Inserting G1 discontinuities into free-form features for aesthetic design

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ABSTRACT

Free form shapes are often used to fulfil both aesthetic and design constraints applied to parametric models currently adopted in CAD environments. Up to now, designers and engineers have mainly access either to indirect manipulations of free form surfaces using their control network or to low-level deformation functions at prescribed points and along a line on a surface.

Based on a study of designers' activity, a free form deformation feature approach is proposed to create CAD tools that better fit their way of working. The proposed category of features aims at enforcing the visual effect of the so-called character lines, extensively used by designers to specify the shape of an object. For this reason, in the proposed approach 3D lines are used to drive surface deformation over specified areas.

One type of these features is based on G0 or G1 discontinuities along the character lines. Traditionally, a designer using a CAD system creates these features by generating several patches. Our approach proposes a method to create discontinuities on a single patch, using the trimming properties of the surface. Examples are provided and analysed using curvature maps to address the quality issue of the resulting shape as well as its capability to generate a wide variety of shapes.

Keywords

Free-form surface, deformation, feature-based modelling and constraints, G1 discontinuities.

1. INTRODUCTION

The stylist's task is the definition of a product generating a certain emotion on the end-user while satisfying the assigned constraints, i.e. marketing and engineering ones.

When creating a new product, a stylist gives first the global effect by drawing some essential curves, which can be considered as an abstraction of the product shape. They are not only structural lines, like profiles, but also lines strongly affecting the product visual impact, commonly named character lines. Such lines can be considered as abstract because they may be not present in the product model but simply perceived, such as gaps or light lines (Fig. 1).

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Figure 1. Character lines: (a) reference lines, (b) virtual lines.

However, a designer may want to enforce the existence of such lines using tangency discontinuities of the underlying surface along the whole character line or some of its sub domains (Fig. 2). The designer creates these discontinuities in order to create light effects on the shape, like breaking the reflecting lines, even if the manufacturing process imposes that the discontinuities do not exist and will be replaced by chamfers.

Figure 2. Tangency discontinuities on character lines.

Such tangency discontinuities are usually complex to be generated by standard CAD modellers since a surface subdivision process is mandatory to fit the character line. This process becomes even more tedious and complex when the tangency discontinuities along a character line must smoothly vanish into a continuous area of the surface. This problem is generally considered as two distinct problems: first, the subdivision of the initial surface has to be generated, and second, we have to create G2 continuities between the surfaces in the continuous area, the G1 discontinuities are reduced to a problem of G0 continuity.

The approach here proposed aims at providing a constrained based surface deformation process as part of a feature-based design environment to generate such complex configurations through a fairly small amount of steps or even in one step.

A feature-based approach, preserving the design intent in terms of character lines insertion, seems to better meet user's requirements. Features are well known in the mechanical engineering field [Sha95] as the key elements for associating specific functional meaning to groups of geometric elements (faces, edges and vertices). They are much more significant for applications than the low-level geometric primitives and can be manipulated by means of a limited set of parameters. Then, using features as design primitives is more efficient when creating the product model and considering alternate solutions.

Differently from the mechanical environment where parts are defined by canonical geometric shapes, free form modelling does not ease the association between shape and function and it is much harder to define a feature classification. One of the first attempts in bringing the feature concept into the free-form domain has been carried out by Cavendish and Marin [Cav92]. They focused on functional surfaces, such as car inner panels, which are highly irregular and multi-featured but with regular shapes. Even if the approach is interesting, it is too limited for aesthetic design, since it deals with quite simple shapes and can hardly be integrated with B-splines models.

An extension of features to NURBS representation has been proposed by Van Elsas and Vergeest [Van98]. In particular, they develop methods for the creation of general displacement features, mainly focusing on transition surfaces. But, in the perspective of defining a full feature-based functionality, the feature set has to be extended. In this field, Fontana et al. [Fon99] identified two categories of form features used in the different phases of a computer-assisted styling activity: structural features and detail features. Structural features include the lines defining the overall shape. Examples of structural features are contours, object profiles and sections or structural character lines having an overall aesthetic impact. On the other hand, detail features correspond to local shape modification for adding aesthetic and functional details and for enhancing the visual effects of the character lines.

