Surface reconstruction from range images

Surface reconstruction

Given a set of registered range points or range images, we want to reconstruct a 2D manifold that closely approximates the surface of the original model.

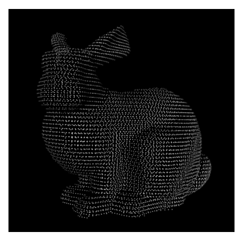
Desirable properties

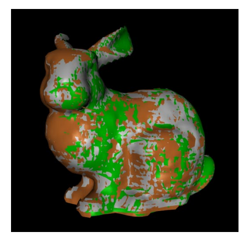
Desirable properties for surface reconstruction:

- *No restriction on topological type*
- *Representation of range uncertainty*
- *Utilization of all range data*
- *Incremental and order independent updating*
- *Time and space efficiency*
- *Robustness*
- *Ability to fill holes in the reconstruction*

Point clouds vs. range images

We can view the entire set of aligned range data as a point cloud or as a group of overlapping range surfaces.





Reconstruction from unorganized points

Methods that construct triangle meshes directly:

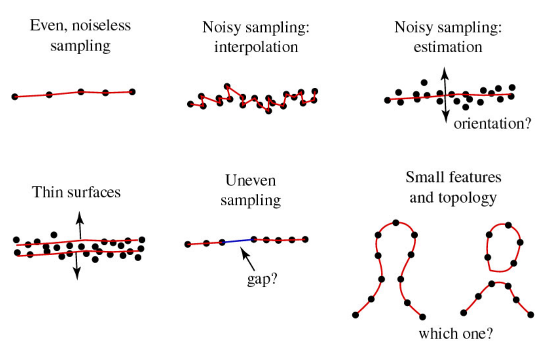
- *Alpha shapes [Edelsbrunner92]*
- *Local Delaunay triangulations [Boissonat94]*
- *Crust algorithm [Amenta98]*

Methods that construct implicit functions:

- *Voxel-based signed distance functions [Hoppe92]*
- *Bezier-Bernstein polynomials [Bajaj95]*

Hoppe treats his reconstruction as a topologically correct approximation to be followed by mesh optimization [Hoppe93].

Reconstruction from unorganized points



Reconstruction with alpha shapes

Intuition:

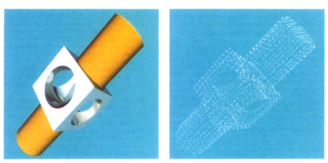
1. Consider a set of points in space to be solid anchors, and fill the rest of space with styrofoam.
2. Now, choose a sphere of radius=alpha and “erase” as much styrofoam as you can. This is the **alpha hull**.
3. Straighten all curved segments and surfaces. This is the **alpha shape**.

Reconstruction with alpha shapes

Implicit surface reconstruction from points

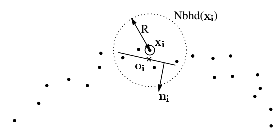
Hoppe developed a method for implicit surface reconstruction from point clouds:

1. Estimate tangent plane for each point
2. Establish orientations of tangent planes
3. Compute sum of signed distanes on voxel grid
4. Extract isosurface



Tangent plane estimation

At each point, $\mathbf{x}_i$, we fit a plane to its neighborhood:

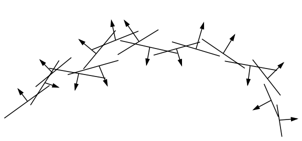


where:

- Nbhd($\mathbf{x}_i$) is the set of points within R of $\mathbf{x}_i$
- $\mathbf{o}_i$ is the centroid of Nbhd($\mathbf{x}_i$)
- $\mathbf{n}_i$ is the normal to the LS best plane through $\mathbf{o}_i$

Tangent plane estimation

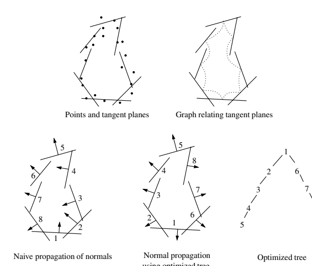
The result is a set of tangent planes, one per point:



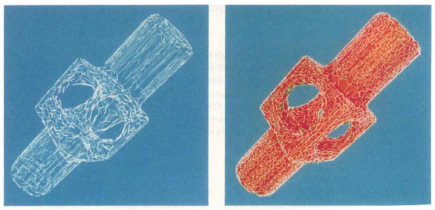
Problem: which way do the normals point?

Tangent plane consistency

One solution: find a consistent labeling.



