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3D Sketching with Fully Free Form Deformation Features (δ-F^4) for Aesthetic Design

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ABSTRACT

This paper addresses the designers' activity and in particular the way designers express an object shape in 2D sketches through character lines. The tools currently available in commercial CAS/CAD systems to manipulate the digital models are still not sufficiently suited to support design. In this paper, we introduce the so-called Fully Free Form Deformation Features (δ-F^4), able to take into account the curve-oriented stylists' way of working. Both the advantages of a free form surfaces deformation method and a feature-based approach are merged to define high-level modelling entities allowing for a direct manipulation of surfaces through a restricted number of intuitive parameters. In addition, a δ-F^4 classification is proposed to permit a fast access to the desired shape according to its semantics. The proposed approach is illustrated with some examples.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modelling & J.6 [Computer Applications]: Computer-Aided Engineering.

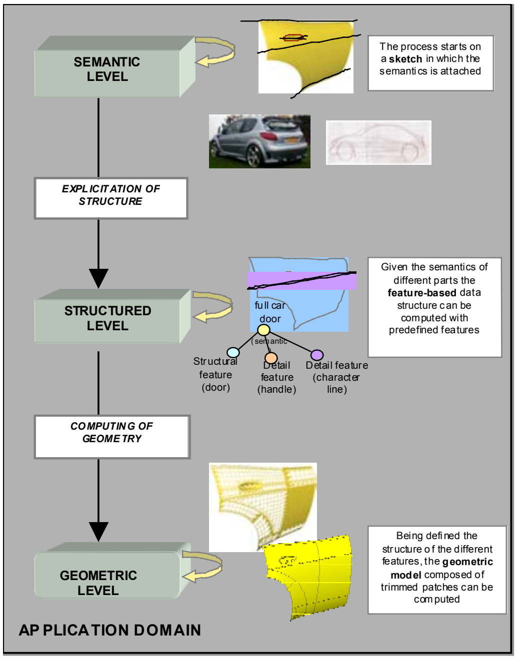
1. Introduction

Styling activity is performed by hand, with sketches drawn on paper [TW88, VM97], still today. Only at a second stage, designers make use of CAS (Computer Aided Styling) systems, usually with the help of an expert in using digital tools to create 3D shapes. It is certainly a matter of mentality, but it is also a lack in the methods provided by the digital tools. In fact, software adopted in this first phase does not support sketching and the related semantics is not included. An improvement in this direction could more easily induce stylists to create directly the digital model and work on it to devise new objects or alternatives to existing ones.

Adding semantics to a digital model in this field means providing capabilities closer to the designer's habits, in order to make creation and manipulation of shapes more intuitive and easier. Semantics is context-dependent and studying styling activity is fundamental to find the meaningful entities for this task. However, not only the geometry of the object has to be conceived, but also information related to functionality is often taken into account. For instance, when defining a handle cavity on a car door, a stylist has to consider that the cavity enables the passage of a hand between the surface and the handle; this information can then be shared with the others actors of the design process, so that the cavity does not become too narrow.

The notion of feature has been traditionally introduced in mechanical engineering [SM95] as the key element for associating specific functional meaning to groups of geometric entities describing an object, thus offering the advantage of treating sets of elements as single entities. Features are much more meaningful for application purposes than simple geometry and can be manipulated through a limited number of significant parameters. Similarly to the mechanical environment, in the styling activity some feature primitives may be identified as high-level modelling entities, but with much more difficulty. In fact, in conceptual design products can have very complex shapes and stylists have a lot of freedom during the creation phase thanks to the availability of new materials and production technology; moreover, higher competition among companies makes the aesthetics of a product crucial to influence customers' decisions.

This paper presents a method to represent the stylist's intent during the creation of the digital model of a product: a tool able to create and manipulate shapes through a free-form feature approach in a way more familiar for designers is introduced. Based on interviews to designers collected during the European projects FIORES I and FIORES II [FIO-I, FIO-II], a feature taxonomy has been proposed and used for aesthetic applications. In this way a link between the geometric level and the semantic one can be established in order to respect the stylist's purpose during all the process of design. In Figure 1, the ideal modelling scenario we propose for storing and maintaining the semantic information directly accessible at the styling phase is depicted, which, if the necessary tools were available, could be applied to the commonly adopted design approaches. A first description of an object is given by a sketching and is usually expressed through some characteristic lines, significant for the stylist. Then, an intermediate structured level of description is introduced, providing a semantic representation of a product through the features capturing the characteristic line essence. Finally, the feature-based representation is associated to the corresponding geometric entities and the characteristic lines are decomposed into low-level constraints used in the deformation process. It should be noted that the standard geometric representation in this context is based on NURBS (Non-Uniform Rational B-Splines), which splits a shape into a collection of patches described by continuous surfaces.



