Three-dimensional garment virtual fitting method with local area geometric feature enhancement based on Voronoi diagram

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Abstract. In order to realize the accurate matching of 3D garment model and human model, a new method for feature extraction of garment and human model is proposed. We first construct local mesh fitting operator based on Voronoi graph and weighted parametric surface. Secondly, on the basis of the use of geometric attributes, the change in the neighborhood is used as the reference value. On this basis, the region is divided and then the feature point extraction of costume model and human body model is realized. Thirdly, a robust feature matching function is established. Finally, the clothing and the human body model can be matched quickly and accurately.

1. Introduction

Online shopping is becoming more and more popular, however, there is a problem of "No fitting, high return rate". In order to solve this problem, the 3D clothing virtual fitting technology has become a research hotspot. The effect of 3D clothing virtual fitting can be regarded as the matching problem between 3D human body model and garment model. The differential geometric property of discrete vertices of mesh model is the breakthrough point of 3D virtual fitting. The geometric information of the discrete vertex includes the normal vector, curvature and torsion, which is the key to the accurate matching of the garment model and the human model. For the vertex grid model to estimate method, there are two kinds of common methods. One is to construct the tangent plane by using the neighborhood point information and to establish the local two-time fitting surface to estimate the vertex method vector [1]. The other is to construct the polygonal mesh surface on the vertex of the grid and the adjacent neighborhood points, and to estimate the method by using the neighboring polygon slices directly [2]. Many researchers try to estimate the normal vector of discrete points by fitting the smoothing parameter surface [3]. OuYang and Feng proposed a method based on local Voronoi diagram and a method of quadratic curve fitting neighborhood point to estimate vertex normal [4], and get a better estimation result. For the mesh model, the estimation of the discrete curvature can be divided into two categories, one is the discrete estimation method [5], the other is the continuous estimation method [6]. Razdan and Bae [7] propose a local fitting operator based on weighted biquadratic Bezier surface, and the weighted parameter surface increases the adjustment matrix and
adjustment factor. The torsion of the mesh vertex is an important geometric invariant of the rigid body transformation.

Because the model data point is huge, this paper constructs the mesh local fitting based on the Voronoi graph and the weighted parametric curved surface, this surface method uses the parametric curved surface equation to establish the model, the fitting effect of the surface is good, and the calculation speed is improved, the information of the point on the surface is easy to obtain. On this basis, a better vertex method vector, curvature and torsion value are obtained, then the model is divided into regions, then the feature points are extracted, and a new matching function between the garment model and the human body model is established to realize the personalized virtual fitting process.