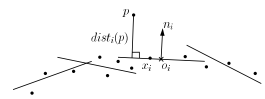
Tangent plane consistency



Signed distance estimation

The signed distance from a point, **p,** to the tangent plane for $\mathbf{x}_i$ is:

$$\text{dist}_i(\mathbf{p}) = (\mathbf{p} - \mathbf{o}_i) \bullet \mathbf{n}_i$$

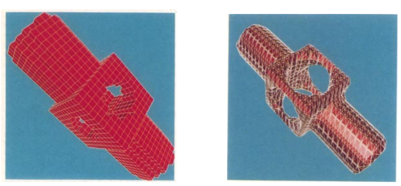


The total signed distance at **p** is:

$$\text{dist}(\mathbf{p}) = \sum_{\{i \mid \|\mathbf{x}_i - \mathbf{p}\| < R\}} \text{dist}_i(\mathbf{p})$$

Surface extraction

The signed distance function is then evaluated and isosurface extracted over a voxel grid using a continuation method.



Reconstruction from range images

Methods that construct triangle meshes directly:

- *Re-triangulation in projection plane [Soucy92]*
- *Zippering in 3D [Turk94]*

Methods that construct implicit functions:

- *Signed distances to nearest surface [Hilton96]*
- *Signed distances to sensor + space carving [Curless96]*

Weight assignment

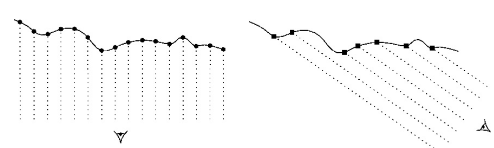
Final surface will be weighted combination of range images.

Weights are assigned at each vertex to:

- *Favor views with higher sampling rates*
- *Encourage smooth blends between range images*

Weights for sampling rates

Sampling rate over the surface is highest when view direction is parallel to surface normal.

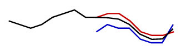


Weights for smooth blends

To assure smooth blends, weights are forced to taper in the vicinity of boundaries:

Two range surfaces

After unweighted blending



After weighted blending

Example

Range surface

Confidence rendering

Zippering

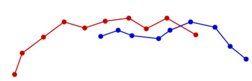
A number of methods combine range surfaces by stitching polygon meshes together.

Zippering [Turk94] is one such method.

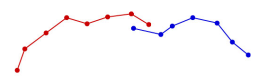
Overview:

- *Tessellate range images and assign weights to vertices*
- *Remove redundant triangles*
- *Zipper meshes together*
- *Extract a consensus geometry*

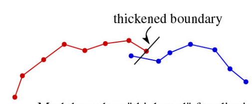
Redundancy removal and zippering



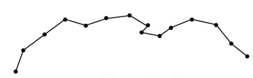
Overlapping range surfaces



Redundant geometry removed

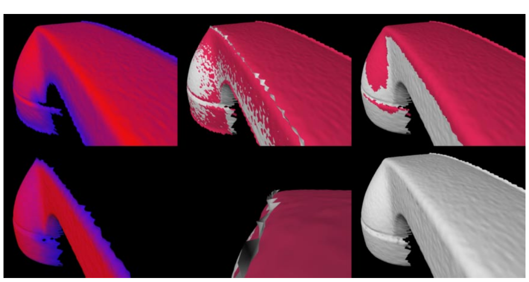


Mesh boundary "thickened" for clipping

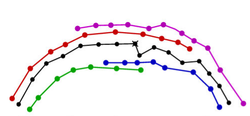


Zippered surface

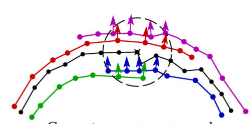
Example



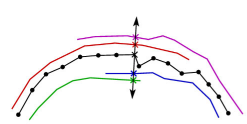
Consensus geometry



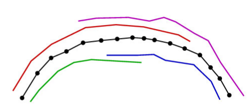
Zippered geometry + range surfaces



Compute consensus normal

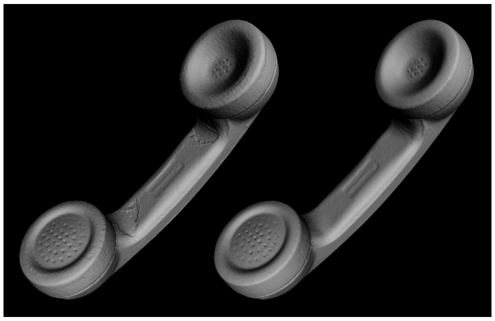


Find vertex positions on range surfaces by intersection with consensus normal



Compute weighted average of vertex positions

Consensus geometry



Volumetrically combining range images

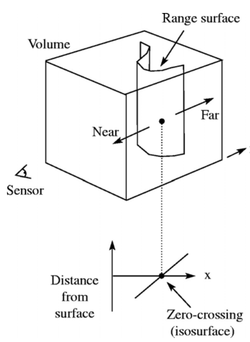
Combining the meshes volumetrically can overcome some difficulties of stitching polygon meshes.

