Princeton University
COS598B Lectures on 3D Modeling

Generating 3D Meshes from Range Data

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Overview

Range Images

- Optical Scanners
- Error sources and solutions
- Range Surfaces

Mesh Generation

- Range surface registration
- Desirable Properties
- Mesh Merging: Zippering
- Volumetric Merging: Signed Distances Functions with Space Carving

Optical range acquisition

Strengths

- ***Non-contact***
- ***Safe***
- ***Inexpensive (?)***
- ***Fast***

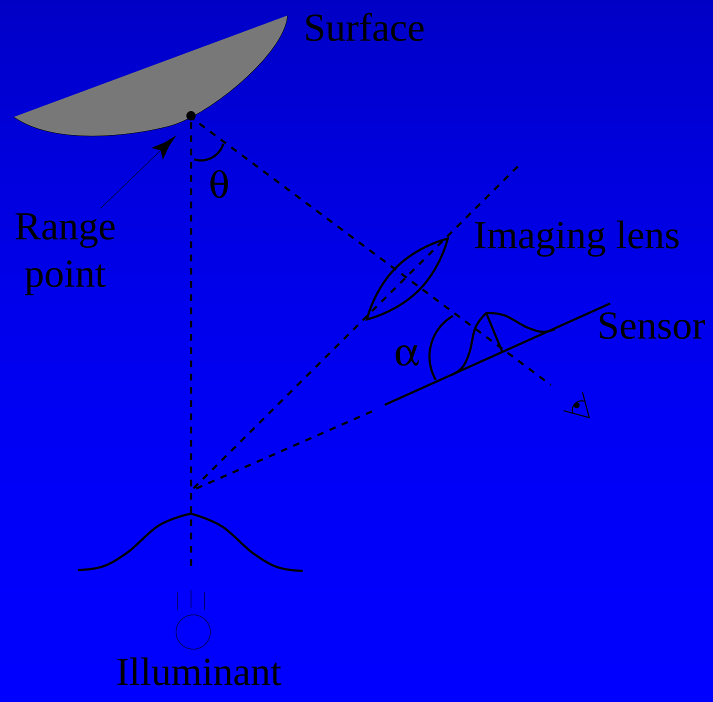
Limitations

- ***Can only acquire visible portions of the surface***
- ***Sensitivity to surface properties***
  - *> transparency, shininess, rapid color variations, darkness (no reflected light)*
- ***Confused by interreflections***

Optical triangulation

A beam of light strikes the surface, and some of the light bounces toward an off-axis sensor.

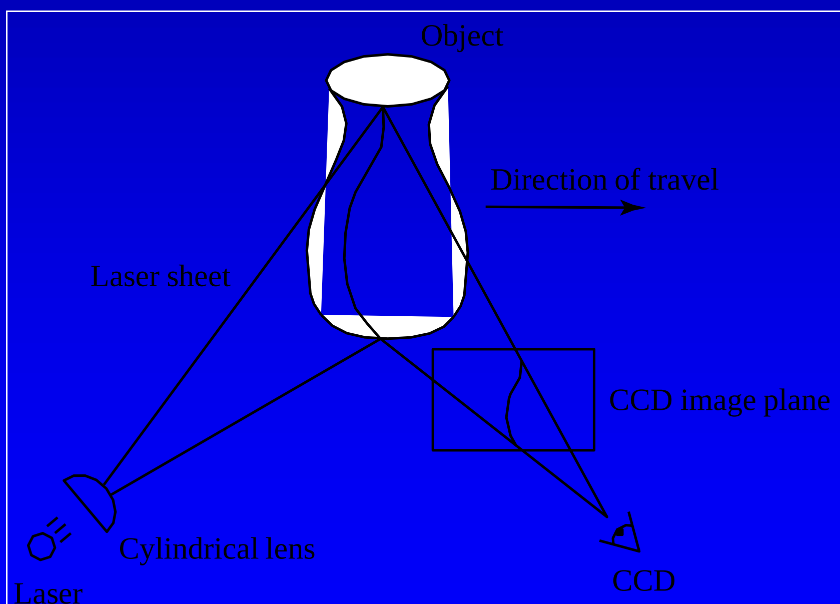
The center of the imaged reflection is triangulated against the laser line of sight.

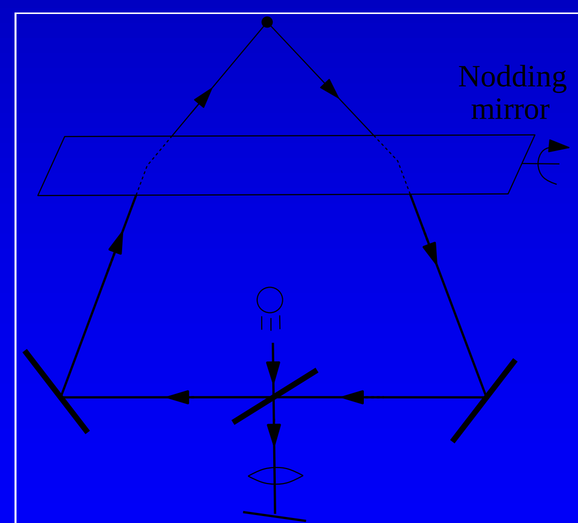


Triangulation configurations

Extension to 3D achievable as:

- ***sweeping light stripe***
- ***flying spot***
- ***hand-held stripe on jointed arm***



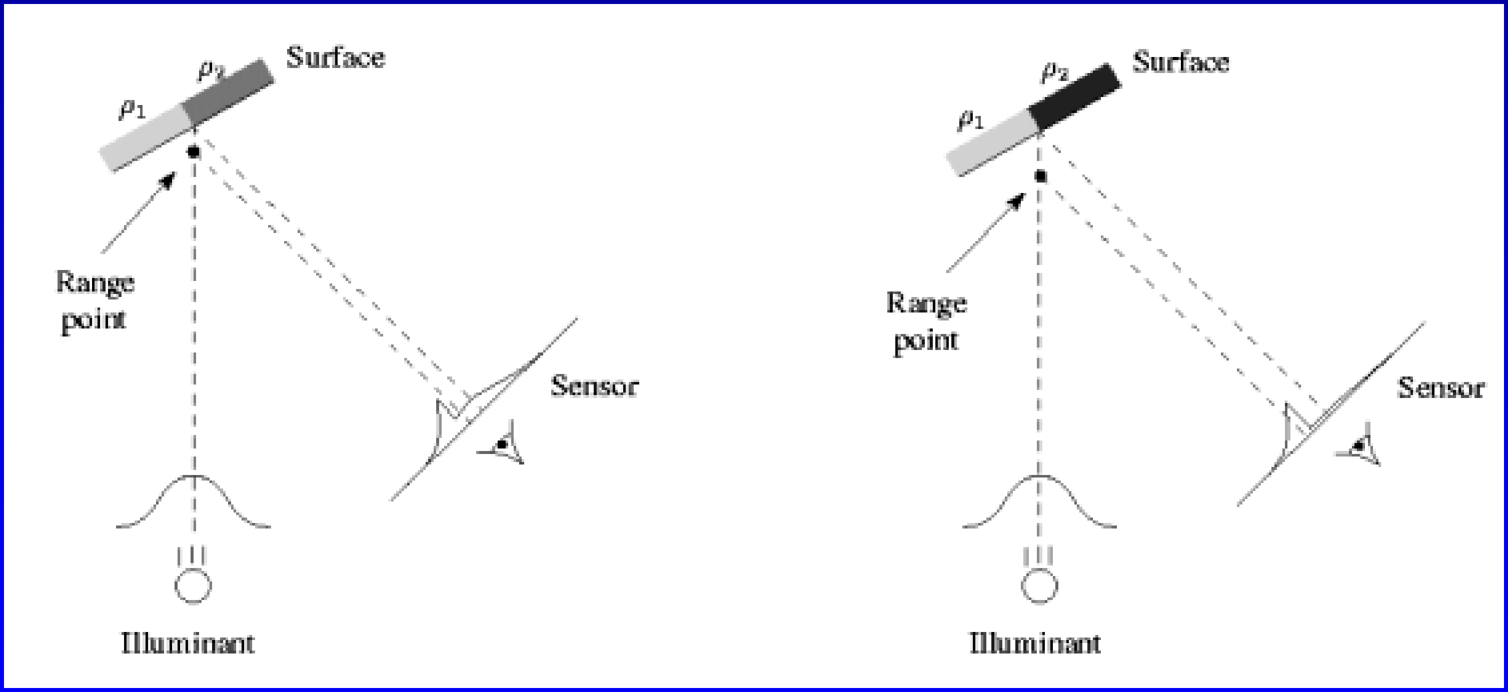


Cyberware Optical Triangulation Scanner

They make big ones, too!

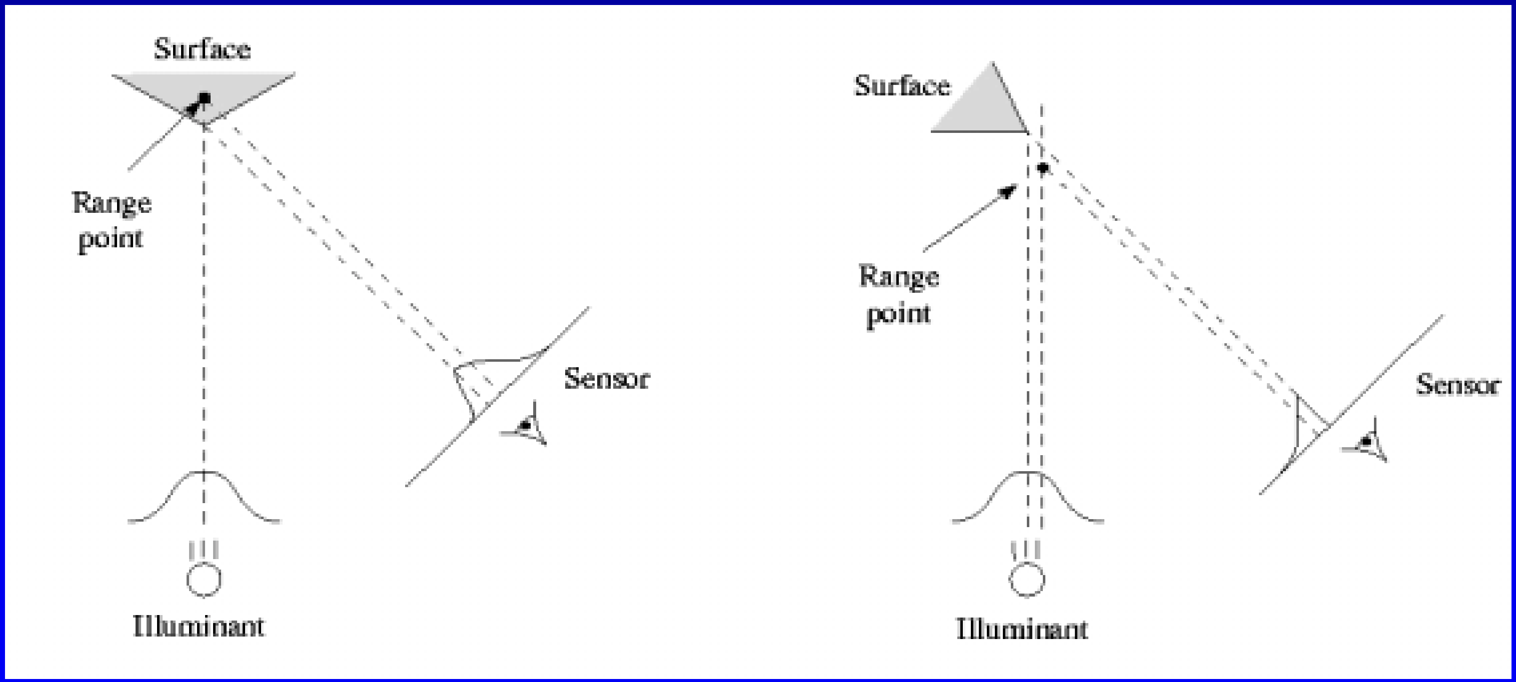
Sources of Triangulation Error

Variable reflectance:



