3D sketching for aesthetic design using fully free-form deformation features

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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 and how these lines form a basis for sketching shapes in 3D. 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, the so-called fully free-form deformation features (δ-F^4) are introduced as a modelling method to take into account the curve-oriented stylists' way of working. Both the advantages of a free-form surface deformation method and a feature-based approach are merged to define these high-level modelling entities allowing for a direct manipulation of surfaces through a limited number of intuitive parameters. Such features incorporate several characteristics designed to handle the uncertainties and/or inconsistencies of the designer's input during a sketching activity. In addition, a δ-F^4 classification is proposed to enable a fast access to the desired shape according to its semantics and characteristics.

Keywords: Computational geometry and object modelling; Computer-aided design; 3D sketching

1. Introduction

Despite the great development of computer-aided tools, still today the styling activity is performed mainly by hand with sketches drawn on paper. Only at a second stage, designers make use of computer aided styling (CAS) systems, usually with the help of an expert in using digital tools to create 3D shapes [1–3]. It is certainly a matter of approach, but it is also due to the limits in the friendliness and flexibility of the modelling methods provided by the tools, which do not adequately support such a sketching activity.

Even if the first digital model derives directly from Reverse Engineering procedures or, more recently, from Virtual Reality and haptic devices, it is difficult to provide the user with suitable tools for an intuitive manipulation of the free-form shapes.

In both cases—the traditional sketch and the new technologies—the semantics related to the conceptual design task is more or less missing.

Adding semantics to a digital model in this field means providing capabilities closer to the designer's habits to allow the use of meaningful entities for the

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creation, manipulation and analysis of shapes in a more intuitive and easier way. 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 the existing ones. Semantics is context dependent and studying styling activity is fundamental to find the meaningful entities for this task.

There are two important aspects to take into account when proposing innovative CAS/CAD tools for the conceptual design phase. The first one is that stylists generally use 2D curves in their sketch to give a certain impression to the product to be designed. On the other hand, when the first digital model is acquired directly in 3D, curves have a leading importance in the subsequent modelling phase. This means that a curve-driven methodology for shaping an object seems quite appropriate. This belief is based on the fact that product style semantics is expressed here through a special use of such characteristic curves, which should be represented opportunely to include the design intent.

The second one is that the early phase of the design is dominated by uncertainty. The global idea is in the mind of stylists, who probably do not focus their attention on the precision of the details at the first step. A modelling tool supporting 3D sketching should incorporate the possibility not to constrain the shape univocally, but giving some freedom. What is relevant in this context is more the visual perception of the object than the precise geometry, which is needed in the further phases of the development process.

This paper presents a method to preserve the stylist's intent once the first digital model of the overall shape of a product has been created: a tool able to generate, manipulate shapes and take into account the possible uncertainties in the designer's inputs through a curve-oriented approach is proposed.

Furthermore, to enrich the 3D model with semantics a feature-based strategy is adopted. Traditionally introduced in mechanical engineering [4] as the key element for associating specific functional meaning to groups of geometric entities describing an object, features offer the advantage of treating sets of elements as single entities. They 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.

Based on some interviews with designers collected during the European projects FIORES I and FIORES II [5,6], a feature taxonomy has been proposed and used for aesthetic applications. Implemented through a deformation technique applicable to the standard NURBS representation as well as to tessellated representations, such styling features establish a link between the geometric level and the semantic one to make easier the maintenance of the stylist's purpose during all the process of design.

The paper, which is an extension of [7], is organised as follows. Section 2 describes the methodology widely adopted by stylists in the automotive context. Section 3 discusses the relationships between the hand-made sketching and the corresponding digital model, highlighting the users' desiderata as well as the uncertainty in their input data. Section 4 introduces the concept of fully free-form deformation features (δ-F^4), while Section 5 reviews the principles of the free-form surface deformation engine and the ones of the curve-based method for modifying free-form surfaces. In Section 6, a feature-based manipulation method in the context of aesthetic design is briefly presented with examples obtained using the developed prototype system.

2. Car sketching

The sketching activity is described in this section for the specific context of car design. In fact, the automotive sector has the advantage of a more structured pipeline in the creation phase, since the product in this case is constrained to strict engineering/technological requirements. For other types of products, depending on their specific characteristics and company habits, shape can be totally free, and thus a formalisation is much harder to obtain. Here we refer to a sketching practice that we have synthesised during discussions with car stylists, in particular with *Pininfarina Ricerca e Sviluppo team* [8].

In the automotive field, the first aspects playing a decisive role in the product judgment is what can be called *graphics*, i.e. some details of the car or the colour; the second is *treatment*, i.e. 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 this 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's 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 in 3D, and the size of the wheels is usually the unit of measure of volumes. Wheels are the first entities designers draw and they build the whole car around them. All the curves successively created in the 2D sketch are aimed at defining a specific volume that is rendered in a second time, adding lights and shades, enforcing the curvature effects, and so on to express the stylist's intent. For example, a family car is characterised by a big volume, while making a car sportier implies reducing its mass (Fig. 1(a)).

Once the volume defined, *character lines*—structuring the object and constituting the treatment—are drawn. These are the meaningful entities, which the approach proposed here 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 curves characterising a car in the profile view are the *roof line*; the *waist* (*or belt*) *line* and the front and rear panel *overhangs* follow in order of importance (Fig. 1(b)). By definition, the waist line is the curve 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 (the *accent line*) just below is considered for the character evaluation. Actually, the accent line may be a light line, a curve only perceived when light is reflected. In fact, it is a common habit for stylists to judge the surface fairness through the reflections of a light beam on the car body.