Starting from the above taxonomy, Vergeest et al. [Ver01] defined a parameter-based formalism for detail features. The proposed formalism for parameterisation is exemplified for the ridge and hole feature categories. Whilst being a valuable attempt to address the problem, this approach still requires improvements to be applicable.

Starting from the same taxonomy, the work of Pernot et al. [Per02] propose an approach for the implementation of a free-form deformation feature that uses a mechanical model to generate the deformation process. The work proposed in this paper is based on this approach and it extends its classification by adding some new feature types, with G1 discontinuities.

The rest of the paper is organized as follows. Section 2 reviews the principle of the deformation method using a mechanical model of bar networks. Section 3 presents the different types of geometric constraints used to shape a surface and describes the free-form feature concept. Section 4 presents the process for generating G1 discontinuities features. In section 5, the resulting surfaces are analysed and some solutions improving the surface quality are proposed. Concluding remarks and future work are discussed in the last section.

2. THE DEFORMATION ENGINE

The adopted free-form surface deformation technique [Gui99] is based on the Force Density Method

(F.D.M) applied to a bar network coupled with the control polyhedron of a B-spline surface [Sch74].

The process starts with an initial surface composed of several trimmed patches connected together with parametric point constraints and submitted to geometric point constraints in the 3D space (Fig. 3a). For each patch, a bar network is built from its control vertices (Fig. 3b and 3c): either it can be topologically equivalent to the control polyhedron or the bar connectivity may differ to permit an anisotropic behaviour. Each bar can be seen as a spring with null initial length and with a stiffness (more precisely a force density in the present case) q_i; to maintain the static equilibrium state of length l_i, f_i external forces have to be applied at the endpoints of the bar: $f_i = q_i \times l_i$ (Fig. 3d). The set of external forces to apply on the initial bar network can be then obtained through the static equilibrium of each node (Fig. 3e). The problem is now to define the new set of external forces on the bar network (unknowns of the equation system) to deform it according to the geometric and parametric points constraints (Fig. 3f). In order to choose one among all the solutions, an objective function is added to the geometric constraints and a minimisation criterion has to be chosen, such as the minimisation of the variation of the external forces or the minimisation of the external forces in the final position. Using the geometric coupling, the new positions of control polyhedron vertices are obtained by the new positions of the bar network nodes (Fig. 3f), thus inducing the surface deformation (Fig. 3g & Fig. 3h).

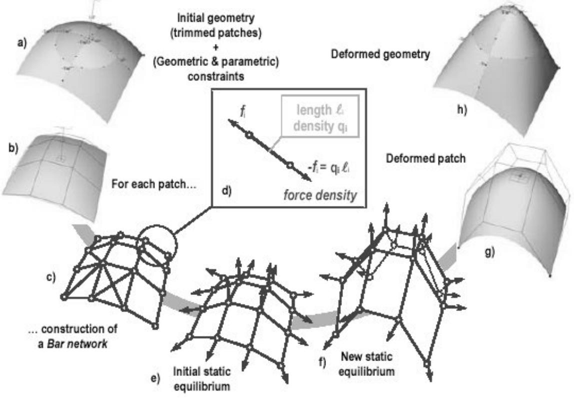


Figure 3. Principle of the free-form surface deformation method.

3. THE FEATURE PARAMETERS

Character lines are very important styling elements. They can be indicated as styling features since they are used to produce a specific impression/feeling when looking at the object [Fon99]. They can correspond to real lines, e.g. lines on surfaces, but generally they are only perceived. Such virtual lines can be induced in several ways: by light effects, like shadow and reflection lines [Leo91], by gaps between different product components or by localized surface deformations having a line behaviour.

