The line drawing of cultural relics should be done according to the measured values based on manual baseline drawing, mesh division and point selection and measurement with a ruler in a traditional orthographic projection manual method, shown in Fig. 1.

The whole process features numerous work procedures, slow drawing, low-precision drawing and diversified drawing quality, and in particular, when archaeological workers continuously overturn and measure the cultural relics in line drawing, they inevitably cause secondary damages to cultural relics with cracks.



(a) Baseline method (b) Mesh method

Fig.1. Manual drawing method of archaeological line drawing

To improve the drawing efficiency and quality, archaeological departments have tried to draw line drawings by using digital photography technology. First, cultural relics which are to be drawn are placed in a specific environment for digital photography, then high-quality cultural relics images obtained in photography are imported into image processing software such as Photoshop and CorelDraw to mark the contour line of cultural relics by using the human-machine interaction mode, and separate the cultural relics and its background through matting technology. Next, images of matted cultural relics are decolorized, transforming them into black and white drawings, and then are denoised and stylized, and finally achieve the line drawing of cultural relics. With this method i for photography, the background of cultural relics should be pure in color, so that there is an obvious contract with the main color of the captured cultural relics. The light in photography should be diffused light or natural light to ensure that the contrast between the light and shades on the cultural relics is not very sharp. strong. In fact, it is very difficult to obtain orthographic project images of cultural relics in the fieldwork. In addition, manual matting is not widely used due to its consumption of time and energy.

The method of contour detection and extraction has been gradually applied to automatic drawing of line drawing of cultural relics in recent years. Typical methods are divided into three, namely, image-based edge detection, image-based non-photorealistic drawing and space-based contour line detection [2]. The project team discovers in the engineering practices that the extracted feature lines are noisy, inconsistent and not ideal when classic operators such as Sobel, Prewitt, Log and Canny are used to detect the edges of digital images of

This work was supported by the National Natural Science Foundation of China (grant number 61373117, 61673319, 61572392, 61202464), by the National Natural Science Foundation in Shaanxi Province of China (grant number 15JK1247), by Natural Science Basic Research Plan in Shaanxi Province of China (grant number 2017JC2-08), by the Natural Science Foundation of Weinan Normal University (grant number 17YKF02).

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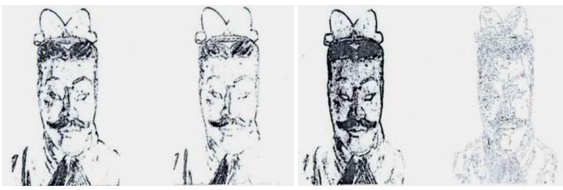
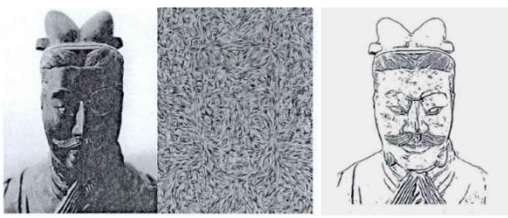
cultural relics, as shown in Fig. 2. The image-based, non-photorealistic drawing method, which can produce the integral region of the filter by constructing the edge tangential flow, can better protect the structure with directional features in the images, and ensure the consistence of the output feature lines. The feature lines of cultural relics extracted by this method are relatively consistent, but too many irrelevant feature lines to the line drawing are left on the flat region of this model, as shown in Fig. 3.



(a)Sobel operator(b)Prewitt operator(c)Log operator(d)Canny operator

Fig.2. Experimental effect of feature extraction of cultural relics of classic operators



(a) Illustration of feature line flow field of cultural relics (b) Extracted feature line of cultural relics

Fig. 3. Experimental effect of non-photorealistic drawing of feature line of cultural relics

The prerequisite for the contour line detection algorithm based on object space is the 3D model of cultural relics based on point cloud data. The direct detection method can detect if a given edge belongs to the contour line or a contour line passes through this triangular mesh sheet by traversing each edge or each triangular mesh in the 3D model. When the viewpoint of the observer changes, all contour lines will be recalculated. For non-static 3D model, this algorithm has very low efficiency. The random detection algorithm is used to detect contour line with local continuity or contour line maintaining continuous while the viewpoint changes but this algorithm does not detect all edges of the 3D model. When a small part of contour edges are found, the adjacent edges of these contour edges need detecting whether they are the contour edges, and then in recursion, keep on searching till the number of searched contour edges is bigger than the threshold. This algorithm has the advantages of easy implementation and high speed, but has the disadvantages of incapable of detecting all contour edges elow-precision in contour detection and local details loss, as shown in Fig. 4.

In fact, different from simple and geometric model-based featuring line extraction, the archaeological line drawing mainly depicts the structure and texture of the cultural relics. However, the existing methods cannot meet the requirements automatic drawing in computer-assisted archaeological line drawing [3] For example, the excessive noise smoothening will lead to details loss on the 3D model surface of cultural relics, global sharpening will make the flat region retain some disturbance featuring lines, and the line drawing by simply connecting the ridge lines or valley lines will show sharpening.

