A New Free-form Deformation Through the Control of Parametric Surfaces

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ABSTRACT

A new free-form deformation method is presented in this paper. The deformation of an object is achieved by attaching it to two parametric surfaces, namely the shape surface $\vec{S}(u,v)$ and the height surface $\vec{H}(u,v)$. A control point or vertex of object is projected onto the shape surface along its normal and a correspondence between the point and its projection on the shape surface is established. The point is then embedded into the parametric space defined by the shape surface. By regarding the height surface as a displacement function, the directed distance from the sample point to its projection on the shape surface can be further adjusted. The proposed method is independent of the representation of underlying object. Experimental results show that the method is intuitive, easy to control and run fast.

Keyword: free-form deformation, shape surface, height surface, B-spline surface

1. INTRODUCTION

Deformation methods have been widely used in the fields of both geometric modeling and computer animation. In fact deformation can be treated as a mapping from R^3 to itself except Bechmann works in R^n [3]. All the deformation methods independent of the representation of underlying objects can be divided into two classes according to whether it requires a deformation tools or not [2].

Barr's global and local deformation [1] belongs to the class which does not require tools. In his method , deformations such as scaling, rotating, tapering, twisting, bending or the combination of them are represented as the matrix function of location of the space points. This method was developed by Watt later [14] to include intuitive interactive tools in controlling deformation and the concept of *factor curve* was introduced. Another kind of deformation method free of tools was space deformation introduced by Borrel and Bechmann [3]. The deformation of object is simply specified by the displacements of arbitrary selected points called *constraints*. The size and the boundary of a bounding box centered around each constrained point allows control of the extent of the deformation. Depending on this extent, the whole object can be included (global deformation) or only a limited area around the constraint point (local deformation). A large range of deformation shapes such as arbitrary shaped bumps can be designed using this technique. Borrel presented a simplified space deformation method later [4].

The other class of deformation methods employ some deformation tools. Representative methods include AxDf (Axial Deformation) and FFD (Free-Form Deformation). The AxDf [12] accomplishes the deformation by adopting a parametric curve as the axis. The object is then attached to the axis and deforms accordingly when the shape of the curve is changed. This method is very effective. Nevertheless as the deformation freedom offered by this method is limited, an object can only be deformed along the axis. It would be difficult to generate an arbitrary shaped bump on an object by AxDf.

The FFD, originally proposed by Sederberg and Parry [13], has been widely used and various generalized forms of FFD have been developed to meet the application demands. The original lattice of the FFD consists of control points along three mutually perpendicular axes, which defines a space of trivariate Bezier volume. Griessmair[9] adopted a trivariate B-spline volume as encompassing space to perform deformation. In the EFFD (Extended Free-form Deformation) [6], the parallelepiped lattice is extended to lattice of arbitrary shape. Later, the AFFD (Animated Free-form Deformation) [7] was developed to generate the shape animation of objects. Chadwick [5] used the FFD to control the deformation of muscles. The RFFD (Rational Free-form Deformation) was introduced by Kalra et.al. [10] to simulate the movement of facial muscles. In RFFD, a rational parametric volume is defined providing user with additional control means. The NFFD (NURBS-Based Free-Form Deformation) was suggested to simulate the movement of legs [11]. The initial lattice of NFFD is a NURBS volume. The unique feature of FFD is that the object to be deformed is first embedded in a space which is defined by a 3D parametric volume. Any shape modification of the volume will produce deformation of the object. The implementation of FFD can be decomposed into four steps:

(1) select the control points of the initial lattice according to the deformation region of the object
(2) embed the object into the lattice space, i.e. , for each sampled point or control point $P(x,y,z)$ on the object, find the corresponding local coordinates $L_p(u,v,w)$ in the lattice space
(3) deform the lattice space by adjusting the positions of the relevant control points in the intial lattice
(4) pass deformation to object: compute the new position of P in the deformed lattice space at the same local coordinates $L_p(u,v,w)$

Although both AxDf and FFD establish a mapping between the global object space and a local parametric space determined by the deformation tool , from the user抯 point of view , the AxDf relates a point on the object to a point on an axial curve and FFD relates that to a point within a 3D volume and it is more intuitive to control the deformation of the object by modifying the shape of a curve rather than modifying a 3D volume. On the other hand , FFD provides much freedom for global deformation of an object. Several FFD blocks of lattice may be required for a single object if a number of local deformation effects are desired , though .

