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## Interactive sculpting of product shape based on constraint manipulation in virtual environment<sup>\*</sup>

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**Abstract:** In product concept design, not only designers with professional CAD skills, but also final customers take part in the design and evaluation of product shape styling. Because customers usually lack surface modelling background and are not familiar with concrete operations of commercial CAD systems, it is difficult for them to express their change intentions of product shape through professional CAD tools if they are not satisfied with the current shape design. This paper puts forward a method for creating, dragging and manipulating constraint and load represented in form of icon entity in interactive sculpting of product shape in virtual environment. The method supports customers manipulation of sculpting constraints or loads on sculpting shapes in virtual reality interaction to control the deformation of product shape. Constraints management based on icon entity is similar to spline lofting operation that is familiar to engineers, so users do not need to know surface details or have any professional knowledge of surface modelling, by only using their physical and engineering experience, they can manipulate the sculpting of product shape intuitively.

**Key words:** Virtual design, Constraint manipulation, Shape sculpting, Concept design

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### INTRODUCTION

In product concept design, not only designers who have professional CAD skills, but the final customers will also take part in the design and evaluation of product shape styling. Because customers usually lack background in surface modelling and are not familiar with concrete operations of commercial CAD systems, it is difficult for them to express their change intentions of product shape through professional CAD tools if they are not satisfied with the current shape design.

Spline lofting operation is familiar to engineers as a common design method of shape sculpting. Using this method, engineers can modify curves and surfaces intuitively by way of mechanical method

without too much surface modelling knowledge. In the course of lofting, engineers can use sculpting constraints interactively so as to let attributes of deformable object (such as data point, control point, tangent vector, normal vector) keep fixed or change the way as defined before. By using sculpting constraints, users' design intentions will be realized effectively. So if we adopt similar methods to control shape sculpting in virtual environment, we will realize intuitive interaction of product shape design as well as effectively capturing the design intentions of users.

In recent years, people studied and explored sculpting of shape in virtual environment from different aspects. Gaylean and Hughes (1991) developed a 3D-input sculpting method based on voxel model. Designers simulating traditional clay modelling procedure, scrapping, chipping, sweeping etc. virtual clay materials through 3D-input device of six degrees of freedom. Hummels *et al.*(1997) developed a

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“MOVE ON” system, which can control the extension of curves in virtual environment by interactive tool named Glob to manipulate car styling. Dani and Gadh (1997) developed a concept shape design system based on virtual reality, which enables the designer to sculpt free surface shape by gestures directly without defining the position of surface control points. Dorman and Rockwood (2001) used 5th Data Glove and position tracking device to design polygon surface. By stretching data glove fingers, designers could change the deformation area of surfaces, then by pushing or pulling movements of fingers, designers could control surface deformation. Fiorentino *et al.*(2002) developed a semi-immersive virtual design environment 3DIVS, wherein users can pick and modify control points by three virtual tools—Picker, Twister and Weighter, which respectively control the position, twist and weights of those control points. Wishing to overcome the shortcoming of single point controlling of surface sculpting in virtual environment, Perles and Vance (2002) put forward an improved controlling method for shape sculpting in the development of DN-Edit system, which can manipulate NURBS surfaces by virtual interactive tools, such as point tool, block tool and normal tool. Van Elsas and Vergeest (1998) proposed a displacement feature modelling method allowing explicit modelling of protrusions and depressions in free-form B-Spline surfaces, and intended to be used by industrial designers during conceptual design. Dumitrescu and Vergeest (2004) presented concept of shape context, which incorporates specific parameters, constraints and shape variation procedures that help designers to reach a desired shape faster.

In view of the need for constraints management in virtual sculpting of product shape, this paper puts forward the method of constraints creation, manipulation and interaction in product shape deformation in virtual environment. The method supports users manipulation sculpting constraints or loads on shape of product through virtual reality interaction. The rest of the paper is organized as follows. Section 2 introduces the deformable surface model of product shape. Section 3 presents the concept of icon entity of constraint and load, and then puts forward the approach to interactively construct and drag icon entity during virtual sculpture. Section 4 explains interactive shape sculpting based on icon entity of constraint and load.