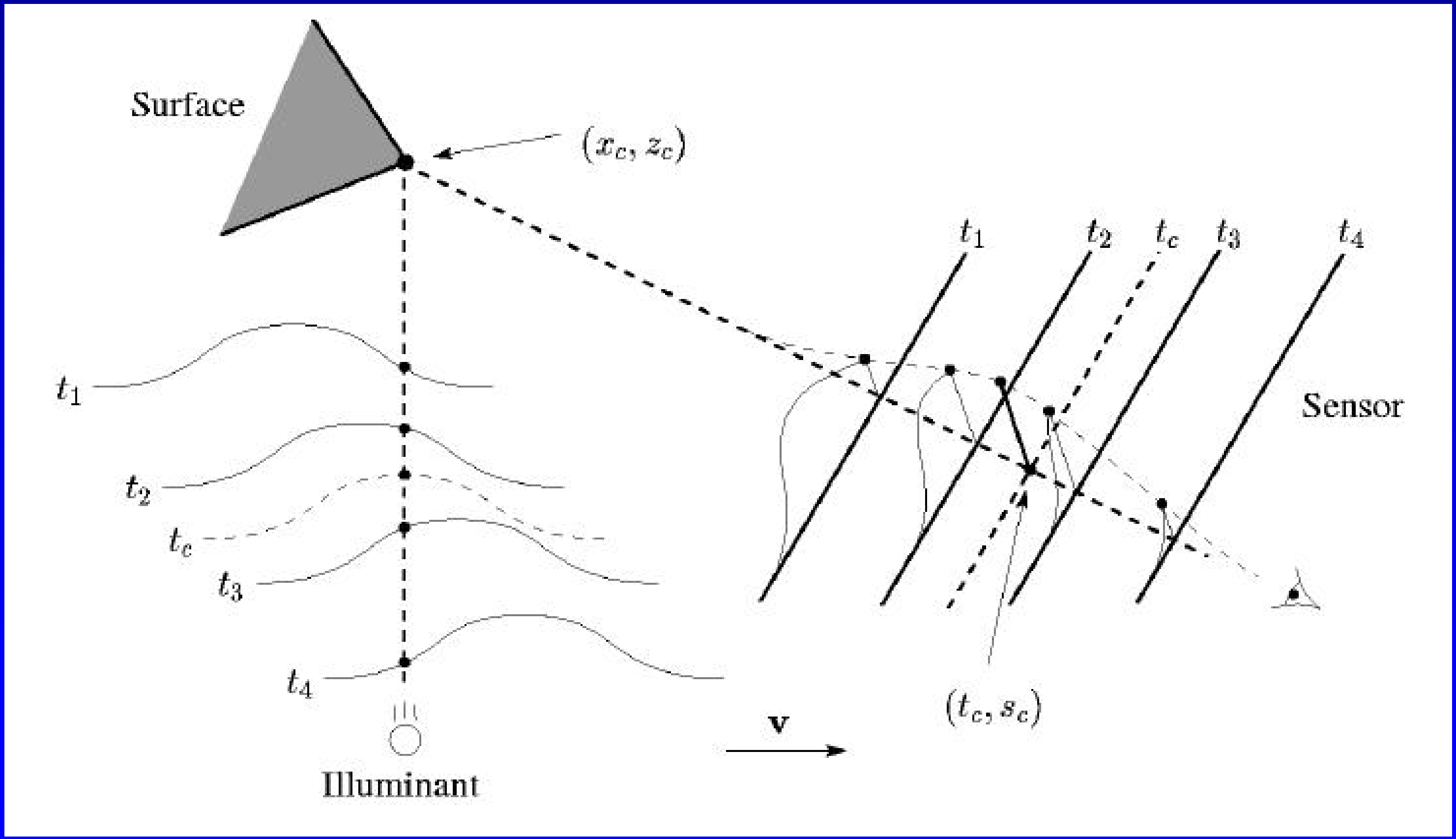
Sources of Triangulation Error

'Sharp' Corner:



Triangulation Error Reduction Method

Space-time Analysis:

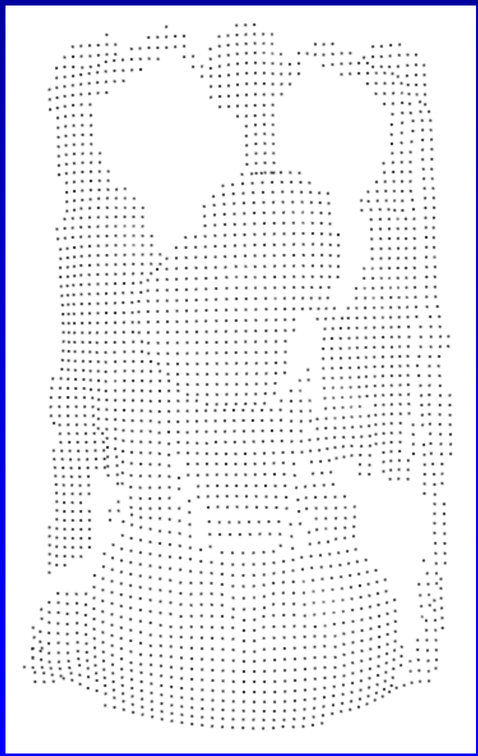


Results of Space-time Analysis

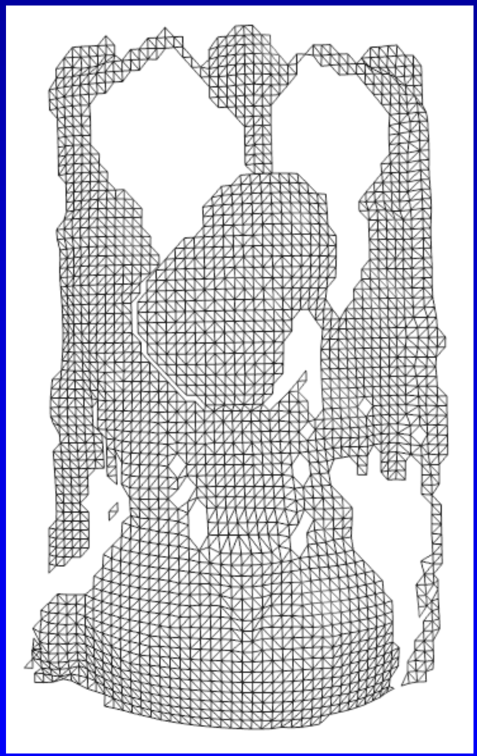
Space-time Analysis:

Range images and range surfaces

Given a range image, we can perform a preliminary reconstruction known as a *range surface*.