To give an idea about how the manipulation of these significant curves affects the car character, few examples are given. As an example, stability is a quality that people consider fundamental for every kind of car. 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 *wheelbase line*, the curve connecting the wheels. In particular, it is best achieved if the curve appears visually symmetric and its position symmetric with respect to the axis of the wheelbase. If the same symmetric curve is located in the back, the car immediately gains dynamism because a displacement of the mass centre occurs (Fig. 1(c)).

Asymmetry of curves gives character to a car: it is not mandatory that 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 a wet waist line, but the roof line needs "tension" in order to balance the effect. Obviously, a line cannot have too many changes of concavity 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.

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 gap in the shape, through a line producing a G^0 continuity or, as already said, through a perceived curve corresponding to a surface area having a strong curvature variation (Fig. 2). Such curves identify not only a linear constraint in the shape, but also a certain aspect of the surface around.

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. 3). As already mentioned, how to act on the characterising lines is a designer's choice as well as how to harmonise them. They are often 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

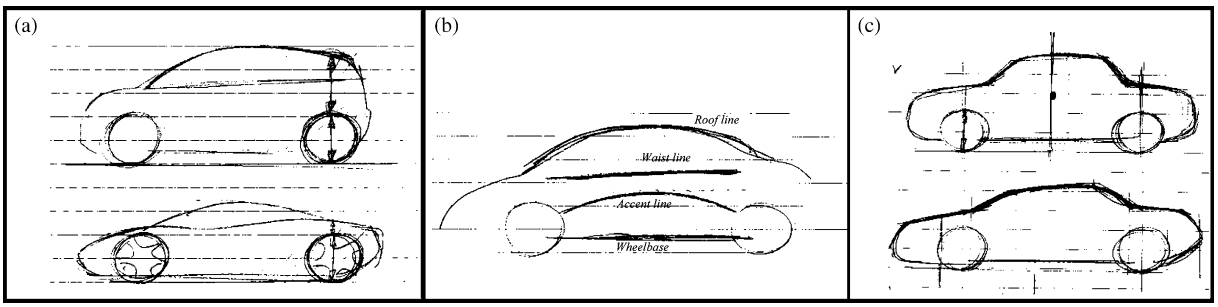

Fig. 1. (a) Character lines in a car. (b) Volumes of different cars. (c) Symmetry vs. asymmetry of the roof line.

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. Incorporating sketch semantics into a digital model

Section 2 stressed the fact that designers' sketching is an activity essentially driven by significant curves and is performed in 2D. This holds not only in the automotive design, but it can be generalised to the other categories of products. However, in all cases, the objective is to generate a 3D model from the 2D data provided by the designer who has the conceptual view of the 3D object. Therefore, a CAS system should be able to handle the prominence of such curves. Anyhow, it must be considered that the accuracy and consistency of the curves, light effects, and so on, are not enforced because the designer works in 2D using perspective representations. In addition, very frequently a sketch does not fully correspond to the real car to be produced since it emphasises some shape aspects to better communicating its character. As a result, the accuracy of lines, i.e. their extrema, and the behaviour of a surface should not be considered as geometric constraints exactly represented in the 2D sketch and forming the input of shape definition process in 3D. As such, the geometric information extracted from a 2D sketch forms input for a 3D sketch, where the designer ought to find tools to carry on the adjustment of the 3D surface generated to his/her intent as it is in his/her mind. Our proposal is to incorporate and structure the line constraints chosen by the designers and to insert capabilities to let them adjust the 3D shape by relaxing some shape constraints for a user-friendly interaction with the system. In this way, digital surfaces can be directly controlled by curves, making creation and manipulation of the product model more intuitive and efficient. Hence, the activity in 3D is not only shape modelling but a real extension to 3D sketching.

Fig. 2. 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).

What currently happens in a product definition workflow is that only one selected sketch is modelled in the computer format in order to allow for the complete 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

Fig. 3. Brand identity (courtesy of Alfa Romeo).

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 because the current approach considers that curves and other geometric elements form constraints that must be exactly satisfied, not taking into account the uncertainty just described. In addition, 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. Furthermore, 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 is very cumbersome when the product model is almost complete, requiring the manual modification of most of the created surfaces. Again, such a situation proves the need for tools allowing the designer to 'relax' some geometric constraints.

In a second step, details characterising the object functionally and aesthetically are added. This corresponds to modifications of the surfaces previously created also with the generation of new surfaces, possibly aimed at the appearance of virtual lines.

Surface modification tools based on the manipulation of specific curves would certainly help designers. Our proposal is going further: in addition to modifications through specific lines, we give the possibility to attach further semantics, that is to include a surface behaviour of the area around these lines to take into account the uncertainty of the shape expressed initially by the designer in 2D. 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. Such requirements are equivalent to the specification of prescriptive surface behaviour constraints, even though the extent of such behaviour may not be accurately defined.

The notion of feature developed for the aesthetic context 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 means to enable high-level shape-oriented 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. 4 left). 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 permits the manipulation of the shape through 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 [9–15]. 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 methods 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 specify a shape, i.e. through the specification of a set of characteristic curves and behaviours between them.

