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点模型的多分辨率形状编辑*

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Multisolution Shape Editing of Point-Sampled Geometry

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Abstract: This paper proposes a technique for shape editing of point-based geometry based on geometric detail mapping. The geometric detail is an important attribute of a surface. It is defined in this paper as the difference between the original point-sampled surface and its base surface which is constructed as a multilevel B-splines approximation. The geometric detail is represented as the set of the local affine coordinates of the base surface and extracted effectively and efficiently in user specified frequency band of geometric signal. It can be mapped onto any arbitrary point set surface including its own deformed base surface. Versatile editing tools are developed for the point sampled geometry that naturally preserves the geometric detail. Experimental results demonstrate the high potentials of the approach for point-sampled geometry modeling.
Key words: point-sampled geometry; geometric detail mapping; multilevel B-spline; free-form deformation; parameterization

摘 要: 提出了一种基于几何细节映射的点模型的形状编辑方法.几何细节是曲面的一个重要属性,定义几何细节为原始曲面及其基曲面之间的向量差,该基曲面由多层次B样条所构成.通过基曲面上的局部仿射坐标,则可以得到与之对应的多分辨率几何细节表示,曲面的低频信息和高频信息易被用户所指定的频段分离.通过调节基曲面的形状,再将这些几何细节映射上去,可以对模型进行保细节的变形;如果将几何细节映射到其他物体上,将可以得到几何细节迁移的结果.为点模型开发了多种特征保持的编辑算子,实验结果表明,所提出的方法是一种有效的点模型造型算法.
关键词: 点采样几何;几何细节映射;多层次B样条;细节迁移;参数化
中图法分类号: TP391 **文献标识码**: A

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1 Introduction

The point primitive enjoyed its renaissance in both modeling and rendering in recent years. Compared with traditional primitives likes triangular meshes, shape representation with point primitives has shown distinct advantage on rendering efficiency and data structure maintenance, especially for highly complex objects or dynamically changing shapes. Considerable amount of research efforts are devoted to the efficient modeling and processing of point-sampled geometry. Zwicker, *et al*[1] presented a Photoshop-like tool for interactive shape and appearance editing of the point-sampled geometry based on normal displacement. By establishing a concept of local frequencies, Pauly, *et al*.[2] introduced a spectral representation that provides a rich repository of signal processing algorithms on point set surface. Pauly, *et al*.[3] presented a framework and algorithms for multiresolution modeling of point-sampled geometry. Soon later, by combining unstructured point clouds with the implicit surface of the moving least squares approximation, they presented a free-form shape-modeling framework with point-sampled geometry[4]. Guo and Qin[5] presented a physics-based dynamic local sculpting paradigm for point-sampled surfaces using volumetric implicit function. Recently, Xiao, *et al*.[6] proposed an approach for interactive point-sampled morphing.based on surface segmentation[7]. An excellent survey can be found in Ref.[8].

The geometric detail is an intrinsic property of point-sampled geometry, and contributes a lot to the appearance of the surface. When the editing operations are performed on the 3D geometry for modifying the shape of a model, they should retain its structural details without details or features distortion. In general, the geometric detail is defined as high frequency component of object from point view of digital geometry processing. It can be extracted and reused via multi-resolution representation approach, no wonder that geometric detail provides a valuable tool for both modeling and rendering[10,12,13].

The wide availability of range scanning devices results in highly detailed geometry data models. In this paper we propose a novel technique of geometric detail mapping for point-based geometry modeling. The region of interest is firstly parameterized onto a rectangle domain by employing a fast parameterization algorithm, then the multilevel B-splines surfaces are constructed to present a multiresolution approximation of the local region on the point-sampled geometry. It acts as the base surface for effective geometric detail extraction. The extracted geometric details are then recorded in the local affine flames of the base surface and can be mapped onto any arbitrary point set surface, including its own deformed base surface. The major contributions of the work are:

Multi-Resolution base surface definition: Based on fast parameterization of point-sampled geometry, we construct a multi-resolution B-splines base surface for the underlying region of interest, which provides a reference for surface detail detection of a parametric embedding space for further geometric details mapping.