In nature , there are also a class of deformation which is affected by the shape of a surface , examples include a snake crawing on the ground , a soft object placed on a rock , etc . In this paper we present a new deformation approach which adopts two parametric surfaces , namely a shape surface and a height surface , as deformation tools . The deformation is quite similar to that of both AxDf and FFD. The shape surface and height surface jointly define a 3D parametric space. A mapping between the object space and the local parametric space is set up to attach the object to be deformed to the two surfaces. While the shape of the two surfaces are modified , the deformation will be passed to the object automatically. Our new approach takes the advantage of both AxDf and FFD : it provides intuitive means for controlling the deformation and it is capable of generating the deformation effects on an object both globally and locally. It also includes Barr抯 deformation as special cases. The rest of the paper is organized as follows. Section 2 provides the definition of two parametric surfaces. Section 3 discribes how to attach an object to the parametric surfaces. Section 4 gives the details of how to deform an object to attain the desire shape. Section 5 shows some examples obtained by this method while section 6 makes the conclusions and suggests future research directions.

2. Initial shape surface and height surface

We define the shape surface and the height surface as Bezier-type B-spline surfaces . A Bezier-type B-spline surface is such that the properties at the boundary of the surface are just like that of a Bezier surface. Therefore the range of surface can be determined by its control net intuitively; the normals at the four corners of the surface can be derived easily from the control polygon , etc. Let $\vec{S}(u,v)$ and $\vec{H}(u,v)$ denote the shape surface and the height surface respectively and

$$\vec{S}(u,v)=\sum_{i=0}^{m_s}\sum_{j=0}^{n_s} S_{ij}B_{i,k_{su}}(u)B_{j,k_{sv}}(v) \ , \qquad u\in\left[u_{k_{su}},u_{m_s+1}\right] \ , \quad v\in\left[v_{k_{sv}},v_{n_s+1}\right]$$

whose knots sequences $\{u_i\}$ and $\{v_i\}$ are defined in the following way:

$$\begin{cases} u_i=0, & i=0,1,\cdots,k_{su} \\ u_i=\dfrac{i-k_{su}}{m_s-k_{su}+1}, & i=k_{su}+1,\cdots,m_s \\ u_i=1, & i=m_s+1,\cdots,m_s+k_{su}+1 \end{cases} \qquad \begin{cases} v_i=0, & i=0,1,\cdots,k_{sv} \\ v_i=\dfrac{i-k_{sv}}{m_s-k_{sv}+1}, & i=k_{sv}+1,\cdots,n_s \\ v_i=1, & i=n_s+1,\cdots,n_s+k_{sv}+1 \end{cases}$$

where k_{su} , k_{sv} and m_s+1 , n_s+1 are the surface degree , the number of control points in u , v direction respectively. The height surface can be defined similarly :

$$\vec{H}(u,v)=(H_x,H_y,H_z)=\sum_{i=0}^{m_h}\sum_{j=0}^{n_h} H_{ij}B_{i,k_{hu}}(u)B_{j,k_{hv}}(v)$$

Initially , the control points $\{S_{ij}\}$ and $\{H_{ij}\}$ lie respectively on the XZ-plane and the plane $Y=1$, each forming a rectangular grid . Note that $\vec{S}(u,v)$ and $\vec{H}(u,v)$ may be of different degree and with different number of control points in their corresponding directions, that is to say it is possible that :

$$k_{su}\neq k_{hu} \quad k_{sv}\neq k_{hv} \quad m_s\neq m_h \quad n_s\neq n_h$$