(a) 3D model (b) Based on image space (c) Based on object space

Fig. 4 Effect of contour line detection method of 3D model

II. Related research

A. Feature line related to viewpoint

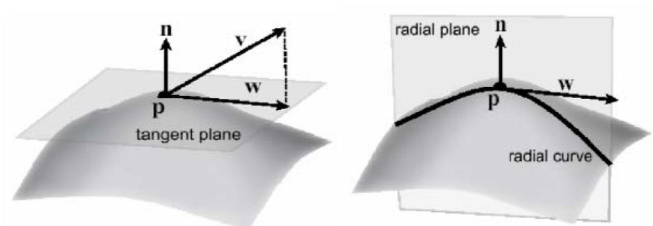
The feature line related to the sight line indicates the need to first identify the viewpoint prior to calculating the feature line. The searched feature line is related to the position of the viewpoint. The representative feature lines are described as follows:

(1) Silhouettes Contours

It indicates the set of points on the curvature in which the viewing direction is perpendicular to the normal direction. The silhouettes contours is the boundary between the visible surface and invisible surface in 3D model and depicts the 3D model shapes viewed from viewpoints with different angles. When the viewpoints change, the silhouettes contours will change. At this time, the dot product of the viewing direction and normal direction on the curvature should be recalculated.

(2) Suggestive Contours[4]

Suppose that the sight line vector v is set, vector w is the projection on the tangent plane of the point p of the sight vector v on the curvature, and the plane formed by the vector w and the normal vector n is called the radial plane, as shown in figure 5. The radial plane intersects with the curvature to form a curve, which is called a radial curve. The curvature of the radial curve on the point p is called the radial curvature of point p, which is marked as $k(w)$.



(a) w is the projection of v on the tangent plane of point p *(b)* Radial plane and radial curvature

Fig. 5 Related concepts of subjective contour

The suggestive contour indicates the set of points on the curvature, in which the radial curvature is 0 and the derivative is more than 0 in w direction. This set is represented as follows:

$$\begin{cases} k(w)=0 \\ D_w k(w)>0 \end{cases} \tag{1}$$

The suggestive contour, proposed by Decarlo in 2003, is Silhouettes contour that is found after the sight line direction is slightly changed. The suggestive contour can show more 3D model details and better reflect the shape features of 3D models. The suggestive contour found by this algorithm is the convex region in the visible region.

(3) Apparent Ridges[5]

The apparent ridge is defined as the set of the points that are the maximum values of apparent curvatures on the surface of the 3D model. Judd et al. projected the normal vector of each point on the surface of the 3D model to the apparent surface and defined the apparent curvature for each point. The apparent curvature can reflect the curvature change of each point on the surface of the 3D model from the viewpoint, as shown in figure 6. In general, computing workload for these feature lines related to the sight line is heavy. When the viewpoints change, the curvature related to viewpoint should be computed again, for which much time is needed. When the triangular meshes are plentiful, the computing efficiency is low.

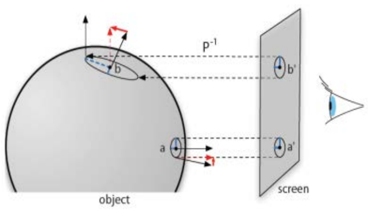


Fig. 6 Apparent curvature size diagram

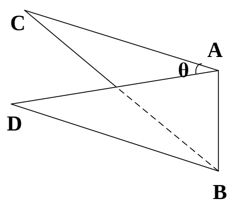


Fig. 7 Crease line

B. Feature line unrelated to viewpoints

The feature lines unrelated to the viewpoints indicate that these feature lines are related to geometric features of the 3D model but not the position of viewpoints. The representative feature lines are described as follows:

(1) Crease Lines

The crease lines indicate common edges in which the angle between two triangular meshes is less than 900, as shown in figure 7. The edge AB is the common edge of △ABC and △ABD. If the edge AB is determined as the crease line, the relation between △ABC and △ABD should satisfy the formula (2)

$$0 < \cos\theta = \frac{n_i \cdot n_j}{\|n_i\|\|n_j\|} < \varepsilon < 1 \tag{2}$$

In which θ is the angle between two adjacent triangular meshes, n_i and n_j are the normal vector of two adjacent triangular meshes and ε is the restriction threshold. For the 3D model of some specific types of cultural relics, a specific threshold can be set to obtain an effective crease line.

(2) Boundary Lines

The boundary line indicates the edge of the triangular mesh outside the model boundary, namely, the set of edges in one triangular mesh. Not all 3D models have boundary lines, e.g., the enclosed 3D model has no boundary line.

(3) Ridge Lines and Valley Lines

To draw the ridge lines and valley lines of a 3D model, first identify the ridge and valley points of the 3D model.

$$\begin{cases} e_{\max} = \partial k_{\max} / \partial t_{\max} = 0 \\ \partial e_{\max} / \partial t_{\max} < 0 \\ k_{\max} > |k_{\min}| \end{cases} \tag{3}$$

$$\begin{cases} e_{\min} = \partial k_{\min} / \partial t_{\min} = 0 \\ \partial e_{\min} / \partial t_{\min} > 0 \\ k_{\min} < -|k_{\max}| \end{cases} \tag{4}$$

In the two formulas (3) and (4), $k_{\max}$ and $k_{\min}$ are the maximum principal curvature and minimum principal curvature of the vertexes, $t_{\max}$ and $t_{\min}$ are the corresponding main directions, and $e_{\max}$ and $e_{\min}$ are called the extreme point coefficients.

After calculation according to the formula (3) and (4), the points on the 3D model are divided into ridge points, valley points and other points.

The points satisfying the conditions in formula (3) are called ridge points and the points satisfying the conditions in the formula (4) are called valley points. The ridge points are connected with the valley points according to the certain connection strategy to obtain the ridge lines and valley lines of the 3D model.