2. Estimation of differential geometry of human body and garment mesh model

2.1. Selection of adjacent points of mesh model and its curved surface construction

Voronoi graph is a kind of partition method of space, which is divided into n parts with given points as control points according to the position of any given n points on the plane. The distance between any interior point of any convex polygon in the Voronoi graph and the control point of the convex polygon is less than the distance from the point to any other control point. The Voronoi graph does not depend on the density and distribution of the data points, but more importantly, the Voronoi graph defines the neighborhood of the local geometry of the surface reliably. The planar graph of Voronoi polygon has the properties of the nearest neighbor and the local dynamics. The points in each Voronoi cell are closer to the current sampling point than the other points in the three-dimensional space, with the following properties: The Voronoi vertex is the center of the sphere determined by the four points of the original set. Generally speaking, two Voronoi units are coplanar, three Voronoi units are collinear, four Voronoi units share the common point, the sampling point in the four Voronoi units is located in the composition of the external ball, the ball is the intersection of Voronoi point. The external ball does not contain other sampling points. Therefore, these properties can be used to provide the basis for the quantitative analysis of the spatial structure of human body model and garment model by using the Voronoi diagram. It is necessary to identify the nearest neighbor points of the local Voronoi mesh, and the effective neighbor identification is necessary for the reliable estimation of the normal vectors at the data points. Amenta et al. [8] proposed the Cocone algorithm to correctly establish the local triangular mesh for the ideal data set. For real-world point cloud data, especially in non-smooth areas, use a heuristic rule called Umbrella Check to remove redundant triangles. Petitjean and Boyer [9] puts forward the concept of minimum interpolation to select local neighbourhood candidates, and the candidate points are grouped according to the simple connection rule. An iterative elimination rule is then used to remove the unnecessary candidate points until all local adjacent points are in a group. Adamy et al. [10] put forward the concept of lambda -interval (through the combination of the concept of alpha sphere and beta skeleton) to select the local candidate. The triangle topology for three specific types of incorrect use called umbrella filter algorithm to evaluate local triangle candidates, and delete the redundant triangles, until all the remaining triangles to form a umbrella event according to heuristic rules. In this paper, a method of OuYang D [4] is proposed to identify the local Voronoi grid neighbors from the points of their global Voronoi neighbors. First, the quickhull algorithm is used to construct the Voronoi graph, and then the local triangular mesh growth algorithm [12] based on the spherical rotation algorithm is adopted to select the local Voronoi [11] mesh neighbor. In differential geometry, it has been determined that the local geometric shape of the point can be approximated by two quadric surfaces. This article takes the selected proximity point to fit to the cubic surface to estimate the surface normal vector. We know that the cubic surface can contain more local geometry than the quadric surface, some mesh models contain noise, so finally use the weighted cubic Bezier surface, increase the adjustment matrix and the weight factor to fit the vertex and its neighbourhood of grid based on the Voronoi graph construction. In this way, the fitting surface has a good adjustment, and the splicing is smooth, for the simulation of clothing, the wrinkle effect is also obvious.

The fitted bicubic Bezier surface matrix representation is as follows:
\[ S(u,v) = \begin{bmatrix} B_{0,3}(u) & B_{1,3}(u) & B_{2,3}(u) & B_{3,3}(u) \end{bmatrix} \begin{bmatrix} P_{00} & P_{01} & P_{02} & P_{03} \\ P_{10} & P_{11} & P_{12} & P_{13} \\ P_{20} & P_{21} & P_{22} & P_{23} \\ P_{30} & P_{31} & P_{32} & P_{33} \end{bmatrix} \begin{bmatrix} B_{0,3}(v) \\ B_{1,3}(v) \\ B_{2,3}(v) \\ B_{3,3}(v) \end{bmatrix} \] (1)

That is,

\[ S(u,v) = \sum_{i=0}^{3} \sum_{j=0}^{3} B_{i,j}(u) B_{j,3}(v) P_{i,j} \quad (0 \leq u, v \leq 1) \] (2)

Where \( P_{i,j} \) is the control vertex of \( S(u,v) \), \( B_{i,j}(u) \) and \( B_{j,3}(v) \) are Bernstein basis functions, specifically expressed as:

\[
B_{i,j}(u) = C_i^j u^i (1-u)^{3-i} \\
B_{j,3}(v) = C_j^3 v^j (1-v)^{3-j}
\] (3)

The surface is constructed from the 4X4 control points, which is shown in figure 1.

![Characteristic mesh of bicubic Bezier surface](image)

**Fig. 1** Characteristic mesh of bicubic Bezier surface

\( P_{0,0}, P_{0,3}, P_{3,0} \) and \( P_{3,3} \) are the four endpoints of a surface, as shown in Figure 1, the 4 endpoints of the bicubic surface, they define four boundaries of the Bezier surface.

The vertices of the Voronoi graph will be fitted with bicubic Bezier surface, then figure out the control points as \( P_{i,j} \) of fitting surface. These control points correspond to the parameters \( (u,v) \) of the fitting surface. The calculation process is as follows:

**Step 1:** Select a feature vertex \( P_i \) of Voronoi graph. The common vector \( N \) of the normal vector of the vertices of the Voronoi graph is obtained by means of arithmetic average.

**Step 2:** Create a tangent plane that is the origin and perpendicular to the normal vector \( N \), then create a Cartesian coordinate system on the tangent plane.