The process starts on a **sketch** in which the semantics is attached

Given the semantics of different parts the **feature-based** data structure can be computed with predefined features

Being defined the structure of the different features, the **geometric model** composed of trimmed patches can be computed

Figure 1: *The top-down life cycle of digital shapes: from high-level semantic concepts to low-level geometric realisations.*

The paper is organised as follows. Section 2 reports the methodology generally adopted for the shape conception in car styling. Section 3 discusses the relationships between the hand-made sketching and the corresponding digital model, highlighting the users' desiderata. Section 4 introduces the concept of Fully Free Form Deformation Features (δ-F^4), while Section 5 reviews the principle of the free-form surface deformation engine and the one of the curve-based method for generating and manipulating free-form surfaces. In Section 6, feature-manipulation methods in the context of aesthetic design is briefly presented, the whole being illustrated with examples obtained using our prototype system.

2. Car sketching

In this Section we focus on car design because it is characterised by a more structured pipeline in the creation phase, being the product in this case constrained to strict engineering/technological requirements. In other types of products, according to product characteristics and company habits, shape can be totally free and thus a possible formalisation is even harder to obtain. Some notes will be given, showing sketches drawn during the interviews with stylists of *Pininfarina Ricerca e Sviluppo s.p.a.* [Cat04].

In the automotive field, the first aspects playing a decisive role in judging a product is what can be called *graphics*, i.e. some details of the car or the colour; the second is *treatment*, which is the character of surfaces and leading lines; the last is *volume*, i.e. proportions and the mass distribution.

Ordinary people perceive the car taking into account the mentioned aspects exactly in that order; on the contrary, designers develop their idea according to the opposite order: at first, they conceive the volume, then draw the character lines and only in the end care about details. Good design is achieved if all these elements are harmonised and consistent, while the stylistic choices within the three categories are related both to the current fashion and to the designer's experience. They have their own curves – those they like to use or respecting the guidelines of the company – and the ability consists in combining the different elements in order to create something new and appealing.

Typically, the search for a specific character is obtained by sequentially modifying a neutral car according to the designer tastes and objectives. A neutral car is the vehicle in which all the characteristics are standard: height, proportions on the one hand and usage of symmetry and curves on the other one. The designer normally focuses on some typical entities and moves them away from the average. Since subjectivity is impossible to be ignored in this framework, it is clear that different approaches can be followed to create a car with the same character.

Stylists think of a car as a volume; therefore, all the curves created are aimed at defining a specific volume which is rendered in a second time, adding lights and shades, enforcing the curvature effects, and so on. For example, a family car is characterised by a big volume, while making a car sportier implies reducing the mass (Fig. 2).

The size of the wheels is usually the unit of measure of volumes. Wheels are the first entity designers draw and they build the whole car around them. The length between the wheels (*wheelbase*) can be measured in terms of the number of wheels contained and the type of the car is given by the ratio between the height of the car and the diameter of the wheel: if the ratio is greater than one, the car is an estate one; if it is less, the car becomes sporty (Fig. 2).

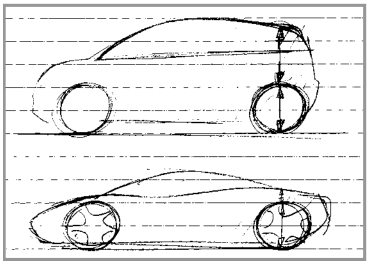


Figure 2: *Volumes of different cars.*

Once defined the volume, *character lines* -structuring the object and constituting the treatment- are drawn. These are the meaningful entities which the proposed approach is able to handle directly. In general, they can be particular sections and profiles; they can divide the boundary areas (e.g. change of materials) or stress curvature variations (e.g. edges). The most important line characterising a car in the profile view is the *roof line*; the *waist (or belt) line* and the front and rear panel *overhangs* follow in order of importance (Fig. 3). By definition, the waist line is the line dividing the side windows and the body side, while the overhang is the distance between the front (rear) part of the car and the centre of the wheel. In practice, rather than the waist line, a curve (an *accent line*) just below is considered for an aesthetic evaluation. In fact, it is a common habit among stylists to judge the surface fairness through the reflections of a light beam on the body. The accent line can be just a light line, a curve only perceived when light is reflected.

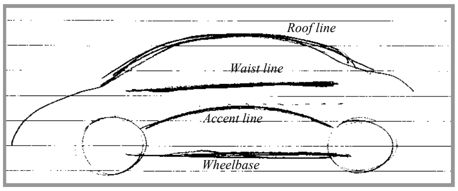


Figure 3: *Character lines in a car.*

To give an idea about how the manipulation of these significant curves affect the character of the object, few examples will follow. Stability is a quality that people consider fundamental, also if the car is sporty. To give stability it is possible to act on the proportions (through the wheels), but also on the position of the line defining the roof with respect to the wheels: it is best achieved if the curve is symmetric and central between the wheels. If the same symmetric curve is located in the back, the car immediately gains dynamism because a displacement of the mass centre occurs (Fig. 4).