Section 5 introduces a virtual sculpting system for the product concept design system developed by us. Finally, Section 6 presents conclusion reached in this work.

## DEFORMABLE SURFACE MODEL OF PRODUCT SHAPE

For each surface in the product model, we constructed corresponding deformable surface model with mechanical attributes (such as resistance to stretch and resistance to bending). The energy calculation model of curve and surface developed by Terzopoulos *et al.*(1987) can be used to obtain the solution of deformable surface by seeking curves and surfaces with minimum physical deformation energy, on condition that constraints on deformable object are satisfied.

The deformation energy equation of curve can be written as (Terzopoulos *et al.*, 1987):

$$E_{\text{curve}} = \int (\alpha \mathbf{w}_u^2(u) + \beta \mathbf{w}_{uu}^2(u) - 2\mathbf{f}(u)\mathbf{w}(u))du \quad (1)$$

where  $\mathbf{w}(u)$  is curve with  $u$  as parameter;  $\mathbf{w}_u(u)$  and  $\mathbf{w}_{uu}(u)$  are respectively order 1 and 2 derivative vectors;  $\alpha$  and  $\beta$  are given parameters corresponding to resistance to stretching and resistance to bending of curve;  $\mathbf{f}(u)$  is external load applied by users.

The deformation energy equation of surface can be written as (Terzopoulos *et al.*, 1987):

$$E_{\text{surface}} = \iint [a_{11}\mathbf{w}_u^2(u, v) + 2a_{12}\mathbf{w}_u(u, v)\mathbf{w}_v(u, v) + a_{22}\mathbf{w}_v^2(u, v) + \beta_{11}\mathbf{w}_{uu}^2(u, v) + 2\beta_{12}\mathbf{w}_{uv}^2(u, v) + \beta_{22}\mathbf{w}_{vv}^2(u, v) - 2\mathbf{w}(u, v)\mathbf{f}(u, v)]dudv \quad (2)$$

where  $\mathbf{w}(u, v)$  represents a surface with  $u$  and  $v$  as parameters;  $\mathbf{w}_u(u, v)$ ,  $\mathbf{w}_v(u, v)$ ,  $\mathbf{w}_{uu}(u, v)$  and  $\mathbf{w}_{vv}(u, v)$  are respectively order 1 and 2 derivative vectors of  $u$  and  $v$ ;  $\mathbf{w}_{uv}(u, v)$  are cross derivative vectors;  $\alpha$  and  $\beta$  are given parameters corresponding to resistance to stretching and resistance to bending of surface;  $\mathbf{f}(u)$  is external load applied by users.

The deformable surface model of product shape draws lessons from thin-plate elastic deformation characteristics in elastic mechanics. Because physical

deformation energies caused by resistance to bending and to stretching are all considered, deformable curves or surfaces will be shrinking to the most to ensure a good fairness and that there will be no redundant folding.

## INTERACTION OF ICON ENTITY OF CONSTRAINT AND LOAD

### Icon entity of constraint and load

For visually expressing all kinds of constraints and loads applied to sculpting shape, we adopt icon entity to represent those constraints and loads. Users could perform add, modify, delete, drag operations to constraints and loads by icon entity interaction. At the same time, the status change of icon entity also reflects the change occurring in the constraints and loads.

Attributes of icon entity consist of ID, type of icon entity, graphic entity node, active state, coordinate value and list of motion sensors associated with icon entity. Where,

ID: the identity of sculpting constraint or load associated with icon entity.

Type of icon entity: includes point icon entity of constraint, point icon entity of load, curve icon entity of constraint, curve icon entity of load, region icon entity of constraint and region icon entity of load.

Graphic entity node: Every icon entity corresponds to a graphic entity (such as sphere, cube, tetrahedron, polygonal line and so on). For example, point icon entity of constraint is represented by a little red sphere while point icon entity of load is represented by a little green sphere.