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 *semi*

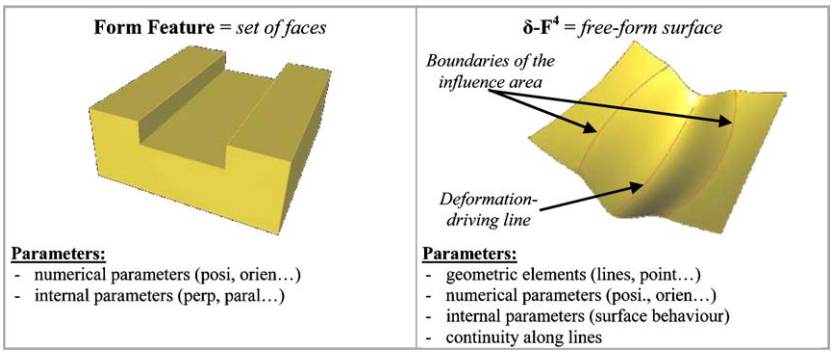

Fig. 4. Comparison between form features and δ-F^4.

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 [15]. The common characteristic of these approaches holds in the fact that the geometric constraints associated to each feature are exactly satisfied.

The second category is based on the free-form features (FFF) taxonomy defined by Fontana et al. [16] and more precisely on the features obtained by deformation (δ-FFF). In particular, the *fully free-form features* (Fig. 4, right) allow for a noteworthy tuning of the feature shape. They are well suited to the styling activity, which requires a great freedom in the definition of the shape. 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 the *fully free-form deformation features* (δ-F^4) [17] as being the shapes obtained by deforming parts of a free-form surface according to adequate 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* controlled by specific algorithms that take into account the uncertainty the users have when defining the shape of their curves.

Moreover, since in product modelling designers very frequently re-use already specified shapes or curves, modelling shape archetypes may be created through a δ-F^4; in these cases some *numerical parameters* are needed to describe the intrinsic position and the shape of the geometric elements defined. More generally, the numerical parameters are used to give a relative position and an orientation to the geometric parameter elements.

To represent shape archetypes, only the *leading line* giving the direction of the shape is not sufficient, and a prescriptive behaviour (e.g. flat, round) of the deformation area must be added through the so-called *internal parameters*, which enable the prescription of feature surface behaviours while at the same time ensuring a great freedom in the shape definition. The uncertainty in the designer's inputs is also taken into account during the shape definition at two different levels: users can either strictly prescribe a predefined behaviour, corresponding to a primitive surface (part of a plane, cylinder, sphere), or they can indicate a tendency for the surface, such as being as stretched/round as possible.

Finally, parameters that define *continuity conditions* 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

Before detailing the δ-F^4 parameters dedicated to handle uncertainty in the designer's input, it is necessary to enumerate the main categories of features representing a decomposition of free-form shapes. For 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 considered for the taxonomy.

Two first levels of classification have been proposed distinguishing those features 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 *complex* δ-F^4 class, which gather together basic shape features (BSF) and complex shape features (CSF), respectively. The basic δ-F^4 class includes those features produced by a single deformation process, which collects the parameters used to completely define the shape on the surface and controls it in a sufficiently interactive way. The complex δ-F^4 are obtained through one or several operations of composition of existing (basic or complex) features to let the user 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* can be considered as ways to directly manipulate sets of shapes.

Due to the great number of possible predefined BSF, a sub-classification is required for rapid access to 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. 5).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. 6(A)) distinguishes bumps, hollows and features mixing these two previous types. Second, the *topological*

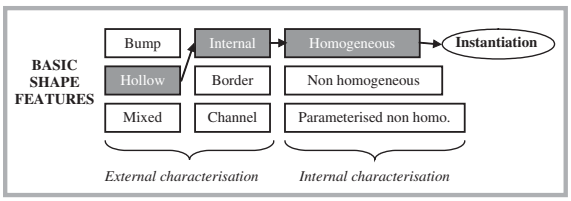

Fig. 5. BSF sub-classifications using internal and external properties.

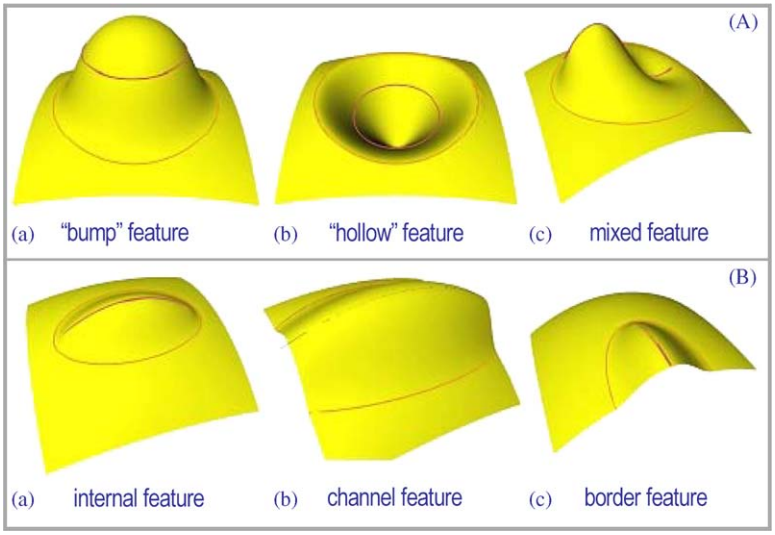

Fig. 6. δ-F^4 shape characterisation according to morphological (A) and topological (B) criteria.

characterisation level (Fig. 6(B)) distinguishes channel, border and internal features.

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 easily choose one solution among the range of possible ones.

At the present stage, the feature taxonomy can comply with any type of configuration of character lines mentioned in Section 2 to let the designer expand his/her 2D sketch into 3D shape.

