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Free-form Surface Design by Model Deformation and Image Sculpturing

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Abstract
Conventional computer aided design systems have been well-developed for the design of general prismatic parts and simple free-form objects. However the available modelling tools and techniques are inadequate for highly "sculptured" objects. This paper presents a new approach for local surface design that provides a rapid and intuitive way to create surface features on a parametric surface. Embossed or depressed patterns can be added to a surface via a 2D grey-level image function. The image function corresponds to a 2D elevation map of the surface. The patterns may included some simple line drawings or 2D contours designs. It allows the user to create peaks and ridges, valleys and pits or other similar shapes by simple sketching over the surface. This module may be used as an additional detailing tool following a global surface design process.

Keywords
Free-form surface, deformation, sculpturing, sketching

1 INTRODUCTION

Many engineering tasks require complex and highly detailed shapes that are not readily describable by traditional modelling systems using either parametric surface representation or Boolean combinations of simple primitives. This is especially true in the design of aesthetic surfaces with intricate shapes and patterns, such as those in the biscuit mold design (Wainwright, 1992), jewellery surface design (Ettagale, 1991) and many other works resulting from highly skillful engraving or carving. This illustrates that the modelling tools and the design environment in existing systems are not sufficient for modelling complex objects.

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Many attempts have been made to providing more efficient and effective design methods for 3D modeling systems, A growing trend is to develop some highly intuitive modelling tools and design interfaces that can provide a familiar way of thinking for a designer. The most widely accepted concept in CAD is sculpting in clay, where the model is to be shaped with flexibility similar to a lump of clay in a sculptor's hand. Two design processes should be considered in a more general and sophisticated modelling system:

- Global Solid Design, which allows the user to deform an object smoothly during the initial phase of modelling. This can be limited to simple, global changes, including bending, tapering, twisting, squeezing and so forth. The process may be regarded as deforming a lump of clay with forces applied by the user.
- Local Surface Design, which allows the user to add surface details on the model, producing embossed or depressed forms (e.g. peaks, ridges, valleys, pits, etc.) over it. This module may provide a simple and friendly design interface to get inputs or actions from the user as if he/she is sculpturing on an object's surface with engraving tools.

These two design modules form the basis of a general computer aided system for object modelling. It is different from the conventional B-rep or CSG systems which are good at defining the nominal shape of a solid, but provide limited control of detailed geometry over the object surfaces. These traditional systems are capable of handling many general machining parts and simple free-form shapes in castings but are weak in handling objects with intricate shapes or carvings resulting from skillful engraving work. This kind of work are commonly found in the mold making and handicraft industry which still relies heavily upon experienced and skilled craftsmen.

2 OVERVIEW OF SOME USEFUL TECHNIQUES

There are a number of useful geometric modelling techniques available for global and local design. A common practice in designing spline surfaces is by *Control Point Manipulation* (Piegl, 1989). It is a simple way of interactively modifying the geometry of free-form surfaces. The basic operation includes moving (and refining if necessary) the control vertices of the spline surface. However the modification on the surface is restricted largely by the position and the number of the control vertices. Although this point-based techniques is widely implemented in many systems, it is only sufficient in modelling simple shapes and shows limited success in handling details.

Another more advanced modelling techniques is known as *Solid Deformation* (Barr, 1984). Barr in his paper suggested a set of new hierarchical solid modelling operations which simulate sketching, bending, twisting, tapering and other similar transformation of geometric models. These operations extend the conventional operations of scaling, rotation, translation, Boolean operations, and can be incorporated into the traditional modelling systems, so that users may apply different operations on simple primitives to form a complex model.

The solid deformation technique was further extended by Sederberg and Parry (1986) to form a more general deformation technique, referred to as *Free-Form Deformation (FFD)*. In FFD, an object to be deformed is enclosed by a 3D parallelepipedical lattice. A deformation of the lattice causes a transformation of all interior points of the enclosed object. The deformation effect of the lattice is transferred to the object by some 3D transformation functions such as the trivariate Bernstein polynomial or trivariate B-splines (Griessmair and Purgathofer, 1989). FFD is a highly intuitive modelling tool, allowing the object to be modelled as if it is a real solid being shaped in his hand. An extended free-form deformation (EFFD) is also introduced by Coquillart (1990). This method used non-parallelepipedical 3D lattices for model deformation.

