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Free hand stroke based virtual sketching, deformation and sculpting of NURBS surface

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Abstract

This research is to make a series of NURBS surfaces for the virtual 3D conceptual design and the styling process by applying arbitrary calligraphic strokes. The surface can be modified in real-time free form deformation and sculpting. The suggested algorithm is used to create 3D NURBS surfaces for styling object using free-hand strokes with the posture information of the input wand. The algorithm presented in this paper can help product designers in the conceptual design stage, even if he or she has no idea about the shape of a target product.

Key words: NURBS, Free-form deformation, 3D sketching, Calligraphic sculpting, Virtual Reality.

1. Introduction

Design is one of the most important aspects of the overall product development process. It determines not only the visual appearance but also the aesthetic and visual impact of the product in order to create the 'added value' and 'desirability'. The shape of a product has a great influence on buying decisions of customers and success or failure of a product. Recently the speed of design development cycles tends to increase in accordance with the change of user requirements. Consequently, companies invest a huge amount of time and manpower in developing the innovative shape of products and the timesaving design process to optimize time investment and costs.

Conceptual design is one of the initial phases of the design process. The designer represents the conceptual ideas, taking account of the market and user requirements, in the form of various solutions by sketching. These ideas are then passed on to the engineering designers for the intricate and detailed design. The engineering design phase nowadays is nearly all computerized. On the other hand in the conceptual design process there has been much less use of computing. Because current CAD software does not provide sketching applications that are as intuitive and flexible as traditional tools such as pencil and paper.

However, we can find the possibility of a novel design paradigm in that the ongoing research and the increase in computer performance are contributing to acceleration of the integration of the design cycle. Use of Virtual Reality (VR) techniques, instead of traditional 2-dimensional devices such as monitor, keyboard and mouse, have made possible sketching directly in 3D space in a more intuitive fashion. They showed the unexploited potentiality of real three-dimensionalities design in VR. Virtual Reality offers a better perception of 3 dimensionalities and provides direct drawing and positioning that in combination with 3D interaction.

There have been a number of 3-dimensional construction systems built up of the VR techniques in recent years. 3-Draw[1] system and FreeDrawer[2] are sketching systems, which have demonstrated that developing 3D models on the computer by drawing directly in three-dimensional space is natural and quick. And in Surface Drawing[3], surfaces are created by moving a hand, instrumented with a special glove, through space in a semi-immersive 3D display and interaction environment. The user's hand is acting as a guide for a plane to construct a surface. The HoloSketch[4] supports several types of 3D drawing objects and animation in three-dimensional space.

The user interfaces of these systems keeping the number of low level interactions to a minimum, as well as the command set, support to express the user's thinking in a fast way, while it provides little functionalities to be capable of sophisticated creation to build complex 3D models. For instance, 3-Draw system allows only the placement of lines and HoloSketch works well for models that are made of theses primitives but do not readily extend to the larger class of all surfaces. Surface Drawing is not suitable to express tidied and beautified 3D models by reason of lack of skill to refine the human hand's irregular shake.

We propose a smart sketching system, a 3-dimensional modeling tool for curve drawing and deformation techniques in an immersive VR system. It provides direct control over the creation of a wide range of intricate and sophisticated shapes by moving the wireless wand through space. Each of the systems discussed above has some similarities to our system, but the novel construction method and the calligraphic stroke based deformation procedure make our smart sketching system functionally quite distinct. In particular construction method for surfaces is achieved through the skinning algorithm including derivatives based on an angle (orientation) of the wand. The deformation is accomplished by means of some calligraphic free-hand strokes that are drawn for the target curve on the final shape. Also the possibility of real-time simulation of dynamic behavior is investigated by using the NURBS-based finite element method. Users are allowed to freely create, modify, and erase surfaces based on the wand's motions. A compact toolset and the construction process by means of gestures which the Smart Styling system combines allow both beginners and experts to have free access to quick and easy 3D form creation and deformation.

