Towards reverse design of freeform shapes

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ABSTRACT

The need for more intuitive, faster and more effective tools for freeform product design is still an outstanding research issue in shape modeling. We propose a new methodology in which the designer can define optimal shape modification tools for the situation at hand. The key to this method is a dialogue between the designer and the computer, in which the details of the requested shape modifier are settled. The proposed tool, called user-defined modifier (UDM), is based on recent techniques from freeform shape recognition and parameterized, template-controlled shape modification. The dialogue between user and the system is described, and the basic techniques for the UDM tool are presented as well.

Keywords
Freeform shape design, freeform features, parameterization, reverse design

1. INTRODUCTION
In the past decade effective freeform modeling tools have emerged. The *creation* of freeform product shapes is relatively well supported by current CAID (Computer-Aided Industrial Design) systems, commonly based on a workflow in which surfaces are defined from planar or 3D curves, and surfaces are subsequently synthesized into a shape model. However, any deviation from this *forward design* paradigm is much less supported, or even unsupported at all, forcing the designer to redo a significant amount of work. A general, effective method for freeform modification is still not available.

The main assumption behind the requirements for such method is the ability of the designer to define a shape modification in terms of displacements relative to the current shape. Recent studies have revealed that for the exploration of freeform shape concepts, designers are able to express intended shape modifications in a natural way by putting displacement vectors in the effect region [Coo02a].

The main research challenge of the proposed tool is the trade-off between user requirements and technical requirements. A sophisticated solution to meet the user requirements may imply a high complexity of the model and even a degradation of the model into low-level geometry.

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Reverse design versus forward design

Forward design is a common workflow of design, where a model is built up from low-level elements to features and parts, which are assembled into a product model. If a strict work plan of the design process exists, this workflow will be efficient. However, the workflow is not supportive to freeform shape modeling decisions in any order other than the sequential one prescribed by the workflow. It does support pure synthesizing of shape by combining elements and features, where constraints within and among the features may be defined during the building process. Also refinements and features can be included in later stages.

Reverse design of freeform shapes, on the other hand, supports referring back to previous designs. Existing shapes or features can be extracted and be inserted into a model, or otherwise reused for the creation of a new design. Here it is essential to note that the existing features might *not be designed as such*, but are perceived as an entity by the designer. In addition, the designer might expect that the feature possesses parameters that he/she can control, whereas such parameters were never defined. An important aspect of reverse design is therefore the interactive assignment of complex controls to shapes or features. These controls are needed by the designer to achieve shape modifications, which could be very situation dependent. The interactive assignment can be dependent on, or expressed in terms of, for example, characteristic points or curves in the shape under construction or in any other existing shape. This referring to features which were not designed as such is one form of reverse design.

This paper presents a new approach towards a tool, called user-defined modifier (UDM), that meets the 6 requirements. A formal problem statement will be provided in Section 3. Whereas the problem formulation applies to classical contexts, a target application is specified in Section 4. In Section 5 the dialogue and workflow concerning the reverse design of styling lines will be presented. In the Conclusions in Section 6 it will be pointed out how recent techniques can form the basis for the implementation of a UDM.

2. RELATED WORK

Forward design

In the prismatic/spherical/cylindrical shape domain, the requirement of high-level parameterization of geometry was early recognized and led to the introduction of features [Sha95a]. Most commercial solid modelers have adopted the concept of feature, and typically a user follows a workflow in which parts are created in a sequence of operations, such as extrusions, intrusions, Boolean operations and parameter setting.

A big contrast between regular-shaped features and freeform features is that the latter can hardly be predefined generically, but should evolve in a specific design context and be customized consequently. This seems to require a different design workflow than the one known for mechanical feature-based design. Yet it has been shown in [Mit00a] that an object-specific feature anatomy enables accurate performance predictions of the product design. In Mitchell's method, a tennis racket design is generically defined as a system of features, with predefined types of relationships. In general, however, the principle of aggregation of feature instances as to form the entire design model seems too restrictive. This may explain the considerable attention that has been paid to the development of detail feature modeling techniques, as for example by [Cav95a], [Els98a] and [Per02a].