FFD has made a significant change from the control point manipulation method, which relies too much on the underlying surface definition. However, FFD is mainly designed for global shape design, and is less useful and less efficient for local surface design. The aim in local design is to find rapid and intuitive methods that can raise or imprint a surface into a desired pattern. Detailed design on a smooth surface, including arbitrarily shaped pits and valleys, peaks and ridges, like the patterns found in carving works are targets for this work.

A modelling technique known as *3D painting* (Williams, 1990) is an innovative design method to sculpture details on a surface. The paper proposed a means by which the conventional methods used in digital painting and image manipulation be extended into the third dimension. The basic approach is to generate a 3D surface from a 2D image function that is designed interactively by the user with different "painting" tools. The 2D image is essentially a functional (single-valued) surface. The canvas on which the painting program operates is a unit rectangular parametrization of the image. The limitation to surfaces which can be represented by such an image is less restrictive than it seems initially because the image may be a visualization aid to surface features. It may be easier for a user to specify the local surface features in a 2D space and subsequently map the specified surface requirements to the surface model. The basic modelling principle of 3D painting is that the intensity on the image is related to the elevation of surface point sets.

The painting tools for designing sculptured surfaces are commonly used in a general painting system. For example, an arbitrarily-shaped rough surface may be created by a seed filling operation that fills a 2D region with specified intensity distribution. Other tools, like blurring or filtering, may be used to soften and smoothen particular regions of the surface, and are effective in blending and filleting sections together. For a more detailed design, arbitrarily-sized and different style of painting brushes can be used to create embossed shapes over the surface description by conventional interpolation techniques. All these operations and painting tools provide a rapid, effective and interactive procedure for designing details on object surfaces through small refinements.

A new approach for surface sculpturing by an image function is presented in the next section. It is a local surface design method which allows a user to create embossed patterns over a surface from a grey-level image. The pattern may include some simple line drawings or 2D contours. Simple surface features, such as peaks and ridges, valleys and pits or other similar shapes may be embossed or depressed over a surface. The module may be used as an additional detailing tool after using the FFD or other similar shape design techniques. The method is derived from traditional 2D painting system (Smith, 1982), and from displacement mapping (Cook, 1984).

3 SURFACE SCULPTURING

Painting methods have been shown (Williams, 1990) to be a simple way of adding small sculptured details on a smooth surface. The basic approach is to generate a sculptured surface via a 2D image function that is designed interactively by a user with different "painting" tools. The image function corresponds to a 2D elevation map of the surface. it may be used as a canvas of a traditional painting system. The user may paint on it with various shades of grey value, with brighter shades of grey producing peaks and ridges, and darker shades producing valleys and pits. The pattern on the surface is subsequently created by "image sculpturing". It uses grey-level value as a measure of the depth, which is to be added or subtracted from the smooth surface. It is a rapid way for a user to create surface sculpture from a 2D sketch.

There are a number of ways to design a grey-level image function, including all the standard methods used in painting systems and image processing techniques. The aim is to create a grey-level image that is smooth enough to be used as depth values on the surface. A contour-based design method (Carlsson, 1989) which makes use of a diffusion algorithm to smooth out the image is attempted here. The method is used for sculpturing simple patterns. For more complex ones, some other techniques on image manipulation need to be explored.

The role of the *image function* for surface detailing is similar in some ways to the *deformation function* defined by a FFD lattice. In FFD, the lattice is used to define a 3D transformation that modifies the global shape of an object, while in image sculpturing, the image is used to define a 2D function that displaces the surface points on the sculptured surface.

Definition of image function

An image function is a 2D function which defines the depth values to be added or subtracted from the parametrically defined surface. For each point (i,j) in the image space, there will have a corresponding point (u,v) in the parametric space of the smooth surface. It is used to evaluate the displacement of each point in the sculptured surface.