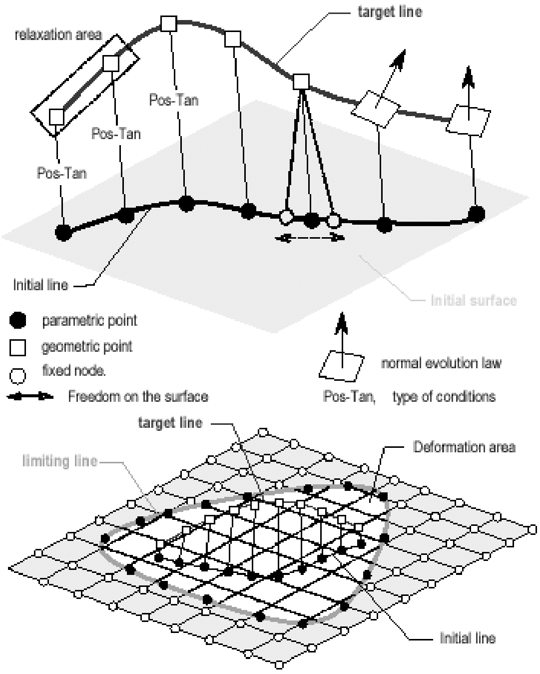


Figure 4. Target line (top) and limiting line (bottom) specification.

This work focuses on the development of a free form feature for the definition of such line-driven deformations. Two kinds of line constraints have been identified and termed as target and limiting lines (Fig. 4). *Target lines* are 3D curves that give the global directions of the deformation which are generally related to a shape characteristic the user wants to impress to the object, whereas *limiting lines* are built on the surface to control the extent of the deformation, and give a shape along the target lines [Per02].

These two types of constraint lines form a set of attributes that allow the specification of very complex shapes using a restrictive set of operations and parameters. Additional parameters are used to manage and control the deformation. Some of them are intrinsic, i.e. transparent for the user whereas others are inputs of the deformation feature. A particular attention has been paid to the minimisation of the input parameters in order to allow designers an easy manipulation of the features without limiting their imagination.

From the geometric definition point of view, target and limiting lines are similar and correspond to curvilinear constraints, which are then approximated by a set of point constraints to be managed in the mechanical model. Optionally, an initial line associated to the target line can be defined on the original surface. These curves are the input parameters of the deformation features.

The deformation process is obtained by pulling points of the surface towards the coupled points of the target line [Per02] (Fig. 5). The points of the surface come from a discretisation of the initial line, if it exists, or from the projection of the points of the target line on the original surface when no initial line has been explicitly defined.

To locate and associate these pairs of points, several parameters are used. Firstly, the point distribution is defined by the number of points and their position by the user-chosen distribution law (e.g. either related to the *u* parameter of the curve or to the curvilinear abscissa or to the curvature of the curve). The result of the distribution function is a set of geometric position constraints; tangency conditions can be added to these points for a better control of the deformation. To increase the range of deformation, an evolution law of the tangent plane along this line can also be added. Moreover, other parameters, like the topology of the network or the choice of the minimisation function, can change the global shape of the surface [Per03b].

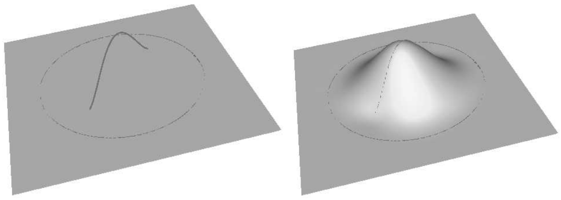


Figure 5. A free-form feature defined by using one target and one limiting line.

Using these basic tools, a shape classification has been proposed, based on both the properties held by shape features and the adopted deformation tools [Per03a]. One level is directly linked to the constraint lines parameters, including simple and composite features, each being directly obtained using only one deformation operation. A simple feature is defined by one target and one limiting line. When the cardinality of the target and/or the limiting line is greater than one, a composite feature is defined.

By creating G1 discontinuities along a part of the target line, we propose to increase one more time the deformation possibilities as well as the shape diversity, while preserving an easy manipulation of the features. So the user deals with a minimal number of parameters to create the features. This G1 discontinuity can appear in both simple and composite feature, but in the next section, we only describe the generation of simple features with discontinuities.

4. CREATING G1 DISCONTINUITIES

Usually, the creation of G1 discontinuities along a line is obtained between at least two patch boundaries, with only G0 constraints between them. But the main difficulty is to altern G1 discontinuities and G2 continuity on a same line. Moreover, specifying a G2 continuity between two patches is very difficult and requires many control points.