Here I describe the method of [Curless96].

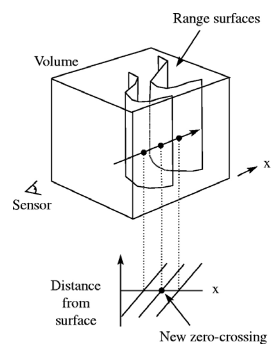
Overview:

- *Convert range images to signed distance functions*
- *Combine signed distance functions*
- *Carve away empty space*
- *Extract hole-free isosurface*

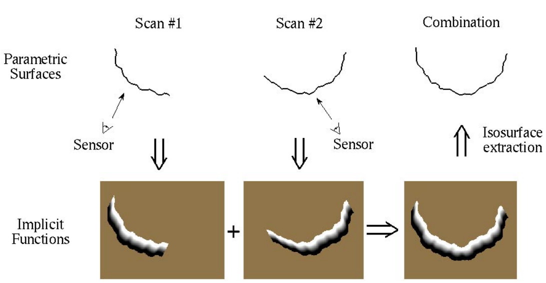
Signed distance function



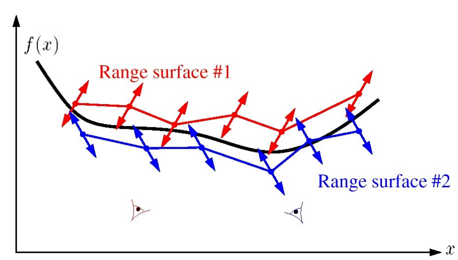
Combining signed distance functions



Merging surfaces in 2D



Least squares solution



Least squares solution

Error per point

$$E(f) = \sum_{i=1}^{N} \int d_i^2(x, f)\,dx$$

Error per range surface

Finding the f(x) that minimizes E yields the optimal surface.

This f(x) is exactly the zero-crossing of the combined signed distance functions.

Hole filling

We have presented an algorithm that reconstructs the observed surface. Unseen portions appear as holes in the reconstruction.

A hole-free mesh is useful for:

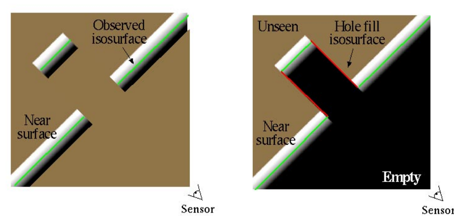
- *Fitting surfaces to meshes*
- *Manufacturing models (e.g., stereolithography)*
- *Aesthetic renderings*

Hole filling

We can fill holes in the polygonal model directly, but such methods:

- *are hard to make robust*
- *do not use all available information*

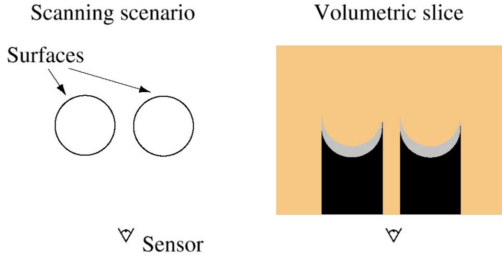
Space carving



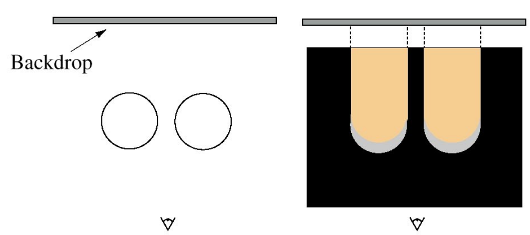
Without space carving   *With* space carving