Let $I(i,j)$ be an image function. In the object space, each point $\mathbf{P}$ of the smooth surface would be displaced in the direction of the surface normal $\mathbf{N}$ by a magnitude equal to the value of $I(i,j)$. The new position vector may be written as:

$$\mathbf{P}'(u,v) = \mathbf{P}(u,v) + I(i,j) \times \frac{\mathbf{N}(u,v)}{|\mathbf{N}(u,v)|} \qquad (1)$$

where, (i,j) is index to the image function,
(u,v) is the parametric values of a surface point.

To create a surface with sculptured details, an image function needs to be established and mapped to the smooth surface. Drawing and painting techniques form the basis for the establishment of this image function.

The image $I(i,j)$ could, of course, be defined analytically as a bivariate polynomial function as that found in traditional CAD surfaces. However, in order to generate a function which embraces a sufficient amount of surface complexity, a large number of coefficients of high degree terms may be required. A much simpler way to define complex functions is by a look-up table. The image function is thus represented as a two dimensional array of intensity values.

By increasing the density of the grid, a greater resolution of the image function, and thus the sculptured details, may be obtained.

There are two stages to add surface details on a smooth surface. First, a 2D sketching canvas, like that used in traditional painting system, would be provided to the user. With the canvas, a grey-level image that gives the user a sense of the sculpture geometry may be created. Second, the user is required to attach the image to a smooth surface by mapping the image space to the parametric space of the surface. Adaptive subdivision and surface triangulation, like that used in FFD, are needed for the display of the resulting sculptured surface.

In short, *Image Sculpturing* techniques for surface detailing pose two problems to be considered: i) the ways to design a grey-level image function, and ii) the algorithms to "sculpture" the image on a smooth surface and the method to render it.

Design of image function

In painting systems, a user may freely design an image by different interactive painting tools, such as painting brushes, and various filtering and blurring operators. The painting canvas is usually a region of the frame buffer memory that allows the user to sketch the image and stores the intensity values of the image in it. By utilizing the frame buffer memory as the defining table for an image function $I(i,j)$, a user may directly define the function values by simple painting on the canvas. Dark areas in the canvas would be interpreted as having small values of $I(i,j)$ whilst bright areas as large values of $I(i,j)$. The variation of the intensity values represents an image function for modelling the wrinkled geometry of a sculptured surface.

A simple design interface for generating grey-level images has been implemented. This is a *contour-based image design method.* In this method, a grey-level image is generated from a simple drawing of contours. The contours are created from common two dimensional geometric entities, such as lines and curves. The contour design represents the salient geometric details of a sculptured surface.

The construction of grey-level image from the contour information is an idea derived from an image compression technique, known as the *sketch-based representation of grey-value image* (Carlsson, 1989). It is an image coding technique that encodes a grey-level image by some important details such as the contour information. The image is subsequently reconstructed as a solution to a constrained optimization problem by a diffusion algorithm. The diffusion algorithm determines the maximally smooth image consistent with the given contour information. The emphasis in this research is, however, not on how precise the contour information may reconstruct the original image, but rather, on how the contour-based design method and the diffusion algorithm may be used to create a grey-level image for modelling sculptured surfaces.

To convert a contour design drawing to a grey-level image is basically a two-dimensional interpolation problem. It is analogous to the surface interpolation problems in CAD. For example, a Coons surface patch is interpolated from four initial boundary curves by a mathematical formulation. In the case of interpolating a 2D grey-level image, it is necessary to input the image contour information. Grey values between contours may be interpolated so as to obtain a smooth grey-level image.