Geometric detail extraction: The geometric detail is a kind of high-frequency signal of the surface. We define it as a set of difference vectors between the sample points of the point set surface and its base surface. Geometric detail can be regarded as the bump texture. It is acquired by calculating the local affine coordinates of each sample point over the base surface.

Interactive surface editing: By embedding all the sampled points onto the parametric space of the base surface, all operations manipulating on the shape of the base surface can be transferred automatically to the underlying point set surface meanwhile the structural detail is still retained.

Geometric detail transferring: The geometric detail can be easily transferred to another target surface. Special investigations on the multi-resolution detail transfer, the feature-constrained detail transfer, and the seamless patch transplanting are conducted.

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2 Multi-Solution Base Surface Definition

Base surface of a point-sampled geometry is a low frequency approximation of its shape. Lee, *et al.*[14] constructed C^2-Multilevel B-splines for scattered data interpolation and approximation. The algorithm makes use of a coarse-to-fine hierarchy of control lattices to generate a sequence of bicubic B-spline functions whose sum approaches the desired interpolation function. However, the above method is applicable to 2D image data only, to define the base surface of a point-sampled geometry using multilevel B-spline surface, the 3D point set must be parameterized into a rectangle domain at first.

2.1 Fast parameterization

Given a sequence of distinct points $X=(p_1,\ldots,p_N)$ in R^3, which are sampled from a patch of some unknown surface in R^3, we assume that the set X can be split into two disjoint subsets: the set of interior points $X_I=(p_1,\ldots,p_n)$, and the set of boundary points $X_B=(p_{n+1},\ldots,p_N)$, where the points $p_{n+1},\ldots,p_N$ are ordered consecutively along the boundary, then parameterization is accomplished in two steps.

In the first step, the boundary points $p_{n+1},\ldots,p_N$ are mapped into the boundary of some convex polygon Ω in the plane, by specifying the corresponding parameter points $u_{n+1},\ldots,u_N$ to lie around $\partial\Omega$ in some anticlockwise order.

In the second step, for each interior point $p_i\in X_I$, a neighborhood $N_i=\{p_j:0<\|p_j-p_i\|<r\}$ is chosen. We then select a set of strictly positive weights $\lambda_{i,j}$, for $j\in N_i$, such that $\sum_{j\in N_j}\lambda_{ij}=1$ and n parameter points $u_1,\ldots,u_n\in R^2$ corresponding to the interior points $p_1,\ldots,p_n\in R^3$ can be found by solving the following set of equations $u_i=\sum_{j\in N_i}\lambda_{i,j}$, $i=1,\ldots,n$ This linear system may be written in the form $Au=b$, where $A=(a_{i,j})$ is the $n\times n$ matrix with $a_{ii}=1$ and $a_{ij}=-\lambda_{ij}$ for $i\neq j$, u is the column vector $(u_1,\ldots,u_n)^T$, and $b=(b_1,\ldots,b_n)^T$ is the column vector with $b_i=\sum_{i=n+1}^{N}\lambda_{ij}u_j$.

This is the main idea of the meshless parameterization[15]. To accelerate the parameterization of such dense surfaces, we employ a hybrid approach proposed in Ref.[6]. The densely sampled patch X is simplified into a sparsely sampled patch S, then the meshless parameterization method is applied to parameterize S onto a rectangle. The remaining point samples of X are embedded into the rectangle by convex interpolation. Since S contains much less sample points, the size of the matrix A is greatly reduced, the time and space cost for parameterization are significantly decreased. Using a 3D grid data structure, the neighborhood can be determined efficiently in constant time. Figure 1 shows the parameterization step of this method.