In our smart sketching system, we can find a compromise between geometric complexity and fast interaction, which will cast a new light on the VR modeling system. We expect that the Smart styling system can contribute to the revolution in the design process. In section 2, our own derivatives by posture based surface construction algorithm are described. A novel calligraphic stroke based deformation and sculpting methods are given in section 3. Finally, we conclude this paper and suggest some future extensions in section 4.

2. Free hand stroke based virtual sketching

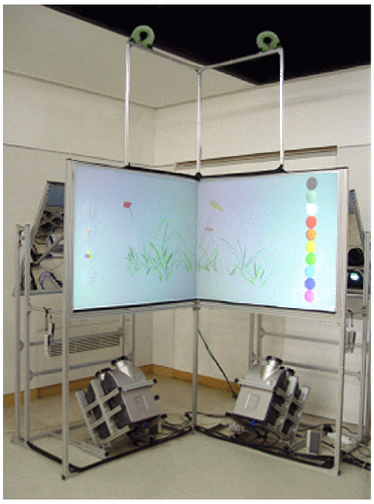

Fig. 1. VR system for virtual sketching

Most 3D modeling software requires artists to create shapes using mathematical controls. We observe that many artists have difficulty conceptualizing with these tools. Therefore, even when presented with sophisticated modeling tools, artists often use pencils to think about models before specifying them with software. This process forces a 3-dimensional task to be conducted in 2 dimensions. Since the object being created is three-dimensional, this thought process would ideally take place in 3 dimensions.
In this paper we propose a three-dimensional sketching and modeling interface that support 3D input and output, running on the immersive VR system as shown in Fig. 1. This medium allows the users to directly create 3D models by moving a 3D input device through space. At first the points of a free hand calligraphic stroke are interpolated into a NURBS curve. Secondly each profile value of selected curves is set equal. Thirdly a set of curves is converted into a single NURBS surface by the skinning algorithm. Finally a user can modify the shape of a NURBS surface by drawing additional calligraphic strokes.

2.1 Free hand calligraphic strokes for NURBS curves

By moving the wand through 3-dimensional space, a user draws lines on free-hand drawings, which are automatically interpolated into a suitable NURBS curve. Using the given data, which consists of drawing points, an appropriate parameter value and the knot vector are computed. And then we can interpolate given a set of points with pth-degree non-rational B-spline curve through the $(n+1)\times(n+1)$ coefficient matrix of linear equations, which is set up by evaluating the B-spline basis functions. Here n is the number of control points.

Before curves are converted into a skinned surface, there are several elements we should consider for its order and profile value. Skinning algorithm is a method that uses more than two curves to form surfaces. However, changing the order yields different skinned surfaces even with the use of the same curves. Thus, setting the order of the curves given for skinning is important. A user has to select certain curves, which will be combined to constitute a network of curves, in the appropriate order.

Moreover, another aspect to consider is that the values contained in each curve on the same network, which will describe the shape of the desired surface, must be identical. Through the degree elevation and the knot refinement algorithm these curves will have the same degree and be defined on the same knot vector. The degrees must be set at the biggest values among those contained in each curve. If smaller than those, the values must be raised via degree elevation. If the knot vectors of curves are not identical, the new knot vector, which is composed of the maximum multiplicity of all knots, has to be defined. The knot refinement algorithm enables the new knots to be inserted into the established knot with their multiplicities. Consequently, these unified curves apply to the section curves of the skinned surface, and their profiles are carried over in the u direction of profiles of the skinned surface.

2.2 The Skinning with derivatives of edges

Skinning is one of the most powerful and widely used methods for surface construction: It defines a surface using two or more given section curves. A series of curves functions as a frame of a skinned surface. Thus it can help a user intentionally find the most efficient way to represent the desired shape before beginning the modeling process. In order to construct a surface, we present the enhanced skinning algorithm differently from the general skinning algorithm. Our skinning algorithm is based on the standard for the skinning process but it shows an advanced construction interpolating both points and derivatives determined from the position and the angle of the wand. The resulting skinned surface passes through the given section curves and assumes the given derivatives at the prescribed points by applying the standard B-spline interpolation method.