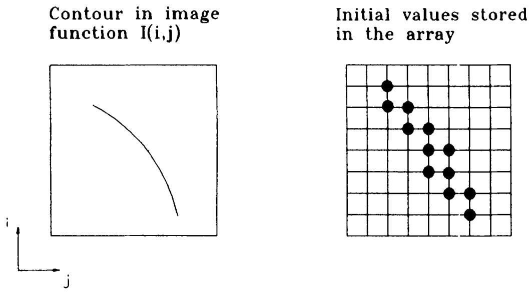

Figure 1a Array of image space

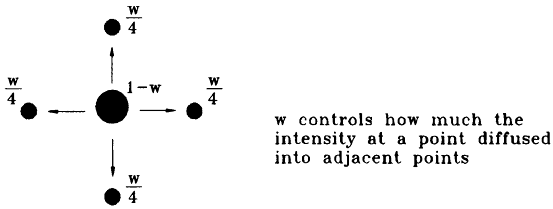

Figure 1b Diffusion of contour point in the iterative algorithm

In the implementation, the initial contour definition contains the significant geometry of a sculptured surface. Each line of the contours may either represent a carving, or an embossing action to be exerted on it. The contours may include combination of two dimensional geometric entities, filled regions and free-hand sketches. In addition to the geometry information, each contour also contains some initial attributes, including:

1. initial intensity value,
2. width of the contour,
3. diffusion rate.

The three attributes for a contour shown above are some of the ways to control the geometry of a sculptured edge. The *initial intensity value* is a measure of depth of cut. For example, a bright intensity may correspond to an embossed edge, and a dark intensity may correspond to a deep cut to the surface. The *width of the contour* is a way of representing the width of the cutting tool used. It controls the width of a trench cut out from the surface or the width of an embossed region added to it. The *diffusion rate* is a parameter used in a smoothing algorithm. It controls the "sharpness" of a cut. A larger diffusion rate would lead to a flatter and smoother cut, while a smaller rate would produce a sharp edge.

The above listed attributes only provide an intuitive way of modifying the geometry of sculptured shapes. They do not provide a precise definition for the sculptured geometry, like the surface definitions used in conventional CAD systems. However, it may be sufficient for some surface detailing applications.

To interpolate 2D contours in the image space, a diffusion algorithm by Carlsson (1989) is used. It may be considered as an algorithm to interpolate given data values over a two dimensional space, just like the case of interpolating contour intensity values over the image space.

The input to the diffusion algorithm is a two dimensional image function defined on the image space. Initial function values are assigned by the user by way of contour design on a drawing canvas. A 2D array representing the image function is constructed from the pixel values on the canvas. The initial intensity values are stored in the array. The output from the algorithm is a diffused image function representing the sculptured geometry.

The interpolation problem is formulated as follows: Suppose there is a two dimensional image space in which an image function I is defined, such that, for any $i, j, N, M \in \mathbf{I} / \{0\}^*$,

$$I \rightarrow I(i,j) \in \mathbf{R}, \text{ for } 0 \leq i < M \text{ and } 0 \leq j < N \tag{2}$$

The image function (2) is defined as a two dimensional array $M \times N$ entries. The initial function values are set to be the intensity values at contour points (Figure 1). An image function based on the initial contour points is to be determined by two dimensional interpolation.

A successive diffusion process (Carlsson, 1989) may be used to generate a smooth grey level image. The corresponding image function $I(i,j)$ is obtained iteratively as:

$$I_{i,j}^{(n+1)} = I_{i,j}^{(n)} + \frac{\omega}{4} \Delta I_{i,j}^{(n)} \tag{3}$$

where ω defines the diffusion rate and $\Delta I_{i,j}^{(n)}$ is computed as:

$$\Delta I_{i,j}^{(n)} = I_{i-1,j}^{(n+1)} + I_{i,j-1}^{(n+1)} + I_{i+1,j}^{(n)} + I_{i,j+1}^{(n)} - 4 I_{i,j}^{(n)} \tag{4}$$

Note that $I_{i,j}$ notes $I(i,j)$ and $i \in [0, M-1], j \in [0, N-1]$.