Active state: includes driving state, passive state and sleeping state. (1) Icon entity in driving state is associated with motion sensor. During sculpting procedure, users actually modify the position and orientation of icon entity in driving state to realize shape deformation; (2) Icon entity in passive state is not associated with motion sensor, but still has constraining effect on sculpting object; (3) Icon entity in sleeping state is rendered in gray and has no influence on sculpting object. Designers can shift the icon entity to sleeping state and then activate it back. During shape sculpting, when users drag icon entity in driving state, surface will deform to satisfy the changed

position and orientation of icon entity. At the same time passive icon entity of load on surface will change correspondingly while other passive icon entity of constraint will keep unchanged, that is, in sculpting procedure, surface always fulfills those constraints. Table 1 shows comparison of icon entity in different state.

Coordinate value: Both  $(u, v)$  and  $(x, y, z)$  coordinate value are recorded.

List of motion sensors associated with icon entity: In virtual environment, designers could control motion of icon entity by multi-modal sensors (such as 3D mouse, data glove and position and orientation sensor). So, we register sensor list associated in driving icon entity.

**Table 1 Comparison of icon entity in different state**

	Active state		Sleeping state
	Driving state	Passive state	
Association with motion sensors	Motion associated with motion sensors	Motion not associated with motion sensors	Motion not associated with motion sensors
Effect on sculpting object	Driving deformation	Has restraint effect if type of icon entity is constraint	No effect

### Construction of icon entity

#### 1. Point icon entity

Users can pick data point on surface to construct point icon entity of constraint or load. During shape sculpting procedure, attributes of point icon entity of constraint, for instance, position, tangent vector and normal vector will keep unchanged. At the same time, users can interactively drag point icon entity of constraint or load while surface will deform correspondingly.

Let parameter coordinate value of point icon entity of constraint on surface be  $(u', v')$ , while corresponding space coordinate value is  $P_i(x', y', z')$ , derivative vector is  $T$  and normal vector is  $N$ . According to their effects on sculpting surface, point icon entity can be divided into four types as follows:

(1) Point icon entity of load: In shape sculpting procedure, users can apply loads on this icon entity. If load applied is  $f'$ , then the data point load can be written as:  $f(u', v') = f'$ .

(2) Point icon entity of position constraint: In shape sculpting procedure, deformable surface should

always interpolate the given points represented by the icon entity. The position constraint can be represented as:  $w(u',v')=P_t$ .

(3) Point icon entity of derivative vector constraint: In shape sculpting procedure, derivative vector on point represented by the icon entity will keep unchanged. For example, tangent vector constraint of  $u$  can be written as  $w_u(u',v')=T$ .

(4) Point icon entity of normal vector constraint: In shape sculpting procedure, normal vector of deformable surface will keep unchanged on the point represented by the icon entity. That is,

$$\begin{cases} N \cdot w_u(u',v') = 0 \\ N \cdot w_v(u',v') = 0 \end{cases} \quad (3)$$

In order to represent the attribute of point icon entity visually, the point icon entity of position constraint will be rendered as little red sphere (Fig.1a), point icon entity of load will be rendered as little green sphere (Fig.1b), point icon entity of derivative vector constraint will be rendered as little yellow sphere with literal label (where, R represents tangent vector constraint of  $u$ , V represents tangent vector constraint of  $v$  (Fig.1c), R2 represents order 2 derivative vector constraint of  $u$ , V2 represents order 2 derivative vector constraint of  $v$ , RV represents cross derivative vector constraint), point icon entity of normal vector constraint will be rendered as a 3D arrow to express the direction of normal vector.

2. Curve icon entity

In shape sculpting procedure, users can interactively construct or choose B-Spline curve and require deformable surface to interpolate this curve. We den-

ote B-Spline applying constraint or load on surface as curve icon entity. Users can directly draw curve icon entity on surface by gestures in virtual environment. Fig.2 shows a curve icon entity drawn by users.