Range image

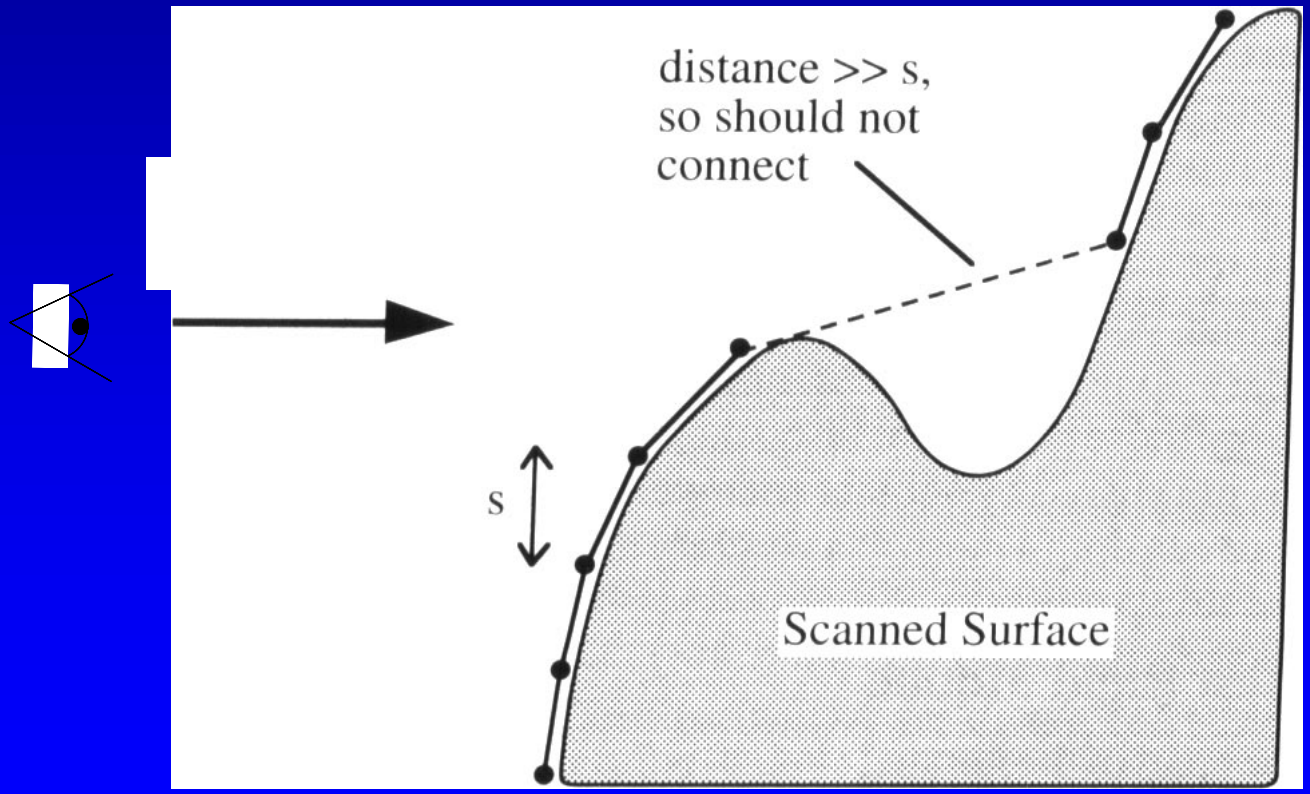


Tesellation

Range surface

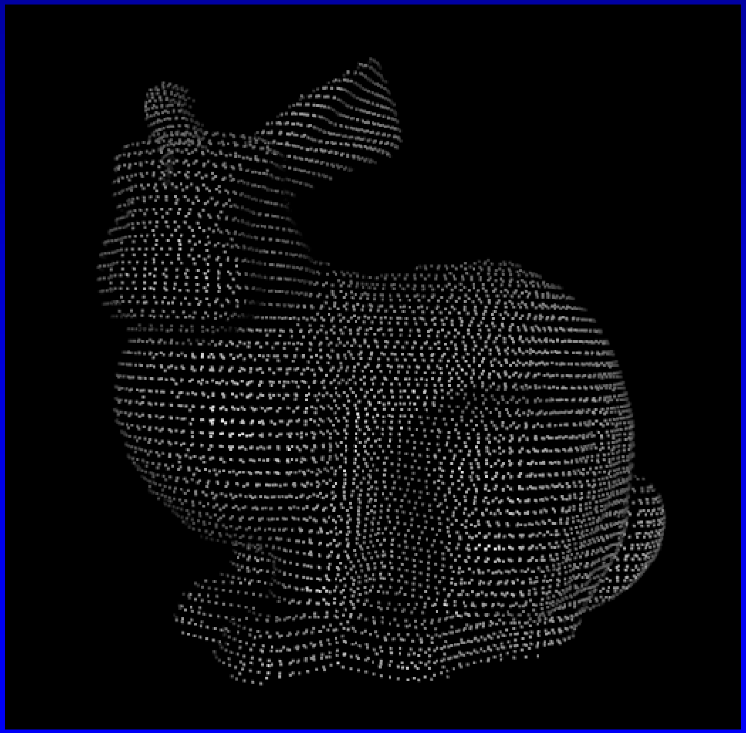
Tessellation threshold

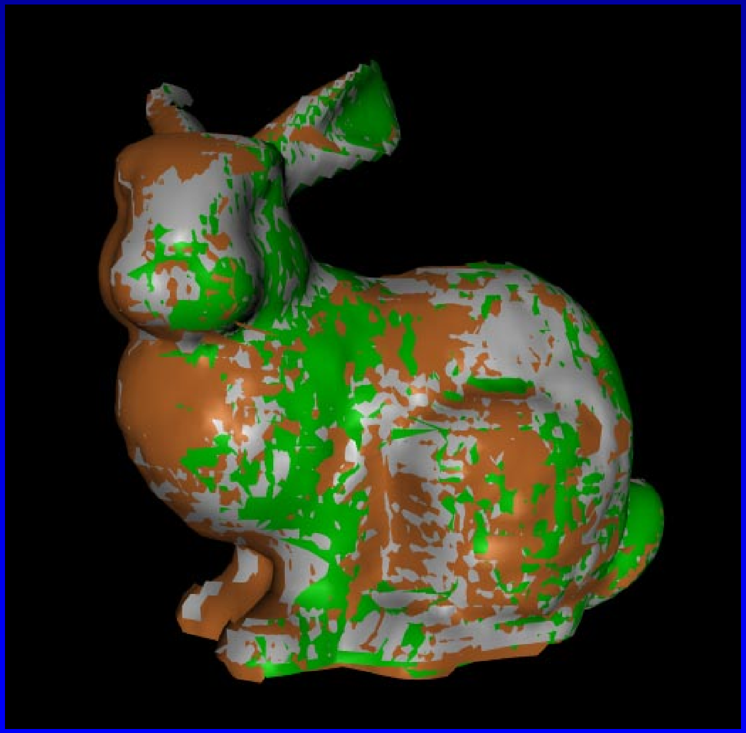
To avoid "prematurely aggressive" reconstruction, a tessellation threshold is employed:



Point clouds vs. range images

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





Registration

Any surface reconstruction algorithm should strive to use all of the detail in all the available range data.

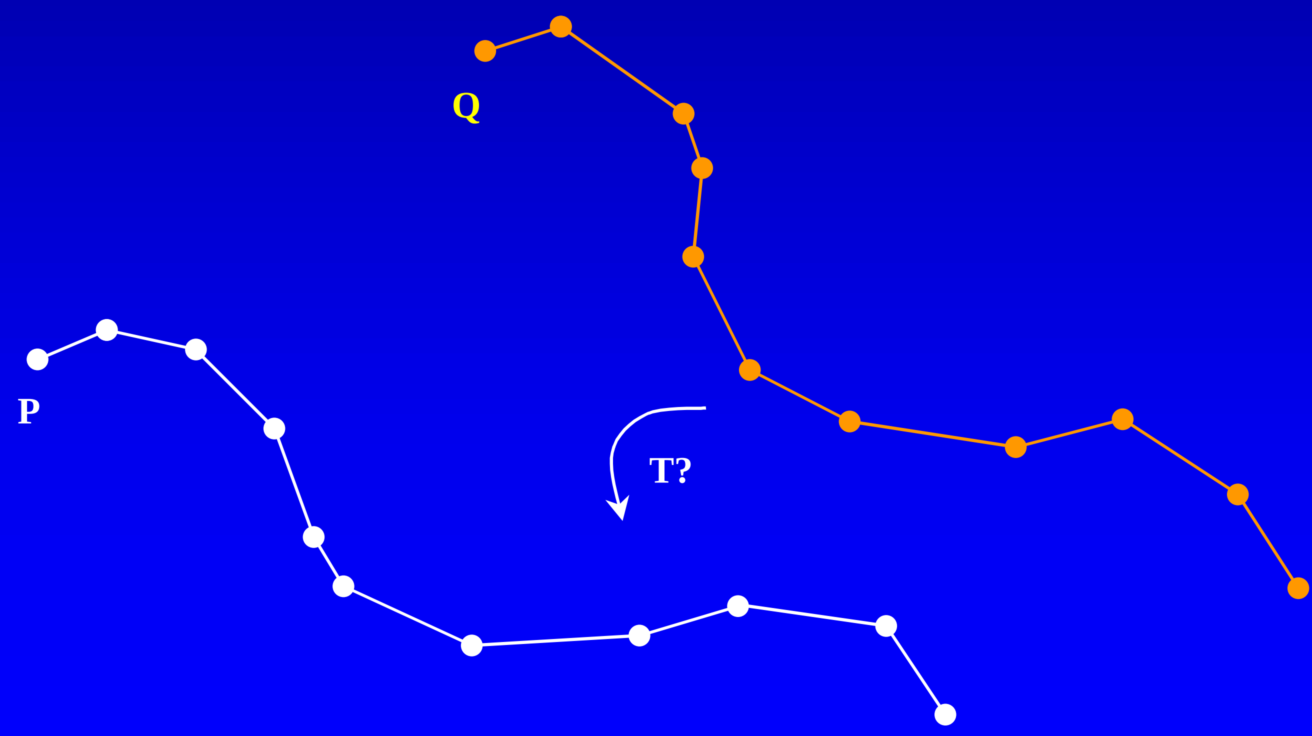
To preserve this detail, all data must be precisely registered.

Accurate registration may require:

- Calibrated scanner/object positioning
- Software-based optimization
- Both

Registration as optimization

Given two overlapping range scans, we wish to solve for the rigid transformation, T, that minimizes the distance between them.

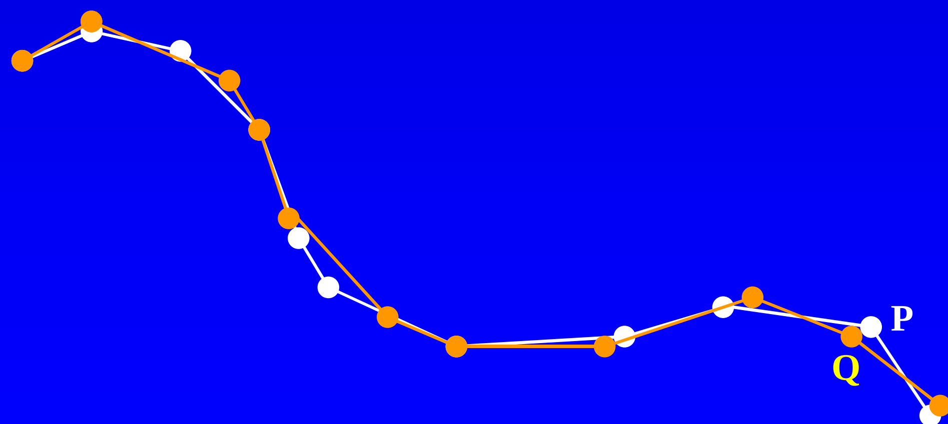


Registration as optimization

An approximation to the distance between range scans is:

$$E = \sum_{i}^{N_P} \left\| Tq_i - p_i \right\|^2$$

Where the q_i are samples from the scan Q and the p_i are the corresponding points on scan P. The points may lie on the range surface derived from P.



Registration as optimization

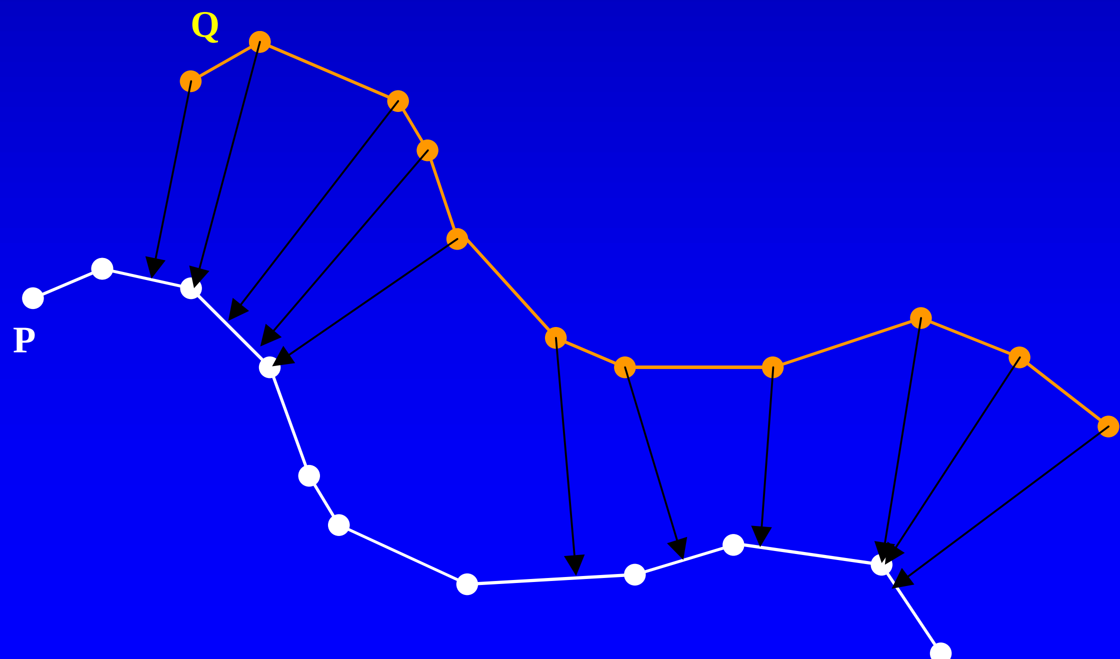
If the correspondences are known a priori, then there is a closed form solution for T.