Asymmetry of curves gives character to a car: it is not mandatory the curve is asymmetric, it can be enough if its position is. Another example of global impression is given by wet curves, i.e. curves with inflection points, which make the car friendlier. Also a sporty car can present the waist line with inflection points, but the roof line needs "tension" in order to balance the effect. Obviously a line cannot have too much changes of direction because otherwise it becomes confusing. Alternatively, the stylist can decide to build quite neutral lines, but give character only to shadow lines at the waist.

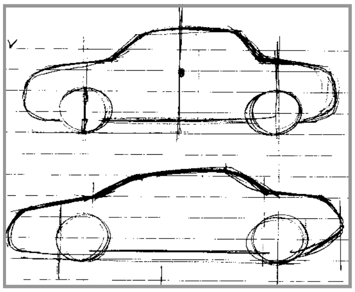


Figure 4: *Symmetry vs. asymmetry of the roof line.*

Sections, profiles and all the real lines are the curves that define the overall surface of the car, while the waist or the accent line can be inserted after and modified opportunely. The last curves can be provided in different ways: either through a smooth deformation, through a line producing a G^0 continuity or, as already said, through a curve stressing a curvature variation (fig. 5).

Figure 5: *Example of an accent line with change of continuity along itself (the green arrow points to G^1 continuity, while the red one to G^0 continuity) (courtesy of Toyota).*

Moreover, some lines are meaningful since they are able to characterise (or stress) the brand identity: the character of the company is easily recognisable thanks to them, as happens with the hoods of Alfa Romeo cars (Fig. 6).

Figure 6: *Brand identity (courtesy of Alfa Romeo).*

As already mentioned, how to act on the characterising lines is a choice of the designer himself/herself as well as how to harmonise them. Often they are used to employing a limited set of curves and to giving their own aesthetic value: each drawing is the result of a different combination of the same entities. Personal tastes have then to marry up with the identity of the company. Some characterisations are interpreted in a standard way by designers: the agreement is due to a common background, more related to the experience developed working in the same environment than to the basic knowledge of the specific field of the conceptual design.

3. From sketches to a digital model

Section 2 stressed the fact that sketching is an activity essentially driven by significant curves. This holds not only in the automotive design, but can be generalised to the other categories of products. Therefore, a CAS system should be able to capture the prominence of such curves. Our proposal is to incorporate and structure the linear constraints chosen by the designer, together with suitable surface deformation capabilities for enforcing their visual appearance, for a more user-friendly interaction with the system. In this way, digital surfaces can be directly controlled by curves, making creation and manipulation of the model of a product more intuitive.

What currently happens in a CAS workflow is that only one selected sketch is modelled in the computer format in order to allow for the complete product development with the support of the available simulation and verification software. The main objective of the CAS user is to create a computer-based model that better fits the impression and the emotion provided by the corresponding sketch on paper. Typically, the selected hand-made sketches are scanned and converted into a digital format, and then used as a framework on which to build up, step by step, the different surfaces starting from those leading curves adopted by the designer in the early conceptual phase. This is often not an easy task, since requiring several steps before obtaining the shape desired by the stylist. Unfortunately, current systems do not allow for high-level tools suitable to manipulation of surfaces and then it is necessary to work directly on low-level geometric entities to modify the shape. In addition, the quality and the aesthetics of the guiding curves is very important since they are used for creating the surfaces enveloping the product, thus the global product impression is strongly dependent on their characteristics. Currently, their modification when the product model is almost complete is very cumbersome, requiring the manual modification of most of the created surfaces.

In a second step, details characterising the object functionally and aesthetically are added. This corresponds to modifications of the surfaces previously created possibly with the generation of new surfaces. While character lines corresponding to specific contours are created as reference curves at the initial surface creation stage, those character lines which are only perceived lines are obtained as a set of surfaces producing strong modifications on the surfaces or through particular relations among surfaces.

Tools permitting surface manipulations according to leading curves would certainly help designers in creating such visual effects. Our proposal is going further: in addition to modifications through specific lines, we give the possibility to attach further semantics, that is, in this context, incorporating a surface behaviour of the area around these lines. Properties which are important to associate to the object are not only continuity and tangency conditions, but also related to the shape itself: for example, it can be useful choosing if the area around a leading line has to be round or flat, if it has a predefined shape or not.

The notion of feature in the aesthetic context that is proposed includes this kind of information and the capability to adapt quickly to design modifications. In the next Section, a formalisation of Fully Free Form Features will be given and the implementation of the geometric tools enabling such a semantic approach will be described.

4. Fully Free-Form Deformation Feature

4.1 Definition of δ-F^4

Well-known in the mechanical engineering domain, the concept of *feature* is a good mean to enable shape-oriented high-level manipulations of a surface. In particular, *form features* have been used to give a meaning to a set of faces defined by analytic surfaces (fig. 7.a). In fact, in the mechanical domain, shape is describable by a composition of simple geometric primitives -such as planes or cylinders- and the definition of a form feature is usually restricted to the manipulation of numerical parameters such as "height" or "width".