Let the defined curve be  $c(t)$ , parameters of deformable surface  $w(u,v)$  and parameters of curve  $c(t)$  be related as follows:

$$u=u(t), v=v(t) \quad (4)$$

Curve icon entity of constraint requires that deformable surface  $w(u,v)$  always interpolates defined curve  $c(t)$  in the sculpting procedure. The constraint can be written as:

$$c(t)=w(u(t),v(t)) \quad (5)$$

In shape sculpting, curve icon entity can also be deformed interactively. Let the curve icon entity before deformation be  $c'(t)$ , while curve icon entity after deformation is  $c(t)$ , then, curve icon entity of load can be constructed according to the difference of  $c(t)$  and  $c'(t)$ , that is:

$$f(u(t),v(t)) = c(t)-c'(t) \quad (6)$$

3. Region icon entity

Region icon entity has restraint effect on local area of deformable surface in sculpting procedure. Users should interactively choose two corner points of this local area to construct the region constraint. Fig.3 shows a region icon entity of constraint. A surface patch  $w_1(s, t)$  will be constructed in the local area defined by users, which will be recognized as region icon entity. That is to say, the surface patch will

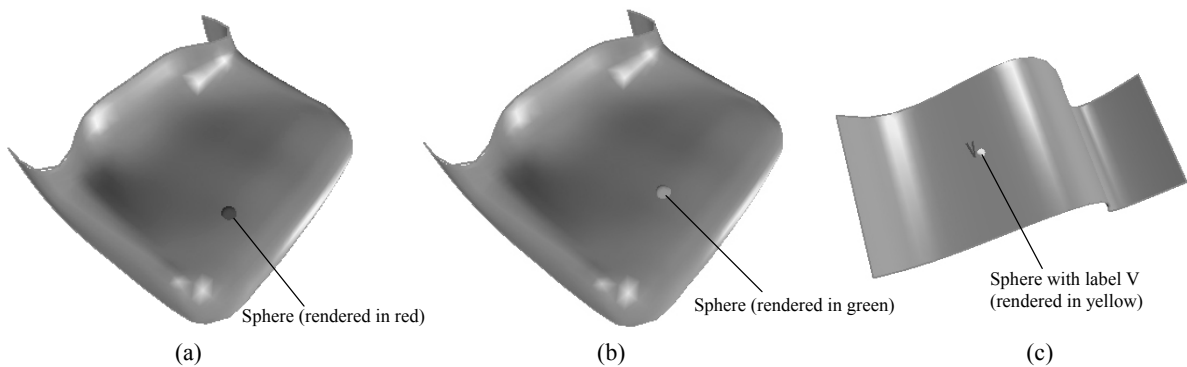


Fig.1 Point icon entity on deformable surface

(a) Icon entity of position constraint; (b) Icon entity of load; (c) Icon entity of derivative vector constraint



Fig.2 Curve icon entity

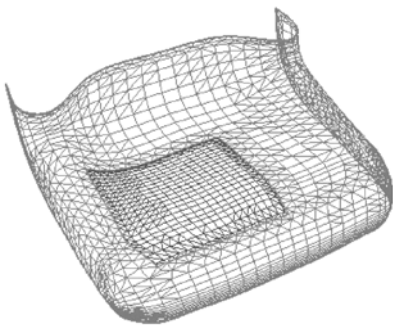


Fig.3 Region icon entity of constraint

be always attach on deformable surface  $w(u, v)$ .