Especially, consideration for derivatives gives emphasis on the importance of the motions of the wand. As the wand is moved in an immersive environment as shown in Figure 2, data including the position and the angle of the wand are sent to the tracking computer. The derivatives are determined from the angle between the right and the left maker of the wand.

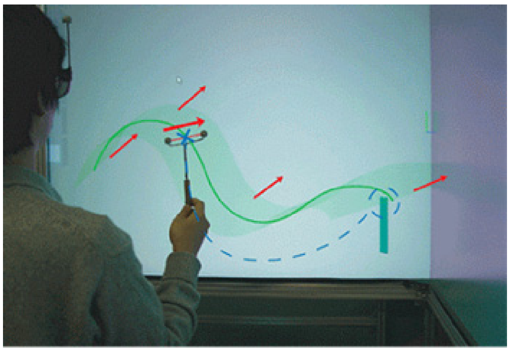

Fig. 2. Derivatives by the tracked motion of a wand

The reason for using the derivatives is that each derivative gives rise to one additional knot and control point, and, hence to one additional linear equation. As the derivatives are added to the skinning algorithm, the number of equations increases double, so we can get a double control points. There are some advantages of using derivatives for the skinning algorithm. We can get double control points by the skinning algorithm including derivatives because the derivatives formula is used to set up the additional equation. Hence, we can approach to the precise and various shapes of a skinned surface due to the doubled control points. Most of all, the final shape of the skinned surface encompasses the posture information of the wand, which implies the extra meaning besides positioning of the 3D input device.

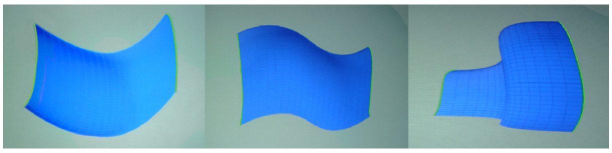

Fig. 3. Various surfaces by different edge derivatives

Figure 3 shows the resulting surfaces through the skinning algorithm with derivatives of similar section curve set. In consideration of these aspects, we improved the modification techniques through manipulating the derivative condition instead of the control point of section curves

2.3 Object construction by skinned NURBS surfaces

When creating an object interactively, we clearly require techniques that enable us to manipulate the shape of the object intuitively. However designing skinned surfaces is often a fastidious process. Mostly the skinned surface is defined, modified, and manipulated with operations on the section curves. A surface shape is difficult to control due to its dependence on the number, shape, and positioning of these curves. Moreover, in commercial computer design tools, designers can obtain more desirable shapes by assiduously manipulating their control points.

This modification method is definitely not suitable if developing the interactive system that supports the 3D input, since exactly selecting spatial positions is hard in these systems. Hence we have implemented the novel modification technique to be fast and easy enough for the user to be able to efficiently work efficiently. In this paper, we propose the method to modify curves and surfaces by drawing additional calligraphic strokes.

A user is allowed to control the derivative condition such as the direction and the size. The derivative conditions play an important role in determining the overall shape of the surface[5]. Even though a set of the section curves is still fixed, just changing direction and size of derivatives can cause wide differences of the control point net, and so the accomplished shapes are diversified.

In an attempt to capture the flavor of our smart sketching system, we initiated construction of each sample model of a boat and a car. To begin, the user first draws four curves which function as the frames of the boat model. Next, the user can construct the surface that links the two curves, step by step, via the skinning algorithm with derivatives. Through several steps to create a boat you can see the completed boat model in Figure 4. And the shape of the boat can be diverse according to the change of derivatives conditions as shown in Figure 5.