C. Apparent curvature of curves

The lengths of the arc of the plane curve can be represented as $c(s) = (x(s), y(s))$, which has significant geometric meaning. To any point v on the curve, $x(s)$ represents the distance from such point to y axis and is called the height in 0^0 direction; $y(s)$ represents the distance from such point to x axis and is called the height in 90^0 direction. In fact, it defines the function $H_\alpha : C \to R$, in which α represents the angle and is called the height function in α direction.

A series of height functions can be obtained by rotating the coordinate axis to form a function space H_α and this space includes infinite height functions. It is apparent that an infinite set cannot be processed, so the function space H_α should be sampled. The frequent method is the uniform sampling, namely taking samples at $\alpha_i = i\pi / N, i = 0,1,...,N-1$ to get N height functions to compose a set $\{H_\alpha, i = 0,1,...,N-1\}$ with N elements.

The Fig. 8(b), (e), (d) and (e) are the height functions of the five-pointed star contour in figure 8(a) in the directions of 0^0, 45^0, 90^0 and 135^0. Each height function includes partial information of the original curve. For a given point on the curve, the more height functions take this point as the extreme point of, the bigger the curvature of the curve at this point is, and the bigger the curvature value is. This indicates that the curvature can be estimated by calculating the number of directions in which the points are the extreme point.

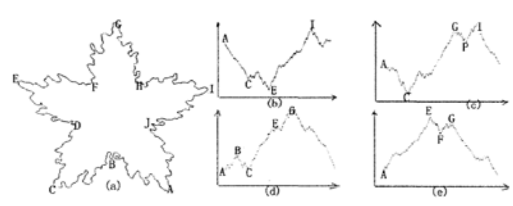


Fig. 8 Height function of five-pointed star contour in $0^0, 45^0, 90^0$ and 135^0 direction

Definition l: Visual curvature: For a point v on the curve C,

$S(v)$ represents that this point is within the ΔS wide neighborhood on the curve. The visual curvature at this point is

$$\mathrm{K}_{\mathrm{N},\Delta \mathrm{S}}(v) = \pi \frac{\sum_0^{N-1} \#\left[H_{\alpha_i}(S(v))\right]}{N\Delta S} \tag{5}$$

In this definition, $\#\left[H_{\alpha_i}(S(v))\right]$ represents the number of extreme points, regardless of maximum or minimum [6], within the neighborhood $S(v)$ of the point v in the height function H_α.

This definition indicated how to calculate the visual curvature. For a point v on the curve, first the extreme points of this height function H_α in its neighborhood are calculated, then the sum of extreme points in all height functions in this neighborhood is calculated, and finally the visual curvature of this point via the formula (5) is calculated.

D. Apparent principal curvature of curved surface

The principal curvature of the curved surface is one important intrinsic shape of a 3D object and plays a critical role in the progressive representation, curved surface analysis, and shape analysis based on visual features of a 3D model. The classical principal curvature definition is applicable to the normal curved surface and is not defined for most frequently used 3D models. Many scholars propose to use a calculation method of the principal curvature based on different scales. One method is to convolve the curved surface and a kernel function with local smoothening effect and obtain a multi-scale principal curvature by changing parameters of this kernel function. Such methods will continuously change the original curved surface, but the geometric meaning of the scale parameters is not apparent, which makes it not easy to set the scale parameters. Another method is to simplify the model and estimate the principal curvature on the simplified model. In essence, these methods belong to local estimation, are sensitive to noises, and make it difficult to eliminate small shape details in large scale. The principal curvature of one point on the curved surface is closely associated with the normal line of this point on the curved surface. In general, the normal line in the differential geometry is first defined and then the principal curvature is defined. The normal line of the curved surface is local and is susceptible to noises. To overcome this contradiction, this paper will simultaneously estimate the normal line direction and the minimization and maximization rule of the principal curvature [6].

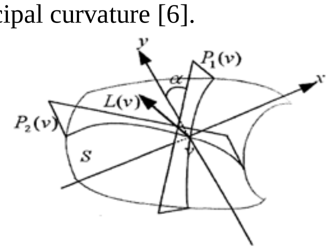


Fig. 9 Orthogonal plane group intersecting with the curved surface via the point v

As shown in figure 9, v is one point on the curved surface S, $L(v)$ is a unit vector with the point v as the starting point, $P_1(v)$ and $P_2(v)$ are two planes which include $L(v)$ and intersect with each other orthogonally, and $L(v)$ is the direction vector of the intersecting line of $P_1(v)$ and $P_2(v)$ plane. $P_1(v)$ and $P_2(v)$ simultaneously rotate around $L(v)$ and produce a series of orthogonal plane group $(P_1(v), P_2(v))_\alpha$. The intersecting line between these planes and curved surface S is the plane curve. For these plane curves, the multi-scale visual curvature is calculated.

When the scale is 0, the intersecting line between the plane group $(P_1(v), P_2(v))_\alpha$ with $L(v)$ as the common line and curved surface S has a curvature at the point v, with $K_{L(v)}$ as the maximum. Based on the differential geometry knowledge, when $L(v)$ is the normal line of the curved surface S at the point v, $K_{L(v)}$ is the minimum. Therefore, $K_{L(v)}$ can reach the global minimum by searching the $L(v)$ space and the normal direction and principal curvature can be obtained.