(a) Original model with 54 250 points (b) Simplified model with 7 756 points (c) Final parameterization result

Fig.1 Parameterization algorithm

2.2 Accelerated base surface construction

So far the point set surface $X=(p_1,\ldots,p_N)$ in R^3 has been parameterized into a rectangle domain $\Omega=\{(u,v)|0\le u\le m,0\le v\le n\}$. Let $p_i=(x_i,y_i,z_i)$. Three uniform bicubic multilevel B-splines surfaces $f_x(u,v)$, $f_y(u,v)$, $f_z(u,v)$

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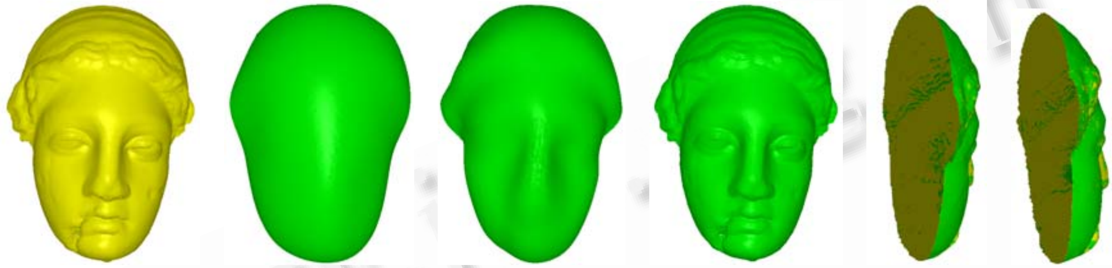
formulated in Ref.[14] are then defined on the domain Ω to respectively approximate the x_i,y_i,z_i in multi-resolution. Now the approximation for the arbitrary 3D point-sampled surface X is acquired. We call f the base surface of X.

Instead of constructing the base surface directly on the original point set surface X, we build the base surface based on the simplified point set S presented in the previous parameterization phase. This accelerates the base surface construction process greatly. Figure 2 shows the experimental results of base surface construction using two different schemes. With the acceleration scheme, our system takes only 0.65 second to build base surface (Fig.2(e)), while the non-accelerated scheme takes 8.891 seconds (Fig.2(f)). As the point set surface is usually densely sampled, the acceleration scheme still produces a high-fidelity reconstruction result as illustrated in Fig.2.



(a) (b) (c) (d) (e) (f)

(a) Original model with 54 250 points
(b) (c) (d) Base surface with one, two, three level control lattice
(e) Overlap the original model and the base surface, average error: 0.001664
(h) Multiresolution representation with non-accelerated scheme, average error: 0.001524

Fig.2 Multi-Resolution base surface construction, the radius of the bounding box of the model (a) is 1.0

To specify a special region for shape editing on a point set surface, as shown in Fig.10(a), the interesting region can be specified by applying the algorithms based on a level set method[7]. Then the base surface can been constructed on the selected region for further editing manipulation.

3 Representation of the Geometric Detail

To detect the geometric detail of a point-sampled surface, we project all the sampled points on to its base surface, and calculate the local affine coordinates of each sample point over the base surface.

Assume that p in R^3 is a sample point on the point sampled surface M, $(u,v)\in R^2$ is the corresponding parameter point. $p'=f(u,v)$ is the corresponding point on the base surface f. Let $d=p-p'$, we set up a local affine coordinate frame $\{f_u,f_v,n\}$ at $f(u,v)$, where f_u and f_v are the partial derivatives of f with respect to parameter u and v, $n(u,v)=f_u\times f_v$ is the normal of $f(u,v)$. Let $r=d\cdot f_u$, $s=d\cdot f_v$ and $t=d\cdot n$, then $d=r\cdot f_u+s\cdot f_v+t\cdot n$ and $p=f(u,v)+d$. See Fig.3.