Figure 6 shows a result obtained using a traditional CAD systems: the surface is composed of 13 patches, with G2 continuity prescrined along the limiting line and G0 continuity only along the target line. The method used in this case can be described in 4 steps, starting at the beginning with the definition of the initial planar patch and the two constraint lines (limiting and target line), as described in fig. 5:

1. Trimming of the initial patch along the limiting line.
2. Creation of line extensions to join the target and limiting lines with G2 continuity constraints (Fig.6a).
3. First operation of blend from the extended target line and one half of the limiting line, with a G2 continuity with the initial patch along the limiting line.
4. Second operation of blend from the extended target line and the other half of the limiting line, with a G2 continuity with the initial patch along the limiting line (Fig.6b).

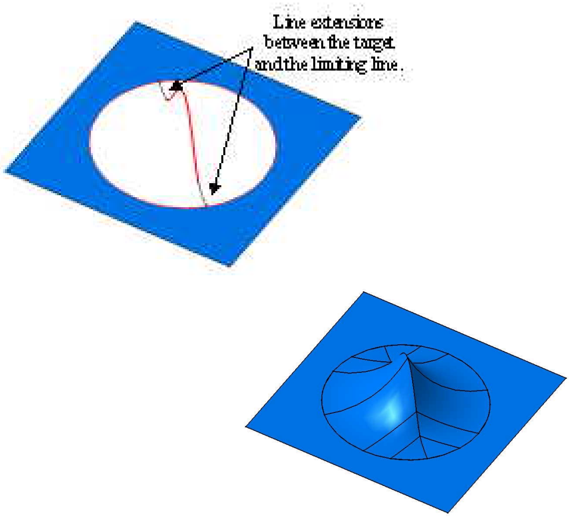


Figure 6. G1 discontinuity along a 3D curve: using a traditional CAD system.

The main idea is to create the discontinuity along a line, which can be not only a classical iso-parametric or patch boundary line, but any 3D line. Here, we want to create the discontinuities with a single patch in one step only, by creating a loop on the surface [Che03]. In this way, the G2 continuity is preserved everywhere on the patch a part from the target line. Additionally, keeping the same topology of the surface is a way to ensure that the semantic attached to the different geometric entities (e.g. patches) is preserved, and thus without any step of hazardous data transfer between the initial patch and the newly created ones at steps 3 and 4.

G1 Discontinuities along a target line

To explify our approach, let us consider a 2D curve (Fig. 7), on which we want to insert a G1 discontinuity at a specific point. At that point, we create a loop (Fig. 7a), and by trimming this loop (Fig. 7b), the user only perceives a G1 discontinuity (Fig. 7c).

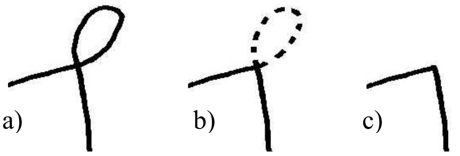
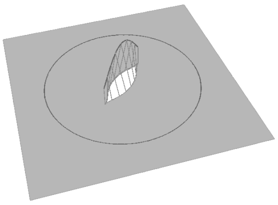
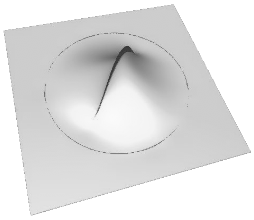


Figure 7. Creation of a G1 discontinuity on a 2D curve.

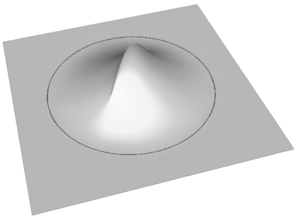
This method can be extended to 3D surfaces, and thus, G1 discontinuities can be obtained along a target line associated to a single patch.



a. Constraints



b. Deformation without trimming



c. Deformation and trimming

Figure 8. Creation of a G1 discontinuity on an initially smooth surface.

In order to create the loop on the surface, the initial line is split into two lines (Fig. 8a), which create a trimming area on the patch. After deformation, these lines coincide with the 3D line specified by the user (target line), and the inner area (area of the patch between the two initial lines) forms the loop (Fig. 8b). The trimming process removes the loop and the user just sees a G1 discontinuity along the target line (Fig. 8c).

To create this discontinuity, the user first has to specify the interval of the target line where the discontinuity has to be generated.