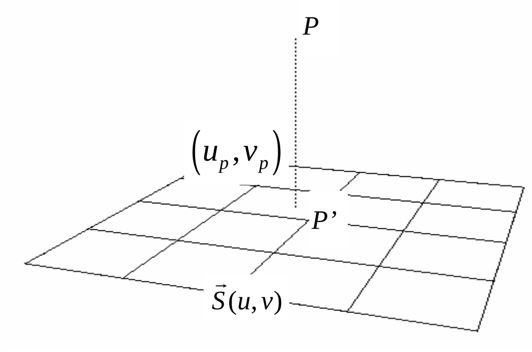
3. Attaching the object to the shape surface

Let $P=(x,y,z)$ be a sampled point or a control point of the object to be deformed and $P'=(x',y',z')$ be the projection of P on $\vec{S}(u,v)$. The projection direction is along the normal of the shape surface at P', Let $\vec{N}_s$ be the unit surface normal at P', then $h_p=PP'\bullet\vec{N}_s$. Here h_p is the directed distance from P to $\vec{S}(u,v)$ and "$\bullet$" means dot product . If P lies above the $\vec{S}(u,v)$, h_p is positive, else it is negative. A numerical method is employed here to solve out (u_p,v_p) such that $\vec{S}(u_p,v_p)=P'$ (shown by Fig. 1). We then set up a correspondence of between P and P' as follows

$$P=\vec{S}(u_p,v_p)+h_pN_s(u_p,v_p)$$

The surface $\vec{S}(u,v)$ can be modified by traditional interactive means, such as pulling the control points selectively etc. Let $\vec{S}_{new}(u,v)$ be the modified shape of $\vec{S}(u,v)$. $\vec{S}_{new}(u,v)$ then provides a base for object deformation. To achieve the local deformation effect , we include an addtional parameter such that the directed distance from P to $\vec{S}_{new}(u,v)$ can also be modified . We adopt one component of $\vec{H}(u,v)$ to perform this function. In the current implementation , the y component of $\vec{H}(u,v)$ is selected. Let $\vec{H}(u,v)$ be modified as $\vec{H}_{new}(u,v)$ where $\vec{H}_{new}=(H_x,H_{newy},H_z)$. Then the new position of P can be determined by

$$P_{new}=\vec{S}_{new}(u_p,v_p)+H_{newy}(u_p,v_p)h_p\vec{n}_{new}(u_p,v_p)$$



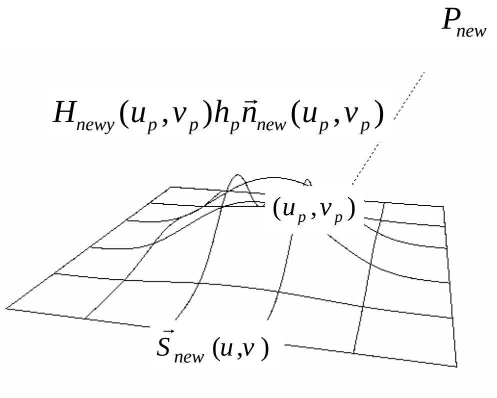


Fig.1 Attach P onto shape surface $\vec{S}(u,v)$

Fig.2 Compute the deformed point P_{new}

where $\vec{n}_{new}(u_p, v_p)$ is the unit normal of $\vec{S}_{new}(u,v)$ at (u_p, v_p) (shown as Fig. 2). Fig.3 , 4 , 5 , 6 illustrate the deformation effects by modifying $\vec{S}(u,v)$ and $\vec{H}(u,v)$.