Some attempts to bring this concept into the free form surface domain -where shape is very complex and analytic surfaces are not sufficient anymore to represent it- have been carried out [Cav95, PH95, TNY98, Vos99, AY00, VHS01, VVB03]. A limit of most of these approaches is that they focus on a restricted set of features and try to define features without starting from a rigorous classification. Some of these approaches suffer also from being explicitly linked to the underlying surface mathematical model, whereas some others are too generic without explaining how a deformation is actually obtained. Moreover, they are often unsuited to the way designers are used to specifying a shape, i.e. through the specification of a set of characteristic curves.

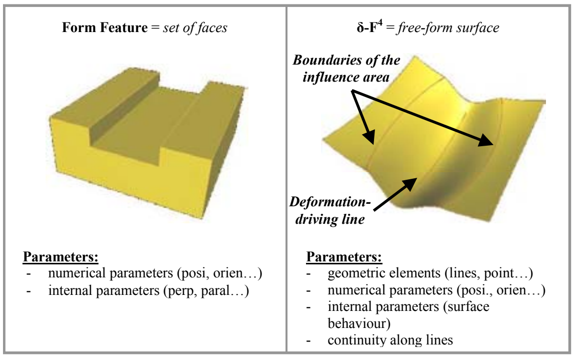


Figure 7: *Comparison between Form Features and δ-F^4.*

In the free-form domain, two types of features can be defined depending on the level of control of the resulting surfaces. The first category includes the so-called *Procedural Free Form Features*, which enable the definition of shapes by free form surfaces resulting from classical operations such as sweeps or lofts. The control of such shapes is restricted to the modification of the parametric curves used during the geometric modelling operation [VVB03].

The second category is based on the Free Form Features (*FFF*) taxonomy defined by Fontana et al [FGM00] and more precisely on the features obtained by deformation (δ-*FFF*). The *Fully Free Form Features* (fig. 7.b) allow for the access to a wider variety of shapes: they are still defined by free form surfaces but controlled by additional parameters aiming at a better definition of their internal areas. They are well suited to the styling activity, which requires a great freedom in the definition of shapes. In fact, the area affected by a character line corresponds to a specific FFF feature, with proper parameters to be instantiated.

Coupling with a deformation process, we have defined *Fully Free Form Deformation Features* (δ-F^4) [PFGL04] as being the shapes obtained by deforming parts of a free form surface according to adequate geometric constraints, which are the *parameters* of the feature.

In addition to the curve giving the direction of the deformation, points and auxiliary curves can be added to bound the deformation area and contribute to define the shape. These constitute the *geometric parameters*.

To model shape archetypes created by designers through a δ-F^4, some *numerical parameters* are needed to describe the intrinsic position and the shape of the geometric elements previously defined. More generally, the numerical parameters are used to give a position and an orientation to the geometric elements.

To represent shape archetypes, only the leading line giving the direction of the shape is not sufficient, and a prescriptive behaviour (flat, round…) of the deformation area must be added: *internal parameters* permit to prescribe such a surface behaviour.

Finally, c*ontinuity conditions* parameters are used to complete the δ-F^4 specification by imposing G^{-1} (discontinuity), G^0 or G^1 continuity connections with the initial unmodified surface area, or along the character line itself.

4.2 Feature taxonomy

To permit a fast definition of a new shape, a feature taxonomy is needed, which structures the different features into classes. At present, only the features defined by character lines have been treated in the elaboration of the taxonomy.

Two first levels of classification have been proposed distinguishing those feature defined either by *direct instantiation* of their parameters (mainly the curves and/or numerical values characterising the shape), or by *composition* of already defined features. Such a distinction gives rise to two main classes called ***basic δ-F^4*** class and ***high-level δ-F^4*** class, which gather together respectively Basic Shape Features and High Level Features. The basic δ-F^4 class includes those features obtainable by a single deformation process, which collects the parameters used to define completely the shape on the surface and control it in a sufficiently interactive way. The high-level δ-F^4 is obtained through one or several operations of composition of existing (basic or high level) features in order to instantiate more complex shapes: for example, a *group feature* gathers distinct BSFs with no mutual relationship, whereas a *pattern feature* repeats a BSF according to specific laws such as some driving lines or scaling factors. Also *Group of Patterns* and *Pattern of Groups* have been proposed as ways to manipulate directly sets of shapes.

Due to the great number of possible predefined BSF, a sub-classification is required to access rapidly a restricted set of parameterised features answering more precisely the designer's needs. The proposed sub-classification is then shape-orientated, which means that users think in terms of shape rather than on how they could obtain it with simpler geometric tools. It is organised in three levels (fig. 8): the user finds the shape had in mind scanning the classification from left to right, selecting the desired feature and setting the defining parameters.