Reverse design

In reverse design, an existing portion of a shape model is regarded as a starting point for shape modification. The user may, however, expect shape handles to be available which were never defined for the selected portion.

In current techniques for reverse engineering of shapes, freeform shapes can be extracted from geometrical data, where the shapes are represented as surface descriptions, typically B-splines. A B-spline surface can be regarded as a geometric object with parameters, where the parameters are the control points of the B-spline surface. It is clear, however, that "recognition" of a shape portion as a B-spline surface is not reverse design; the designer will normally expect higher level shape handles than the control points are.

3. PROBLEM STATEMENT

We formally state the problem of supporting reverse design in the freeform domain as follows.

Given: A shape S in 3D space. We assume that S is all or part of the boundary of a compact subset of 3-space and can be considered as a 2-manifold. There are a number of implicit control elements (points, curves or surfaces) e_i, i=1, ..., n associated to S. The e_i are not explicitly represented and therefore called implicit. The e_i have significance for the user as a reference object to control a shape modification. We assume that there exists a derivation procedure D that derives the elements e_i from the given shape S, so that $\{e_1, ..., e_n\} = D(S)$. D specifies the association between the shape and the implicit control elements. For each e_i there is a target element t_i. Each t_i specifies an intention of the designer concerning the shape modification.

Wanted: A shape S' such that $D(S') = \{t_1, ..., t_n\}$. Furthermore we need for i=1, ..., n a control function f_i of a real variable a_i such that $f_i(0) = e_i$, $f_i(1) = t_i$, where f_i produces a smooth transition from e_i to t_i when a_i increases from 0 to 1. Instead of [0,1], any other parameter interval could be chosen.

Although the formal problem statement is dedicated to reverse design in the freeform domain, the basic principle can be clarified in the prismatic domain, where the e_i and t_i happen to be explicitly defined. The problem statement is even relevant for forward design. Below we will, for didactic reasons, provide an example situation to which the problem statement applies.

4. TARGET APPLICATIONS

A more complicated example can be given in case of car body development. A styling line is a contiguous set of points of high curvature in the car body's surface. Although the styling line may never have been explicitly constructed as a curve, the styling line is generally perceived as a curve. Let us denote this curve as s. Let us assume that the designer wants to achieve a shape modification local to s. He/she selects a point p_j on s. If we determine the intersection curve e_i of the car body surface with a plane containing p_j, perpendicular to the direction of s at p_j , then the curvature of e_i will have a maximum in p_j, due to the definition of the styling line. Suppose that the designer intends to reduce the sharpness of the entire styling line s. He/she can specify this intent by modifying the profile of the intersection curve, which is now a controlling element, e_i to a curve t_i which is less sharp near p_i. Formally, the shape of the car body should now modify in such a way that the new intersection curve at p_j becomes consistent with t_i. Moreover, the surface should not be modified at point p_j only, but everywhere along the styling line s. The modification specified at point p_j should be applied to all other points of s, because that is typically what the designer expects. The modification specified at point p_j is thus a kind of exemplar of the modification of the surface shape. Obviously, the exemplar does *not* specify a unique modification of the surface. However, some "most likely" modifications can be implemented and be offered to the designer as options. It should be noted that the amount of curvature reduction can be represented by a continuous parameter a_i.

5. TYPICAL WORKFLOW

The whole process is illustrated with Figures 1 to 4. The surface of the computer mouse in figure 1 appears to have a rounded edge (indicated by arrows) which could be called a styling line. It should be emphasized that "line" is a terminology only; it is neither known nor assumed that the design of the shape of the mouse contains or is based on a line or curve.

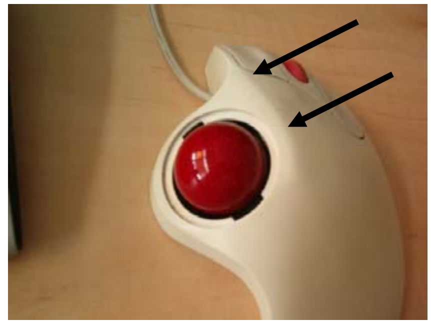

Figure 1 Computer mouse and perceived styling line indicated.