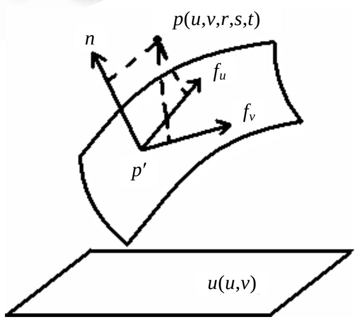


Fig.3 Projecting points to the B-spline base surface

The geometric detail of the point-sampled surface is defined as the set of difference vector d of all sample points. We call (u,v,r,s,t) the local affine coordinates of point p in the parametric space of the base surface. The bump component (r,s,t) is called the geometric detail coefficients defined in the local frame $\{f_u,f_v,n\}$.

Let $\tilde{M}$ be the base surface of M. The geometric detail D is defined as $D=M-\tilde{M}$. D is expressed by the set of bump component (r,s,t). The geometric detail can be extracted conveniently and mapped to other surface.

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4 Shape Modeling Based on Geometric Detail Mapping

Free form deformation (FFD) plays an important role in 3D shape modeling. We employ FFD for shape editing of point-sampled model. One important issue is how to keep the geometric details during the shape deformation. In this section, we will describe several modeling operators based on FFD capable of maintaining geometric details during operations.

Assume that the base surface $\tilde{M}$ of original surface M is a B-spline surface, the geometric detail D is defined as $D = M - \tilde{M}$ and extracted. Assume the surface $\tilde{M}$ is deformed to a new shape $\tilde{M}_{new}$. Let (r,s,t) in D keep constant for each point during the deformation. Suppose $\tilde{p}_{new}$ be the corresponding point of $\tilde{p}$ in the deformed base surface with its new local frame $\{f_u', f_v', n'\}$. Let $\Delta' = r \cdot f_u' + s \cdot f_v' + t \cdot n'$, then $p_{new} = \tilde{p}_{new} + \Delta'$ is the deformed position of p. The whole process resembles attaching the point p to $\tilde{M}$. While $\tilde{M}$ changes its shape, the "attached" point p moves accordingly.

Now we get the corresponding deformed sharp $M_{new} = \tilde{M}_{new} + D$ of the original surface M. We call it geometric detail preserved deformation. Any deformation on the specified local area of the base surface will be passed automatically to the underlying point-sampled surface. Compared with classic FFD approach that embeds the entail set of samples into the parametric space of 3D lattice, our new approach offers more flexibility of local shape editing with geometric features preservation. Under this scheme, we develop several modeling operators for the point set surface.

4.1 Sculpturing operator

We provide a sculpturing operator allowing a user to draw interactively on a point set surface, then the surface bends locally along the stroke. The user is allowed to interactively stroke on the point set surface, the displacement of each point is passed to the corresponding base surface. Then the Direct FFD method[9] is applied to achieve the sculptured base surface .By adaptively defining the size of the control lattice, it is convenient to set the width of the sculpturing stroke. The editing results are then propagated to the underlying point set surface by the geometric detail mapping, Fig.4 shows two sculpturing examples.

(a) (b) (c) (d) (e)

(a) Original surface
(b) With a negative displacement coefficient, a "w" is engraved into surface (a)
(c) With a positive displacement coefficient "A B" is embossed on the deformed surface (a)
(d), (e) different number of cirques is drawn along the surface normal (a)

Fig.4 Normal displacement

4.2 Twisting and stretching

We firstly define a handle x_0 on the surface, $x_0 \in M$. The twisting operation is to rotate the points around the handle while the stretching operation is to let the handle move interactively with a mouse or move along a pre-defined path curve. As the point sampled surface consists of enormous discrete points, twisting and stretching of the surface with fine control of the local shape is not a trivial task. R. Forsey, *et al.*[11] presented a hierarchical B-spline refinement method. Since we adopt the multilevel B-splines surface as the base surface, this hierarchical refinement method can be performed naturally on it. The twisting and stretching operation is then performed by