Definition 2: Minimization and maximization rule: Support that $C(v)$ is the intersecting line of the plane $P_1(v)$ and curved surface S and $K_{C(v)}$ is the visual curvature of $C(v)$ at this point, the visual principal curvature of the curved surface is defined as follows: For any point v on the curved surface S, $K^\lambda_{L(v)}$ is the maximum of the visual curvature of the intersecting curve of the plane with $L(v)$ and curved surface S at the point v in case of λ scale. When $K^\lambda_{L(v)}$ reaches the global minimum, the corresponding $L(v)$ is the visual normal of the curved surface S at point v and is represented as $N^\lambda(v)$. $K^\lambda_{N^\lambda(v)}$ is one visual principal curvature and is represented as pair $k_l^\lambda(v)$, seen in the following formula

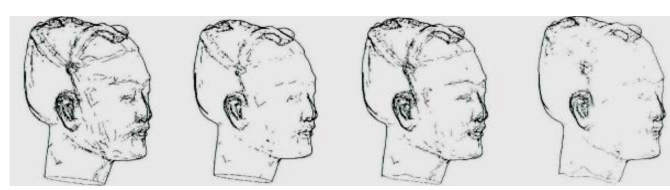
$$k_l^\lambda(v) = \frac{\min\max}{L(v)C(v)} K^\lambda_{C(v)} \tag{6}$$

The formula (6) is called the minimization and maximization rule. This rule is the method to calculate the visual normal and visual principal curvature of the curved surface.

III. Problem analysis

A. Smooth Transition leads to loss of texture details

Most point cloud models of the cultural relics are coarse and full of noises due to low precision, silhouettes and scanning environment. The project team reduces noises for the 3D model of the head of Terra-cotta Warrior by using the Taubin smoothing algorithms, but the effect is not ideal, as shown in Fig. 10.



(a) λ =0.97 prior to smoothing (b) λ =0.93 prior to smoothing (c) λ =0.97 for slight smoothing (d) λ =0.97 for heavy smoothing

Fig.10 Comparison of smoothing effect of Taubin algorithm for Terra-cotta Warrior model

Fig.10 (a) shows the feature lines extracted before smoothing treatment of the cultural relic model. Fig. 10 (c) and (d) are the feature lines extracted after smoothing treatment of cultural relic models using Taubin smoothing algorithm. The project team discovered that the change in λ value can reduce the mixed and disorderly feature lines and the boundary lines will not change the shape, but the texture details like the texture details of eyes cannot be drawn in the experiment, as shown in Fig. 10 (a) and (b). The comparison of Fig. 10 (a), (c) and (d) shows that if the cultural relic model is not smoothed, a large number of mixed and disorderly feature lines will be extracted due to noise influence. However, slight smoothing cannot fully remove influences of noises on extraction of the feature lines and excessive smoothing will lead to loss of the texture. So, how to avoid texture detail loss of culture relics in excessive smoothening becomes urgent in the research.

The experiment shows that generally the apparent concave and convex parts have bigger curvature on the curved surface. These apparent concave and convex regions are also the important region for detailed drawing in the line drawing. The Gauss curvature and mean curvature calculated using the Voronoi method proposed by Meyer have smaller errors and the feature region of the detected triangular mesh model is more accurate. Therefore, the extracted feature line has better effect and can better distinguish the region (namely feature region) and flat region where the normal vector of the curved surface changes quickly.

Definition 3: The feature region is the region on the 3D model of the cultural relic where the curvature changes significantly and the absolute curvature is bigger.

Definition 4: The flat region is the region on the 3D model of the cultural relic where the curvature changes slightly and the absolute curvature approximates to zero.

Definition 5: Mean of λ field is the reference threshold for the local smoothing of cultural relic model of specific type as identified by referring to the archaeological experiences and analyzing experimental statistics.

The archaeological persons focus on the curves which reflect geometric change on the surface of cultural relics in completing the cultural relic line drawing. Although the ridge lines and valley lines occur at the extreme point of the 3D model curvature of cultural relics and the important structural properties of cultural relics can be captured, the line drawing will be sharp and unable to form the natural and visual line drawing of the cultural relics because the ridge line and valley lines are embedded in the object's surface and will not slide with the changes of viewpoints.

B. Introduction of minimization and maximization rule

The visual curvature and the classic curvature measure the bending degree of the curve at a point. The visual curvature uses the N-sample set $\{\mathrm{H}_\alpha, i = 0,1,..., N-1\}$ of the function space H_α, which indicates that the visual curvature depends on the sampling rate. The sampling process can reduce information. If the sampling rate is higher, the calculated visual curvature is more precise. In theory, when the number of the height function approximates to infinite number, the more precise visual curvature can be obtained. All extreme points, regardless of their significance, will be counted and generate same contribution in the definition of the visual curvature, , so the curvature is susceptible to noises.

Fig. 8 shows that if the curvature of a point is bigger, this point is the extreme point in the height function in more directions. It is important that significance of different extreme points is different in height functions. Noises can generate a large amount of extreme points on the curve, but generally these extreme points correspond to smaller "peak" or "valley" in their height functions and the end points in bigger convex region or concave region correspond to bigger "peak" or "valley" in many height functions. It indicates that the shape details can be measured by measuring the corresponding "peak" or "valley" size of the extreme points via the height function, which is a new method to distinguish the shape details of different scales.

Definition 6: Multi-scale visual curvature: for any point v on the curve C, if $S(\mathrm{v})$ is the ΔS wide neighborhood, the multi-scale visual curvature at the point v is represented as follows:

$$\mathrm{K}^{\lambda}_{\mathrm{N},\Delta\mathrm{S}}(v) = \pi \frac{\sum_{0}^{N-1} \# \left\lfloor H_{\alpha_i}(S(v)) \right\rfloor}{N \Delta S} \tag{7}$$

In the formula, λ is the scale factor, $\# \lfloor H_{\alpha_i}(S(v)) \rfloor$ represents the number of extreme points, whose scales are not less than λ, of the height function H_α within the neighborhood $\Delta S(\mathrm{v})$. In the multi-scale visual curvature, only relatively important extreme points are counted and the extreme points whose scale is less than λ will be ignored.