5. From semantics to geometry

To create and manipulate δ-F^4, a number of tools are required, linking the features to the geometric representation of the surface and handling the uncertainty in the designer's input. The basic mechanism used to transform an initial shape into a new one is based on a surface deformation mechanism. 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 [17]. During the process, the different types of geometric entities (patches, lines, etc.) used to define a shape are preserved by the modification process because they reflect in some way the semantics attached to a shape. Here the visual perception of the shape is more important than its geometric correctness. As a consequence, our approach tends not to change the topology of the initial surface, being the sequence of trimming and blending operations, time consuming for successive modifications.

In the 3D context, several concepts are used to handle the uncertainties characterising the sketching activity. Tuning the 3D shape through appropriate minimisations (Section 5.4) is a first level to let the shape fit designer's needs. Since the shaded representation of a shape in a 2D sketch is not defining explicitly the corresponding 3D surface, the deformation mechanism should not provide a unique solution to a set of geometric constraints. Such a mechanism can be seen as an element of a 3D sketching concept. Taking into account the uncertainty of a sketch around the extremities of lines (Section 5.2) is another example of such concepts. The main idea is to give users tools as intuitive as possible in order to avoid low-level manipulations and to let them cope with the uncertainties embedded in the 2D sketch through appropriate adjustment of 3D constraints, i.e. 3D sketching tools. In the same scope, the insertion of planar areas and the generation of surface discontinuities are provided in Sections 5.5 and 5.3, respectively.

Here only the basic principles of the proposed tools are presented to highlight their effect on the 3D sketching activity; for more details concerning the implementation, please see the given references.

5.1. The deformation engine

Methods for surface deformation subject to point, line or surface constraints, needed for the generation of δ-F^4, have been widely studied [18–25]. Nevertheless, these approaches 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 (see [26] for a recent survey and a detailed analysis of these various approaches).

The free-form surface deformation technique [27] adopted here is based on a mechanical model applied to a bar network coupled with the control polyhedron of a B-spline surface [28], where a bar network corresponds to a set of nodes linked with bars having a certain stiffness, more precisely a force density, and external forces applied to maintain the static equilibrium of this structure. This technique, which has been also extended to deal with both meshes and NURBS, is well suited to the definition of δ-F^4, stated in the previous section.

The deformation 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. For each patch, a bar network is built from its control vertices: 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 a 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 to the endpoints of the bar: $f_i = q_i l_i$. The set of external forces to apply to the initial bar network can then be obtained through the static equilibrium of each node. Thus, the problem is 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. 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, as it will be described in Section 5.4. Using the geometric coupling, the new positions of control polyhedron vertices are obtained by the new positions of the bar network nodes, thus inducing the surface deformation.

5.2. Implementation of basic geometric elements for 3D feature-based sketching

For the features emphasising the effect of a character line as described in Section 2, the basic geometric parameter elements are curves, which can be divided into two types of constraint lines:

- *the target lines* (Fig. 7(a)), which are 3D curves that give the global directions of the deformation (the deformation-driving lines in Fig. 4, right),
- *the limiting lines* (Fig. 7(b)), which specify the extent of the deformation and help defining the shape of the feature (the boundary lines in Fig. 4, right).

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

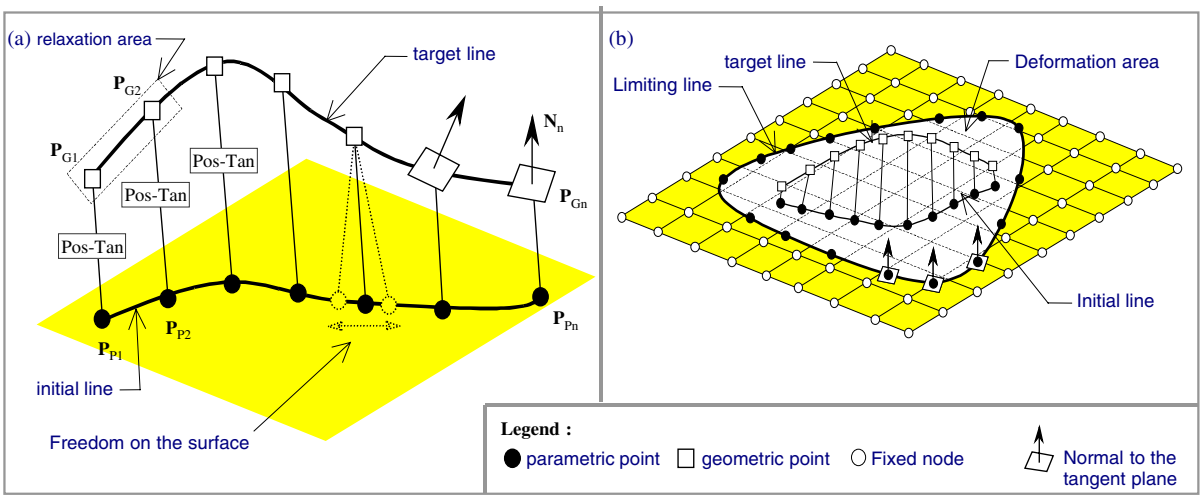

Fig. 7. Target (a) and limiting (b) line specification.

and tangency conditions are considered. They are used to specifying 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 (Fig. 7(a)).