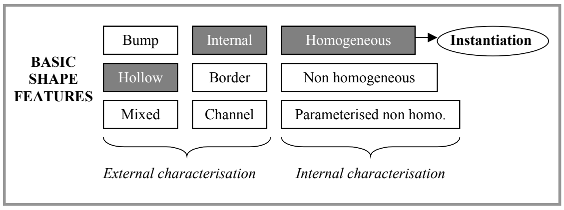


Figure 8: *BSF sub-classifications using internal and external properties.*

The first two levels classify the BSF according to two *external properties* characterising the shape in accordance with the surface. First, the *morphological characterisation* (fig. 9.a) distinguishes bumps, hollows and features mixing these two previous types. Second, the *topological characterisation* level (fig. 9.b) distinguishes channel, border and internal features.

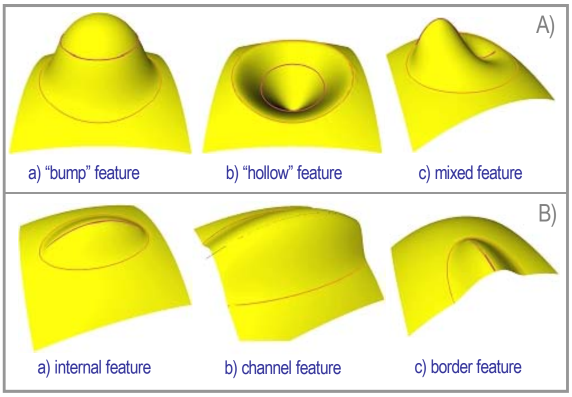


Figure 9: *δ-F^4 shape characterisation according to morphological (A) and topological (B) criteria.*

The third level classifies the features according to *internal properties,* defining the behaviour of the surface in the area where the feature is inserted. As seen in Section 4.1, the shape strongly depends on internal parameters. Thus, the user should be able to choose easily one solution among the range of possible ones, deciding if the deformation area has to be preserved or not.

5. Feature implementation

In order to create and manipulate these features, a number of tools are required, linking the features to the geometric representation of the surface. A deformation engine based on the feature constraints, i.e. a curve-based deformation method, has been implemented, trying to be as flexible as possible [PFGL04]. During the process, the different geometric entities (patches, lines, …) used to define a shape are preserved by the modification process because they reflect in some way the semantics attached to a shape.

Several concepts are used to handle the uncertainties characterising the sketching activity, such as tuning the 3D shape through appropriate minimisations (section 5.3) and taking into account the uncertainty of a sketch around the extremities of lines (section 5.2). The main idea is to give the user as intuitive as possible tools in order to avoid low-level manipulations.

Here only the basic principles of the proposed tools are presented; for more details concerning the implementation, please see the given references.

5.1 The deformation engine

The methods for surface deformation subject to point, line or surface constraints, needed for the generation of δ-F^4, have been widely studied [JP99, RN99, ZCG99, HLJZ01, XQ01, ZQ01, Hui02, MKB02]. Nevertheless, these tools are far from being intuitive, the manipulations often limited and the shape behaviour badly controlled. In fact, the problem is not only to deform a surface but also to allow the user a high level and intuitive control of the resulting shape while guarantying the quality of the result in terms of smoothness and accuracy. Regarding the existing approaches, it can be noticed that very few of them are able to meet these criteria. Most of them provide a unique and non-tuneable solution, thus requiring tedious adjustments by the designer. Other approaches assume skilled control point manipulations as well as a sufficient knowledge of the underlying deformation method and high expertise in the identification of the right control parameters.

The adopted free-form surface deformation technique [GL98] is based on a mechanical model applied to a bar network coupled with the control polyhedron of a B-spline surface [Sch74]. This technique is well suited to the definition of δ-F^4, stated in the previous Section.

The process starts with an initial surface composed of several trimmed patches connected together with parametric point constraints and subject to geometric point constraints in the 3D space (fig. 10.a). For each patch, a bar network is built from its control vertices (fig. 10.b & 10.c): either it can be topologically equivalent to the control polyhedron or the bar connectivity may differ to generate an anisotropic behaviour. Each bar can be seen as a spring with null initial length and with a stiffness q_i (more precisely a force density). To maintain the static equilibrium state of length l_i, f_i external forces have to be applied at the endpoints of the bar: $f_i = q_i.l_i$ (fig. 10.d). The set of external forces to apply on the initial bar network can be then obtained through the static equilibrium of each node (fig. 10.e). 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. 10.f). 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. 10.f), thus inducing the surface deformation (fig. 10.g & 10.h).