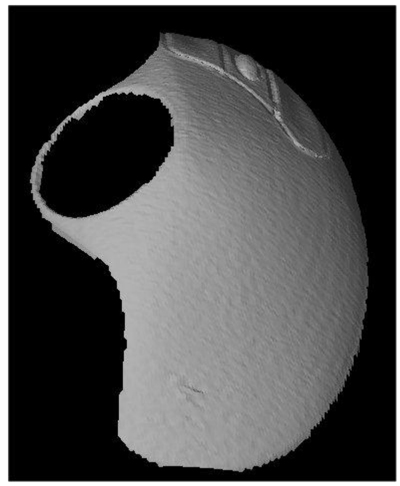

Figure 2. Surface mesh *S* obtained after 3D scanning of the mouse.

The visibility of the styling line is obviously depending on the positions of the light sources, the viewing direction etc. Suppose that for aesthetic, ergonomic or other reasons, the shape should be redesigned in such a way that the styling line would be "more rounded" (or oppositely "sharper"). The intent is then to leave the shape and the location of the styling line unchanged and to make the transition between the surface parts on both sides of the styling line smoother (or sharper). If the shape were designed with CAD, using a curve forming the connection between the two surface parts, then the redesign could have taken place by editing the geometric elements of the model. However, if the model would have been created differently, or if no CAD model is available at all, then the "standard" reverse engineering method could be applied to obtain a solid or surface model from a 3D digitization from the physical shape.

In our proposed methodology, the user designates the styling line on the surface mesh (Figure 2) obtained from 3D digitization. The curve following the locus of points at maximal curvatures is shown in Figure 3. A number of planes perpendicular to the curve are generated to determine the intersection profiles associated with the styling line (Figure 4). These profiles constitute the elements e_i which the user can manipulate.

6. CONCLUSIONS AND ONGOING RESEARCH

Locally a styling line can be characterized by the intersection curve of a plane with shape S. Along the styling line this intersection profile may vary, but in general the variation will be moderate, otherwise the styling line would not have been perceived as such. Therefore, the various profiles will have something in common, which helps to recognize them and the similarity also simplifies the user interaction with the UDM system: a modification made to one profile should be applied to all profiles.

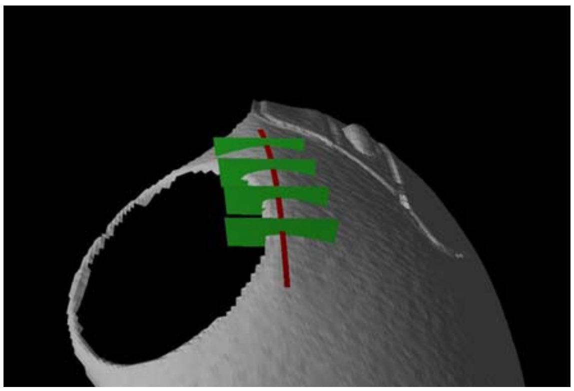

Figure 3. Intersection profiles can be generated using planes perpendicular to the curve approximating the styling line.

However, much of the reverse design tool UDM still requires theoretical investigation and algorithm development.

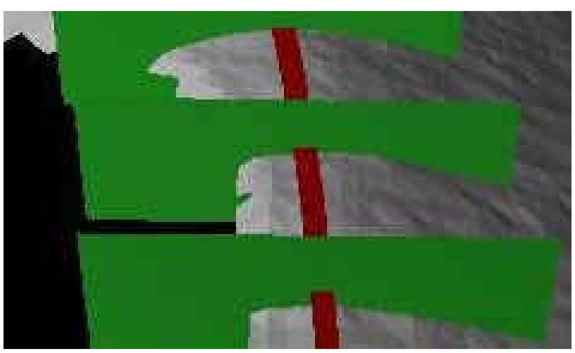

Figure 4. A closer look at the intersection between plane and surface mesh.

The styling line tracking have been developed based on the marching template method. Tthe adaptation of the shape S to the modified profiles t_i can be based on template-based deformation [Son04a].

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