This is not the case.

Registration as optimization

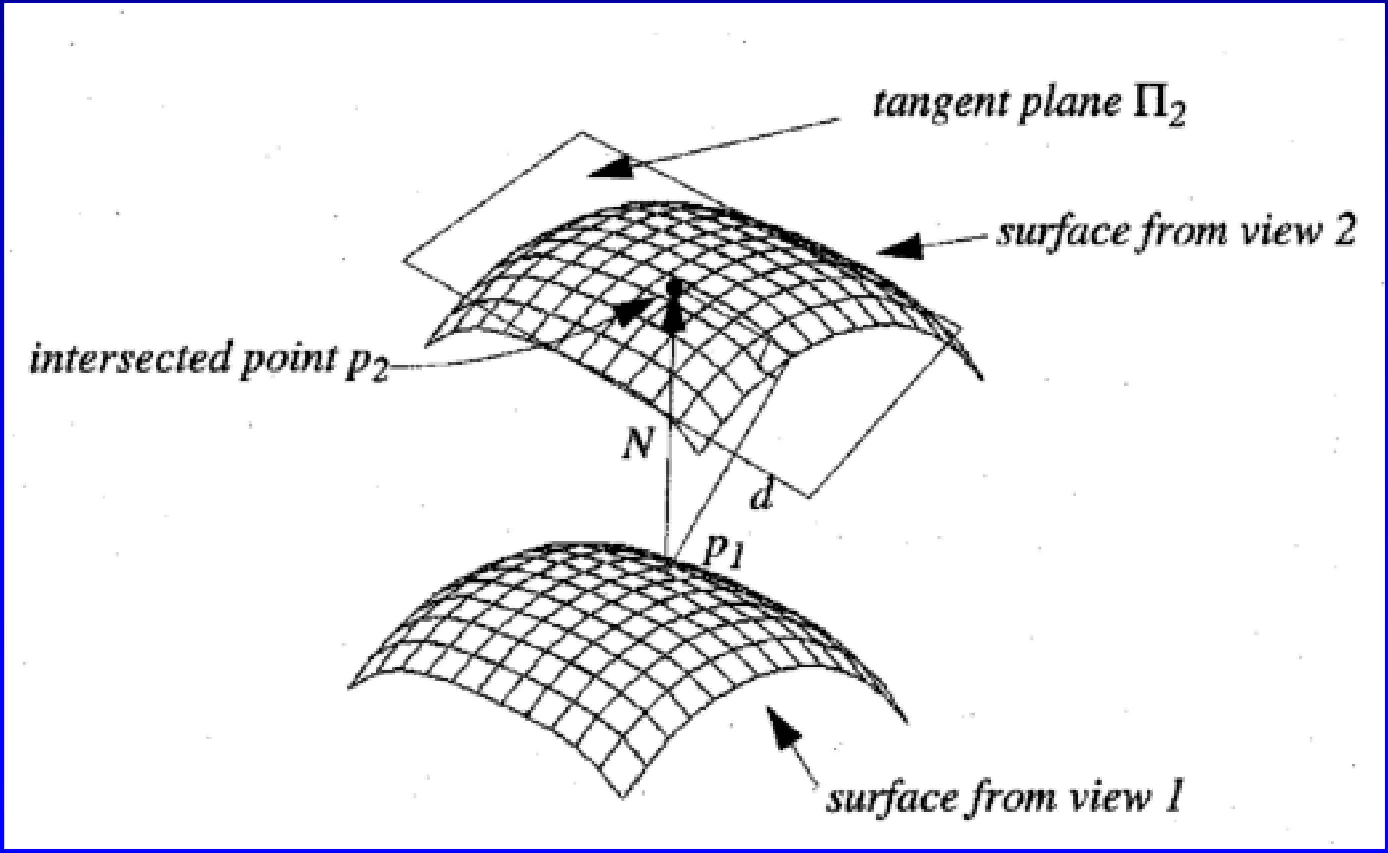
Iterative solutions such as [Besl92] proceed in steps:

- Identify nearest points
- Compute the optimal T
- Repeat until E is small



Registration as optimization

In 3D:



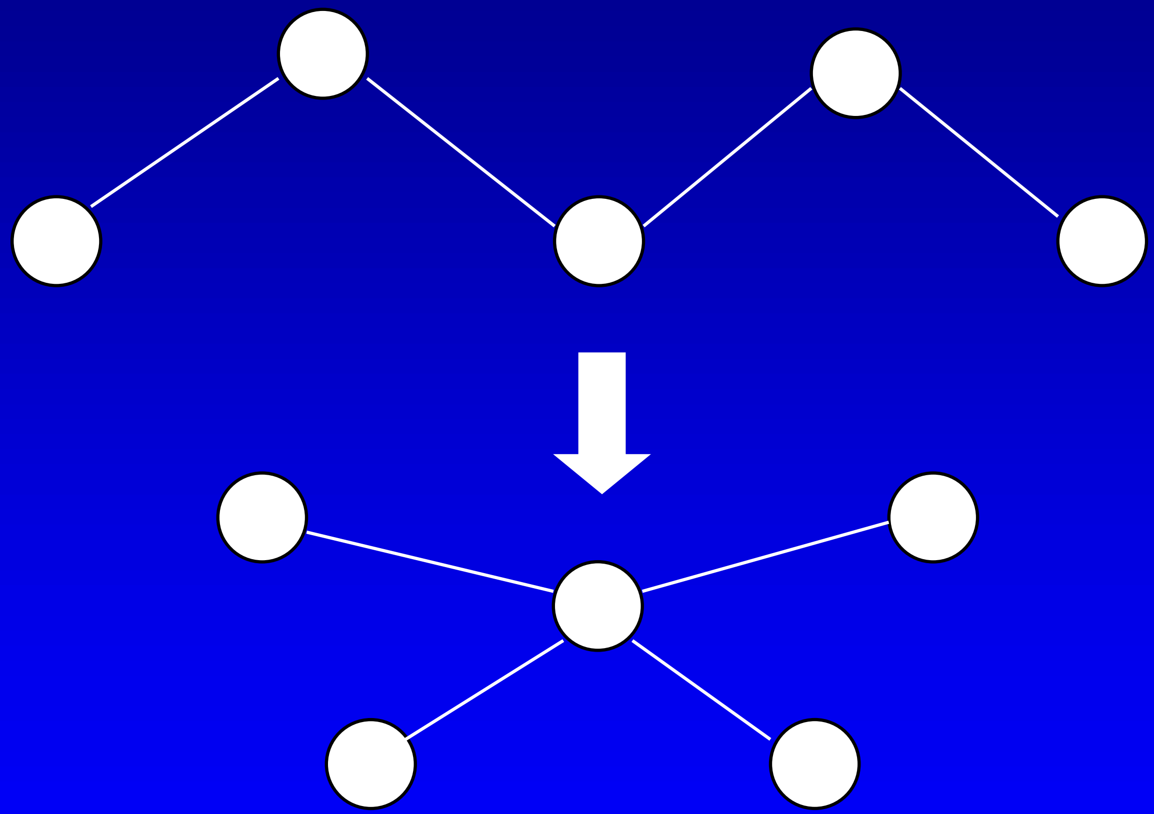
Registration as optimization

Sequential registration and integration is not optimal.

Multiple range scans could be simultaneously registered. This provides greater information to assist in generating a more accurate registration.

Global Registration

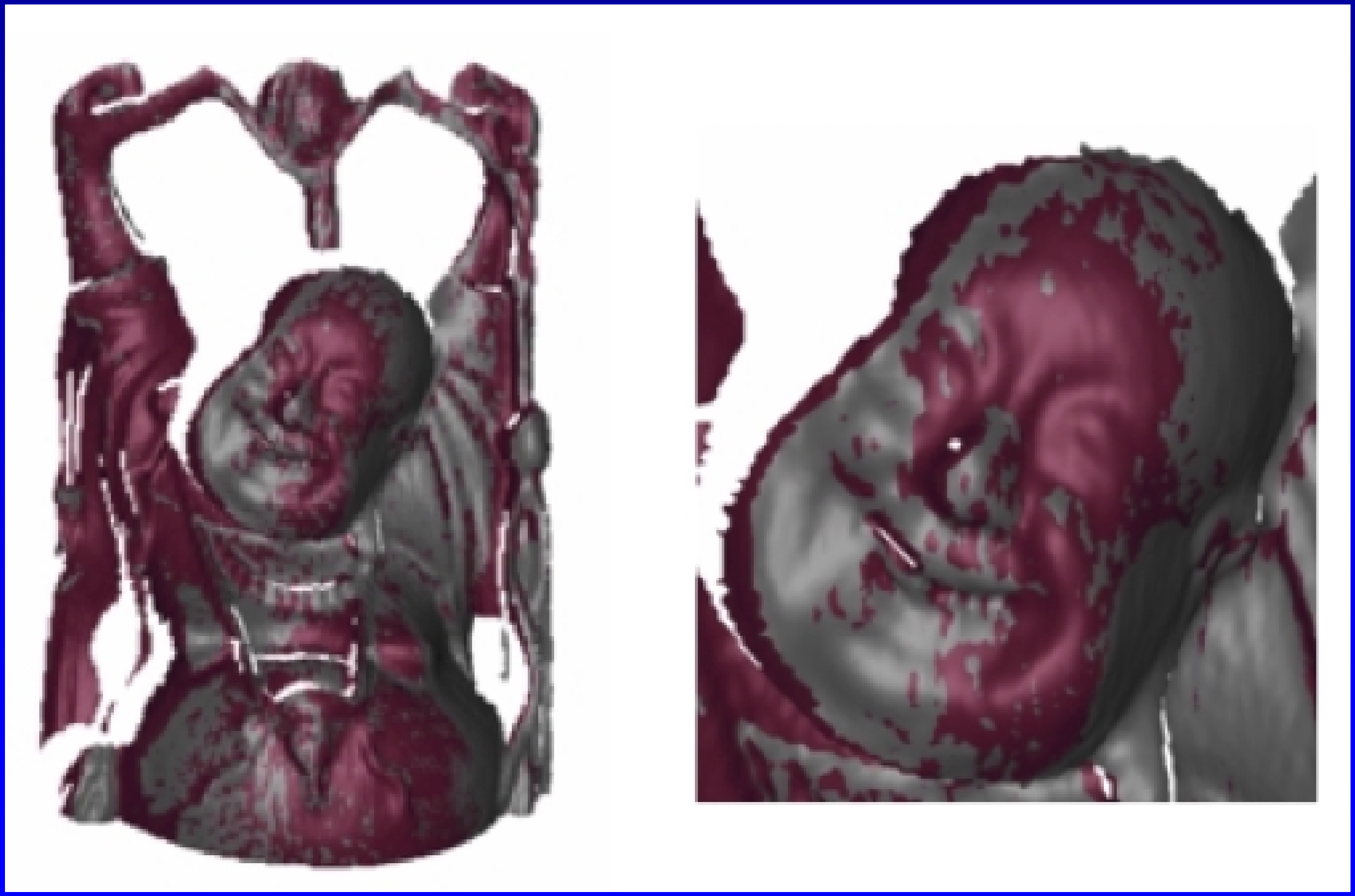
Network of Range Views [Gagnon94]:



Well balanced: similar registration error for all range surfaces.