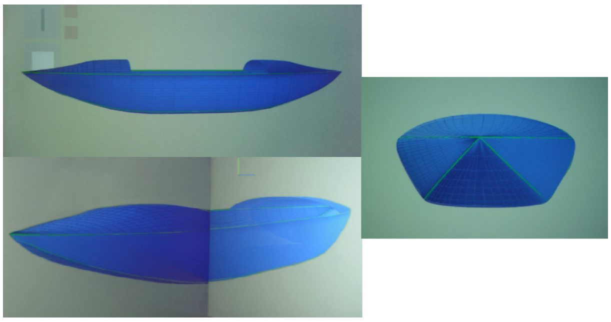

Fig. 4. A boat model by skinned surfaces

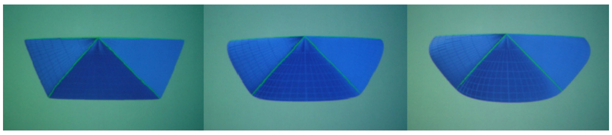

Fig. 4. Diverse hulls by applying different derivatives

A car model is constructed in a similar manner with the boat; first drawing the curves that describes the frame of the car, and then expanding these curves into the skinned surface via the skinning algorithm. Finally, both sides of the car are wrapped with the Coons surfaces. Moreover user can attempt to create the various edge shapes of the model by changing the derivative condition, as illustrated in Figure 6.

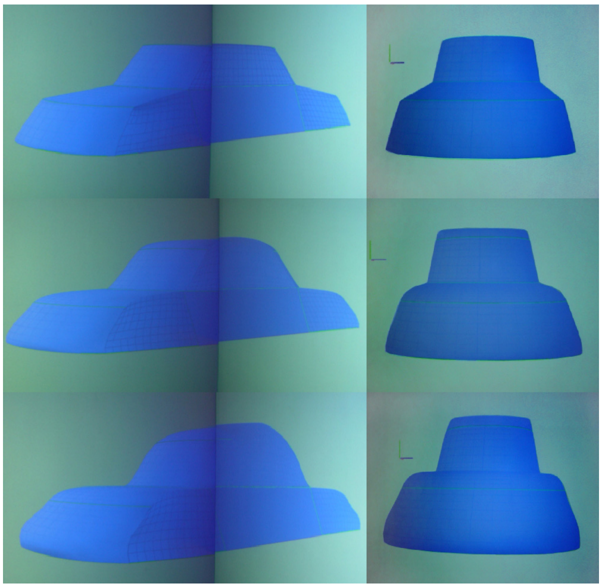

Fig. 6 . Car model by skinned and Coons surfaces

3. Deformation and sculpting of NURBS surface

3.1 NURBS surface deformation with calligraphic stroke

The constructed surface can be deformed by free-hand calligraphic strokes proposed in the last chapter. The input stroke will be a target curve of deformation. The original surface will be updated into a new surface including the target curve by calligraphic stroke deformation. A designer can complete a rough 3D sketch using 3D strokes as if he or she sketches directly on a 2D sketchbook. Calligraphic strokes for deformation can be drawn at any side of surface such as upside and underside, as shown in Figure 7.

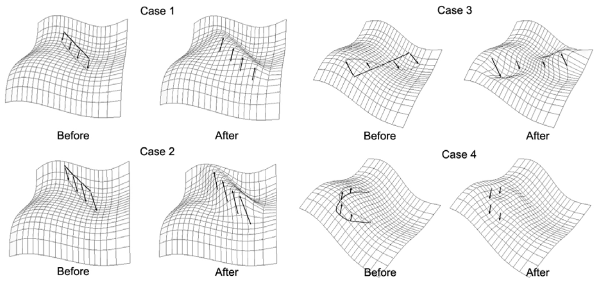

Fig. 7. Sample calligraphic strokes for the target curve

Sederberg & Parry[6] proposed a method by which solid geometric modeling could be deformed using tensor product Bernstein polynomial and lattices. Various deformation methods using lattices were proposed by Coquillart[7], MacCracken and Joy[8]. Hsu, Hughes, and Kaufman[9] found a new way of free-form deformation using pseudo-inversed direct manipulation. Paul Borrel[10] deformed a surface, locally displacing with constraint area. Wesche and Seidel[2] and Schkolne, Pruett and Schröder[3] proposed another deformation method, which use special tool or motion in virtual 3D environments.