It has to be considered that several control points influence both the area inside and outside the limiting line; thus, 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 trim the surface and insert 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 [26]: 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. This process is a way to simplify the task of the designer rather than requiring long and tedious actions to produce a very accurate free-form surface. It reduces the topological modifications, thus avoiding the insertion of additional continuity conditions to be managed during later modifications steps. It also bypasses the problems arising when transferring the semantic information possibly related to the initial set of patches. Even if the result is not directly usable for manufacturing purposes, the goal is to produce a solution close to the designer's needs as fast as possible.

Moreover, the quality of the deformed surface is even more critical at the end points of the target lines, whose positions with respect to the surface may result in either over constrained, incompatible configurations or just unacceptable undulations. This is due to the fact that the lines built from the 2D sketch cannot accurately prefigure the position where the surface resulting from the deformation process becomes smoothly tangent to the target lines. This configuration clearly illustrates the need to handle the uncertainty in a 2D sketch as well as the 3D representation of the corresponding lines since these 3D lines are still too close to the expression of the designer's view of the shape, whereas the corresponding geometric constraints are not necessarily compatible with the desired smoothness of the resulting surface. To provide a friendly tool that 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 [26], see Fig. 8.

5.3. Generation of discontinuities

Introducing a sharp behaviour along the lines characterising the shape might be desirable in order to give a strong visual impact to curves lying on the surface (Figs. 2 and 9). 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

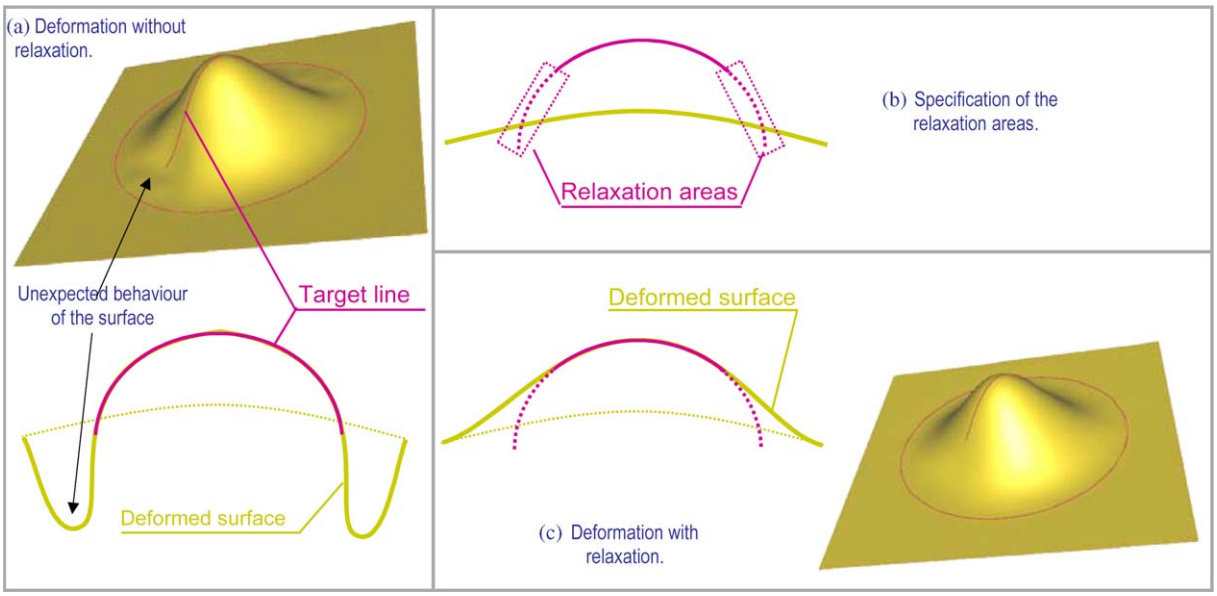

Fig. 8. Specification of the relaxation areas on a target line.

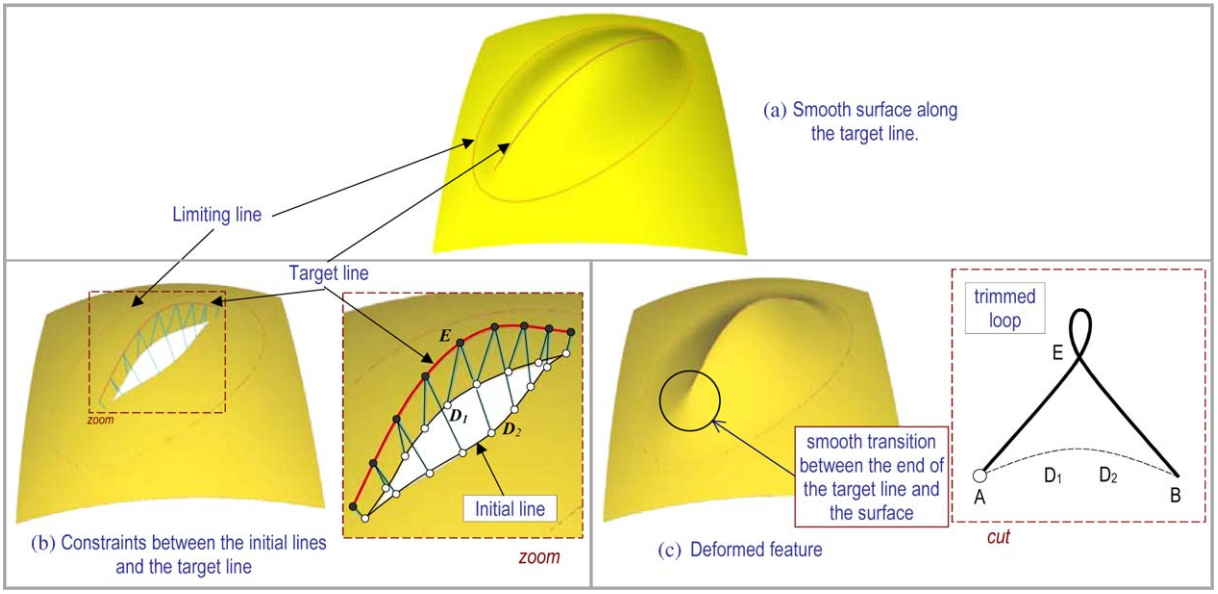

Fig. 9. Insertion of G^1 discontinuity along the target line.

position discontinuities are generally avoided in the definition of geometric models because of their bad mechanical and numerical behaviours.