**Step 3:** The coordinate value of the projection point on the tangent plane of the adjacent vertex in the Voronoi grid of \( a \) is defined as the parameter corresponding to the fitting point on the surface.

After the above steps, a set of equations \( Ax=B \) can be obtained. Where,
The normal vector model of the garment model is shown in Fig.2
The curvature of a surface near a known point can be determined by how fast the surface leaves its tangent plane. But in the given point, the curved surface is different in different directions, while the normal curvature reflects the bending degree and bending direction of the curved surface at one points, so the curvature of the curved surface at one points is completely quantifiable. But actually, because the tangent plane at one points is not the only one. For a given point P on the surface S: r (u, v), the normal curvature $k_n$ is the tangent direction of the function, called that each critical value of the normal curvature is the principal curvature at this point on the surface, the corresponding direction is called the main direction at this point on the surface. $k_1$ and $k_2$ represent the principal curvature of the surface at the point p and they have the following relationship:

$$k_n = k_1 \cos^2(\theta) + k_2 \sin^2(\theta)$$

Where, $\theta$ is the angle between the main direction, which is also called the Euler formula, which shows the law of the normal curvature changing with the direction.

In addition to the principal curvature, the Gaussian curvature and the mean curvature are particularly evident in the curvature of the surface.

2.3. Estimation of curvature

About surfaces in space, the situation is more complicated, and the arc appearance of the curve corresponds to the first basic form of the surface (a positive definite two-order differential form), commonly referred to as the surface of the form of measurement, it can be used to calculate the length of curved surface, angle of two tangent vectors and the area of a piece of surface. The shape of the descriptive surface also requires another two differential form, called the second basic form of the surface. These two basic forms together form the complete invariant system of the surface, and the sufficient and necessary condition for the two surfaces in space to coincide with one another is that they have the same first basic form and second basic form after a parametric transformation.

The mean curvature and Gaussian curvature of the discrete vertices are estimated by the local fitted surfaces obtained in the first section above. The parametric equation with curve C is $r=r(s)$, where $r$ is the arc length parameter of the curve, and $r(s)$ has second-order continuous vector $r''$. The curvature of the curve C at the point of the arc length S is $|r''(s)|$, also known as the curvature vector of C. When $k(s) \neq 0$, $\rho(s) = \frac{1}{k(s)}$ is the curvature radius of the curve at that point. According to the calculation formula of principal curvature and Vedic theorem, we can get the geometric formulas of mean curvature $H$ and Gauss curvature $K$:

$$H = \frac{LG-2MF+NE}{2(EG-F^2)}$$  \hspace{1cm} (6)

$$K = \frac{LN-M^2}{EG-F^2}$$  \hspace{1cm} (7)
Where E, G and F are the first basic quantity, L, N and M are the second basic quantities. They can be calculated by $E = B_u \cdot B_u$, $F = B_u \cdot B_v$, $G = B_v \cdot B_v$, $L = B_{uv} \cdot n$, $M = B_{uv} \cdot n$ and $N = B_{vv} \cdot n$ respectively. The Gaussian curvature model of the garment model is shown in Fig. 3, and the average curvature model of the garment model is shown in Fig. 4

![Fig. 3 Gaussian curvature diagram of garment mesh model](image1)

![Fig. 4 Average curvature diagram of garment mesh model](image2)

Both the Gaussian curvature and the mean curvature are intrinsic geometric invariants, which can describe the curvature of the surface at the sample point P. The Gaussian curvature of any vertex reflects the general curvature of the surface, depending on the angle associated with the vertex and the area of the triangular mesh. The average curvature describes the degree of curved surface, which is related to the angle of triangular meshes and the length of the edge.

Gaussian curvature refers to the product of the maximum curvature and the minimum curvature. The curvature of a surface at a given point reflects the degree of curvature of the surface at the point, and is often used to check the concave and convex changes of the surface.

