FREE-FORM DESIGN IN SOLID MODELLING

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Surface modelling techniques have a long history, which can be traced back well before the beginning of the computer era. Their origins are rooted in the aircraft, automotive and shipbuilding industries. Solid modelling is a more recent art, dating back only fifteen years or so, and was originally developed as a means of representing the shapes of components used in the less specialised mechanical engineering industries.

At first the two types of systems were developed largely independently of each other, and used very different techniques. Surfaces were represented in terms of parametric geometry capable of representing very general free-form shapes. Solids were modelled in terms of set operations involving simple volumetric primitives such as blocks, cylinders and cones, whose surfaces were usually represented by more classical implicit equations. In recent years, strenuous efforts have been made to bring together the virtues of both approaches, with varying degrees of success. Several commercially available solid modellers and even more research-oriented systems have now reached the stage where they can model solids with free-form surfaces; in some cases parametric geometry is used exclusively, while in others there is mixed use of parametric and implicit geometry.

From the designer's point of view the methods available to him for designing solids with free-form geometry are not ideal. They fall into three main classes, as follows:

1) Methods based largely on 'traditional' surface modelling techniques such as, for example, the construction of objects whose surfaces interpolate families of specified cross-sectional curves. Such methods are fine for aircraft fuselages and ship hulls but not easily applicable for the design of cylinder blocks or gearbox casings (see, for example, Tiller (1983)).

2) Methods using techniques which have proved relatively easy to implement in solid modellers of the boundary representation type. These are based, broadly speaking, on the initial definition of an object composed of blocks, cylinders and so on, followed by the use of a separately defined free-form surface to modify the object in some way. The object may be cut into two sections by the surface, or one or more of the object faces may be moved to lie on the new surface, for example. Objects defined in this manner usually have sharp edges uncharacteristic of many typical engineering components, whose geometry exhibits subtle blends and fillets stemming traditionally from the art of the mould-maker or pattern-maker. Methods of the type described are implemented, for example, in BUILD (Anderson, 1983).

3) Methods based on techniques which have proved relatively easy to implement in solid modellers of the constructive solid geometry (CSG) type. Here a consensus seems to be emerging that 'swept volume' solids provide a useful design method, based on the use of the volumes swept out by the motion of a simple primitive such as a sphere along a specified path. The volume of the sphere may vary, and the path may be curvilinear. This permits a wide range of interesting shapes to be generated, and has a useful application for defining surfaces of the 'rolling ball' type for filleting internal corners. As a general design method these techniques have limited application, however. References to this type of approach include Rossignac and Requicha (1984), van Wijk (1984). A fuller survey of all these methods is given in Várady and Pratt (1985).

The theme of this paper is that what is really needed is a much closer synthesis of parametric surface techniques with conventional solid modelling techniques. There are many engineering components whose gross geometry can be approximated in terms of the primitive volumes customarily provided such as blocks, cylinders, cones, etc., but whose precise modelling requires changes of a local nature involving the 'sculpturing' of edges, the rounding of internal corners and the construction of general blending surfaces over limited regions. It is not appropriate to try to construct the required free-form surfaces as separate entities and then to graft them onto the solid model, since the boundary constraints which must be applied in practical cases are actually determined by the model. The most satisfactory approach appears to be to use the gross model as a framework, and to provide means for modifying the surfaces composing its boundary in a free-form manner. This appears to imply the use of a modeller of the boundary representation type, but in fact there is no reason in principle why the bounding surfaces of primitive volumes in a CSG system may not be similarly dealt with. However, since the writer's own leanings are towards boundary representation the ideas which follow will be outlined in that context.

Consider first a cube, whose faces we will consider to be labelled 'front', 'back', 'left', 'right', 'top', and 'bottom'. Most boundary representation modellers will represent the plane surfaces containing the faces in some implicit manner, though parametric representations are used in a few cases. For our purposes the most convenient formulation is in terms of Bézier or B-spline surfaces. For example, if a uniform 3x3 grid is imposed upon the top face of the cube then the 4x4 set of resulting mesh nodes could be considered to be the control points of a bicubic Bézier representation of this plane face. So far, there is no geometric change in the cube, but at this stage it becomes possible to modify the geometry of the top face by moving the control points. The possibilities are

(i) manipulation of the four interior control points. This permits the creation of a bulge or a depression, for example, and leaves the four edges of the face unaltered.

(ii) manipulation also of the boundary control points. Here a limitation must be imposed; the movement must be constrained to lie in the planes of the adjoining faces. This ensures that the modified edge curves still lie in the planes of these faces, whose associated geometry has so far not been redefined.

Now suppose that the front face is also redefined as a Bézier patch. One set of four control points will be common to both the top and the front face, and these lie along the shared edge. It is therefore possible to blend this edge and obtain C^1 continuity between the two faces simply by relocating these four control points so that each lies midway between its immediate neighbors on the top and front faces respectively. Similarly, we could round off the corners of the cube completely by redefining the side faces as Bézier patches and adjusting the positions of the shared corner control points appropriately.

The types of procedure described have a number of advantages. In particular, the initial undeformed Bézier representation is set up automatically using the original model as a framework, and also in the examples given there are no toplogical changes in the model resulting from the deformation. The computational overheads are few, and it is worthy of note that no surface/surface intersection curves need to be computed. On the other hand, a practical implementation will require careful attention to the facilities available for the user to manipulate Bézier control points. He will probably need to work with whole lines or blocks of points for some purposes, though fine tuning of his surfaces will also require manipulation of single points.

Finally, it must be noted that certain refinements of the basic procedure are necessary to make it applicable in more general cases. For example, if it is desired to modify a cylindrical face then an exact parametric representation of the initial face will require the use of a rational form (Faux & Pratt, 1979). The same is true for the other simple quadric surfaces and the torus, all of which may be represented as rational biquadratics. In practice it will probably be better to use an equivalent formulation of higher degree, however, to give more freedom in imposition of boundary constraints on the deformed surfaces.

Next consider the situation where the modification to a particular face must be local to one particular edge, the remainder of the face remaining undeformed. This is easily achieved by the initial splitting of the original face into two by the insertion of a new edge, which will in many cases be parallel to the edge whose local region is to be modified. It will also be necessary to interpolate a new edge in this way if the face to be modified has more or less than four edges, since it is not then possible to parametrise the entire face in a natural way as a four-sided Bézier patch.

It is also simple to modify any four-sided region which can be expressed as a Bézier patch and which lies totally interior to a face of the model. The region to be modified must first be defined as a new face, and a parametrisation imposed upon it as described. Manipulation of the geometry of the new face is by means of control points as previously, but the use of a formulation of higher than cubic degree will probably be advantageous in this case. Then there will be enough freedom to allow the modified face to retain tangency across its edges with the surface of the original face if desired. It must be pointed out that the achievement of such results using Boolean operations is fraught with difficulties arising from the resolution of tolerance problems associated with tangencies of surfaces between the separate objects involved.

To summarise, the method suggested for the free-form modification of solid models has several important advantages. In particular, it avoids the use of 'detached' surfaces, Boolean operations and surface intersection computations.

It involves, at worst, only minor topological changes to the model, and will therefore be computationally efficient. The ideas put forward here will be tested in the near future using a simple boundary representation solid modeller recently developed at Cranfield.

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