The process used in today's digital tools creates the different continuities by using *approximated geometric continuities of order i* (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 have proposed an alternative method in [29], where discontinuities can be added along a part of a constraint line without any topological modification, i.e. without any patch insertion. 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* (Figs. 9(a), (b)). 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 (Fig. 9(c)). As a result, the principle of the devised approach can be applied to exhibit geometric discontinuities at any user-prescribed points or along lines while incorporating a smoothly varying transition between the line of discontinuity and the smooth surface (Fig. 9(c)). Similar to the characteristic lines mentioned in Section 5.2, these lines of discontinuities can be combined with relaxation mechanisms to take into account their uncertainty from the 2D sketch. Moreover, depending on the level of perception of the future shape, the user can vary the angle between the two sides of the discontinuity.

5.4. Multi-minimizations for shape control

Once defined the target and limiting line constraints, there could be several feature shapes satisfying them, therefore, providing the user with tools for selecting the wished shape should be provided. To control the surface behaviour according to the specified geometric constraints, three main aspects of the devised mechanical model can intervene:

- 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 nonhomogeneous 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, the first one has been studied in detail and it seems quite appropriate to both global and local shape control in a sufficiently predictive and intuitive way [30]. When dealing with free-form surfaces where the degrees of freedom, corresponding to the number of unknowns, are greater than the number of constraints, various shapes are possible and must be accessible to the designer. Most current approaches provide only one solution, which is the result according to a predetermined criterion, like the minimisation of the strain energy.

As already stated, it is important to be able to handle the uncertainty concerning the shape of the object in between the characteristic lines (e.g. shaded areas appearing on the 2D sketches). Providing a unique shape as solution to a set of line constraints would not reflect this uncertainty since it would be necessary to modify these lines in order to obtain a new shape. 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 and geometrical parameters that vary during the process. Moreover, by using a generalisation of these criteria, the user is allowed to select one shape among a continuous set of solutions, using a single control parameter: the user chooses two predefined behaviours of the shape, i.e. two predefined criteria, and a solution can be generated as a linear combination of these initial ones. To further increase the range of solutions, different criteria over a set of connected sub-domains covering the surface deformation area may be defined.

Some of 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 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 forces minimises the shape variation. Designers can also prescribe multiple minimisations, and generate asymmetry from an object initially symmetric. Some other criteria are directly related to the geometry of the object thus facilitating the association of predictive behaviours (e.g. minimisation of the nodes displacement).

All these possible configurations are well suited for surface manipulation and feature-based modelling and permit to define locally the shape without defining additional geometric constraints. Two examples are depicted in the Figs. 10(a) and (b). No geometric constraints are specified here and the various shapes are obtained playing with the parameters of the multi-minimisations. The pipe is immersed inside a bounding sphere centred at a user-specified point C_i, i.e. C_1 for the example (Fig. 10(a)) and C_2 for the example (Fig. 10(b)), and used to define locally the basic quantities to be minimised [30]. More precisely, in the proposed examples, the more the control vertices of the geometry are far from the centre of the sphere, the more the initial shape defined by these vertices is preserved (min. of the external forces variation), whereas the more the control vertices are close from the centre, the more the initial

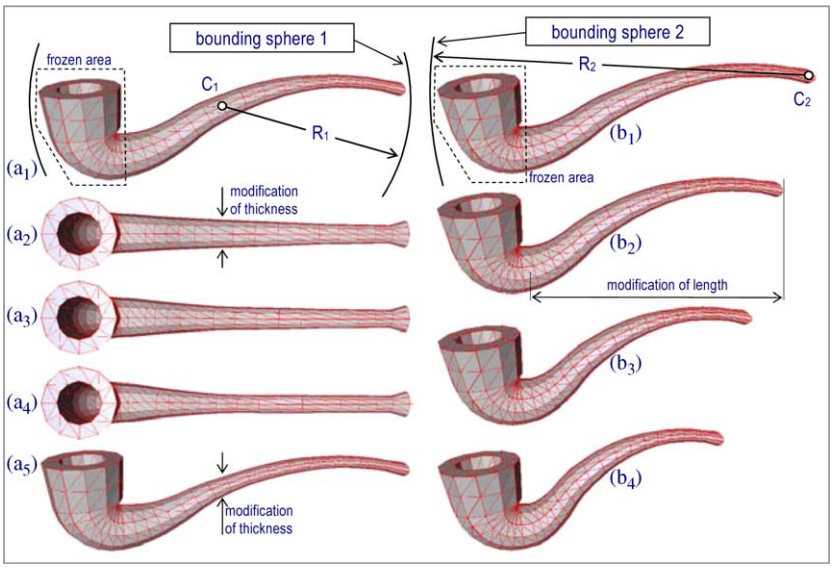

Fig. 10. Global shape modifications using solely the multi-minimisations and their predictive behaviours.

shape is forgotten (min. of the external forces). The relative influence between these two types of quantities is controlled by a single parameter which enables the generation of a wide variety of shapes (figures a_1–a_5 and figures b_1–b_4). The sphere of the example (Fig. 10(a)) has been centred in the middle of the pipe which enables a modification of the thickness of the pipe. If the bounding sphere is moved at the extremity C_2 of the pipe (example, Fig. 10(b)), a modification of the length of the pipe is obtained. In a next version of the presented system, the surface manipulation will be possible through intuitive parameters such as *flatten* or *round* applied to a given surface area.