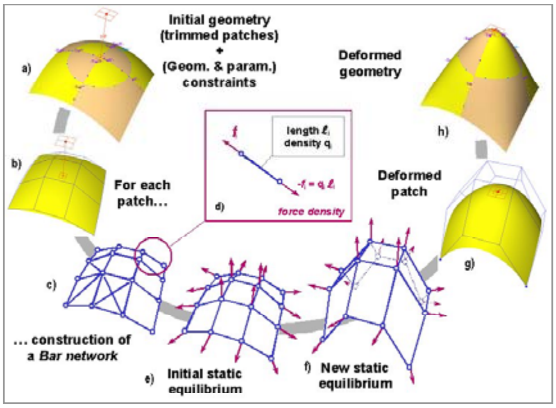


Figure 10: *Principle of the free-form surface deformation method.*

5.2 Implementation of basic elements

For the features emphasising the effect of a character line, the basic geometric elements are curves, which can be divided into two types of constraint lines:

- *A target line* (fig. 11.a), which is a 3D curve that gives the global direction of the deformation (the deformation-driving line in fig. 7.b),
- *A limiting line* (fig. 11.b), which specifies the extent of the deformation and helps defining the shape of the feature (the boundary line in fig. 7.b).

For each type of constraint line, the curve is initially continuous and then discretised to reduce the number of constraints on the surface to a finite value: given the number of points and a distribution law (according to the length of the curve or similar criteria), the positions of the sampled points are defined.

To define the way the deformed surface fits the objective geometric points, either position or position and tangency conditions are considered. They are used to specify the behaviour of the deformed surface according to the tangent plane defined at the geometric points. Moreover, to increase the deformation possibilities, an evolution law of the tangent plane along the target line can be added at the geometric points (see fig. 11.a).

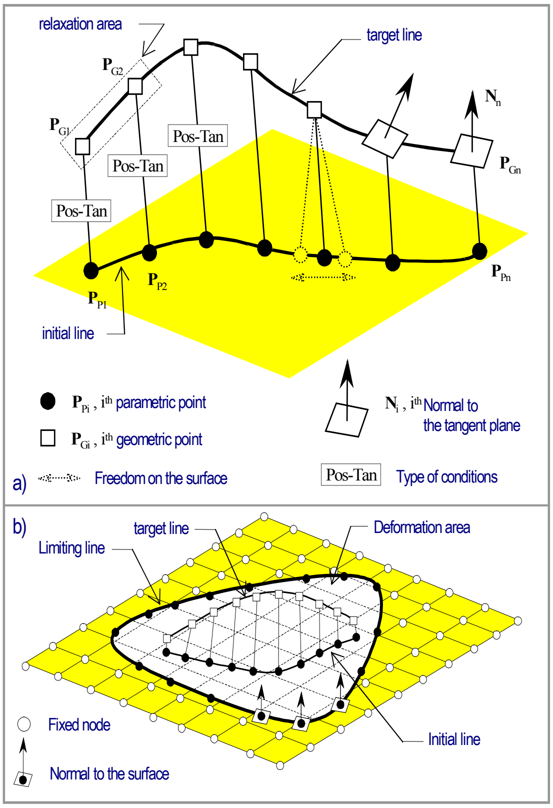


Figure 11: *Target (a) and limiting (b) line specification.*

Since the designer's sketching activity produces only an approximation of the desired shape, the δ-F^4 must incorporate various mechanisms to let the designer tune the shape and get it closer to the desiderata.

Considering that several control points influence both the area inside and outside the limiting line, fixing all the control points affecting the external area could result in a bad and insufficiently deformed shape around the limiting line. In such a configuration, most of the currently available tools would have inserted new patches inside the area defined by the limiting line. To maintain the same topology, a compromise must be found to reduce such artefacts. In the proposed method, it is possible to set the *rate of acceptable deformation outside the limiting line*, which is the input parameter of an automatic fixation algorithm of control points: only those control nodes having a limited influence in the interior are fixed. As a consequence of this approach, a slight modification of the surrounding surface is obtained, but under suitable rate value it is quite insignificant.

Moreover, since a target line constrains the surface, the quality of the resulting surface is affected by such an interpolation. Surface quality is even more critical at the end points of the target lines, whose positions with respect to the surface may result in over constrained or incompatible configurations or just unacceptable undulations. To provide a friendly tool which does not force the user to be very precise, the possibility to relax the boundaries of a target line is offered, through the parameter *area of relaxation* around the target line end points.

5.3 Minimisation for shape control

Three main aspects of the devised mechanical model can intervene to control the surface behaviour according to the specified geometric constraints:

- The *minimisations* used to solve the system of equations often under-constrained, and to prescribe a general behaviour to the deformation either globally or locally (e.g. minimise the surface area or the shape variation);
- The *distribution of the force densities* in each bar enabling to spread the general behaviour in a non homogeneous manner;
- The *connectivity* of the bar network used to insert an anisotropic behaviour by prescribing some specific directions of deformation on the surface.

Among these aspects, the first one has been studied in detail and seems well suitable to both global and local shape control in a sufficiently predictive and intuitive way [PGL*04].

The surface deformation is performed through the static equilibrium modification of a bar network built on the surface control polyhedron. In the free form domain where the degree of freedom, corresponding to the number of unknowns, is greater than the number of constraints, various shapes are then possible and should be accessible for the user. Most current approaches provide only one solution, which is the result according to a predetermined criterion, as the minimisation of the strain energy.

