2004

Computational Geometry Column 45

Joseph O'Rourke
Smith College, jorourke@smith.edu

Computational Geometry Column 45

Joseph O'Rourke*

Abstract

The algorithm of Edelsbrunner for surface reconstruction by "wrapping" a set of points in $\mathbb{R}^3$ is described.

Curve reconstruction [O'R00] seeks to find a "best" curve passing through a given finite set of points, usually in $\mathbb{R}^2$. Surface reconstruction seeks to find a best surface passing through a set of points in $\mathbb{R}^3$. Both problems have numerous applications, usually deriving from the need to reconstruct the curve or surface from a sample. Both problems are highly underconstrained, for there are usually many curves/surfaces through the points. Surface reconstruction in particular is notoriously difficult to control. Although significant advances have been made in recent years [Dey04]—especially in the direction of performance guarantees based on sample density—we turn here to a beautiful and now relatively old "wrapping" algorithm due to Edelsbrunner, which, although implemented in 1996 at Raindrop Geomagic, has been published only recently [Ede03] after issuance of a patent in 2002.

Sample results of the algorithm are illustrated in Figs. 1 and 2.[1] Although both of these examples reconstruct surfaces of genus one, we concentrate on the genus-zero case (a topological sphere) and only mention extensions for higher genus reconstructions.

An attractive aspect of the algorithm is that it reconstructs a unique surface without assumptions on sample density and without adjustment of heuristic parameters. Although the algorithm uses discrete methods, underneath it relies on continuous Morse functions. The discrete scaffolding on

*Dept. of Computer Science, Smith College, Northampton, MA 01063, USA. orourke@cs.smith.edu. Supported by NSF Distinguished Teaching Scholar Grant DUE-0123154.

[1] `.stl` (stereolithography) files for shapes from `http://www.cs.duke.edu/~edels/Tubes/`.

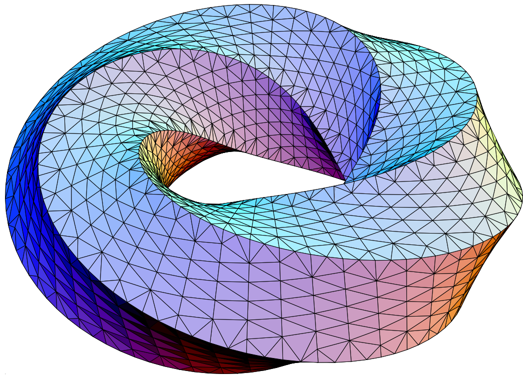

Figure 1: Torus, pentagonal cross-section.

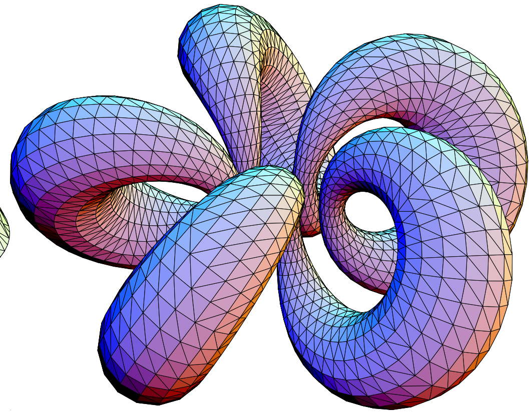

Figure 2: Smooth, twisted torus.

which the algorithm depends is the Delaunay complex, which we now informally describe. A *simplex* is a point, segment, triangle, or tetrahedron. A *simplicial complex* $\mathcal{K}$ is a "proper" gluing together of simplicies, in that (1) if a simplex σ is in $\mathcal{K}$, then so are all its faces, and (2) if two simplices σ and σ' are in $\mathcal{K}$, then either $\sigma \cap \sigma'$ is empty or a face of each. Let S be the finite set of points whose surface is to be reconstructed. The *Delaunay complex* Del S is the dual of the Voronoi diagram of S. Under a general-position assumption, Del S contains a simplex that is the convex hull of the sites $T \subset S$ iff there is an empty sphere that passes through the points of T. The outer boundary of Del S is the convex hull of S. Augmenting Del S with a dummy "simplex" $\emptyset$ for the space exterior to the hull, covers $\mathbb{R}^3$.

The algorithm seeks to find a "wrapping" surface $\mathcal{W}$, a connected simplicial subcomplex in Del S. It accomplishes this by finding a simplicial subcomplex $\mathcal{X}$ of Del S whose boundary is $\mathcal{W}$. The vertices of $\mathcal{X}$ will be precisely the input points S, and the vertices of $\mathcal{W}$ will be a subset of S.