The two initial lines are automatically generated, using as a reference the projection of the target line on the patch, according to the following algorithm (Fig. 9):

- discretisation of the target line and creation of a set of points M_i,
- normal projection of each point on the patch to obtain the points P_i,
- creation of the projected line by interpolation of the points P_i,
- for each projected point P_i, creation of two points, P_i^1 and P_i^2, on both sides of the projected line, according to eq. (1):

$$\overrightarrow{P_iP_i^1}=\alpha_i*O_p*D*\frac{\overrightarrow{M_iP_i}\wedge\vec{t_i}}{\left\|\overrightarrow{M_iP_i}\wedge\vec{t_i}\right\|} \quad \text{and} \quad \overrightarrow{P_iP_i^2}=-\overrightarrow{P_iP_i^1} \qquad (1)$$

where: $\alpha_i(s)$ is the law of opening ($0\leq\alpha_i\leq1$),

O_p is a parameter named opening,

D is the maximal distance between the target line and the patch,

P_i is the tangent vector of the projected line at the point P_i.

- projection of P_i^1 and P_i^2 onto the patch to obtain the points R_i^1 and R_i^2,
- creation of the two initial lines by interpolating R_i^1 and R_i^2, with end tangents parallel to the projected line in the parametric space.

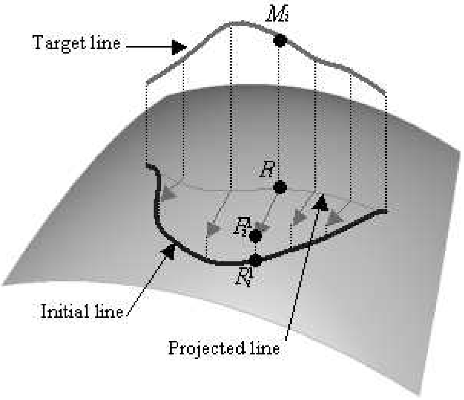


Figure 9. Generation of one of the initial lines.

The opening law $\alpha_i(s)$ can be chosen among many possibilities. Meanwhile, some conditions are necessary: $\alpha_i(s)=0$ and $\frac{d\alpha_i}{ds}(s)=0$ for the end points, $\alpha_i(s)=1$ for the middle point. The opening law chosen in this algorithm is the simplest one: a polynomial law.

Thus the two initial lines are controlled by one parameter: the opening parameter that has two main goals. Firstly, it helps to check if the number of control points to generate the loop is large enough with regards to the number of constraints (see next section). Secondly, the modification of the opening parameter value has also a visual consequence: the higher the value, the larger the loop and, as a result, the stretcher the non-trimmed surface area.

After the creation of the two initial lines on the patch, the algorithm automatically creates the constraints between the target line and each of the initial lines (Fig. 8a). These constraints can be position constraints but also tangency constraints between each initial line and the target line. Thus, the user can specify on each side of the target line a different evolution law of the tangent plane.

New tangency constraints

The generation of G1 discontinuities requires the coincidence of the two computed initial lines along a 3D line (target line), defined by the user. These lines have assigned position or tangency constraints only. Hence, the behaviour of the initial lines after deformation is unpredictable between the constrained points. In particular, holes or over-lapping areas of the surface along the target line may appear. As a consequence, the quality of the surface may decrease (see Fig. 10).

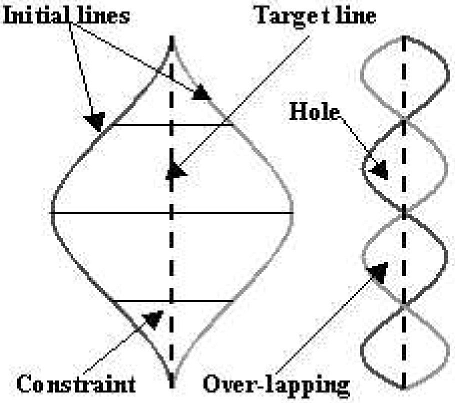


Figure 10. Simplified 2D behaviour with holes and over-lapping.

One idea to minimise this type of problem could be to increase the number of constraint points, but using this solution, we can quickly have local over-constrained configurations without any significant improvement of the quality.