5.5. Insertion of functional areas

The product geometry may need the simultaneous definition of free-form surfaces and primitive surfaces (part of plane, cylinder or sphere), most of the time attached to functional constraints, such as assembly constraints. In traditional CAS/CAD systems, the insertion of this type of areas normally requires surface trimming operations and the addition of new surfaces, blending the functional surface and the trimmed patches.

Without changing the topology, the insertion of primitive surfaces into the δ-F^4 may happen through different user-interaction scenarios, but all of them require at first the definition of the plane defining the planar area, and then the definition of the boundary lines of the planar area inside the plane.

The simplest setting could be as described in Sections 5.2 and 5.4: the user specifies a target line as a boundary and the minimisation criterion which minimises the bar length; this is the most suitable for the insertion/preservation of planar areas since it tends to minimise the area of the domain on which it is applied. This option can be adopted when only a primitive surface is prescribed and there is consistency with all the constraints imposed. For example, in Fig. 11(a), the user exactly knows the shape of the surface (i.e. the definition of the plane and of the shape inside the plane). Thus, he/she can define a planar closed target line, with only position constraints specified: in this way, the patch boundary is fixed and the target line splits the patch into two domains D_1 and D_2 on which different deformation behaviours may be assigned.

Unfortunately, this method is too prescriptive and may be adopted only when the user fixes the plane exactly by providing a planar target line. Moreover, the result strongly depends on the consistence when combining constraints and minimisations. As an example, the specification of a non-planar target line together with the minimisation of the surface area will never produce a planar area. Here, the system finds a solution that satisfies the constraints while minimising the surface area inside the bounded domain.

As a consequence and according to the user's needs, the planar areas specification process can be decomposed in four main steps: partitioning the surface with boundary lines, specification of co-planarity constraints on some of these sub-domains, specification of additional constraints to define the level of freedom for positioning and orientating the final planes, definition of the shape of the target boundary lines (an example is provided in Fig. 11(b)).

Different types of constraint have been devised, and each of these ones ensures the coincidence of a given point $\boldsymbol{P}_i$ with the future plane and can be written as

$$\boldsymbol{n}_0 \cdot \boldsymbol{P}_0\boldsymbol{P}_i = 0$$

where $\boldsymbol{P}_0$ corresponds to a reference point of the plane and $\boldsymbol{n}_0$ to the reference normal to this plane. When applying constraints at surface points, the difficulty lies in the specification a priori of the right number of constraints: too few constraints will produce undulations whereas too many constraints will result in over-constrained configurations. Indeed, the constraints specified along the boundary line are worthy of note, since they smooth the boundary of the area covered by the co-planarity constraints. Details on this technique can be found in [31].

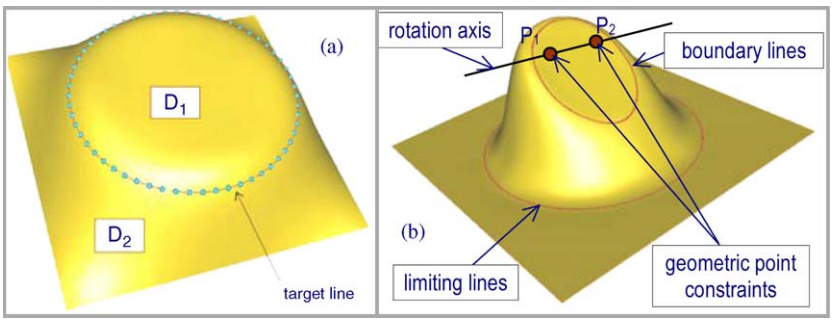

Fig. 11. (a) Planar area obtained by minimisation. (b) Planar area obtained by constraints (only a line of the final plane is prescribed).

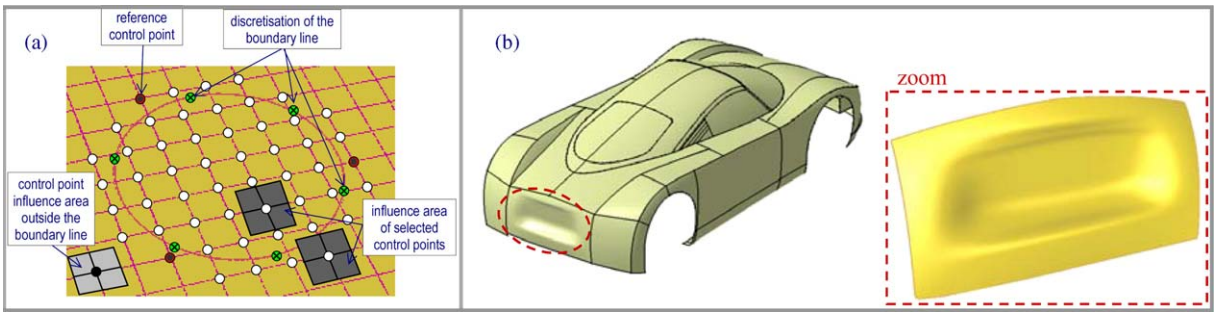

Fig. 12. (a) Co-planarity constraints on selected nodes and on points of the boundary line, with 3 nodes as references. (b) Insertion of a planar surface for the number plate of a car (courtesy of *Pininfarina Ricerca e Sviluppo*).