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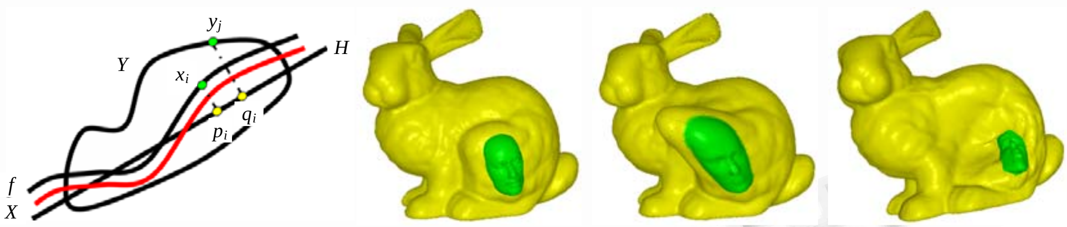
hierarchically editing the control points around the handle. Figure 5 shows the deformation results.

(a) Hierarchical deformation on Fig.4(a) (b) Twisting and stretching operation are manipulated on Fig.4(a)

Fig.5

4.3 Cut and paste

Assume that the point set patch $Y=\{y_1,\ldots,y_m\}$ is cut and pasted to another point set surface $X=\{x_1,\ldots,x_n\}$. When the point set surface X is deformed, the pasted patch Y should change its shape accordingly. The intersected curve of both the point set surface X and Y is estimated by applying an octree space subdivision algorithm. Then the sub-region X_s on the point set surface X covered by Y is outlined. The reference frame Y of patch X_s is computed using the covariance analysis method. The points on Y and X_s are then projected onto the common reference frame H. A correspondence between sample points of Y and X_s is built by performing the nearest point searching among their projections on H. Then we can freeze each point of Y to its corresponding point on the base surface of X_s and it moves when the base surface of X_s deforms. Figure 6 shows an example of deformation of the pasted surface.



(a) (b) (c) (d)

(a) The detail Y is embedded into a point set surface X. The red curve shows the region X_s, H is the reference frame
(b) A Mannequin model is pasted on the Bunny model
(c), (d) Mannequin changes its shape when Bunny is deformed

Fig.6 Cut and paste

5 Geometric Detail Transfer

Based on the multi-resolution representation of the base surface of point-sampled geometry and the geometric detail extraction operators, it is easy to separate the geometric detail, i.e., the high frequency feature from the original point-sampled geometry. In this section we will focus on geometric detail transfer between two arbitrary homeomorphous parameterized surface patches.

5.1 The machinery of geometric detail transfer

Suppose that the detail of the source model M is to be transferred to the target model N. We interactively specify the boundary of the region on M with desired geometric detail and that on N to which the geometric detail is to be attached. Both regions are mapped to one common unit square adopting the fast parameterization method. Assume $\tilde{M}$, $\tilde{N}$ be the base surface of the corresponding models M and N over the common parameter domain.

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Let the geometric detail $D=M-\tilde{M}$. Then $N'=\tilde{N}+D$ presents a new surface with the geometric detail of M.

Specifically, assume that the detail of point p in the M will be transferred to the point $\tilde{q}$ of $\tilde{N}$, both the points p and q share the common parameter point $u\in R^2$. The geometric detail $d=p-\tilde{p}$ is firstly extracted and represented by detail affine coordinate coefficients (u,v,r,s,t), where $\tilde{p}$ is the corresponding points in the base surface $\tilde{M}$ with the local frame $\{f_u,f_v,n\}$. The point $\tilde{q}$ on $\tilde{N}$ has the local frame $\{f_u',f_v',n'\}$. Let $(r',s',t')=\omega\cdot(r,s,t)$, where ω is a scale factor accounting for the difference between the scale of $\tilde{M}$, $\tilde{N}$; and $\Delta=r'\cdot f_u'+s'\cdot f_v'+t'\cdot n'$, then the new point $q'=\tilde{q}+\Delta$ has the coating of point p. With this technique, all the geometric detail of the source patch M can be transferred onto the corresponding point on the base surface $\tilde{N}$, the detail transfer is accomplished.