On the contrary, we propose here a larger set of solutions, by providing a larger set of criteria (or minimisations), related to all the mechanical parameters that vary during the process. Moreover, by using a generalisation of the considered criteria, the user is allowed to select the shape along a continuous set of solutions, using a single control parameter: the user chooses two predefined behaviour of the shape, i.e. two predefined criteria, and he/she can generate a solution as a linear "combination" of these initial ones. To increase the range of solutions further, different criteria over a set of connected sub-domains covering the surface deformation area may be defined.

The considered criteria are deeply connected to the mechanical model of deformation, but their use has also consequences on the surface behaviour, which can be predictable. For example, in figure 12, some minimisations are presented, and the surface behaviour is analysed according to these. For instance, the minimisation of all the external forces in the mechanical model can be seen as a way to express the minimisation of the surface area from a geometric point of view; or the minimisation of the variation of these efforts minimises the shape variation. Designers can also prescribe multi-minimisation, and generate asymmetry from an initial symmetric object.

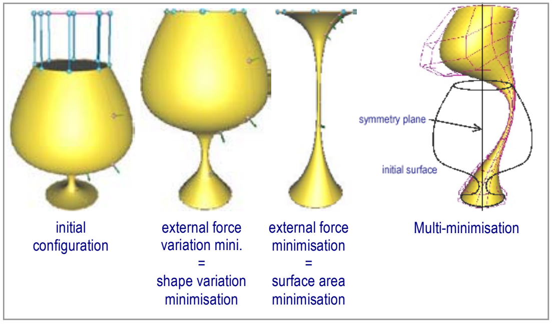


Figure 12: *Global minimisations and their predictive behaviours.*

All these possible configurations are well suited for surface manipulation and/or feature-based modelling and permit to define locally its shape without defining additional geometric constraints. In a next development of the presented system, the surface manipulation will be allowed through intuitive parameters such as "*flatten*" or "*round"* applied to a given surface area.

5.4 Generation of discontinuities

Introducing a sharp behaviour along the lines characterising the shape might be desired in order to give a strong visual impact to the surface in such an area (fig. 5, fig. 13). In addition, sharp lines form in some sense a 3D sketch of the final shape because blending radii required to smooth the surface and fit manufacturing requirements will be added at the functional design stage. Unfortunately, curvature, tangency or position discontinuities are generally avoided in the definition of geometric models because of their bad mechanical and numerical behaviours.

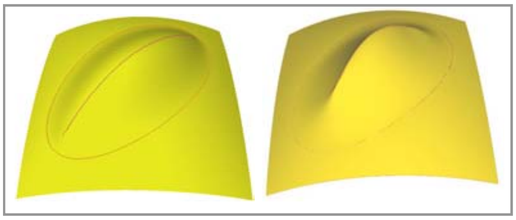
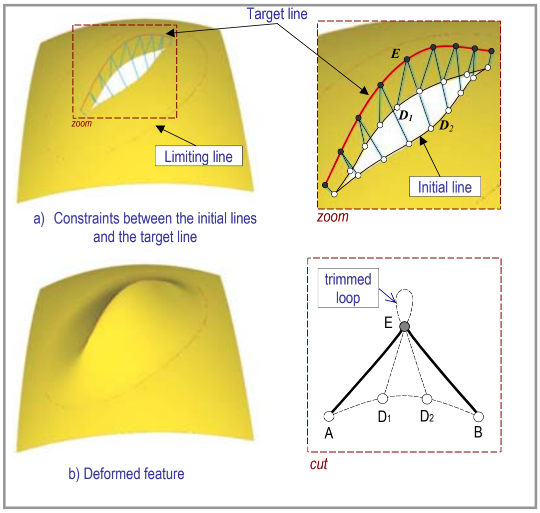


Figure 13: *Comparison between smooth surface and surface with tangent discontinuity prescribed along a target line.*

The process used in today's digital tools creates the different continuities by using *approximated geometric continuities* (G^i) between patches. This process requires a topological modification of the surface to obtain a configuration where each constraint line (either target or limiting line) corresponds to one or several trimming lines of one or several new patches inserted in the deformation area. The discontinuity in the parameter domain is in this case the consequence of the decomposition of the initial parametric domain. The connection between two patches is then expressed by discretising the trimming lines in order to obtain a set of bi-parametric points connected with position or/and tangency conditions. However, this approach is not intuitive since the designer must perform the corresponding surface decomposition, which is tedious and not related to his/her intents.