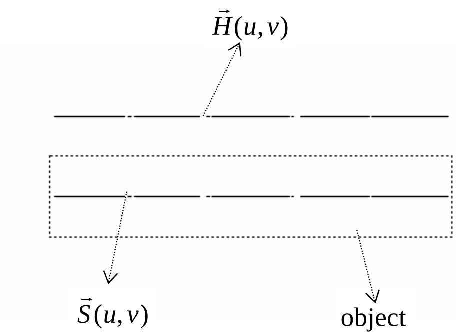


Fig.3 The object and the two surfaces

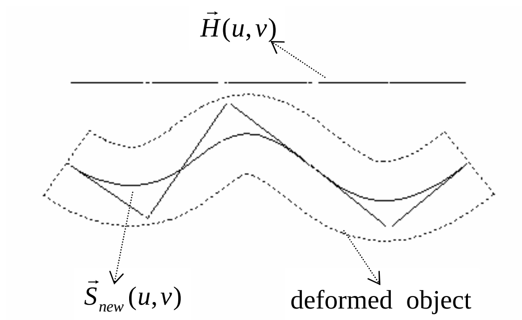


Fig.4 The deformation effect by modifying the shape surface

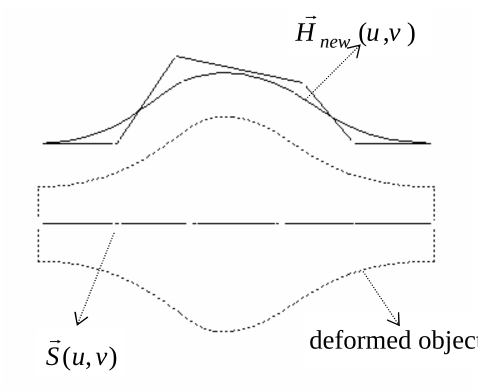


Fig.5 The deformation effect by modifying the height surface only

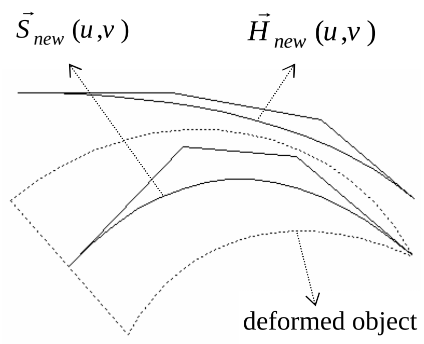


Fig.6 Joint deformation effect by modifying both shape surface and height surface

4. Object Deformation

Let B_0 be the projected area of the bounding box of the object on the XZ-plane. User first defines a quadrate S_0 as the boundary of $\vec{S}(u,v)$ in the XZ-plane. Then the control net of initial shape surface is determined interactively. The height surface is defined similarly .

If B_0 lies inside S_0 totally, the deformation is global. Some elementary deformations such as bending, tapering, twisting can be accomplished by global deformation. They can be defined as stardard operations of our approach.

(1). Bending: The object will be bent if the shape surface $\vec{S}(u,v)$ is bent . Fig.7 and Fig.8 show an example where $\vec{S}(u,v)$ is defined by a 2×1 degree B-spline surface with control points distributed uniformly. The height surface just remains unchanged.

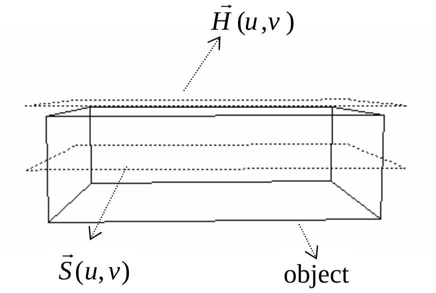


Fig.7 the original object

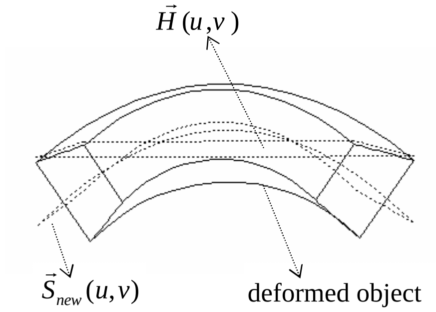


Fig.8 the bent object

(2). Tapering: When the shape surface $\vec{S}(u,v)$ is changed into a triangle and the height surface $\vec{H}(u,v)$ is defined by a plane with slope , the deformed object will be tapered. The simplest way is to set $\vec{S}(u,v)$ and $\vec{H}(u,v)$ as an 1×1 degree B-spline surface. Then the two control points on *u=0* of $\vec{S}(u,v)$ are merged into its middle point, the two control points on *u=0* of $\vec{H}(u,v)$ are dragged down to the *Y=0*. This is illustrated by Fig.9 and Fig.10 .