Let the parameters of  $w_1(s, t)$  and  $w(u, v)$  satisfy  $u=u(s), v=v(t)$ . Then, region icon entity of constraint can be written as:

$$\iint [w_1(s, t) - w(u(s), v(t))]^2 dsdt = 0 \quad (7)$$

In shape sculpting, region icon entity can also be deformed interactively. Let the region icon entity before deformation be  $w_1'(s, t)$ , while the region icon entity after deformation is  $w_1(s, t)$ , then, the region icon entity of load can be constructed according to the difference of  $w_1(s, t)$  and  $w_1'(s, t)$ , that is:

$$f(u(s), v(t)) = w_1(s, t) - w_1'(s, t) \quad (8)$$

**Position and orientation updating of icon entity**

In shape sculpting procedure, users' sculpting intention captured by motion sensors (such as data glove, 3D mouse) will directly reflect on change of position and direction of driving icon entity (Fig.4). Icon entity of constraint in sleeping status and icon entity of load in passive status have no constraint effect on sculpting object, so when object deforms,

position and orientation of these kinds of icon entities must be updated in real-time so that icon entity can always attach on the sculpting object. Because parameter coordinate value  $(u, v)$  of icon entity remains unchanged after sculpting, updating position and orientation of icon entity is actually recalculating new space coordinate value  $(x, y, z)$  of icon entity.

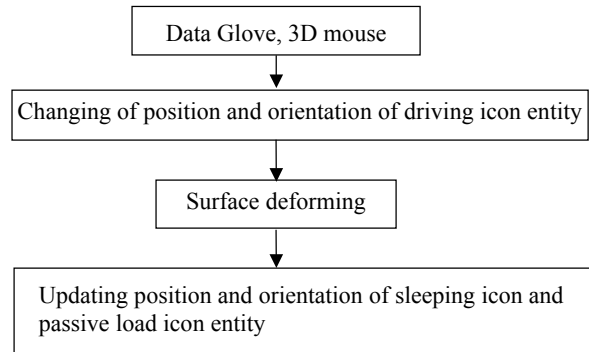


Fig.4 Updating of icon entity

In virtual sculpture procedure, whenever attributes of driving icon entity have been changed, that is to say surface has been deformed, the system will traverse all sleeping icon entity and passive icon entity of load to recalculate their space coordinates, thus realizing position and orientation updating of icon entity.

**Interactive dragging of icon**

In shape sculpting procedure, interaction without force feedback equipment can only realize tracking change of spatial poses of users' hand to capture geometry displacement but cannot capture any sculpting loads. We adopt spring model to establish a mapping relation between displacement (including linear and angular displacement) and sculpting loads (including force and torsional moment). That is to say, in this system, users will input force through extension spring while inputting moment of torque through torsional spring. By Hooke's law, elongation of extension spring and torque angle of torsional spring can be mapped to force and moment of torque. Then, input of geometric displacement can be transformed into physical force. Thus, interactively inputting of sculpting forces in our systems can be realized.

Note parameter coordinate of icon on the surface as  $(u', v')$ , where displacement on time  $t_0$  is  $\Delta x$ ,  $k$  is

spring stiffness. Thus sculpting load applied by user at time  $t_0$  is:

$$f(u', v') = -k\Delta x \quad (9)$$

Stiffness of spring model  $k$  defines the scale mapping relation between displacement and load. In fact, same displacement of icon entity acting on different objects will result in different forces. Therefore, stiffness  $k$  has to change continuously according to the state of the sculpting object.

In terms of experience in real life, the stiffness of spring model during the course of virtual sculpting can be defined as follows:

Firstly, calculate the area of deformable surface or the length of deformable curve defined as  $S$ , and then according to initial coefficient  $\alpha$  predefined in the system, calculate the initial stiffness of spring model  $k_0 = \alpha S$ .

Secondly, map displacement  $\Delta x$  to force  $f_1$  according to coefficient  $k_0$ , then calculate actual displacement  $\Delta y$  of icon entity under the action of force  $f_1$ : (1)  $\Delta y/\Delta x < 0.8$ , means current spring stiffness is too small and  $\alpha$  must be increased; (2)  $\Delta y/\Delta x > 1.2$ , means current spring stiffness is too large and  $\alpha$  must be decreased until  $0.8 \leq \Delta y/\Delta x \leq 1.2$ . When  $\Delta y/\Delta x$  is stabilized between 0.8 and 1.2, that means  $\alpha S$  is just the appropriate stiffness for controlling the sculpting of shape.