The principal curvature of the 3D plane is a local differential component and is susceptible to noises. In general, calculation depends on the normal line of the curved surface and the normal line of the curved surface is susceptible to noises, so it is difficult to be accurately estimated. Therefore, the calculated principal curvature error is bigger. To solve this problem, this paper introduces the minimization and maximization rule.

In essence, the minimization and maximization rule gets the best normal direction by searching all possible normal directions of the curved surface and calculate multi-scale visual curvature of the intersecting lines of the plane and curved surface passing this normal line in each possible normal direction. All possible normal directions will be searched and the multi-scale visual curvature of the intersecting lines of the plane and curved surface passing this normal line will be calculated in each possible normal direction, so this algorithm is very complicated. Suppose there are t possible normal directions, for each possible normal direction, m planes passes through this direction. The mean number of points on the intersecting line of these planes and curved surface is n. For each intersecting line, the mean number of height functions is k. The complexity of the minimization and maximization rule is $o(tmkn^2)$.

To reduce the number of normal directions to be searched, one normal direction is roughly estimated and the samples are taken around this normal direction in order to ensure t minimization under the prerequisite of ensuring the normal precision and reach maximal precision at minimal cost. For each possible normal direction, infinite planes will pass through this normal line. Generally, m planes passing through this normal line can be obtained via the uniform sampling. For each intersecting line, N height functions can be obtained via the uniform sampling for the angle interval $[0,\pi]$ by referring to the visual curvature calculation formula of the plane curve. For each height function, calculate the scale of each vertex and ignore smaller extreme points to estimate the visual curvature. Finally, the best normal direction of the curved surface is selected and the visual principal curvature of the curved surface is obtained using the minimization and maximization rule.

IV. Algorithm Design

A. Basic flow

Firstly, the visual curvature of the 3D model vertex is calculated by counting the number of height functions in which the vertex is the extreme point for each vertex based on the N sample set $\{H_\alpha, i=0,1,...,N-1\}$ of the function space H_α.

Secondly, then the model is divided into a flat region and a feature region based on the visual curvature distribution of vertexes under the λ scale constraint.

Thirdly, the vertexes in the feature region are sharpened and filtered based on the mean of the archaeological field and the vertex coordinates of new triangular mesh model are calculated.

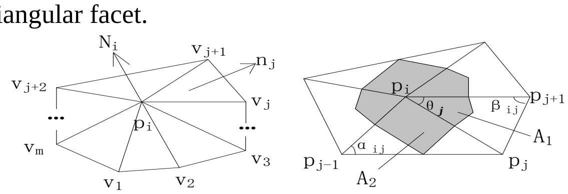
Finally the feature contours of the cultural relic model are extracted and the line drawing of the cultural relics is drawn which can satisfy the visual perception of the archaeological persons and effectively preserve the texture details.

B. Estimation of visual curvature

To calculate the visual curvature, discretization is the key and first step. To comprehensively analyze the performance of the estimation method of discrete curvature [7], this paper estimates the discrete curvature of the triangular mesh model using the Voronoi method proposed by Meyer et al. The detailed steps are described as follows:

Store neighbored points and facets of each vertex and record the total neighbored points (n) and neighbored facets (m) of each vertex.

(1) Calculate the normal vector n_j and region s_j of each triangular facet.



(a) Normal vector N_i **of vertex** p_i**; (b) mixed area** A_M **of vertex** p_i

Fig. 11. Normal vector and mixed area of vertex

As shown in Fig. 11(a), suppose that the vertex p_i includes m neighbored triangles, the corresponding vertex p_i includes m neighbored vertex v_j $(1 \le j \le m)$, n_j is the normal vector of the triangle $p_i v_j v_{j+1}$, and N_i is the normal vector of vertex p_i. The calculation formula is described as follows:

$$n_j = \frac{(v_j - p_i)\times(v_{j+1} - p_i)}{\left\|(v_j - p_i)\times(v_{j+1} - p_i)\right\|} \tag{8}$$

The triangle area s_j formed by p_i, v_j and v_{j+1} is calculated as follows:

$$s_j = \frac{(v_j - p_i)\times(v_{j+1} - p_i)}{2} \tag{9}$$

Wherein $1 \le j \le m$

(2) Calculate the normal vector of each vertex.

The normal vector of the vertex is estimated taking the neighbored triangle area at the vertex as the weigh factor. The calculation formula is described as follows:

$$N_i = (1/\sum_{j=1}^{m} s_j)\sum_{j=1}^{m} n_j s_j \tag{10}$$

(3) Calculate the total projection area A_M of neighbored triangles of each vertex.

a) If the triangle is the acute triangle, link the circumcenter of the triangle to the midpoint of two edges connected with vertex p_i and get the area A_1 as shown in Fig. 11(b).

b) For the right angled triangle or obtuse angled triangle, link the midpoint of the opposite edge of the right angle or obtuse angle to the midpoint of two edges connected with the vertex p_i and obtain the area A_2 as shown in Fig. 11.

A_M is the whole mixed area calculated using the above two methods, shown as the shadow area in Fig. 11.