Some combinations of the type of points to constraint can be considered. The most interesting configuration is certainly the one that uses both the constraints applied to the nodes and those applied to surface points obtained by discretising the boundary line (Fig. 12(a)). Using such a configuration, the complexity in the definition of the appropriate number of discretisation points is reduced and the boundary of the planar area is smoothed. In Fig. 12(b), an example of insertion of the car number plate is shown, where the plane has been constrained only with one 3D point, letting free two rotations.

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 (see Fig. 13). In this case, stylists are mainly concerned with the geometry of the curves, which finally will produce the expected shape;
- the *instantiation of numerical parameters* defining the dimensions, the relative position and orientation of the target and limiting lines. This is useful when designers want to insert predefined features corresponding to shape archetypes, adjusting proportions to the object. Here the geometric elements are moved and deformed according to the prescribed numerical parameters (see Fig. 14).

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 [32], 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 [26]. For instance, in Fig. 15 the user deforms the limiting line by "pushing" it at one of its curvature extrema (red arrow), to generate a modification of the shape.

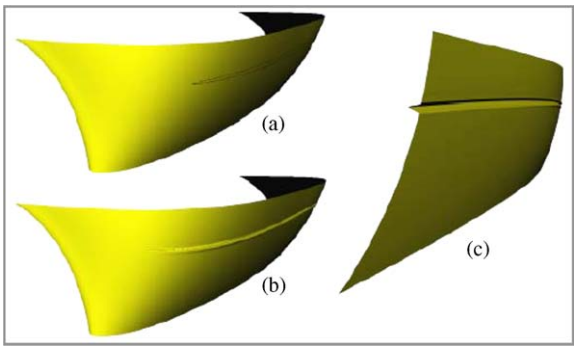

Fig. 13. Shape modification by direct instantiation of character lines, applied to a car rear bumper.

Here again, this type of modification process fits into the category dedicated to the shape adjustments required to adapt a 2D sketch to the consistency requirements of the 3D object, i.e. it contributes to the 3D sketching activity introduced so far. The shape grammar operators act qualitatively over the limiting lines rather than the target line at the current stage of development. This is a different way of working compared with the 3D sketching tools previously described.

7. Conclusion

In this paper, we have presented the introduction of the δ-F^4 concepts in the styling activity, showing how

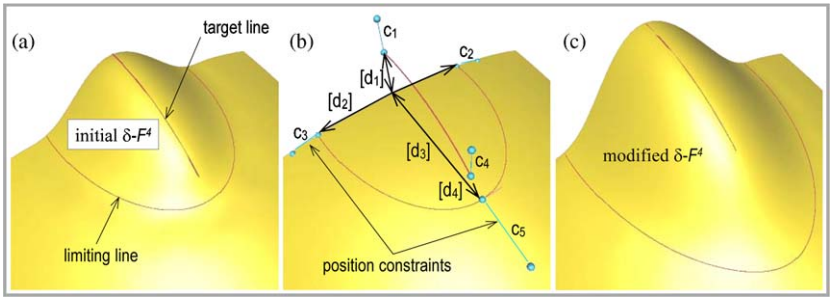

Fig. 14. Modifications of numerical parameters defining a δ-F^4: increase of the length (d_3), the heights (d_1 and d_4) and the depth (d_2).

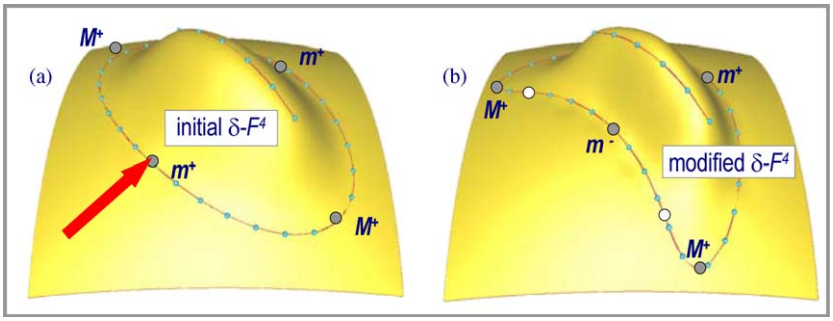

Fig. 15. Modification of δ-F^4 shape by Leyton's operator of continuation.

the uncertainty in the initial 2D sketch of the designer can be extended to the 3D level and how such an uncertainty can be handled through specific characteristics of δ-F^4. The definition of these features is deeply connected to the way designers work. They have been conceived as shape oriented, so that the user can directly think in terms of shapes and semantics, without worrying about the geometric tools to obtain such shapes in the available CAS/CAD systems.

Basic (geometric) building blocks to deform the geometry through higher-level constraints have been developed, both enabling the use of a real feature technology in aesthetic design and incorporating specific tools contributing to an effective 3D sketching activity, whereas an efficient interface is still under development.

In the future, additional effort will be devoted to semantic product annotation aspects, by finalising the specified feature taxonomy and defining a suitable feature-based representation. Such a research activity will be carried on within the European Network of Excellence AIM@SHAPE [33], which faces the issue of attaching semantics to geometric models in a more general setting.

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