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Sweepers: Swept deformation defined by gesture

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Abstract

Sweepers is a framework for defining space deformation operations for interactive shape modeling. The artist describes a basic deformation as a path through which a tool is moved. Our tools are simply shapes. So we can use shapes already created as customized tools to make more complex shapes or to simplify the modeling process. When a tool is moved, it causes a deformation of the working shape along the path of the tool. More complicated deformations are achieved by using several tools simultaneously in the same region. It is desirable that deformations for modeling are 'foldover-free,' so that the deformations are reversible. Our deformations can satisfy this criterion. We have an efficient formulation for a single tool following a simple path and we have a formula for blending conveniently the effects of multiple tools used simultaneously. For representing shapes, we provide a mesh refinement and decimation algorithm specially adapted to our deformations.
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1. Introduction

In the context of interactive shape modeling, a common characteristic of popular techniques is the possibility for the artist to operate on a shape by modifying directly the shape's mathematical description: e.g., the control points of a subdivision surface also define the surface. But with the constant increase of computing power, it is realistic and more effective to insert some interface between the artist and the mathematics describing a shape. As Foley and Van Dam remark, "The user interfaces of successful systems are largely independent of the internal representation chosen" [14].

Space deformation is a family of techniques that permits describing operations on a shape independently from that shape's description. With this separation, new shape descriptions can easily benefit from existing space deformation, and further development on operations and descriptions can be carried in parallel. While space deformation has been used for solving a wide range of problems in Computer Graphics, it is missing a framework specific to interactive shape modeling. Sweepers is a framework for defining shape operations, in which the basis of operations is simply gesture.

Shapes produced with sweepers are coherent because sweepers are foldover-free: there is no

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ambiguity as to which points of space belong to the shape. A deformation that would create foldovers would produce a self-intersection of the shape, which cannot be cured with any space deformation. With the exception of [11,21,16] and sweepers, other deformation operations do not prevent surfaces from self-intersecting.

Sweepers can be applied in principle to any standard model. All the examples in this paper, however, are deformations of a single sphere. Using a sphere has the advantage of being simple to implement, as well as showing shapes with features genuinely created with our technique.

Our deformation operations are specified as transformations of tools where a tool is any shape. They are continuous (at least C^0 and in most cases C^2). They are local within some user-defined distance of the tools, and most importantly they are foldover-free, preserving the shape's coherency. The remainder of this paper is organized as follows. In Section 2, we overview existing space deformation techniques. In Section 3 we introduce our new deformations, and we present efficient closed-forms. In Section 4 we propose several ways of defining tools. In Section 5, we propose a shape description suitable for modeling with sweepers. We discuss our results in Section 6.

2. Modeling by deformation

In a system for modeling by deformation, the currently observed shape is the result of repeated deformation of the space in which the initial shape is embedded. A convenient formalism can be used for specifying any modeling operation by deformation: the *deforming equation* gives the final shape $S(t_n)$ as a function the initial shape $S(t_0)$:

$$S(t_n) = \left\{ \mathop{\Omega}_{i=0}^{n-1} f_{t_i \mapsto t_{i+1}}(\mathrm{p}) \mid \mathrm{p} \in S(t_0) \right\}, \tag{1}$$

where $\mathop{\Omega}\limits_{i=0}^{n-1} f_{k_i \mapsto k_{i+1}}(\mathrm{p}) = f_{k_{n-1} \mapsto k_n} \circ \cdots \circ f_{k_0 \mapsto k_1}(\mathrm{p})$.

The operator Ω expresses the finite repeated composition of functions. Each function $f_{t_i \mapsto t_{i+1}} : \mathbb{R}^3 \mapsto \mathbb{R}^3$ is a deformation that transforms every point p of space at time t_i into a point of space at time t_{i+1}. Section 3 focuses on defining a set of functions $f_{t_i \mapsto t_{i+1}}$ useful for modeling.

Normal deformation. Computing accurate normals to the surface is very important, since the normals' level of quality will dramatically affect the visual quality of the shape. With space deformation, each normal is updated by multiplying the previous normal by the co-matrix[1] of the Jacobian [3]. Let us recall that the Jacobian of f at p is the matrix $J(f,\mathrm{p}) = \left(\frac{\partial f}{\partial x}(\mathrm{p}), \frac{\partial f}{\partial y}(\mathrm{p}), \frac{\partial f}{\partial z}(\mathrm{p})\right)$, and that by using the cross product $\times$, there is a convenient way to compute the co-matrix of $J = (\vec{\mathrm{j}}_x, \vec{\mathrm{j}}_y, \vec{\mathrm{j}}_z)$:

$$J^{\mathrm{C}} = (\vec{\mathrm{j}}_y \times \vec{\mathrm{j}}_z, \vec{\mathrm{j}}_z \times \vec{\mathrm{j}}_x, \vec{\mathrm{j}}_x \times \vec{\mathrm{j}}_y), \tag{2}$$

where the vectors $\vec{\mathrm{j}}_x$, $\vec{\mathrm{j}}_y$, and $\vec{\mathrm{j}}_z$ are column vectors.

The remainder of this section overviews existing deformation techniques in the context of interactive modeling. We organize them in three groups: deformations that are not suitable for modeling and can produce a relatively limited set of shapes, deformations that can produce a large set of shapes given enough parameters for a few functions $f_{t_i \mapsto t_{i+1}}$, and deformations that can produce a large set of shapes given enough simple functions $f_{t_i \mapsto t_{i+1}}$.

2.1. Global deformations

Barr [3] defines space tapering, twisting, and bending transformations via a matrix that is a function of a space coordinate. Blanc [4] generalizes this work to deformations that are functions of several space coordinates. Chang and Rockwood [8] propose a polynomial deformation that efficiently achieves "Barr"-like deformations and more, using a Bézier curve with coordinate sets defined at control points. Mikita [22] extends this method to triangular Bézier surfaces. A restriction of these methods is the initial rectilinear axis or planar surface. Crespin [10] proposes a technique based on recursive subdivision to use an initially deformed tool.

These methods can be easily controlled by the user with a few control parameters. However, their non-locality makes them unsuitable for surface modeling.

2.2. Many parameters, few functions

Sederberg and Parry [26] introduce free-form deformation (FFD): the artist defines a deformation by moving the control points of a Bézier volume. A major restriction of FFD is the regularity of the grid. Coquillart [9] and Blanc [5] extend this work for non-regular lattices. Note that with these methods, defining a deformation requires the placement of the control lattice with respect to the shape. Hsu et al. [18] propose a way of doing direct manip-

[1] Matrix of the co-factors.

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