(4) Traverse all vertexes of the triangle mesh model, and calculate the Gauss curvature $k_G(p_i)$, mean curvature $k_H(p_i)$, maximal principal curvatures $k_1(p_i)$ and minimal principal curvatures $k_2(p_i)$ of the vertex p_i [8].

The Gauss curvature of the vertex p_i is calculated as follows:

$$k_G(p_i) = \frac{1}{A_M}\left(2\pi - \sum_{j\in N(i)} \theta_j\right) \tag{11}$$

The mean curvature p_i of the vertex is calculated as follows:

$$k_H(p_i) = \frac{1}{4A_M}\sum_{j\in N(i)}\left(\cot\alpha_{ij} + \cot\beta_{ij}\right)\left(p_j - p_i\right)\cdot N_i \tag{12}$$

In the above formula, A_M is the mixed area of the triangle, θ_j indicates the angle between the edge $p_i p_j$ and $p_i p_{j+1}$, α_{ij} indicates the angle between the edges $p_i p_{j-1}$ and $p_{j-1} p_j$, β_{ij} indicates the angle between the edge $p_i p_{j+1}$ and $p_j p_{j+1}$, and N_i is the normal vector of the vertex p_i.

The maximal principal curvature and minimal principal curvature of the vertex p_i can be directly calculated by the Gauss curvature and mean curvature of the vertex p_i via the following formula:

$$k_1(p_i) = k_H(p_i) + \sqrt{k_H^2(p_i) - k_G(p_i)} \tag{13}$$

$$k_2(p_i) = k_H(p_i) - \sqrt{k_H^2(p_i) - k_G(p_i)} \quad (14)$$

The uniform sampling method is used based on the discrete curvature calculation and the visual principal curvature of the vertex in the model is calculated using formula (5) and rule (6).

C. Detection of feature region

The feature region of the 3D model is detected to highlight the sharpening operation of the details feature and prevent noises in the flat region from being expanded due to global sharpening. Generally, the normal vectors or curvature of the noise points in the flat regions are not continuous but isolated. To determine if a point is within the flat region of the model, it is necessary to determine if the absolute curvature of this vertex approximates to zero and calculate the absolute curvature of the vertexes in the neighborhood of this vertex. If the absolute curvature of more than two neighbored vertexes of this vertex does not approximate to zero, this vertex is regarded as isolated noises of the flat region and belongs to the flat region.

D. Local sharpening

Local sharpening aims to amplify the feature details of the 3D model of the cultural relics. If the vertexes in the feature region of this model are locally sharpened, it can effectively prevent global sharpening from amplifying the model noises. The steps are described as follows:

(1) Traverse all vertexes of the model and determine the region of the vertexes.

(2) If the vertex belongs to the flat region, skip to step (1).

(3) If the vertex belongs to the feature region, skip to step (4).

(4) If the vertexes in the feature region of this model are locally sharpened, the new coordinates of the vertexes in this region will be recalculated.

a) For the vertex p_i and its neighbored vertex p_j to be sharpened in the triangular mesh model, the position offset Δp_i of the vertex p_i must be calculated via the following calculation formula:

$$\Delta p_i = \sum_{j \in i} w_{ij}(p_j - p_i) \quad (14)$$

In the formula, w_{ij} is the weight function and satisfies $\sum_{j \in i} w_{ij} = 1$. For easy calculation, the value is $1/n$, namely reciprocal of the number of neighbored points of the vertex p_i;

b) Calculate the new coordinate $p_i^{'}$ of the vertex p_i via the following formula:

$$p_i^{'} = p_i + (\mu - \lambda)v(\Delta p_i) - \mu\lambda\Delta p_i \quad (15)$$

Here, μ and λ are the scale parameter and meet $0 < \lambda < \mu < 1$. $v(\Delta p_i)$ represents a vector and is the square root of three components of the vertex p_i. If the calculated result is $\Delta p_i = (x, y, z)$, then $v(\Delta p_i) = (\sqrt{|x|}, \sqrt{|y|}, \sqrt{|z|})$.

Smoothing will make the 3D model shrink toward the center. On the contrary, sharpening will make the 3D model expand outward. The formula (15) changes the mark "+" of the final item on the right side of the Taubin smoothening formula into mark "-" to get the effect opposite to the smoothing, thus highlighting the local features of the model. To prevent such expansion from affecting extraction of the feature line, $(\mu - \lambda)v(\Delta p_i)$ is added to the formula (15), whose symbol is contrary to the third $\mu\lambda\Delta p_i$, which can effectively reduce outward expansion degree of the 3D model, and ensure that the local features of the 3D model can be amplified [9].

If steps 1-4 are performed once, the procedure is called "sharpening". The sharpening time is identified by the model type till the extracted feature lines are sufficient to describe the details of cultural relics.

E. Extraction of feature lines

The contour extraction is the core element in the drawing of the line drawing of cultural relic, including outer contour and internal details. The internal details include the painted ornamentation on the surface of the cultural relic and apparent ridges. The crease lines and boundary line mainly describe the details inside the cultural relic and can be extracted according to related concepts. The silhouettes lines indicate the outer contours of the cultural relics. The extraction method [10] is described as follows:

First, the triangles of the mesh model are divided into visible triangle, invisible triangle and contour triangle.