The algorithm starts with the given intensities at the contour points. The function values at non-contours (i, j) is then obtained in the $(i+1)$**th** iteration by a five point operator centred at (i,j). The values at the contour points are kept during all iterations. The algorithm may be regarded as equivalent to a recursive smoothing operation applied to the image starting at the upper left and proceeding down to the lower right. The repeated smoothing operation may be interpreted as a diffusion process whereby grey values at the contour points are diffused into the regions between contours. Formulae (4) and (5) can be shown to be the heat diffusion equation describing how a quantity evolves by diffusion over time with a constant rate of diffusion.

Thus, by using the diffusion algorithm, a grey level image represented as an image function created from the input contours. The image function may be considered as a look-up table to define the complex pattern to be added on to a 3D smooth surface.

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* I/{0} is set of integers excluding zero.

Image mapping and sculpturing

To create a sculptured surface from a smooth one, the image function is mapped to the continuous parametric space of the surface. The image function $I(i,j)$, which is defined on the image space, represents the complex sculpture details by a look-up table. For convenience, a continuous 2D function of normalized parametric values is used, just like defining a conventional CAD surface in a parametric space.

The continuos image function may be obtained by interpolating values between the image array entries. A simple interpolation technique is, for example, the bilinear interpolation. Such an algorithm would look like:

```
Function I_val ( u , v )
    IV = int ( N * v );
    IU = int ( M * u );
    I_val = I ( IU , IV ) * ( 1 - u ) * ( 1 - v )
       + I ( IU , IV + 1 ) * ( 1 - u ) * v
       + I ( IU + 1 , IV ) * u * ( 1 - v )
       + I ( IU + 1 , IV + 1 ) * u * v ;
    return ( I_val );
```

This gives a continuos image function representing the geometry of a sculpture pattern. A sculptured surface would then be obtained by applying the image function onto the parametric space of a 3D surface. To evaluate a point $\mathbf{P}'(u,v)$ on the sculptured surface, the original surface $\mathbf{P}(u,v)$ is displaced in the direction of the surface normal $\mathbf{N}(u,v)$ by an amount defined by the image function $I(i,j)$. The new surface point may be calculated from (1).

To display the sculptured surface, an adaptive subdivision technique (Von Herzen, 1987) may be applied and the steps involved are similar to those used to display a deformed surface by the FFD lattice. However, in image sculpturing, a new surface point is determined from a 2D image function instead of using a 3D lattice as in FFD. Both tools are functionally the same for re-mapping the original surface points to new positions.

Examples

Plates 1 and 2 show some of the surfaces created by the image sculpturing technique. In Plate 1a, a simple line pattern drawing is drawn on a 2D canvas. The pattern is mapped to a 3D parametric surface as shown in Plate 1b. Plate 1c displays the resulting surface with sculptured details. Another surface created with a larger diffusion rate is shown in Plate 1d. Plate 2 gives another example of the technique, and the corresponding 2D pattern design is also shown.

4 DESIGN METHODOLOGY FOR IMAGE SCULPTURING: A SUMMARY

Drawing and painting techniques as a basis for surface detailing were explored in the previous section. The basic principle is to sketch on a 2D elevation map of the surface with brighter shades representing peaks and ridges and darker shades representing valleys and pits. The coordinates of this map roughly correspond to the lines of principle curvature on the surface so that details that blend naturally with the overall shape of the object can be easily modelled. The design techniques may be conducted in four steps:

1. Designing a sketch - The user is provided with a set of drawing tools to design a 2D sketch. The sketch is converted into a grey-level image by the diffusion algorithm. All design sketches may be stored as grey-level images into a library.
2. Associating the sketch with a surface - A surface may have a list of sketches associated with it. This step involves extracting the sketches from the library and adding them to a list.
3. Attaching the sketches to the surface - After adding the selected sketches to the list, they can be applied to the surface one by one. This process involves positioning, resizing and fixing a sketch on the surface.
4. Raising/Impressing the sketch - After the sketch is attached onto the surface, each surface point may be raised or impressed along the corresponding normal by a magnitude proportional to the color intensity at that point in the grey-level image of the sketch.

The creation of image data may be supported and supplemented by other display rendering methods. For instance, a 3D rendering system which outputs an image and Z-buffer may be used to create an unlimited number of painting primitives.