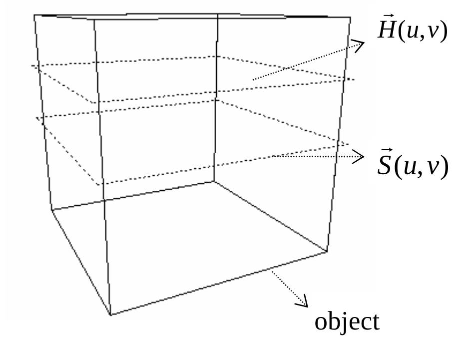


Fig.9 the original object

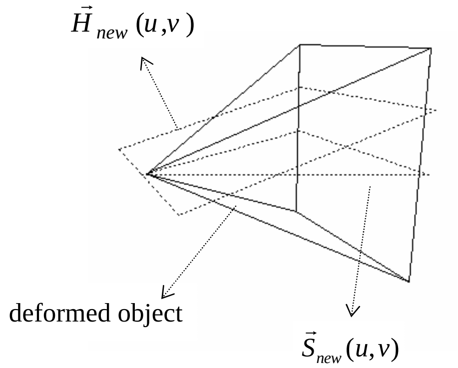


Fig.10 the tapered object

(3). Twist: When the shape surface $\vec{S}(u,v)$ is twisted, so does the deformed object . (shown as Fig.11 and Fig.12)

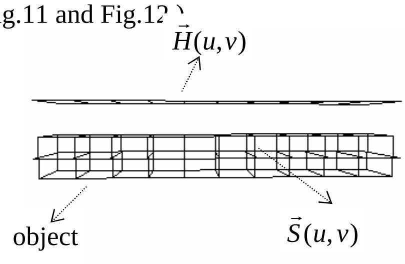


Fig.11 the original object

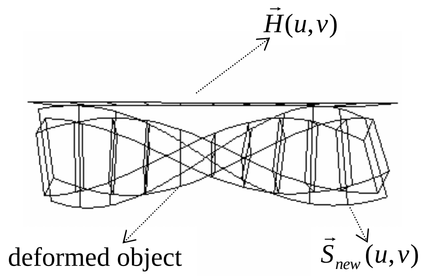


Fig.12 the twisted object

If B_0 lies partially inide S_0 , the deformation of object is local. We adopt a polygon clipping algorithm to find the intersection of B_0 and S_0 . Let BS denote the intersection. If continuity of surface of the deformed object is desired , the positions of some control points in the BS which are adjancent to the boundary will remain unchanged in the process of deformation. Fig. 13 shows an example.

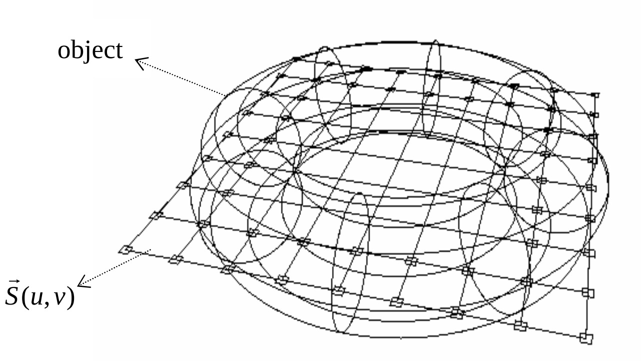


Fig.13 The control points labeled with small squares will remain unchanged.

In practice the deformation attained is only an approximation [8]. The deformation could not be pricise if the object to be deformed is sampled insufficiently. So there is a compromise between the requested shape and the computation cost. This is justified by users.

How to avoid the self-intersection during object deformation is a common problem for both AxDf and FFD. Our proposed method faces the same problem. For example when the shape surface has a tight concave bent, the deformed object may be self-intersected. In our current implementation this problem is solved with user's interaction .

5. Experimental result

We have implemented the proposed algorithm on HP720 graphics workstation. The test object is a teapot which is composed of four B-spline surfaces. In all of the following wire frame figures, $\vec{S}(u,v)$ is marked with green , $\vec{H}(u,v)$ is in yellow color. Red grid represents the plane *Y=0*. The deformation is passed to the control points of the object. Fig.1 shows the original teapot. Fig.2 and Fig.3 show the tapered teapot. In Fig.4 and Fig.5, $\vec{H}(u,v)$ is deformed while $\vec{S}(u,v)$ remains unchanged. Fig.6 and Fig.7 show the teapot with wave shape. In Fig.8 and Fig.9, the teapot undergoes taper and wave-shaped deformations. Fig.10 and Fig.11 show the arbitrary shaped deformation of the teapot.