The algorithm uncovers $\mathcal{X}$ in Del S by "sculpting" away simplices from Del S one-by-one, starting from $\emptyset$, until $\mathcal{X}$ remains. The simplices are removed according to an acyclic partial ordering. It is the definition of this ordering that involves continuous mathematics.

A function $g(x)$ assigns to every point $x \in \mathbb{R}^3$ a number dependent on the closest Voronoi vertex. In particular, if x is in a tetrahedron T of Del S whose empty circumsphere has center z and radius r, then $g(x) = r^2 - ||z - x||^2$. Thus $g(x)$ is zero at the corners of T and rises to r^2 at z, the closest Voronoi vertex. Points outside the hull are assigned an effectively infinite value. $g(x)$ is continuous but not smooth enough to qualify as a Morse function, needed for the subsequent development. It will suffice here to claim that g can be smoothed sufficiently to define the vector field ∇g, and from this, by a limiting process, *flow curves* through every point $x \in \mathbb{R}^3$ aiming toward higher values.

These flow curves are in turn used to define an acyclic relation on all the simplices of Del S and $\emptyset$. Let τ and σ be two simplices (of any dimension) and v a face shared between them. For example, if τ and σ are both tetrahedra, v could be a triangle, or a segment, or a vertex. Define the *flow relation* "$\rightarrow$" so that $\tau \rightarrow v \rightarrow \sigma$ if there is a flow curve passing from int τ to int v to int σ.[2]

A sink of the relation is a simplex that has no flow successor. $\emptyset$ is always a sink (recall $g(x)$ is large outside the hull), with the hull faces of Del S its immediate predecessors. Sinks are like critical points of the flow, with the simplices that gravitate toward a sink corresponding to a stable manifold in Morse terminology.

A key theorem is that the flow relation on simplices is acyclic, which reflects the increase of $g(x)$ along every flow curve. The algorithms starts with $\emptyset$ and methodically "collapses" its flow predecessors until no more collapses are possible, yielding the complex $\mathcal{X}$.

Let v be a face of τ; then τ is called a *coface* of v.[3] Assume $\tau \rightarrow v$; for example, τ might be a tetrahedron and v one of its edges, with the flow from τ through v. We give some indication of when the pair (v, τ) is collapsible, without defining it precisely. First, τ must be the highest dimension coface of v, and v should not have any cofaces not part of τ. Thus, v is in a sense "exposed." Second, the flow curves should pass right through every point of v (as opposed to running along or in v). Collapse of the pair removes all the cofaces of v, thus eating away the parts of τ sharing v.

A second key theorem is that any sequence of collapses from $\emptyset$ leads to the same simplicial complex $\mathcal{X}$. Collapses also maintain the homotopy type, which, because Del S is a topological ball, result in $\mathcal{X}$ a ball and $\mathcal{W}$ a topological sphere.

To produce surfaces of higher genus, the contraction is pushed through

[2] int v is the interior of v; for a v a vertex, int $v = v$.

[3] One can think of this is a *co*ntaining *face*, although its origins are more in complementary topological terminology.

holes: the most "significant" sink (in terms of $g(x)$) is deleted (changing the homotopy type), and then the collapses resume as before. This is how the shapes shown in Figs. 1 and 2 were produced. Repeating this process on the sorted sinks results in a series of nested complexes $\mathcal{X} = \mathcal{X}_0, \mathcal{X}_1, \ldots, \emptyset$.

Finally, the algorithm works in any dimension, although most applications are in $\mathbb{R}^3$.

References

[Dey04] T. K. Dey. Curve and surface reconstruction. In J. E. Goodman and J. O'Rourke, editors, *Handbook of Discrete and Computational Geometry*, chapter 30, pages 677–692. CRC Press LLC, second edition, 2004.

[Ede03] H. Edelsbrunner. Surface reconstruction by wrapping finite point sets in space. In B. Aronov, S. Basu, J. Pach, and M. Sharir, editors, *Discrete and Computational Geometry—The Goodman-Pollack Festschrift*, pages 379–404. Springer-Verlag, 2003.

[O'R00] J. O'Rourke. Computational geometry column 38. *Internat. J. Comput. Geom. Appl.*, 10(2):221–223, 2000. Also in *SIGACT News*, 31(1):28–30 (2000), Issue 114.