Note that the surface patch M and the target patch N are usually in different size and contain different numbers of points. Unlike the precondition of morphing between two point-sampled models which calls setting the correspondence between points of the two objects[5], this approach projects all the sample points of the source patch to the base surface of the target patch, and this actually executes a re-sampling in the parametric space of the target base surface. The original sample points of the target patch play only the role of determining the extent and the shape of its base surface.

5.2 Multi-Resolution geometric detail transfers

The multi-resolution representation $\tilde{M}_i$, $\tilde{N}_i$ are constructed for the corresponding models M, N. $M=\tilde{M}_i+D_i$. So model M can be encoded as a set of different levels of base surface $\tilde{M}_i$ and their corresponding levels of detail D_i. By transferring different levels of detail D_i to the corresponding level of base surface $\tilde{N}_i$ of the target model, the multi-resolution geometric detail transfer is achieved. The result is illustrated in Fig.7. Both base multi-resolution B-splines surfaces $\tilde{M}$ and $\tilde{N}$ are defined at the common parameter domain and provide global consistent local frame for all vertices on them. The geometric detail is extracted and transferred to target base surface simultaneously with little distortion.

(a) (b) (c) (d) (e)

(a) The source model Mannequin
(b) The target surface
(c), (d), (e) is the results that different level of details of Mannequin are transferred to target surface (b)

Fig.7 Multi-Resolution detail transfers

5.3 Constrained geometric detail transfer

Sometimes, it is desirable to transfer the geometric detail of one surface to another satisfying some global constraints. For example, in Figure 8, we would like to transfer the detail of Fig.8(a) to the surface of Fig.8(b), such as the nose and the wrinkle, to their corresponding feature regions on the target model of Fig.8(b). This problem is regarded as constrained geometric detail transfer.

We first parameterize both patches over the parameter domain. To transfer the detail between the feature regions of both the models, it is necessary to set up a finer match between the corresponding feature regions

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specified by the users. By employing a warping function, the corresponding feature points are projected to the same position on the common parameter domain[6]. This makes a natural assignment for the corresponding features on both models as well as a natural smooth transition between them. We then build the corresponding base surface $\tilde{M}$, $\tilde{N}$ for M, N based on the modified parameterization. Using the technique presented in subsection 5.2, the geometric detail of the features of the source can be transferred to the corresponding region of the target region.

(a) (b) (c) (d) (e)

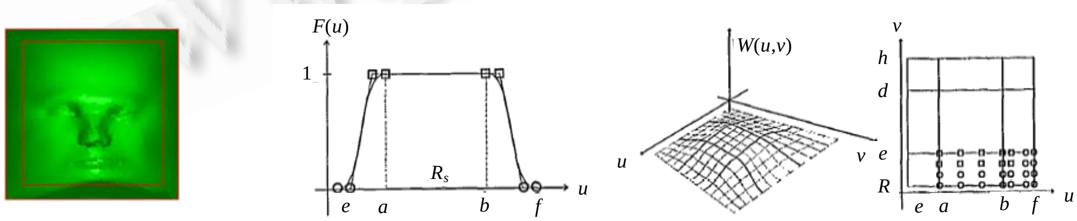
(a) Source model Max Planck
(b) Target model Mannequin
(c),(d) are the results of feature-preserved detail transfers technique with different levels of detail
(e) is the result that the geometric detail of (a) is transferred to the deformed surface of (b)

Fig.8 Feature-Preserved details transfer method

5.4 Boundary continuity of geometric detail transfers

As the boundaries of the source and target patches at the joint do not fit completely when the detail of patch M is transferred to S, it may result in discontinuous boundary. To eliminate the discontinuity around the boundary, we firstly define a transitional region on both the source patch and the corresponding patch on the target model, then we apply a blending operator to blend both the transition belts. Unlike meshes, there is no connectivity between the points of the point-sampled geometry. Fortunately, with the common parameter domain, it is easy to define a transition belt on the domain as shown in Fig.9(a). Then the corresponding transition belts on the patches can be defined respectively.