But the deformation methods in the previous literature require completely different procedure compared with the modification of 2D sketch in the general design process. Using 3D stroke, however, much of researcher's concern is placed on drawing surface, instead of surface deformation. The deformation method, which is adopting and using the calligraphic stroke as target curve on the final shape make a designer draw and modify a model easily and efficiently by using drawing skill of the general 2D sketch.

A user's stroke in 3D sketching system is to be target curve of surface deformation. And the orientation of wand in 3D stroke defines the direction that determines deformation area in the surface. The sequence of the deformation by calligraphic strokes based on the above equation become as follows:

1. The user drawing calligraphically a stroke with 3D input system. The stroke becomes the target curve on NURBS surface for deformation.
2. We now calculate corresponding projected points on surface using the position and the orientation of stroke. First of all, we consider only one point in the target curve. Surface is translated by using the matrix by which target point is translated into origin of axes of coordinates, and rotated by using the matrix by which target normal is rotated to positive direction of z-axis. Next, we search parametric values of u and v on the surface that become the nearest point to the origin, which is now the same as the target point. The values of u and v become deformation point on the surface. The distance from deformation point to target point (deformation value) becomes diagonal element of surface

points, $\Delta q^{k,l}$, matrix. NURBS basis functions are determined with the value of u, v at the calculated deformation points.

3. The rest elements of $\Delta q^{k,l}$ matrix except diagonal element are interpolated by two third order polynomials. We use the polynomial at both sides of the target curve. The rest elements of the matrix are determined by referencing Figure 8. After calculating the displacement in both directions of u, v, and then the values are averaged to fill in the matrix $\Delta q^{k,l}$.

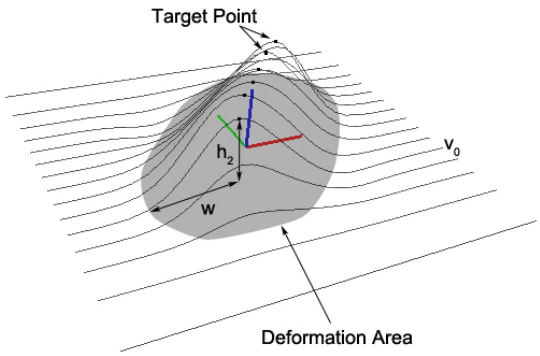

Fig. 8. A series of two polynomials for the approximation of deformation

4. The basis functions are calculated and pseudo-inversed to determine the change of the control points of the deformed surface.

When a designer draws an object, he or she expresses the volume and area by drawing its outlines. The deformation by calligraphic strokes is the deformation of NURBS surface using designer's intentional strokes in 3D space such as outline drawings on a 2D sketchbook.

3.2 NURBS surface sculpting by multi-resolution trimming

NURBS surfaces are widely used in the engineering design since it could create smooth surface using minimal number of data. But its intuitive deformation is quite difficult especially for the detailed modification. Most literatures show a rough deformation so that these techniques may results some distortion or even separation when applied in the sharp deformation. Coquillart[7] applied a lattice to deform a certain area into the special shape. Coons[11] surface can be used for filling in a space for deformation. Wang [12] showed that the separation of surfaces with knot insertion could be used in the detailed trimming with continuous curvature. Virtual sculpting tool [13][14] is developed using the surface feature constraints, but this deformation requires many control points for conserving the whole deformed shape. Deformation can be implemented by trimming the target surface and the selected area rendering.[15] Similar idea is applied in the sub-division surface with multi-resolution.[16]

In this paper, both the surface trimming and multi-resolution surface are used for the detailed sculpting including sharp edge of free form surface. The calligraphic free-hand strokes are also used for the target sculpting curves. In order to triangulate the surface, the NURBS surface is stored in grid type UV map that can be expanded into the multi-resolution grid for detailed sculpting edge. Free-hand calligraphic curves have to be projected onto the free-form NURBS surface. In curve projection by Newton iteration, the Equation (1) is used to update the u value.