## INTERACTIVE SHAPE SCULPTING BASED ON ICON ENTITY OF CONSTRAINT AND LOAD

### Sculpting process

In virtual environment, interactive sculpting based on icon entity includes the following processes:

Step 1: User picks a surface or curve to be sculpting object;

Step 2: Setting up the energy model of sculpting object;

Step 3: User applies icon entity of constraint and load to sculpting object (note the set of icon entity of constraint as  $\mathcal{R}$ );

Step 4: Under constraint set  $\mathcal{R}$  and sculpting load applied by user, take energy model as object function and then solve control points of deformable surface or curve;

Step 5: Draw new sculpting object;

Step 6: User interactively edits, modifies and drags icon entity of constraint or load on sculpting object, repeat Step 4 to Step 5;

Step 7: Once a desired shape is found, the result will be submitted to update the CAD database. If not found, recover initial shape of the sculpting object.

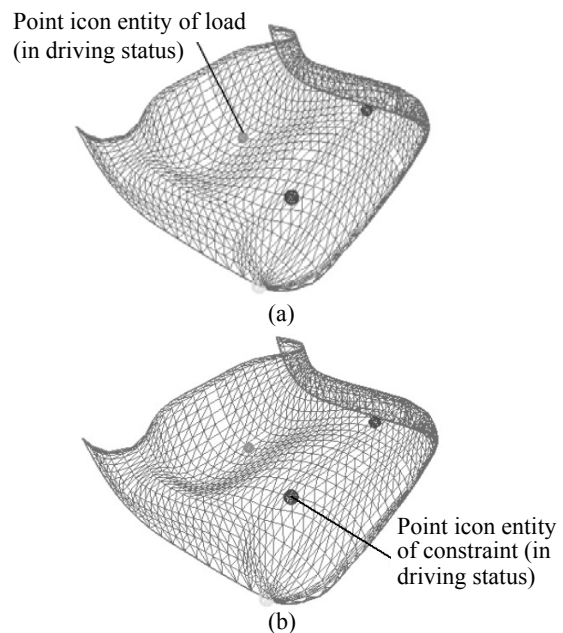
### Interactive sculpting based on point icon entity

For virtual sculpting based on point icon entity, users perform creation, drag operations of point icon entity on surface. There are two modes of sculpting:

(1) User drags point icon entity of constraint to change the position and orientation of icon entity. Then, the deformable surface will change correspondingly in order to satisfy this point constraint.

(2) User drags point icon entity of load to apply sculpting loads to deformable surface.

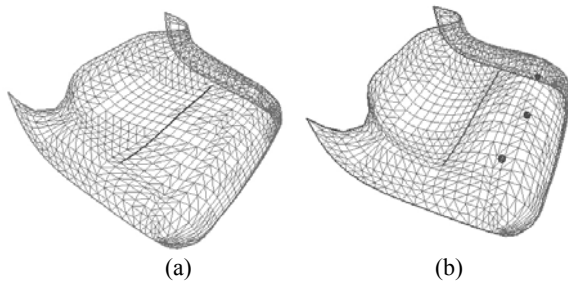
At the same time, users can interactively modify the state of point icon entity, consisting of switch action mode between position constraint, tangent vector constraint and normal vector constraint of data point, de-activating or activating point icon entity, switch point icon entity of constraint to point icon entity of load and vice versa. Fig.5 shows an example of interactive sculpting based on point icon entity.



**Fig.5 Sculpting based on point icon entity**  
(a) Sculpting by dragging point icon entity of load; (b) Sculpting by dragging point icon entity of constraint