Suppose that the sight line vector of the vertex p_i is $w_i = p_i - c$, wherein c is the coordinate of the viewpoint. If the dot product of the normal vector of the vertex p_i and the sight line vector w_i of this vertex are more than 0, this vertex is visible. If the value is less than 0, it indicates that this vertex is invisible. If three vertexes of a triangle are visible, this triangle is visible. If three vertexes of the triangle are not visible, it is called an invisible triangle. The contour triangle is the triangle in which not all three vertexes are visible or invisible, as shown in Fig.13.

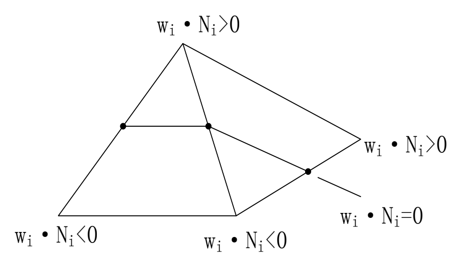


Fig. 12 Silhouettes contour extracted via linear interpolation method

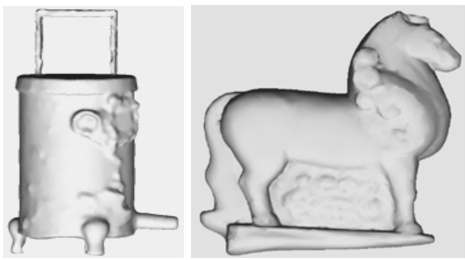
As shown in figure 13, the contour triangle should include the passing Silhouettes contour. The contour triangle is found by traversing the triangular mesh model. Two vertexes with different invisibility are linearly interpolated as follows:

$$p = \frac{|t_j|}{|t_i| + |t_j|} p_i + \frac{|t_i|}{|t_i| + |t_j|} p_j \quad (16)$$

Here, $t_i = \frac{w_i \cdot N_i}{\|w_i\|\|N_i\|}$, after $w_i \cdot N_i = 0$ is found, link them together and draw them on the screen to obtain the Silhouettes contour of the 3D model.

V. Experimental verification

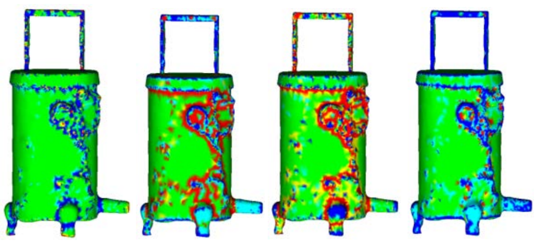
The experimental data is the 3D model of the cultural relics of Clepsidra, a funeral object of Zhangtang tomb in Western Han Dynasty, and Stone Horse of Emperor Xuanzong's Tomb, which were collected via 3D laser scanning technology under cooperation between the National and Local Joint Engineering Research Center for Cultural Relic Digitalization, and Emperor Qin's Terra-cotta Warriors and Horses Museum and Shanxi Archaeological Research Institute, as shown in Fig. 13.



(a) Clepsidra of Zhangtang tomb (b) Stone Horse of Emperor Xuanzong's Tomb

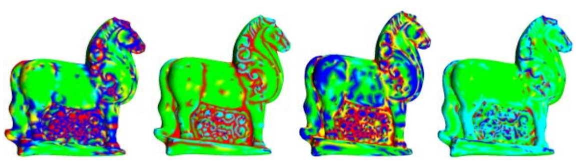
Fig. 13 Orthogonal projection view of experimental model

Step1 Estimate the visual curvature of the vertexes of triangular mesh model of the cultural relic and draw the distribution diagram of the curvature.



(a) Gauss rate (b) Mean curvature (c) Maximal principle curvature (d) Minimal principal curvature

Fig. 14 Curvature distribution diagram of Clepsidra



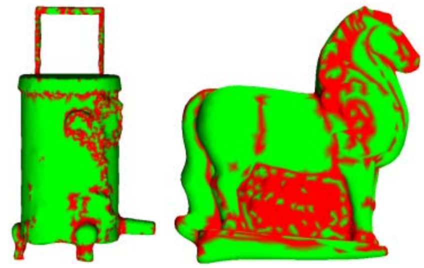
(a) Gauss rate (b) Mean curvature (c) Maximal principle curvature (d) Minimal principal curvature

Fig. 15 Curvature distribution diagram of Stone Horse

Fig. 14 and Fig. 15 show the curvature distribution diagram of the triangular mesh model in Fig. 13 (a) and (b) after discrete curvature estimation, of which the green part shows that the curvature is assigned by the interval approximate to the zero. Sampling curvatures more than zero are divided into two groups and are assigned in red and green colors based on the curvature. The sampling curvatures less than zero are divided into two groups and are assigned in green and blue colors.

Step2 Detect the feature region, which can fully embody the model details according to the visual curvature of the vertexes of the triangular mesh model under λ scale constraint.

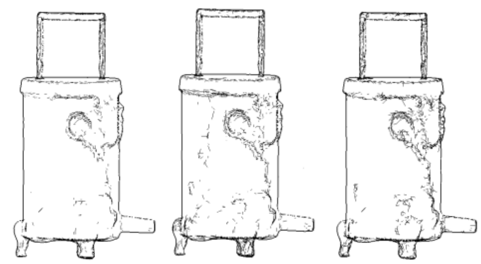
The triangular mesh model of cultural relic is divided into a feature region and a flat region based on the visual curvature of the model vertexes. The red part is the feature region of the model and the green part is the flat region of the model, as shown in Fig. 16. The comparison of the curvature distribution diagram of the corresponding model indicates that the algorithm in this paper can effectively remove the noise points in the flat region.