$$u_{i+1} = u_i - \frac{C'(u_i)\cdot(C(u_i)-P)}{C''(u_i)\cdot(C(u_i)-P)+\left|C'(u_i)\right|^2} \qquad (1)$$

where, $C(u_i)$ is the projection point and P is the point for projection. The conditions for termination are similar to the curve case in the surface projection but are simply extended to both u, v directions as follows.

a. Point coincidence

$$\left|S(u_i,v_i)-P\right| \le \varepsilon_1 \qquad (2)$$

b. Zero cosine

$$\frac{\left|S_u(u_i,v_i)\cdot(S(u_i,v_i)-P)\right|}{\left|S_u(u_i,v_i)\right|\left|(S(u_i,v_i)-P)\right|} \le \varepsilon_2 \quad \frac{\left|S_v(u_i,v_i)\cdot(S(u_i,v_i)-P)\right|}{\left|S_v(u_i,v_i)\right|\left|(S(u_i,v_i)-P)\right|} \le \varepsilon_2$$

(3)

c. The parameter does not change significantly

$$\left|(u_{i+1}-u_i)S_u(u_i,v)+(v_{i+1}-v_i)S_v(u_i,v_i)\right| \le \varepsilon_1 \qquad (4)$$

where, ε_1 is a measure of Euclidean distance and ε_2 is a zero cosine measure. Figure 9 shows a sample projection of free-hand calligraphic curve on surface.

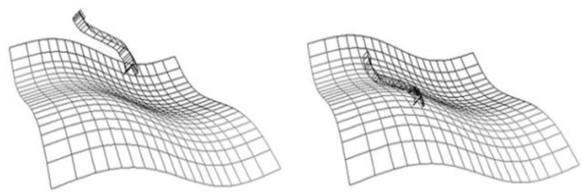

Fig. 9. Projection of calligraphic stroke

Since the surface is stored in the grid type UV map, curve projection is actually the process to find boundary grids as shown in Figure 10. Jordan curve theorem is used to determine the exterior, interior and boundaries of all 2 dimensional UV grids.

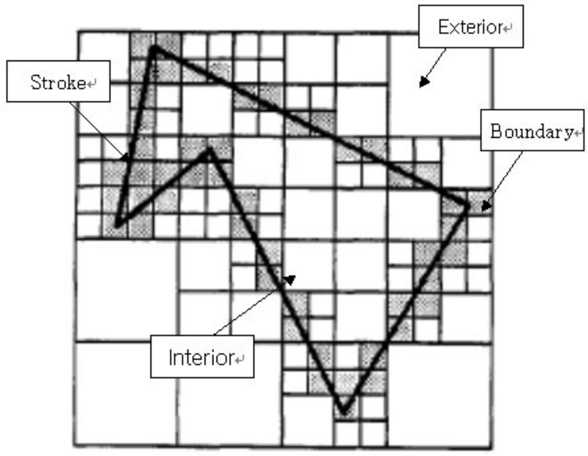

Fig. 10. Projected strokes on 2 dimensional UV map

Sculpting is implemented by two separate surfaces, the original NURBS surface and sculpting curves which have generally constant cross sectional shape. The boundary area is required to be defined by smaller grids, so that the sculpting effect is maximized. The Figure 11 shows the sharp boundary by quad-division interpolation of UV map.

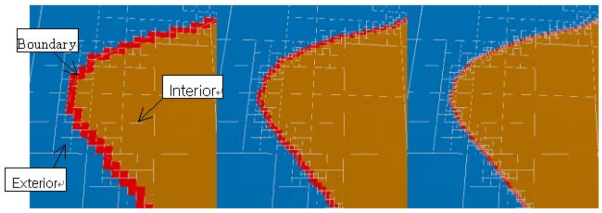

Fig. 11. Boundary grids by quad-division interpolation

This multi-resolution surface can be used for the surface trimming without changing the topology of the target surface. Boundaries and interior grids are simply replaced with the sculpting effect in different levels as shown in Figure 12.