Carving *without* a backdrop

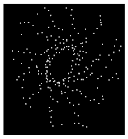
Scanning scenario   Volumetric slice



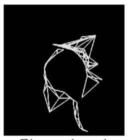
Carving *with* a backdrop

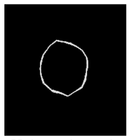


Merging 12 views of a drill bit


Scattered points

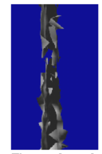

Range surfaces

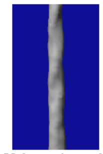

Zippered mesh


Volumetric mesh

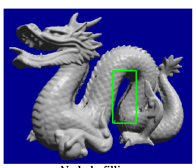
Merging 12 views of a drill bit

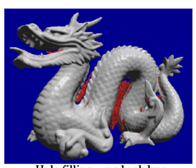

Photograph of painted drill bit

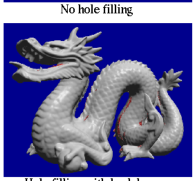

Zippered mesh

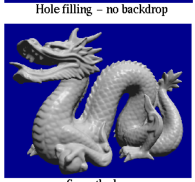

Volumetric mesh

Dragon model

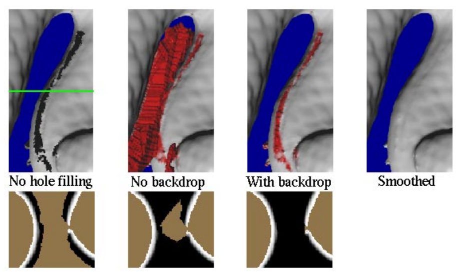

No hole filling


Hole filling – no backdrop

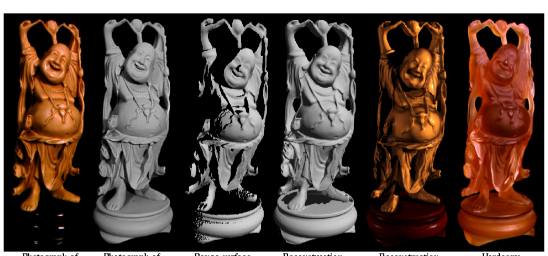

Hole filling with backdrop


Smoothed

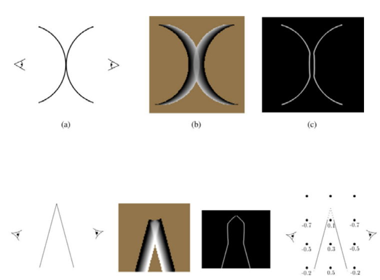
Dragon model


No hole filling · No backdrop · With backdrop · Smoothed

Happy Buddha


Photograph of original model · Photograph of painted original · Range surface from one scan · Reconstruction before hole-filling · Reconstruction after hole-filling · Hardcopy

Limitation: thin surfaces and sharp corners



Bibliography

Amenta, N., Bern, M., and Kamvysselis, M., “A new voronoi-based surface reconstructino algorithm,” SIGGRAPH '98. Orlando, FL, USA, 19-24 July 1992. p. 415-421.

Bajaj, C.L., Bernardini, F. and Xu, G, "Automatic reconstruction of surfaces and scalar fields from 3D scans,” SIGGRAPH '95 (Los Angeles, CA, Aug. 6-11, 1995, ACM Press, pp. 109--118.

Boissonnat, J.-D, “Geometric Structures for Three-Dimensional Shape Representation,” ACM Transactions on Graphics, October, 1994, 3(4), pp. 266-286.

Curless, B. and Levoy, M., “A volumetric method for building complex models from range images.” In Proceedings of SIGGRAPH ‘96, pp. 303-312. ACM Press, August 1996.

Edelsbrunner, H., Mucke, E.P. “Three-dimensional alpha shapes.” ACM Transactions on Graphics (Jan. 1994) vol.13, no.1, pp. 43-72.

Hilton, A., Stoddart, A.J., Illingworth, J., and Windeatt, T, “Reliable Surface Reconstruction from Multiple Range Images,” Fourth European Conference on Computer Vision, April 1996, vol. 1, pp. 117-126.

Hoppe, H., DeRose, T., Duchamp, T., McDonald, J., Stuetzle, W., “Surface reconstruction from unorganized points.” SIGGRAPH '92. Chicago, IL, USA, 26-31 July 1992. p. 71-8.

Bibliography

Hoppe, H., DeRose, T., Duchamp, T., McDonald, J., Stuetzle, W., “Mesh optimization.” SIGGRAPH '93. Anaheim, CA, USA, 1-6 Aug. 1993, pp. 19-26.

Soucy, M. and Laurendeau, D., “Multi-resolution surface modeling from multiple range views,” Proceedings 1992 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, held in Champaign, IL, USA, 15-18 June 1992, pp. 348-353.

Turk, G. and Levoy, M., “Zippered polygon meshes from range images.” In Proceedings of SIGGRAPH ‘94, pp. 311-318. ACM Press, July 1994.