To obtain an effective quality improvement, a new type of constraint is created for the initial lines. At each constraint point, the algorithm imposes a parallelism between the tangents of the initial line and target line. In this way, around a constraint point, these two lines stay close to each other. And, if the target line is not varying too much, this neighbourhood becomes large enough to achieve an overall good quality of the resulting surface along the target line (see Fig. 11).

This new constraint can be written as in eq. (2):

$$\begin{aligned}\overrightarrow{T_{3D}} = & \left[\frac{\partial U}{\partial s}(s_0) * \frac{\partial X}{\partial U}(U_0,V_0) + \frac{\partial V}{\partial s}(s_0) * \frac{\partial X}{\partial V}(U_0,V_0)\right]\vec{X} \\ & + \left[\frac{\partial U}{\partial s}(s_0) * \frac{\partial Y}{\partial U}(U_0,V_0) + \frac{\partial V}{\partial s}(s_0) * \frac{\partial Y}{\partial V}(U_0,V_0)\right]\vec{Y} \\ & + \left[\frac{\partial U}{\partial s}(s_0) * \frac{\partial Z}{\partial U}(U_0,V_0) + \frac{\partial V}{\partial s}(s_0) * \frac{\partial Z}{\partial V}(U_0,V_0)\right]\vec{Z}\end{aligned} \qquad (2)$$

where: $\overrightarrow{T_{3D}}$ is the tangent vector of the target line at the considered point,

$U(s)$, $V(s)$ are the parametric equations of the initial line in the parametric space of the patch,

$X(U,V)$, $Y(U,V)$, $Z(U,V)$ are the parametric equations of the patch,

U_0, V_0, s_0 are the coordinates of the current point on the patch.

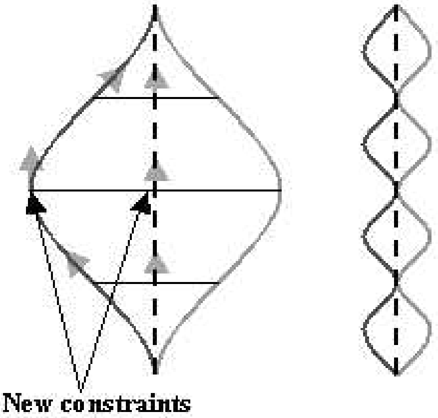


Figure 11. Addition of new constraints.

This solution provides a better quality with the same number of constraints. But, we have added to each constraint point 3 scalar constraints, thus we have to take care to generate no local over-constraints. As a consequence, we specify a fewer number of constraints. The quality is still better: for example, the undulations decrease of 50% in most test cases.

Relaxation area

Another problem may arise with the resulting surface: an inversion of the direction of the loop can appear at the endpoints of the target line. The loop is not above the surface but below and, as a consequence, the discontinuities are in the reverse direction (Fig. 12).

This problem is due to a bad definition of the target line ends with regard to the initial patch: the ends can be too close to the patch, or/and the end tangents can have too large slopes with regard to the patch. The existence of inflexion points on the target line, near its ends, can also originates a loop inversion.

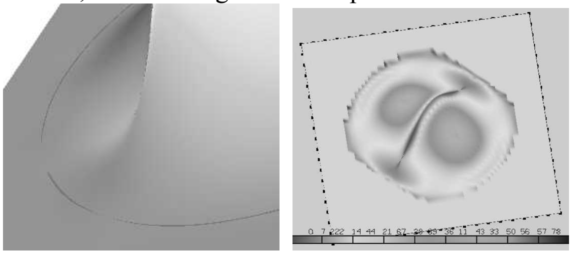


Figure 12. End problems on the surface: surface and map of gaussian curvature (positive gaussian curvature near the extremes of the target line locates the incorrect areas).

However, during the shape design process, the designers do not know very well where the target line ends exactly. They only sketch the character of the surface and the transition area between the target line and the surface is rather uncertain. So, one idea to avoid these undesirable behaviours at the extremities is to induce some relaxation: considering only a reduced part of the line. In this case, the generated surface has a better quality since the end hollows disappear (Fig. 13).