6. Conclusion

A new kind of free-form deformation method has been presented. The deformtion of an object is controlled by two parametric surfaces which are termed respectively the shape surface and the height surface. The deformation can be either global or local.

There is one degree of freedom in the AxDf and three degrees of freedom in the FFD. Our approach offers two and a half degrees of freedom for object deformation. The application domain of the presented deformation is much wider than the AxDf and it can simulate most effects created by

FFD , however the implementation of the proposed method is more intuitive and convenient than FFD. Future research directions include:

(1) develop an adaptive subdivision method or sampling method to obtain the desired shape deformation ;

(2) identify the self-intersection automatically during deformation.

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NOTE:

Colors in wireframe figures are illustrated as follows:

(1) The shape surface $\vec{S}(u,v)$ is in green color.

(2) The height surface $\vec{H}(u,v)$ is in yellow color.

(3) The plane $Y=0$ is in red color.

(4) The deformed teapot is in white color.

Fig.1 The original teapot

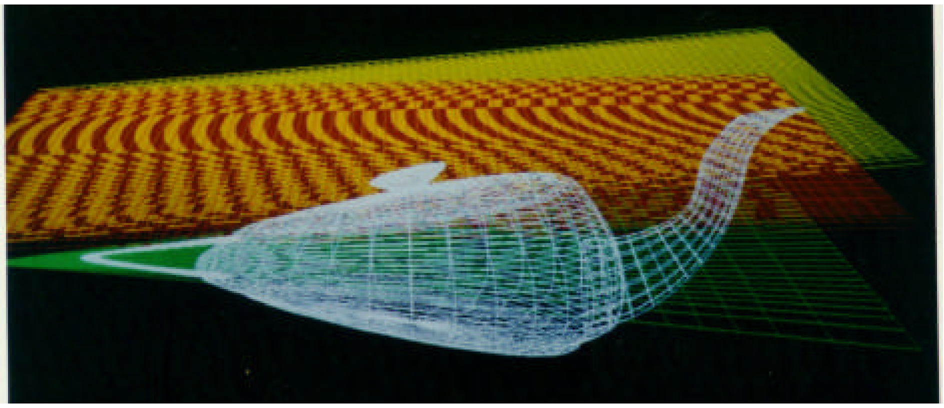

Fig.2 The wireframe figure of the tapered teapot, height surface and shape surface

Fig.3 The shaded image of the tapered teapot

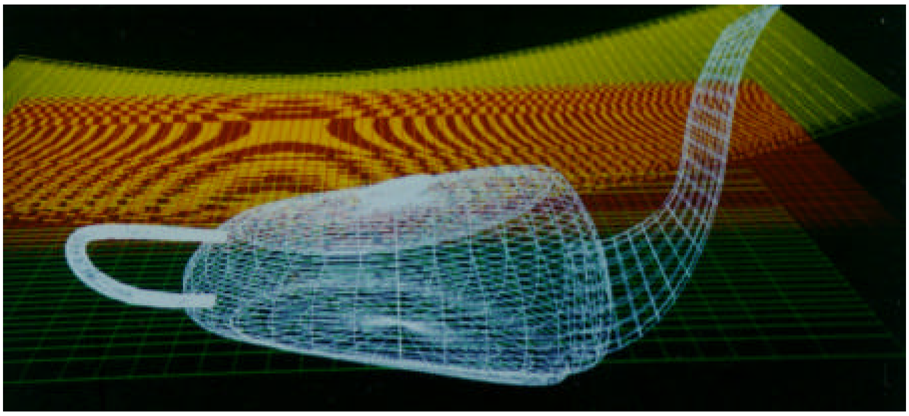

Fig.4 The wireframe of the deformed teapot, where the shape surface remains unchanged and the height surface is edited as the shape in the figure