Registration Results

Registration Error < Measurement Uncertainty



Surface Reconstruction

Given a set of registered range images, we want to reconstruct a 2D manifold that closely approximates the surface of the original model. A good method should incorporate the following properties:

- ***No restriction on topological type***
- ***Representation of range uncertainty***
- ***Utilization of all range data***
- ***Incremental and order independent updating***
- ***Time and space efficiency***
- ***Hole filling capability***

Reconstruction from Range Images

Methods that construct triangle meshes directly:

- Venn diagrams and re-parameterized range image merging [Soucy92]
- Zippering in 3D [Turk94]

Methods that construct volumetric implicit functions:

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

Zippering

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

Zippering [Turk'94] is one such method.

Overview:

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

Weight assignment

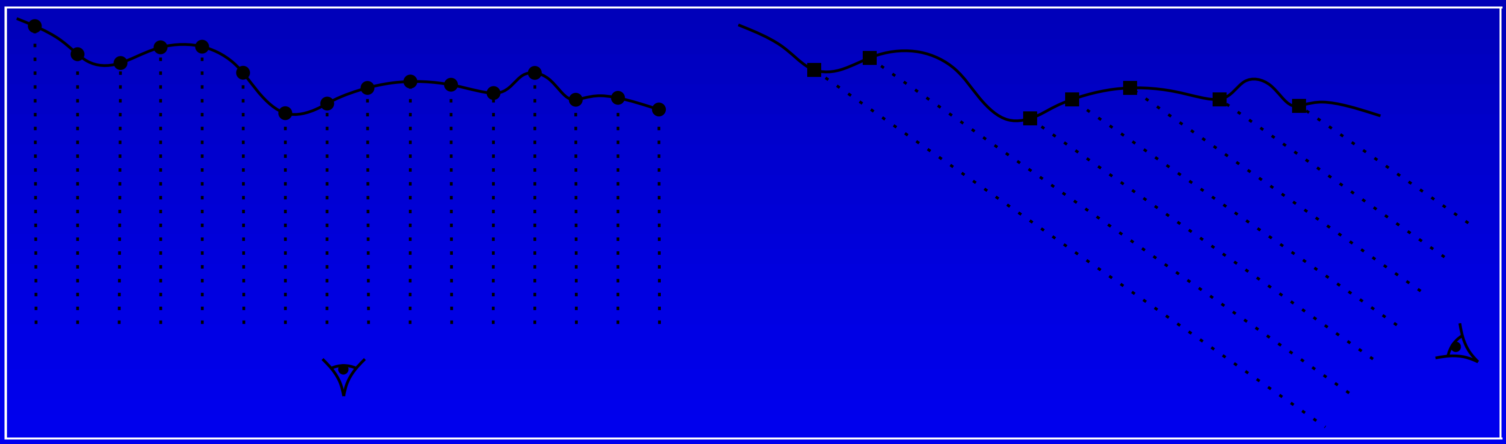
Final surface will be weighted combination of range images.

Weights are assigned at each vertex to:

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

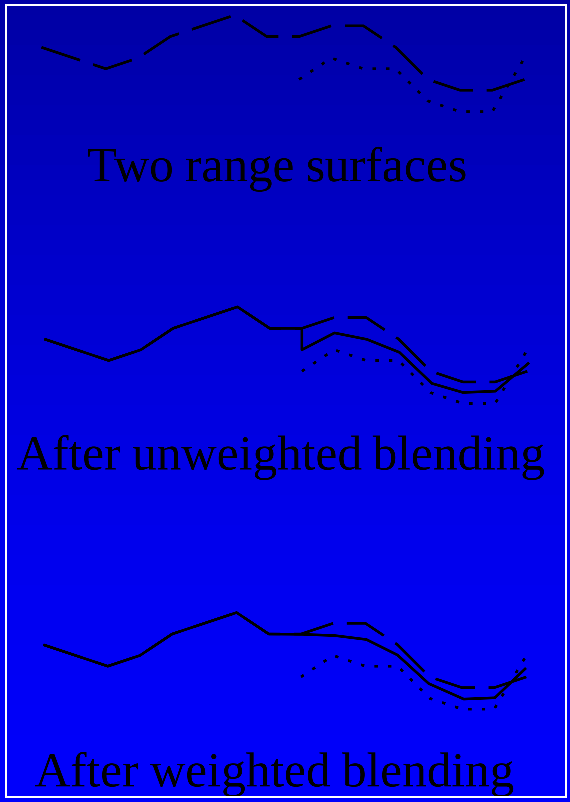
Weights for sampling rates

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

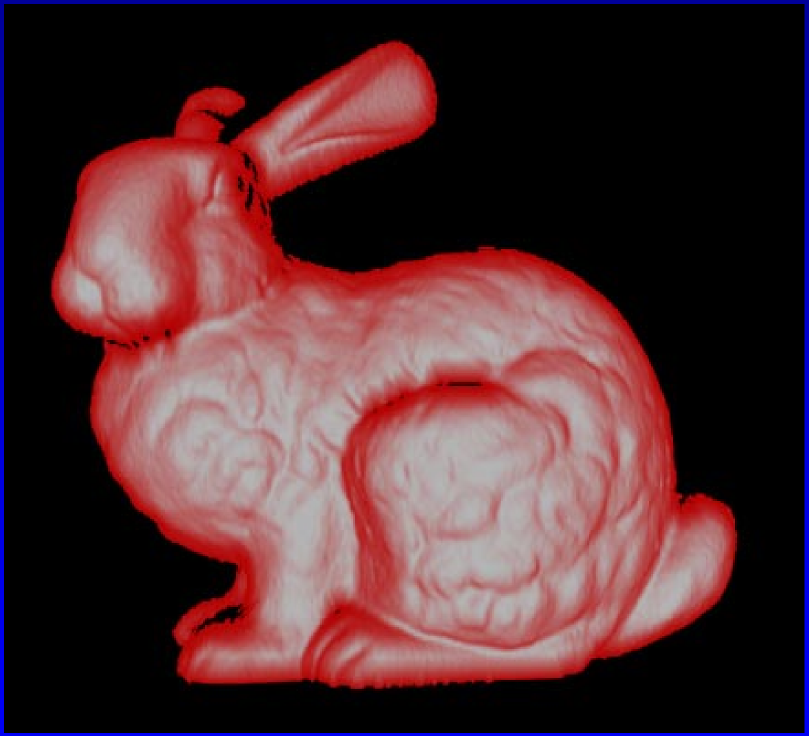


Weights for smooth blends

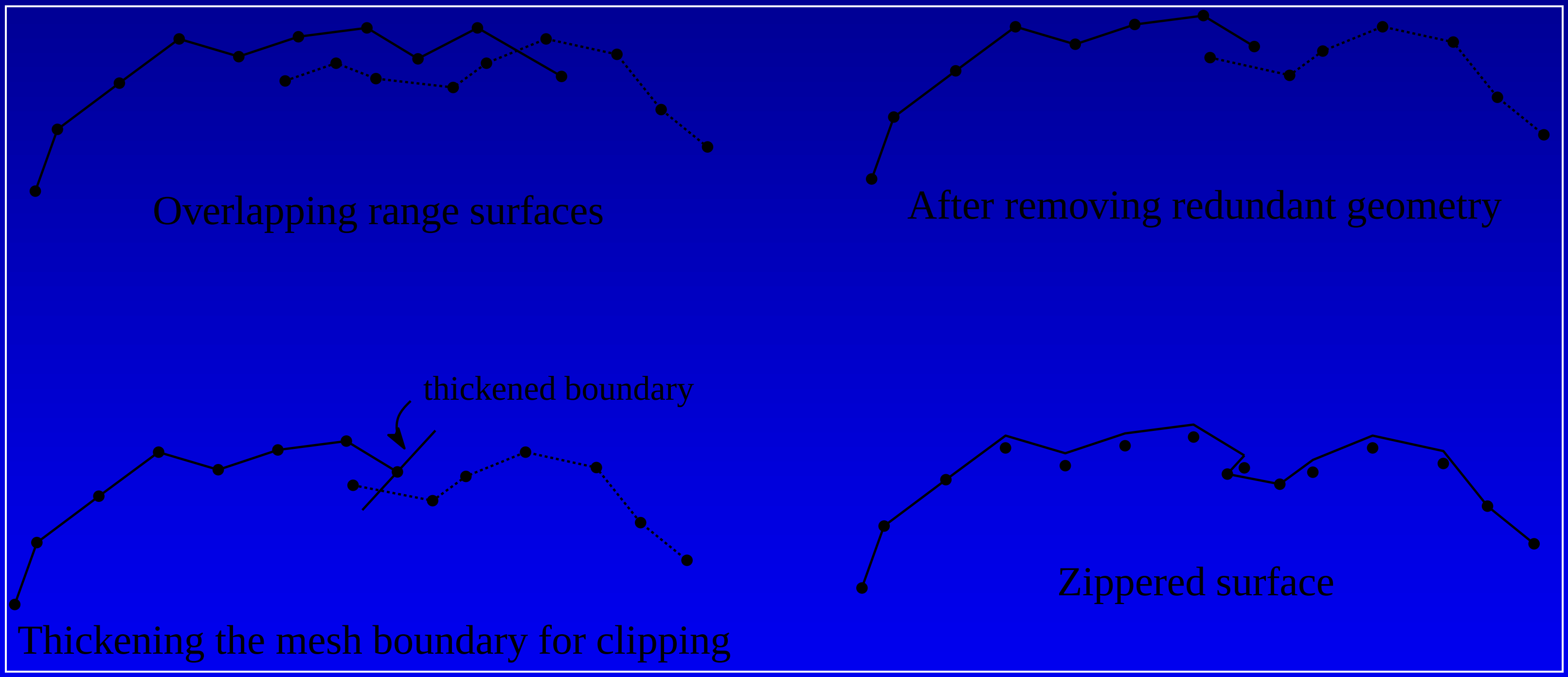
To assure smooth blends, weights are forced to taper in the vicinity of boundaries:



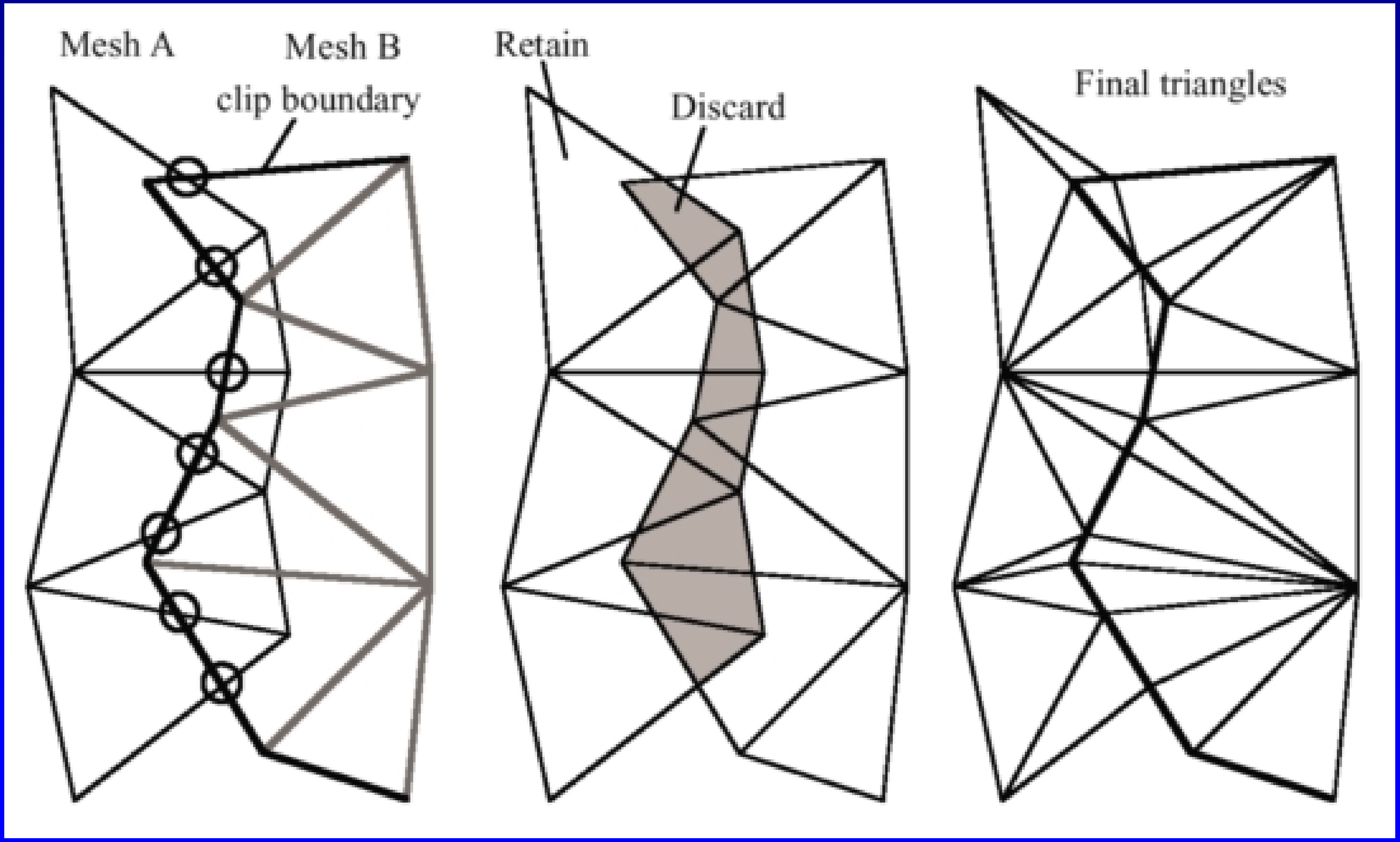
Example



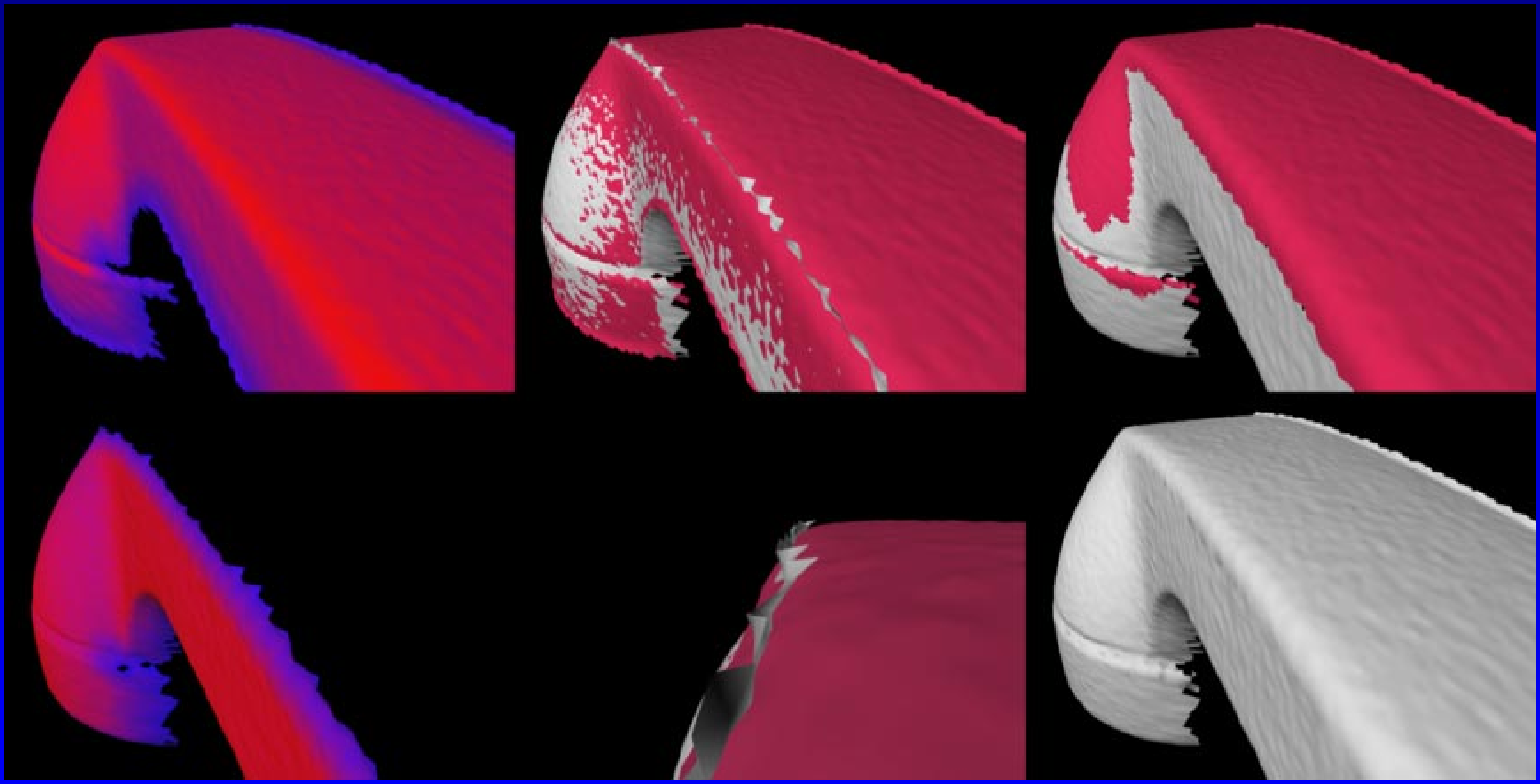
Redundancy removal and zippering



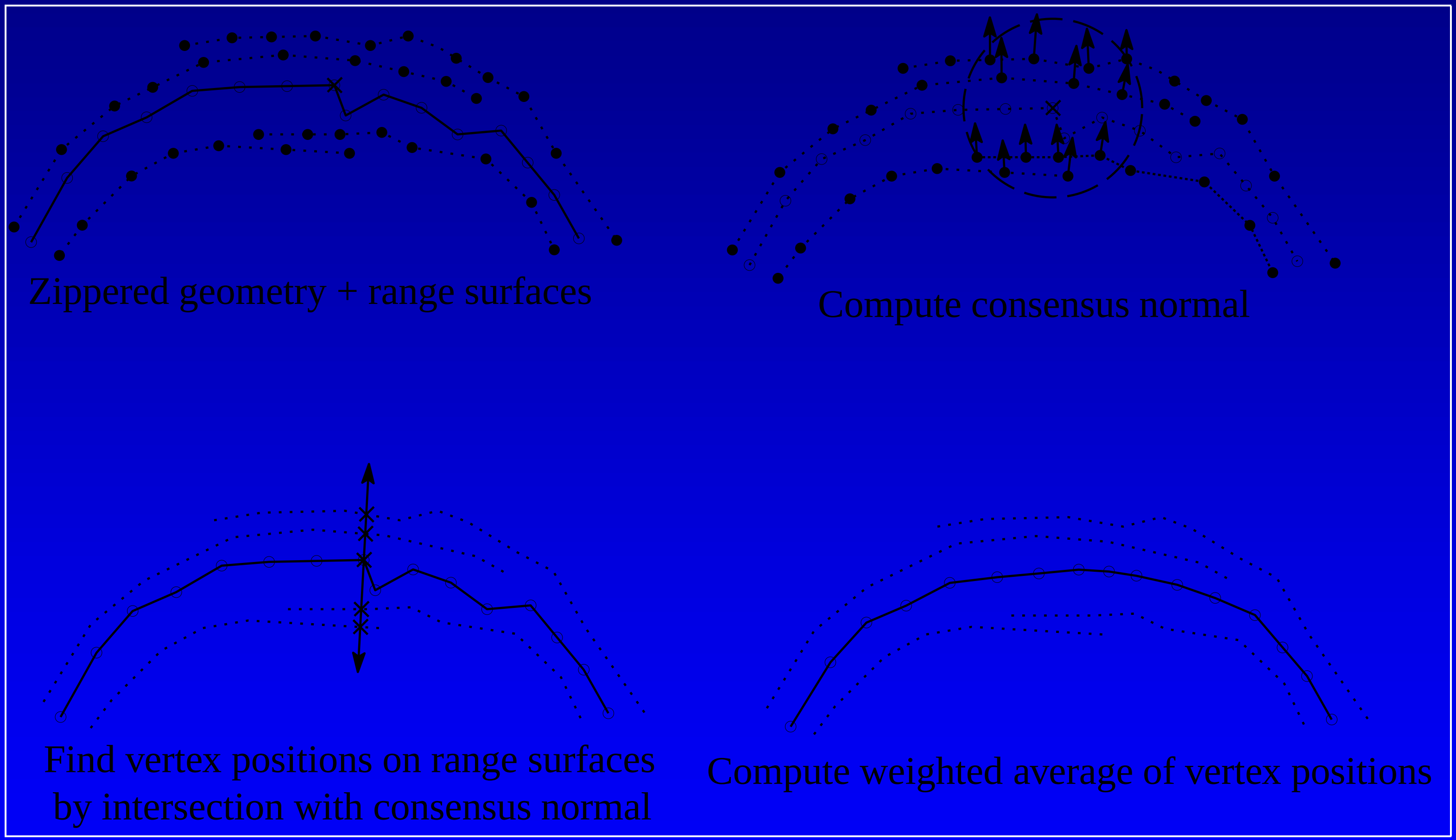
Redundancy removal and zippering



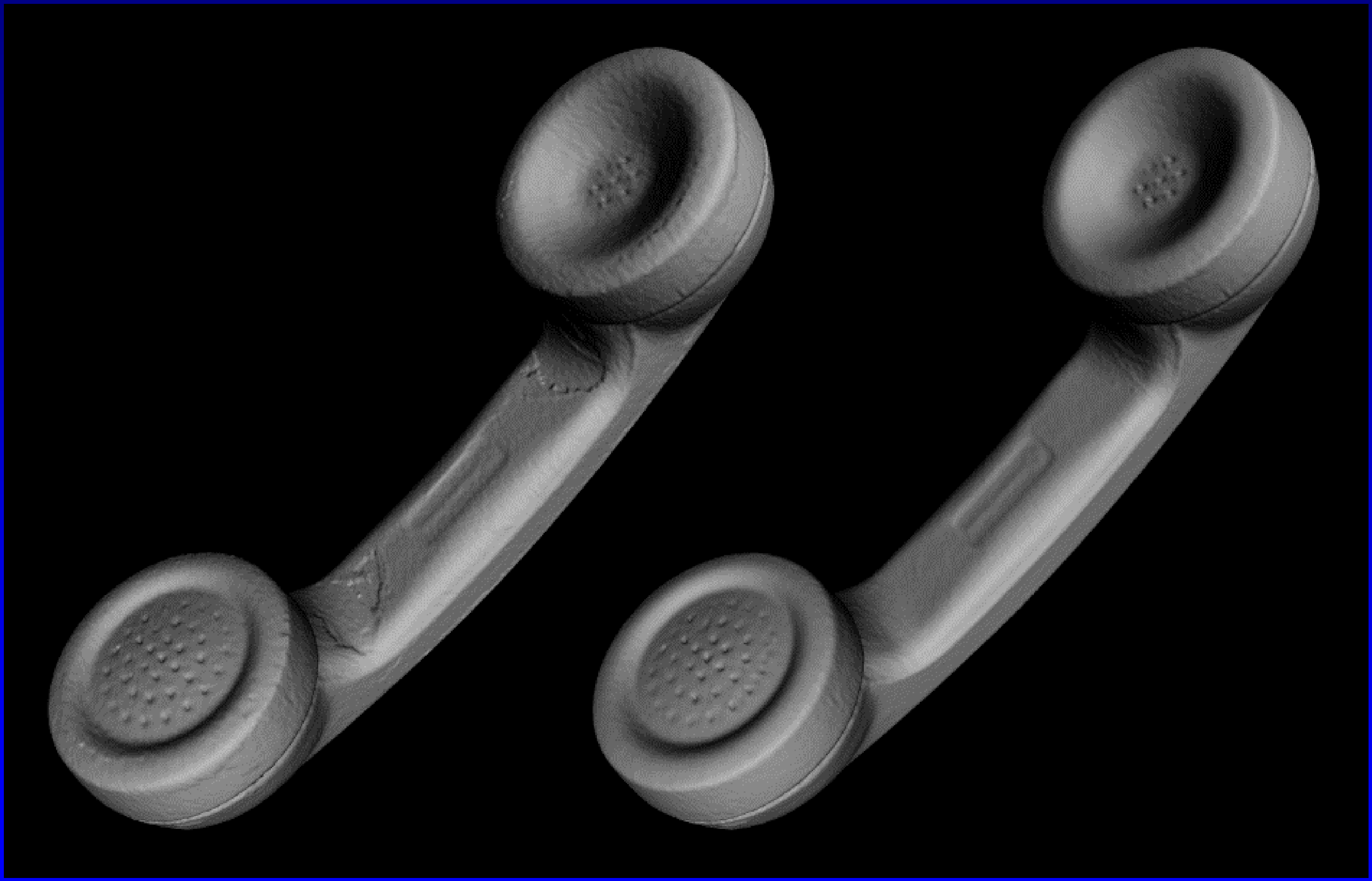
Example



Consensus geometry