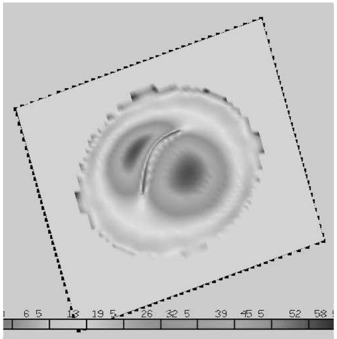


Figure 13. Relaxation on target line (gaussian curvature map).

This process can be transparent for the users: in case of incorrect shape of the surface, they can just prescribe the relaxation to the algorithm that chooses a better pair of points to relax the surface.

5. RESULTS

Designers are rigorous about the quality of the deformation results and the smoothness of the deformed surface. Therefore, it is necessary to provide a visual tool to amplify undesired undulations caused by fast variations of a shape. Curvature analysis allows at once local and global studies of the surface behaviour. The evaluation of the curvature at a point represents the local behaviour of the surface and the concatenation of this information over the entire surface highlights the imperfections in the global appearance of the surface. Texture environment mapping is also a tool to evaluate the quality of a surface.

A particular attention has to be paid to the accuracy of the results in terms of the maximum distance between the constraint lines and the deformed surface, and also between the trimming lines (width of holes). This second criterion is very important for engineers and allows a control of the functional constraints accuracy.

Some test cases have been studied, like a simple feature on a planar patch (see Fig. 5), but also more complicated ones. Here is the example of a complex feature on a multi-patch surface: the mouse model (Fig. 14) is composed of 38 patches, with continuity constraints between them. We create a complex feature with 3 intersecting characters lines: 2 with tangency discontinuities and the last one with continuity. The global problem represents more than 3800 scalar constraints.

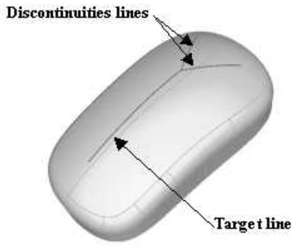


Figure 14. A mouse model with the definition of a complex feature.

In figure 15, the deformed mouse is obtained by only one deformation operation embedded into one free-form feature. In terms of accuracy, the maximum relative deviation is $3,1.10^{-3}$ along the target line and the maximum relative width of hole is $2,7.10^{-3}$. These values are similar to the classical tolerances in CAD systems, which proves the validity of this method.

Figure 15. The deformed mouse.

One problem during the generation of the resulting surface was the consequence of over-constraints. The surface satisfied the constraints of position and/or tangency, but the global behaviour was not the expected one (Fig. 16). For this feature, we expressed too many constraints and locally, there were not enough free degrees of freedom for the surface. The algorithm can perform some computation because, globally, there are enough degrees of freedom, but the result is totally unexpected. The result is also unacceptable because it does not respect all the constraints.

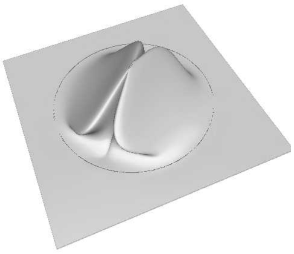


Figure 16. Local over-constraints behaviour.

6. CONCLUSION

In this paper, a method for inserting G1 discontinuities on a given surface is presented. With respect to the traditional methods, the one described here does not require the generation of new patches. It has been implemented in Defsurf software, developed by the L3S team and adopted in the framework of our free-form feature modelling approach aimed at expressing character lines often used in styling activity to express shape changes. In particular the presented method handles tangency discontinuities along a target line. The proposed approach, which can be integrated in existing CAD environments, uses a mechanical model for the generation of the modification process.

This method has been tested and the quality of the resulting surfaces is good, as seen in the previous sections. The comparison with the traditional multi-patch method, discussed in section 4, shows that it produces shape of the same good quality, but with a faster computation time useful for an interactive use. In addition, the resulting surface, generated by the new method, is obtained through one step only. With the traditional approach, a fair amount of time is required to generate a smooth transition area at the ends of the target line, which makes a significant difference with the proposed method.

The management of over-constraints is a real problem, non-intuitive for the user but also for us: there is not any simple rule to predict this. So further research work is needed to develop analysis tools to predict and avoid these configurations.

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