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An approach for the integration of subdivision surfaces in a hybrid CAD system

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Abstract

The project NIIT4CAD aims to effectively integrate subdivision surfaces in a computer-aided design modeling environment. To this end, a new CAD system paradigm with an extensible geometric kernel is introduced, where any new shape description can be integrated through the two successive steps of parameterization and evaluation, and a hybrid boundary representation is used to easily handle different kinds of shapes.
To overcome the irregular behavior of subdivision surfaces in the neighborhood of extraordinary points, the limit surface of the subdivision scheme is locally modified, so as to tune the analytic properties without affecting its geometric shape.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Curve, surface, solid, and object representations

1. Background and project description

Subdivision surfaces have a long history, being studied for more than 30 years now. Since the first time they were used in Pixar's movie "Geri's game", they had a big success in entertainment industry and they are now widely supported in nearly all modeling graphics programs. Their flexibility and the fact that some subdivision surfaces represent a superset of the standard Non-Uniform Rational B-Spline (NURBS) representation easily suggest that they can be the future descriptive form of all geometric data.
However, after all these years, their use in computer-aided design (CAD) systems is still negligible. On the one hand, this is due to the fact that subdivision surfaces do not have a closed-form representation, which means that most subdivision schemes can not be parameterized and evaluated exactly. On the other hand, the quality achieved by current subdivision schemes is still far from the requirements that a geometric model must satisfy for being suitable in the engineering and manufacturing phases of design. In fact, in the neighborhood of extraordinary vertices, subdivision surfaces suffer from unbounded or not convergent curvature, shape artifacts, and bad parameterization. This undermines application of common CAD tools (e.g., offset, local approximation in Taylor expansion, intersections, Boolean operations), which make extensive use of iterated interrogations of the surface and its first and second derivatives.

The European Eurostars project NIIT4CAD (New Interactive and Innovative Technologies for CAD) aims at overcoming the traditional approach to surface and solid modeling of current 3D CAD systems, tackling the mentioned roadblocks and introducing new effective methodologies based on subdivision surfaces. An innovative class of subdivision surfaces has been integrated in the geometric kernel of the ThinkDesign CAD system developed by think3, together with a module for fast design and editing of meshes for subdivision. The new form of representation relies on a suitable local modification of the well-known Catmull-Clark surfaces, aimed at guaranteeing the analytic accuracy required in CAD. At the same time, a seamless integration of subdivision surfaces is realized exploiting two main features of the system: an extensible geometric kernel and the possibility of handling a hybrid B-rep representation. As a result, any pre-existing CAD tool is automatically inherited by subdivision surfaces, which can coexist and interact with the other available forms of representation, such as NURBS and analytical shapes. This is a major advancement with respect to other systems, where subdivision surfaces (or in alternative T-splines) need to be converted to NURBS, prior to interacting with the CAD modeling environment.

2. The CAD system paradigm

We have based our integration approach on a system architecture with the following features (which reflects the ThinkDesign geometric kernel): *i)* "parameterization and evaluation" paradigm; *ii)* B-rep representation; *iii)* support for hybrid geometric descriptions. This means that any geometric representation should be parameterizable over a rectangular domain, and it should be possible to associate with each point in such domain a surface value and derivatives up to second order. This makes so that all pre-existing operators and tools can be easily and directly applied to any newly introduced form of representation.
Moreover, ThinkDesign supports hybrid modeling based on a B-rep, extended to allow special, non-solid model types, which are used to represent thin-plate objects and integrate surface modeling into a solid modeling environment. The faces of the B-rep may be of hybrid nature, namely they need not all be of the same type.

3. Subdivision B-rep

A subdivision surface is a single entity describing an arbitrary topology geometric model by means of its control mesh. However, an exact evaluation algorithm, compatible with a CAD environment, requires that each quadrilateral face of the control mesh be associated with a rectangular parametric domain. To this aim, the limit surface $\mathbf{S}$ of the subdivision scheme is handled as a parametric multipatch surface in which each patch $\mathbf{S}_i$ corresponds to a quadrilateral face of the control mesh, or to a quadrilateral face generated by refining an n-sided face. The resulting geometric model is conveniently stored in a B-rep, called *Subd B-rep*. In the Subd B-rep, the control mesh is used to infer the B-rep topological information, whereas the geometry associated with each B-rep face consists of a parametric surface patch of the limit surface. A suitable reparameterization strategy makes so that each B-rep face can be evaluated by standard approaches, such as [Sta98].

4. Surface tuning around extraordinary points

Since Catmull-Clark surfaces exhibit nice shapes, we are interested in maintaining their appearance and B-spline nature in the widest possible area, while improving their analytic properties only where needed. The pursued approach consists in blending, in the neighborhood of the extraordinary points, the Catmull-Clark limit surface with a proper polynomial that approximates its shape. More precisely, denoted by $\mathbf{S}_i$, $i = 0, \ldots, n-1$, the n surface patches containing an extraordinary point $\mathbf{p}_{\mathrm{ev}}$, we replace each of them with a modified patch $\mathbf{S}_i^*$, defined on the same parametric domain, according to

$$\mathbf{S}_i^* := \begin{cases} w\mathbf{S}_i + (1-w)\mathbf{P}, & \text{inside the "blending region"}, \\ \mathbf{S}_i, & \text{elsewhere}, \end{cases} \tag{1}$$

where w is a bivariate blending function and $\mathbf{P}$ is a polynomial surface which approximates a small area of the Catmull-Clark surface centered at $\mathbf{p}_{\mathrm{ev}}$.
If the function w is chosen properly, the construction guarantees C^2 continuity, altering the Catmull-Clark surface only in a neighborhood of extraordinary points, which, although very small, is sufficient to overcome the aforementioned numerical problems.
Compared to the first approaches based on the idea of polynomial blending [Lev06,Zor06], which return as output a set of discrete points on the final surface, our technique generates a parametric surface, which can be evaluated at arbitrary points of the domain. To this aim, locally, the patches $\mathbf{S}_i$, $i = 0, \ldots, n-1$, the polynomial $\mathbf{P}$, and the function w in (1) are parameterized over a common star-shaped domain, whose construction is based on the *characteristic map* of Catmull-Clark surfaces.

5. System assessment

The design and development of the subdivision software prototype integrated in ThinkDesign went in a feedback loop with the validation of some end-users, among which the Italian-based firm of household appliances Alessi. One of the major benefits reported by Alessi is the integration between the conceptual and the engineering phases of design, which can be achieved only by a perfect integration of subdivision surfaces in the geometric kernel of a CAD system. This allows to approach subdivision as any other CAD feature in a history-based CAD system where a model description is stored and successively redefined interactively. Thus a geometric model based on subdivision can be modified shortly after some features, such as shells, fillets, chamfers, Boolean operations, parting lines, have been applied to it, and these features are automatically updated. This potential represents a real advance over existing CAD methodologies.
The original research developed during the NIIT4CAD project is reported in [ABC*, BFL*10].

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