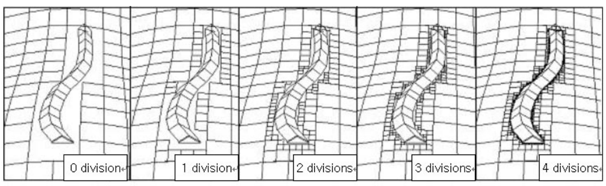

Fig. 12. Multi-resolution surface and sculpting effect

To show the effectiveness of the NURBS surface sculpting using multi-resolution trimming, direct deformation with knot insertion and surface trimming with separation are compared with the proposed method. Two folding strokes are applied on the 10 by 10 cubic NURBS surface for sculpting. As shown in Figure 13, the sculpting effect is not satisfactory and the numbers of control points are increased to 39 by 39, which is a burden for further deformation and sculpting.

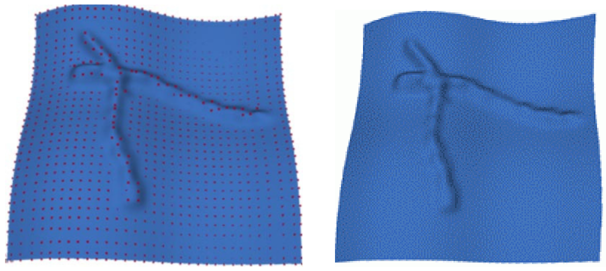

Fig. 13. Direct deformation with knot insertion

In the sculpting with trimming by surface splitting, Coons surface is used to fill up the split interior. Too many surfaces are generated by two sculpting curves, which will cause the wave effect for further deformation as shown in Figure 14.

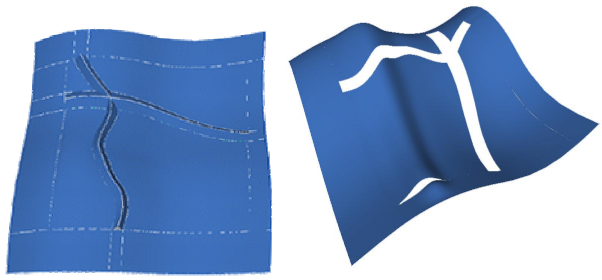

Fig. 14. Sculpting with trimming by surface splitting

NURBS surface sculpting using multi-resolution trimming shows satisfactory result without distortion as shown in Figure 15. Maximum resolution is set for preventing the unwanted precise quad-division for the repeated sculpting curves.

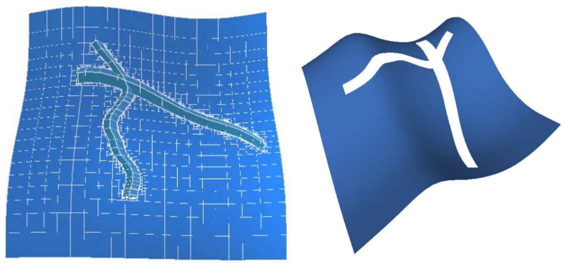

Fig. 15. Sculpting by multi-resolution trimming

4. Conclusion

We describe a smart sketching system, which demonstrates an innovative 3D modeling technique to construct and deform 3-dimensional models. The user directly draws free-hand strokes using a wireless wand as an input device. A set of curves with derivatives is converted into a surface by the skinning algorithm, of which the shape can be interactively modified by additional stokes. We can explain that the significant point of this construction method is the intimate relations between the shape of surfaces and the motions of the wireless wand.

Our smart sketching system is expected to solve the problems of the 2D interfaces, which force users to comprehend a rigid mathematical structure and a complex toolset. Its compact toolset and the effective and sophisticated manipulation is enough to accomplish complex projects, yet accessible for both experts and beginners.

Most of existing surface deformation algorithms makes a user learn how to use the new deformation tool to design model. But surface deformation with calligraphic strokes helps the user approach easily to the intuitive 3D deformation interfaces. The general users don't need to learn new skill or the way of using tool, and are able to design model in 3D virtual space as they draw on a sketchbook. Some detailed sculpting interfaces are required to be implemented to finish the precise styling such as filleting, grooving and making a hole in the surface.

Acknowledgements

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