Fig.5 The shaded image of Fig.4

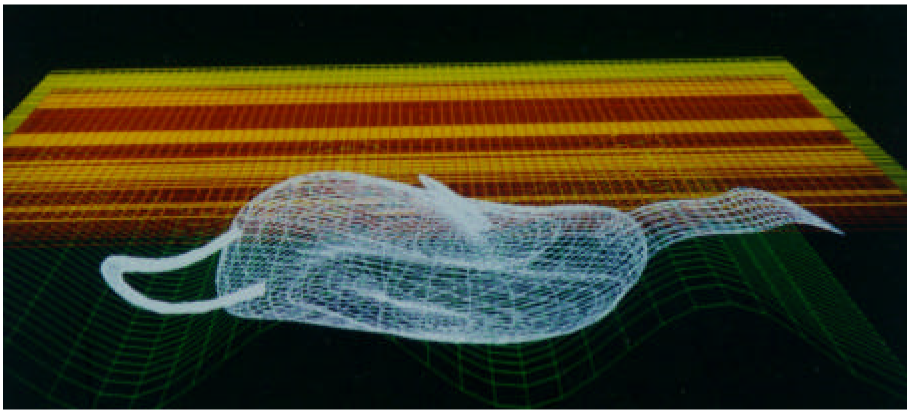

Fig.6 The wireframe of the deformed teapot, where the height surface is scaled with a factor 0.4 and the shape surface is a wave-shaped surface.

Fig.7 The shaded image of wave-shaped teapot

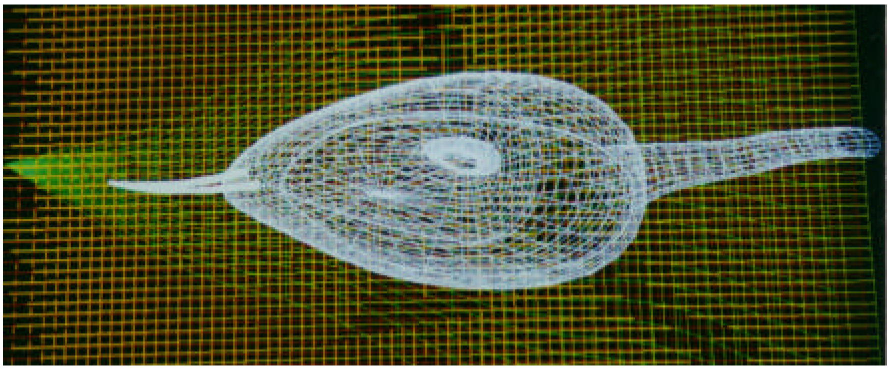

Fig.8 A top view of teapot deformed by tapered and wave-shaped deformations,in which the height surface is a slope plane and the shape surface is in a tapered and wave-shaped form

Fig.9 The shaded image of teapot with tapered and wave-shaped deformation

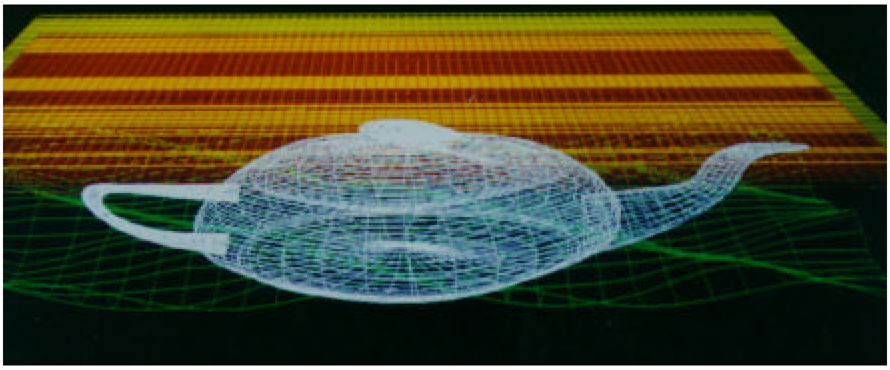

Fig.10 The wireframe of the deformed teapot, where the height surface is scaled with a factor 0.4 and the shape surface is in an arbitrary form

Fig.11 The shaded image of arbitrary-shaped deformation teapot