We specify the filter region, R_f=[e,f], the effective region, R_s=[a,b], as shown in Fig.9(b), Fig.9(c) for the 1D and 2D cases, and a C^1 continuous blending function on 1D and 2D can be defined as explained in Ref.[27]. The detail of the source patch D_M is $M-\tilde{M}$, the detail of the target patch $D_N = N - \tilde{N}$. We blend both D_M and $\tilde{N}$ using the blending function $F(u,v)$. Let N' be the result of geometric transferring, $N' = \tilde{N} + (1-F)D_N + FD_M$. Hence, we achieve the seamless detail transfer results as shown in Fig.8(c)~Fig.8(e), and Fig.11(d).



(a) A transition belt is defined on the parameter domain

(b) The 1D blending function

(c) The 2D blending function

Fig.9

Employing the techniques presented in the previous subsections, we can also manipulate the additional modeling operators such as details mixing and surface patches transplanting as in Ref.[10].

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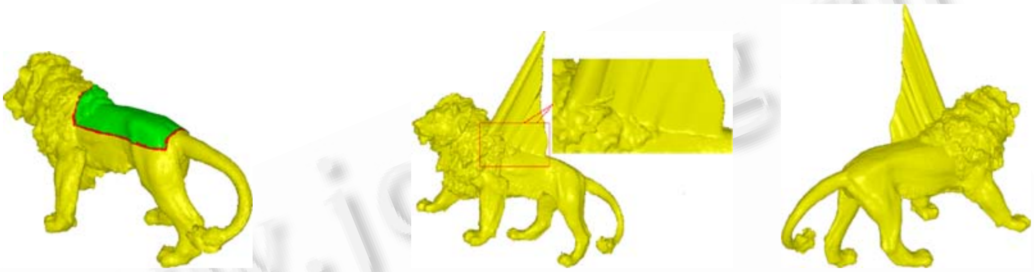
6 Implementation and Discussions

Fig.8 shows the results of feature-preserved detail transfer method. Especially, in Fig.8(e), the geometric detail is transferred seamless to the deformed base surface of the source model, resulting in cartoon model Fig.8(e). Re-sampling is one of the key problems regarding the deformation of a point-sampled model. We apply the Re-sampling method presented in Ref.[6]. In Fig.4(d), Fig.4(e), by performing a FFD deformation on the base surface, the corresponding number of cirques is drawn along the surface normal. Note that we only need to re-sample the deformed region on the surface. In Fig.10, a wing is drawn out from the lion model by local deformation. Figure 11 illustrates another example that the geometric detail transferring operator is performed.



(a) Red curve is the closed decomposition curve. The green region on the lion model is deformable region

(b) A wing is drawn out from the lion models

(c) A different sight of (b)

Fig.10

(a) The mannequin model

(b) Its base surface

(c) Bunny model

(d) The result of seamless geometric detail transfer

Fig.11 Seamless detail transfer

Note that the approach presented here performs the deformation and editing of the point-sampled geometry at interactive speed. There are two procedures that cannot run at interactive speed in the preprocess step. One is the parameterization of the deformable region. Nevertheless, it is performed only once. With the fast hybrid methods, it can be finished within half minute. The other is the construction of the multi-resolution base surface. Using the acceleration technique, we can accomplish it in several seconds.

7 Conclusions and Future Work

We have presented a versatile modeling framework for 3D point-sampled geometry based on a novel idea of geometric detail mapping. The geometric detail is an important feature of a surface. It can be extracted from the original surface. Then it can adhere to the base surface of any model to achieve various appealing editing results. Thus, the modeling framework supports a broad range of editing operators for efficient 3D shape creation. As the only property of the point set surface that we use is the geometric information, not the connectivity information between the discrete points, and therefore, the algorithm can be adapted to meshes.

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