2.4. Estimation of torsion

Torsion is also an important geometric property of the object rigid body transformation. The spatial curve not only to bend, but also to distort, that is, to leave its close plane. To characterize this distortion, it is equivalent to study the variation rate of the arc length by the auxiliary vector of the curve, and adding the torsion in the process of modeling to make the model more accurate and smooth. Set $\rho(s)$ and $r(s)$ respectively is the main normal vector and the secondary normal vector of curve C, where S is the arc length parameter of the curve, then $\tau(s) = -r(s) \cdot \rho(s)$ is the torsion rate of curve C. When $\tau(s) \neq 0$, the derivative $\frac{1}{\tau(s)}$ is called the torsion radius. The torsion rate reflects the speed of the close plane, that is, the degree of distortion of the curve. For the deflection of a point on the fairing surface, can be expressed by the geodesic torsion $\tau$, and there is a relationship between the measured deflection and the Gauss curvature and the mean curvature:

$$r_{\text{max}} = \sqrt{H^2 - K}$$
Therefore, for the point on the surface, the maximum measured deflection can be obtained according to the Gauss curvature $K$ and the mean curvature $H$ of the point. Figure 5 shows the model of the torsion of the garment model.

![Fig. 5 The torsion of the garment mesh model](image)

3. Matching of 3D human body model and garment model

3.1. Extraction of model feature points pairs

Whether the matching of clothing model and human model is accurate depends on the extraction of key points. Draw lessons from the feature extraction algorithm such as Hong Mei [13], in this paper, according to the general symmetry of the human body and clothing characteristics, the human body and clothing in the vertical, only need to find the side of the feature points and then mirror. First, the extreme point of the Gauss curvature is used as an initial point $Q$, then search for the Voronoi mesh adjacent point of $Q$ point. Using the least squares method to fit local bicubic Bezier surfaces. Searching for the Gaussian Curvature Extreme Point on the Local Cubic Bezier Surface with Point $Q$ as the Starting Point. When the curvature extremum point $Q_1$ is found on $B_0$ ($u, v$), the Voronoi mesh adjacent point of point $Q_1$ is then fitted into a bicubic Bezier surface $B_1$ ($u, v$), and the point $Q_1$ is used as the starting point to search for the curvature extremum point $Q_2$ on this local quadric surface. Secondly, the local three double Bezier surface of the Voronoi grid is fitted by the point of $Q_2$. Sequential analogy, until the extremum point of curvature on the entire surface is searched. Then the characteristics of the cloud points of the human body and the cloud points of the clothing are obtained and corresponding to the key points set as:

$$\{B_i\} = \begin{bmatrix} B_{x1} & B_{y1} & B_{z1} \\ B_{x2} & B_{y2} & B_{z2} \\ \vdots & \vdots & \vdots \\ B_{xn} & B_{yn} & B_{zn} \end{bmatrix} \quad \{C_i\} = \begin{bmatrix} C_{x1} & C_{y1} & C_{z1} \\ C_{x2} & C_{y2} & C_{z2} \\ \vdots & \vdots & \vdots \\ C_{xn} & C_{yn} & C_{zn} \end{bmatrix}$$
After obtaining the point cloud feature point set of the human model shown in Fig. 6 and the point cloud feature point set of garment model shown in Fig. 7, in order to find more accurate corresponding feature points of human model and clothing model, we add the following constraint to the Gaussian curvature and mean curvature of the searched points on human model and the garment model [14]:

\[
\frac{|K(B_i) - K(C_i)|}{K(B_i)} \leq \delta_k \\
\frac{|H(B_i) - H(C_i)|}{H(B_i)} \leq \delta_h
\]  

(9)

Where \(\delta_k\) and \(\delta_h\) are user-defined thresholds. Only when the human body model and the garment model both meet the above constraints, the point pair will be used as the matching point pair. Instead, the point pair will be removed as a matching point pair. Until all the points on the search finished. However, the human body model and the garment model have different geometries and topologies, and when the human body changes or try different styles of clothing, only rely on the Gaussian curvature and the average curvature to extract the feature point pairs, may introduce the wrong match point or a one-to-many correspondence. In the case of these, we introduce the geometric characteristics of torsion based on the study of Gal and Cohen-Or [15], and construct a new function below for matching the key points:

\[
S = \sum_{u_i \in F} w_1 Area(u) \left( Curv(u_i)^2 + Tors(u_i)^2 \right) + w_2 NC(F)VarC(F) + w_3 NT(F)VarT(F)
\]  