We propose an alternative method in [CPL*04], where discontinuities can be added along a part of a constraint line without any topological modification, i.e. without any patch insertion (fig. 14). At first, two initial lines lying on the surface are computed from the target line as projections of the target line subject to a successive *opening law*. Then, the deformation process is performed through a set of constraint points between the initial lines and the target one, such that these three lines coincide. Imposing this condition generates a self-intersection of the surface, i.e. a loop, which will be properly trimmed, producing the desired sharp behaviour along the target line. However, the principle of the devised approach can be applied to exhibit geometric discontinuities at any user-prescribed points or along lines.



a) Constraints between the initial lines and the target line

b) Deformed feature

Figure 14: *Insertion of G^1 discontinuity along the target line.*

6. δ-*F*^{4} manipulation

The main advantages provided by adopting a feature based methodology are not only in the shape creation phase, but also in its adjustments and modifications. In our approach, we took into consideration two types of parameter instantiation for the basic δ-F^4 class, depending on the needed freedom in the shape to be created:

- The *direct instantiation of the curve parameters*, possibly by using predefined curves coming from another environment, e.g. by digitalisation or laser scanning (fig. 15). In this case, stylists are mainly concerned for the geometry of the curves, which finally will produce the expected shape.
- The *instantiation of numerical parameters* defining dimensions, position and orientation. This is useful when designers want to insert predefined features, adjusting proportions to the object. Here the geometric elements are moved and deformed according to the prescribed numerical parameters (fig. 16).

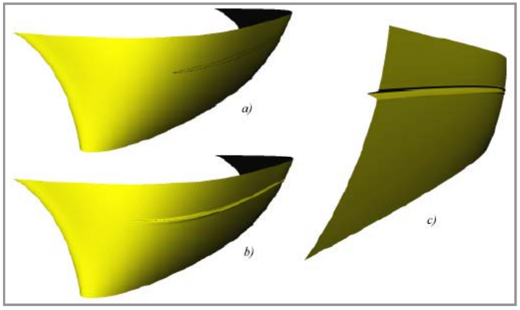


Figure 15: *Shape modification by direct instantiation of character lines, applied to a car rear bumper.*

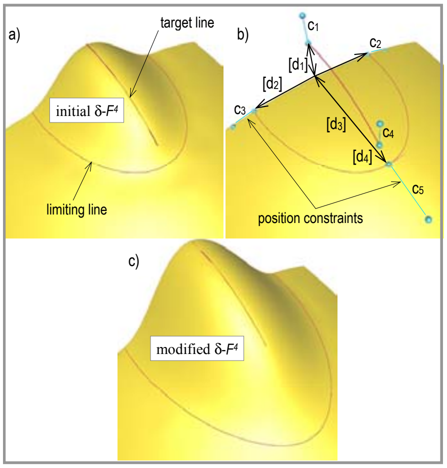


Figure 16: *Modifications of numerical parameters defining a δ-F^4: increase of the length (d_3), the heights (d_1 and d_4) and the depth (d_2).*

Therefore, while in the second case the feature modification can occur by simply changing the defining numerical values as in the mechanical field, in the first a modification of the defining curves might be necessary. Based on Leyton's shape grammar [Ley88], which provides a full description and manipulation of free-form 2D curves, a set of operators has been identified to perform intuitive 3D manipulations of a limiting line on a surface in order to tune the deformed shape. For instance in the figure 17, the user deforms the limiting line by "pushing" it at one of its extremes (red arrow), to generate a modification of the shape.

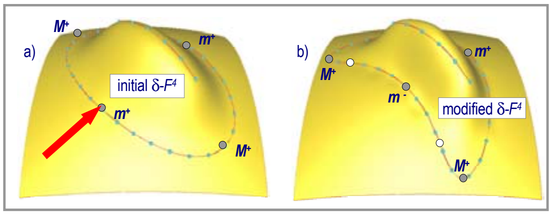


Figure 17: *Modification of δ-F^4 shape by Leyton's operator of continuation.*

Such a method seems to be particularly suitable to be adopted for shape modification in a Virtual Reality Environment. Virtual Reality is emerging an alternative way to reduce the time and money-consuming generation of physical models. In fact, stylists do not only use sketches on paper to create products: they also create physical models (with foam, clay), which they modify as a sculptor would do. When the desired shape is obtained, such models are scanned and the digital objects are achieved through a long and tedious Reverse-Engineering process.

7. Conclusion

In this paper, we presented an overview of the insertion of δ-F^4 in styling activity. The definition of these features is deeply connected to the way designers work. They have been primarily conceived as shape-oriented tools for the insertion of character lines in a surface model, such that the user can directly think in terms of shape and semantics, without worrying about the geometric instruments to obtain such shapes in the available CAS/CAD systems.

Basic (geometric) building blocks to deform the geometry through higher-level constraints have been already developed, enabling a real feature technology in aesthetic design. At present, an efficient interface for stylist is still lacking to use the tools according the presented scenario.

The next step will be more devoted to the semantic aspect: the feature taxonomy will be finalised in order to develop a free-form feature-based system. In this way, the geometric description will be enriched with semantics through an intermediate structured representation level.

Such a research activity will be carried on within the European Network of Excellence AIM@SHAPE [A@S], which faces the issue of attaching semantics to geometric models in a more general setting.

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