### Interactive sculpting based on curve icon entity

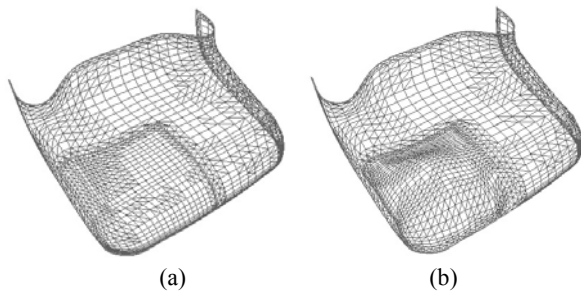
In virtual environment, interactive sculpting based on curve icon entity is performed through interactive operations such as dragging or modifying curve icon entity, consists of curve icon entity of constraint and curve icon entity of load. Sculpting based on curve icon entity of constraint requires that the surface always interpolates the defined curve icon entity. While, sculpting based on curve icon entity of load takes curve icon entity as carrier, and applies loads to realize surface deformation. Fig.6 shows an example of interactive sculpting based on curve icon entity of constraint.



**Fig.6 Sculpting based on curve icon entity**  
(a) Before sculpting; (b) After sculpting

### Interactive sculpting based on region icon entity

Compared to virtual sculpting based on point icon entity, interactive sculpting based on region icon entity lets users control not only a single point but also a region on the surface. This local region will be considered as a constraint to confine the sculpting object to interpolate the area. As deformation can happen inside or outside the local region, there are internal deformation and external deformation of region on surface (Fig.7).



**Fig.7 Sculpting based on internal deformation of region on surface**  
(a) Before sculpting; (b) After sculpting

## EXAMPLE AND DISCUSSION

The virtual sculpting system for product concept design developed in this paper, uses CyberGlove™ Data Glove and Flock of Birds™ position and orientation tracker to input users' gestures, and uses 3D mouse to shift the interaction mode while adopting CrystalEyes 3D glasses to display the stereo scene. The system performs the controlling process of surface sculpting by combining gesture interaction with 3D mouse operation. In the process of virtual design, the user, wearing a data glove in his/her right hand, can change the shape of objects freely by directly pointing out the position of icon entities on the surface or interactively dragging them. At the same time, by pressing the key of a 3D mouse in his or her left hand, the designer can trigger 3D MENU to input icon parameters and to switch the status of sculpting interaction. Thus, user can easily choose, drag or manipulate icon entity on sculpting object directly by gestures or 3D mouse.

We have tested the real-time performance of the virtual sculpting system on a PC with 2.5 GHz Pentium IV processor, Wildcat 7110 graphics accelerator and 512 M memory. We imported 5 groups of surface models on different complication level from CAD systems, then tested the frame rate when performing sculpting design in the system. The results are listed in Table 2.

The experiment showed that the method performs very well in real-time when the surface DOFs (Degree of Freedoms) count is less than 2500, while the real-time performance decreases when the surface DOFs count increases above 2500.

## CONCLUSION

This paper puts forward a constraint management method in virtual sculpting of product shape in concept design. Users are supported in their efforts to apply and manipulate constraints or loads on product shape to control sculpting interactively. The main contributions of this work are as follows:

1. We realized interactive management of sculpting constraints and loads in form of icon entity. By interaction of sculpting icon entity, users can add, modify, delete and drag sculpting constraints and

**Table 2 Real-time performance test of system**

	Surface DOFs count	DOFs count in <i>u</i> direction	DOFs count in <i>v</i> direction	Polygon count	Frame per second
1	300	20	15	1533	47
2	1216	38	32	2028	18
3	1680	42	40	3956	13
4	4914	91	54	13000	5
5	12879	81	159	48536	0.8

loads on deformable object intuitively.

2. We achieved interactive sculpting of product shape based on point icon entity, curve icon entity and region icon entity. In sculpting procedure, attributes of the icon entity such as position, tangent vector or normal vector keep unchanged. When user drags icon entity interactively, product shape will be deformed correspondingly.

3. Developed a virtual sculpting system for product concept design. In virtual environment, designers can directly control sculpting via icon entities by gestures and 3D mouse. The method has proved to be effective in automobile concept design in virtual environment.

Several open questions remain. One is real-time performance of energy algorithm must be improved in the case of increasing number of control points on the surface. Another is to realize haptics interaction, the system should provide users with haptics feedback so that they can feel the shape in a more realistic way during the process of sculpting. Researches on these topics are ongoing.

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