(10)

Where, \(Area(u)\) is the local Voronoi mesh region of the \(u_i\) point, \(Curv(u_i)\) and \(Tors(u_i)\) represent the curvature and the geodesic torsion at the point \(u_i\), \(NC(u)\) is the number of maximum curvature and minimum curvature in the Voronoi mesh region. \(NT(u)\) is the number of the maximum geodesic torsion and the minimum geodesic torsion in the Voronoi mesh region. \(VarC(F)\) and \(VarT(F)\) are the variation of curvature and geodesic torsion in local Voronoi mesh region. \(w_1, w_2\) and \(w_3\) are the set thresholds, where we are set to 0.33.

Thus, the matching effect between human body model and garment model is more accurate.

3.2. Exact match of the model
Because the surface matching between the human body model and the clothing model is a rigid body transformation process, so we should consider the rigid transformation between the surfaces [16], we
can know the transformation of the model surface to be matched. The rigid body transformation only has the rotation transformation and the translation transformation, therefore, we set the characteristic point coordinate vector of the human model is $B_i$, and the feature point coordinate vector of the garment model is $C_i$. Coordinate transformation of the feature points on the two model satisfies the following equation:

$$B_i = sR(\theta_x, \theta_y, \theta_z)G_i + T$$  \hspace{1cm} (11)

Where $R(\theta_x, \theta_y, \theta_z)$ is rotation matrix, $T$ is translation vector, and $s$ is scaling factor, here we set $s=1$. Then the final coordinate transformation matrix $R$ and $T$ are obtained according to the minimum distance objective function. The objective function is as follows:

$$\Phi = \sum_{B_i \in B} \|B_i - (R(\theta_x, \theta_y, \theta_z) + T)\|^2$$  \hspace{1cm} (12)

We solve the problem of minimum objective function by SVD matrix factorization. The coordinate transformation matrix is used to realize the coarse matching of human model and garment model. At this point, we can adjust the size of the $s$ to overall scale the garment model, until the human body model and clothing model matching effect is better.

3.3. Three-dimensional fitting show

The main steps of 3D virtual garment fitting are as follows:

Step 1: Constructing local bicubic Bezier fitting surface of mesh Model of Human Body Model and Garment Model. Using the formulas (5), (6), (7) and (8) to estimate the differential geometry of the mesh model includes vertex normal vector, mean curvature, Gaussian curvature and torsion respectively.

Step 2: The use of constraint formulas (9) and (10) on the human body model and clothing model feature point pairs to search and extract.

Step 3: According to the coordinate transformation equation of Eq. (11) and the minimum distance objective function of Eq. (12), the coordinate transformation matrix is obtained to realize the rough matching of human body and clothing, and then adjust the scaling factor to scale the garment model and perform the second matching until get more accurate three-dimensional clothing dressing effect. The fitting effect diagram shown in Fig. 8.

![Fig. 8 The fitting Effect Chart](image)

4. Summary

This paper presents an algorithm for 3D garment fitting based on local feature enhancement. This method firstly uses the Voronoi diagram’s nearestness, the properties of adjacency and the local
dynamic characteristics to provide the basis for the quantitative analysis of the spatial structure of the human body and the garment model. At the same time, a new structure method of third-order local fitting surface is proposed, so as to better obtain the model information. Second, the use of the symmetry characteristics of the human body and clothing, the human body and clothing vertical division of the realization of the regional division, and then look for a side of the characteristics of the region after the mirror, which quickly get the characteristics key match point set of the human body and clothing model. And then through the constraints of the geometric feature of the grid model, especially the introduction of the geodesic torsion to reflect the distortion of the grid vertices, to construct a new model matching function. Then, under the constraint of the minimum distance objective function, the human body model and the clothing model are matched with many times to achieve the better three-dimensional garment dressing effect.

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