(a) Clepsidra of Zhangtang tomb (b) Stone Horse of Emperor Tangxuan's Tomb

Fig.16. Region division diagram of cultural relic model

Step3 Based on the mean value of the archaeological field, sharpen and extract the feature contours of the triangular mesh mode to generate the line drawing of the cultural relics with enough detailed features.



(a) No sharpening (b) Four-time global sharpening (c) Four-time local sharpening (method in this paper)

Fig. 17. Plane line diagram of Clepsidra

(a) No sharpening (b) Five-time global sharpening (c) Five-time local sharpening (method in this paper)

Fig. 18. Feature line extraction result of stone horse

In the experiment, three pairs of line drawing are derived. Line drawing directly extracted from the triangular mesh model without sharpening in Fig. 18 (a) and Fig. 19 (a) is , incomplete in extraction and incapable of fully expressing the detailed features of the objects. The plane line diagram extracted after global sharpening the triangular mesh model in Fig. 18 (b) and Fig. 19 (b) show rich lines, bur the lines are also drawn on a flat region due to disturbance of local noises, which makes the whole line drawing confused. While, the line drawings in Fig. 18 (c) and Fig. 19 (c) are extracted by using the method in this paper after feature region detection, based on the visual curvature estimation, and then local sharpening. These two line drawings indicate that the method proposed in this paper cannot only drawrich details, but also effectively prevent the disturbance of the noises in the flat region.

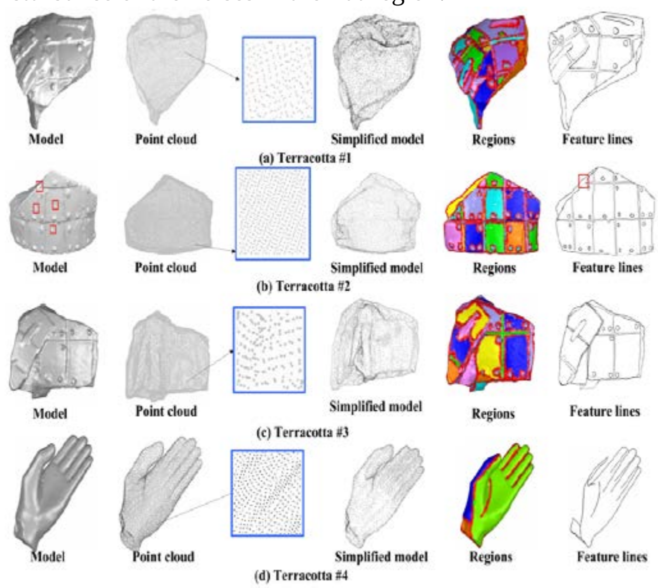


Fig. 20. The line drawing of Terra-cotta Warriors debris

VI. Conclusions

For the 3D model of cultural relic with coarse surface and much noise, how to precisely select the feature region for sharpening and extract the cultural relic drawing satisfying the visual features of human beings is the main difficulty in finding a solution to automatic drawing for archaeological line drawings. The traditional principal curvature estimation depends on the estimation of the normal lines, which are susceptible to noises. The normal lines of the curved surface and principal curvature are estimated in accordance with the minimization and maximization rule to get the highly robust normal line and principal curvature. The obtained multi-scale visual principal curvature can display the shape details of the object in different scales in the continuous scale space and satisfy the specific visual processing requirements in the drawing of the cultural relic line drawing.

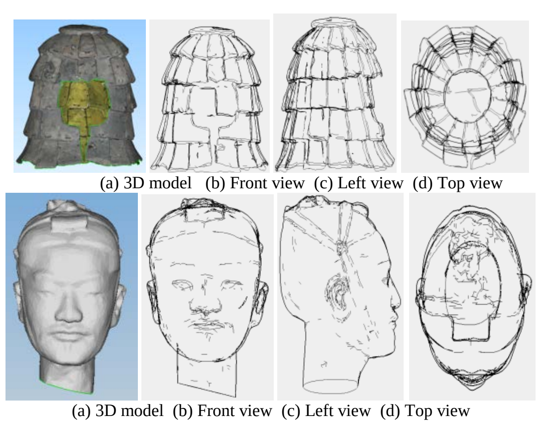


Fig. 21. 3D view of the Terra-cotta Warriors

The practice in our team work show that the method proposed in this paper can preserve more details, reduce noise line in drawing, and effectively prevent massive calculation resulting from viewpoint change. The line drawing by using our method can satisfy actual archaeological work requirements better and effectively solve the problems in manually drawing of the archaeological drawing such as low speed, low precision and heavy workload. In our future research work, the machine learning method will be introduced to solve the problems of automatic setting of λ values in the multi-scale visual curvature calculation formula (6) and precise and automatic division of the model region, which will provide a technical support for the large-scale automatic and accurate drawing of the archaeological line drawings.

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Table1. The information about Terra-cotta Warriors debris

Models	Original model					Simplified model				
	Points	Feature points	Minimum d_p	Average d_p	Total Time (s)	Points	Feature points	Minimum d_p	Average d_p	Total Time (s)
Terra-cotta #1	32748	4867	0.5737	1.9854	18.245	10702	4379	0.8814	2.3345	9.841
Terra-cotta #2	36347	6467	1.9513	3.2456	20.141	10904	5762	2.3145	4.2445	10.895
Terra-cotta #3	25184	5270	1.2178	2.7659	12.816	8355	4841	1.6541	3.0014	8.441
Terra-cotta #4	11839	3102	1.5742	2.4789	10.566	4982	2814	1.8845	3.6874	3.876