For a complete sculpturing system, a roughing stage and a detailing stage of design should be considered. The image sculpturing technique may be used as a detailing tool in conjunction with other conventional modelling techniques, such as the free-form deformation technique.

5 CONCLUSIONS

A design interface for surface detailing is described. The method is based on grey-level image design and mapping. This involves a contour-based design interface, a diffusion algorithm for image creation, and also a subdivision algorithm for rendering the sculptured surface.

Since the contour-based design method is a rapid way of designing grey-level images, it has limitations in covering the design of a wide range of images, as compared to the conventional painting system. It is sufficient for producing embossed edges and contours, or adding simple embossed shapes on a surface. However, only simple geometric pattern designs can be sculptured on a surface. A more versatile system for creating a wide range of grey-level images is necessary. For example, image synthesis algorithms which use Z-buffers or depth buffers to perform hidden surface removal may be considered. The actual Z values left in the depth buffer after executing the algorithm may be used to define the table entries for an image function. A large set of grey-level images may be created in this way, providing an unlimited number of primitives to be sculptured to the surface.

Emphasis also needs to be put on investigating and using a general grey-level image for 'sculpting' a surface and on combining the image sculpturing technique with conventional global design techniques. The subdivision algorithm is important for rendering the deformed solids and sculptured surfaces. Efficient algorithms for surface triangulation require further detailed investigation.

6 ACKNOWLEDGMENT

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8 BIOGRAPHY

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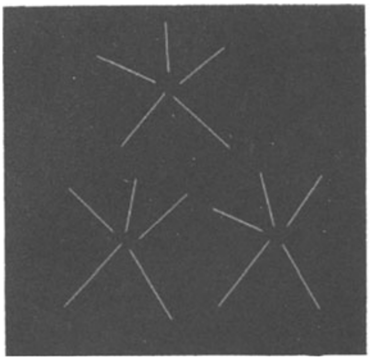


Plate 1a A simple line pattern drawing on a 2D canvas.

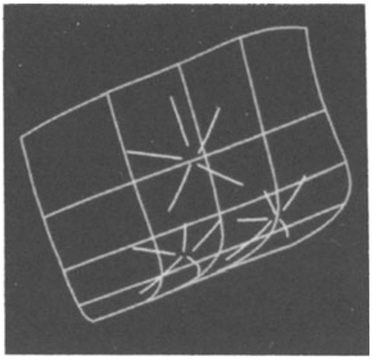


Plate 1b A parametric surface mapped with the line pattern.

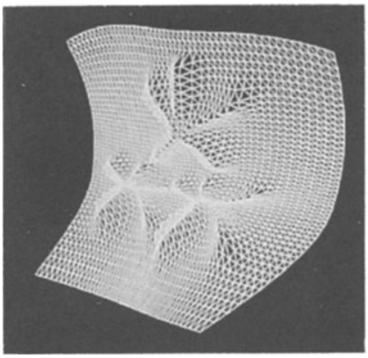


Plate 1c The resulting surface with sculptured details.

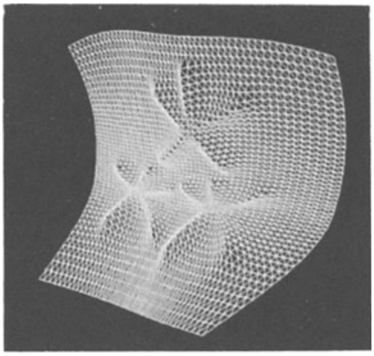
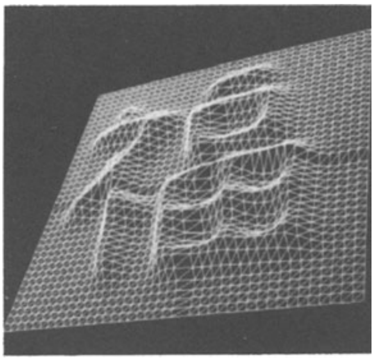


Plate 1d The same surface created with a larger diffusion rate.



Another example showing how a Chinese character is sculptured on a smooth surface.