Example



Volumetrically combining range images

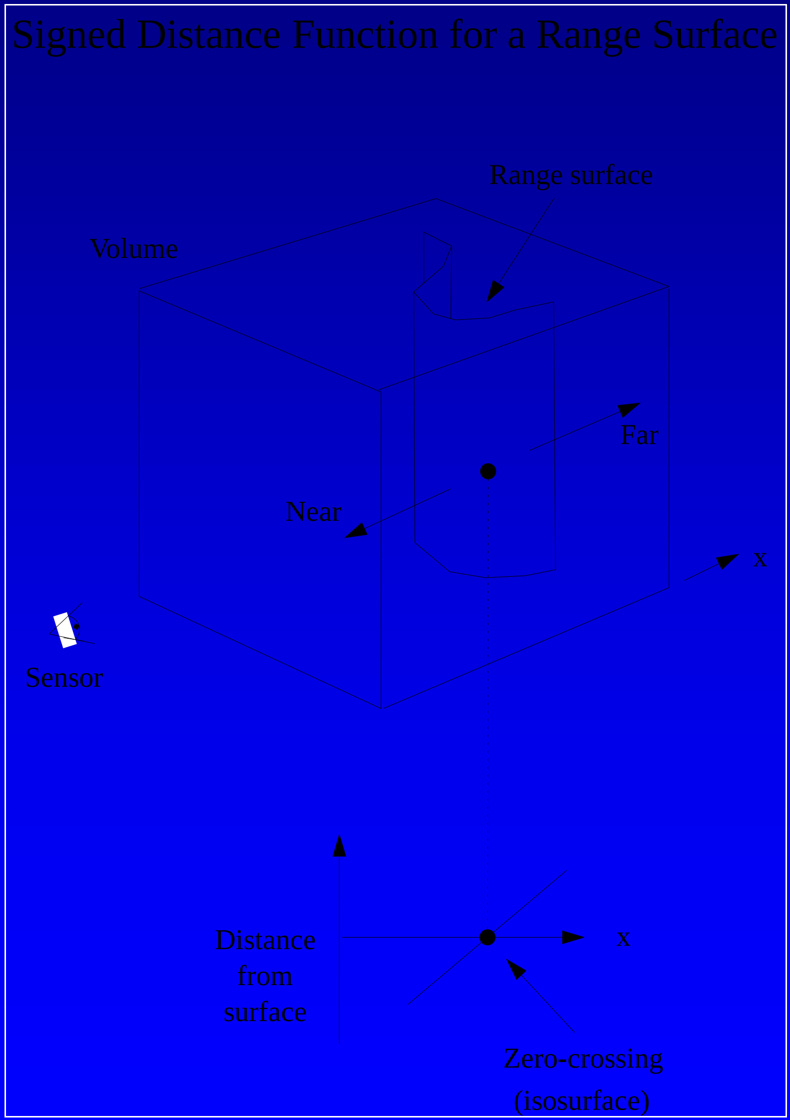
Combining the meshes volumetrically can overcome difficulties of stitching polygon meshes.

Here we describe the method of [Curless'96].

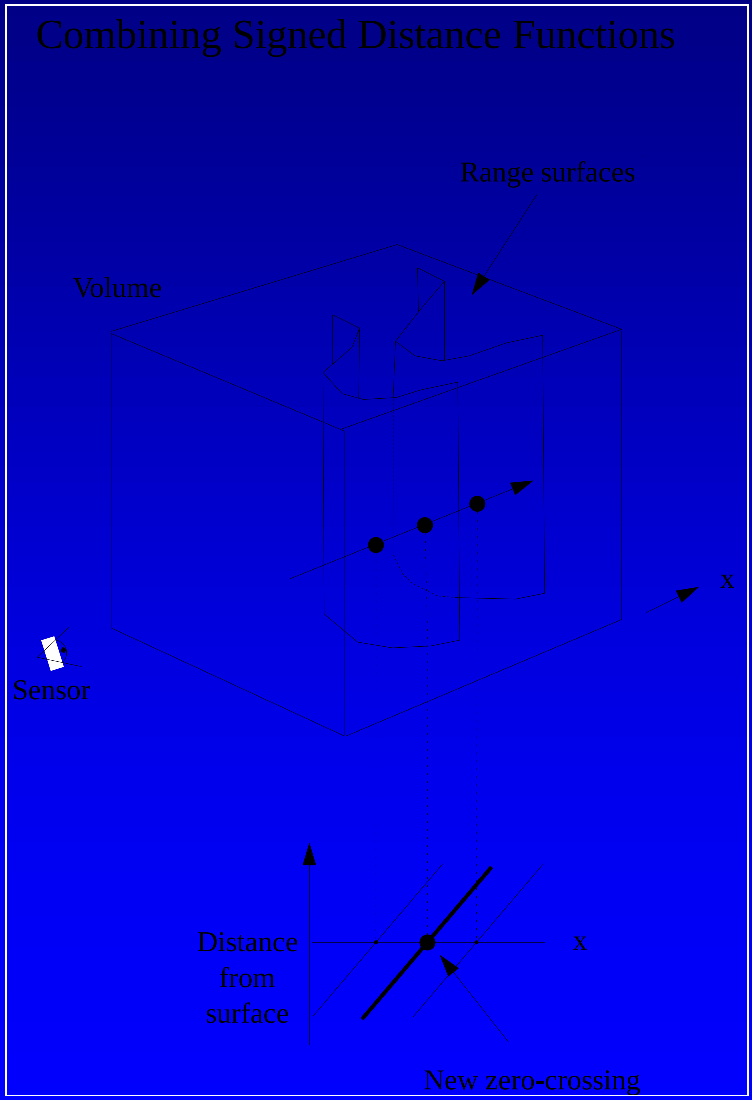
Overview:

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

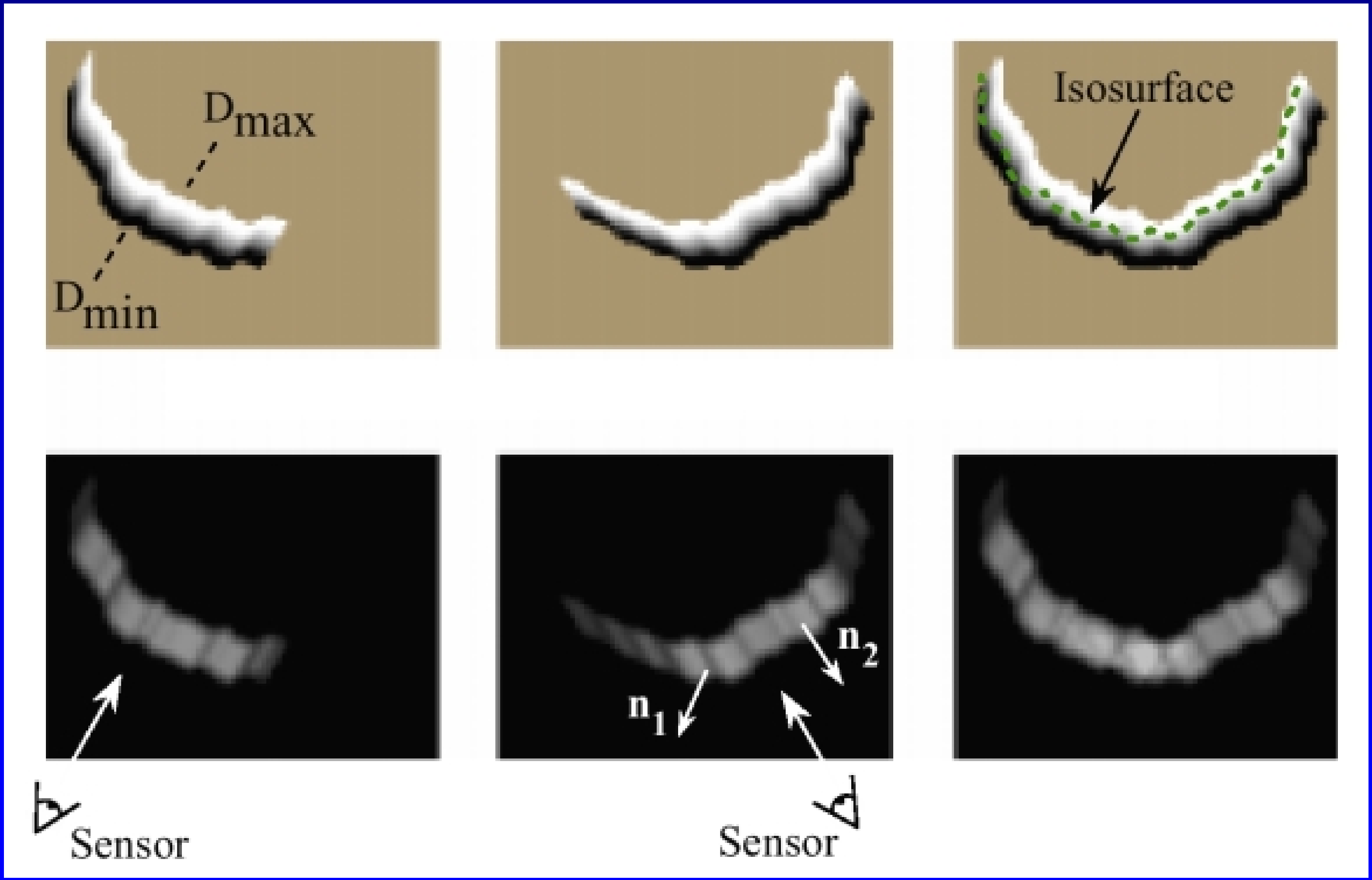
Signed distance function



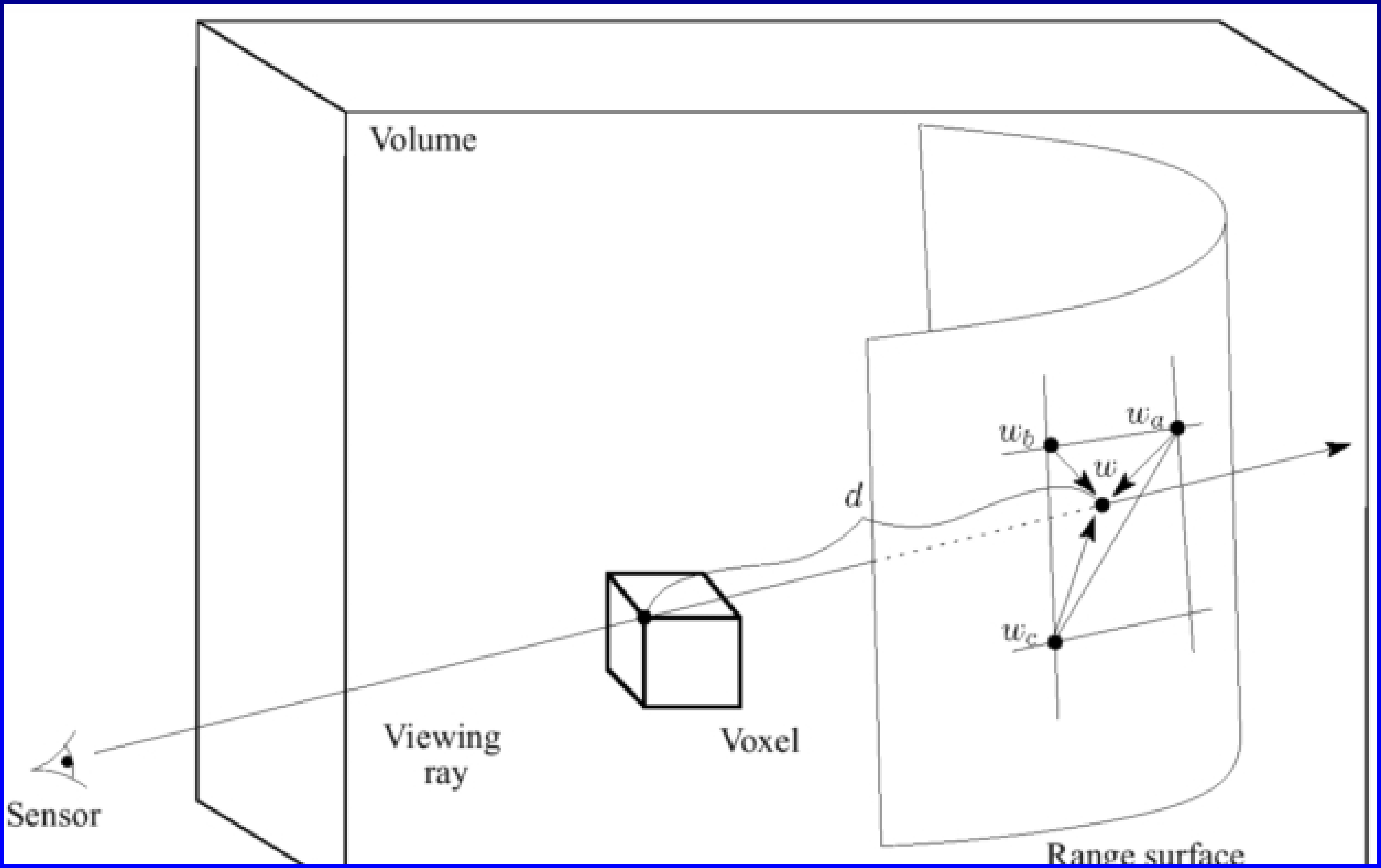
Combining signed distance functions



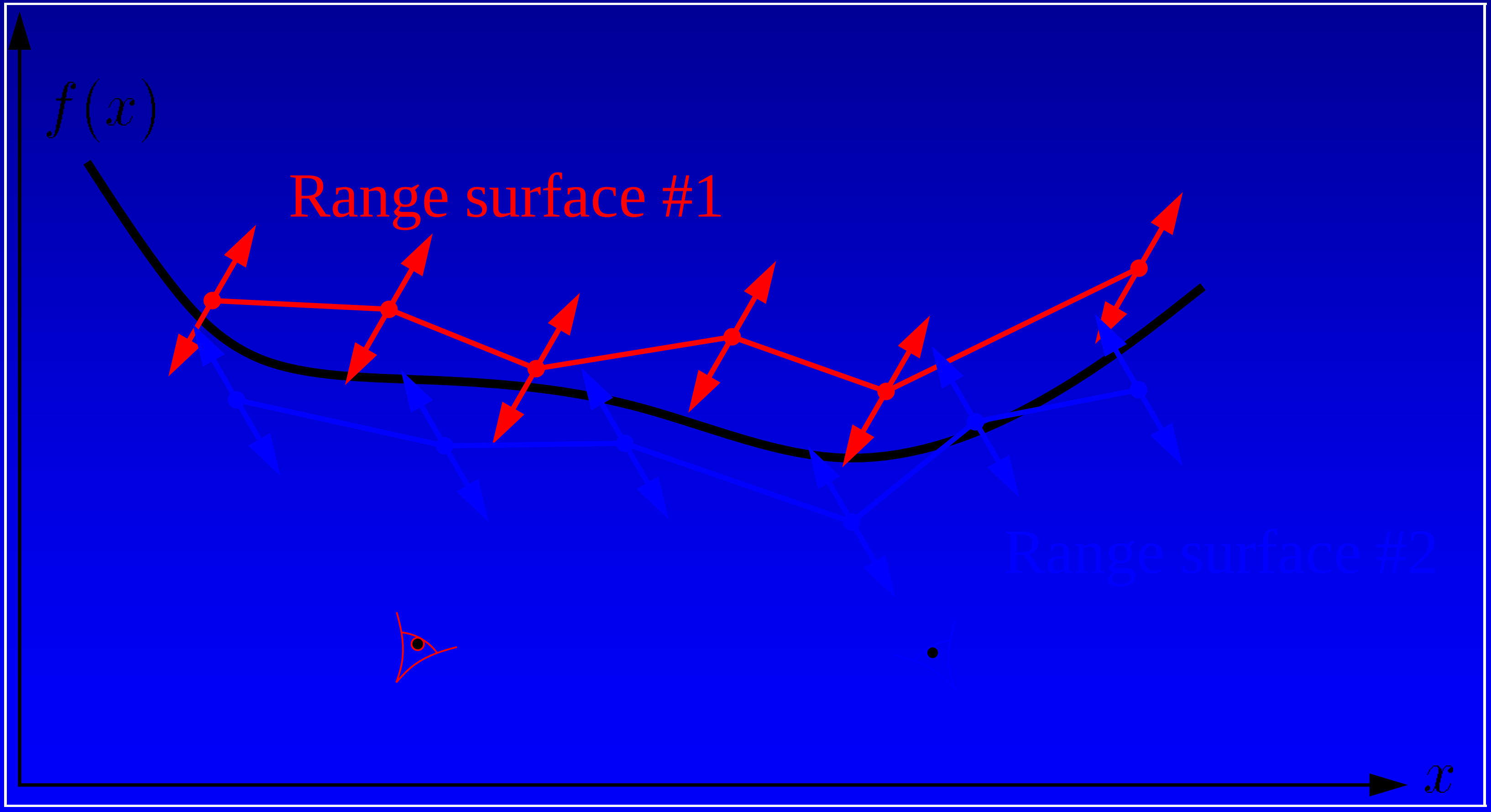
Merging surfaces in 2D



Merging surfaces in 3D



Least squares solution



Least squares solution

Error per point

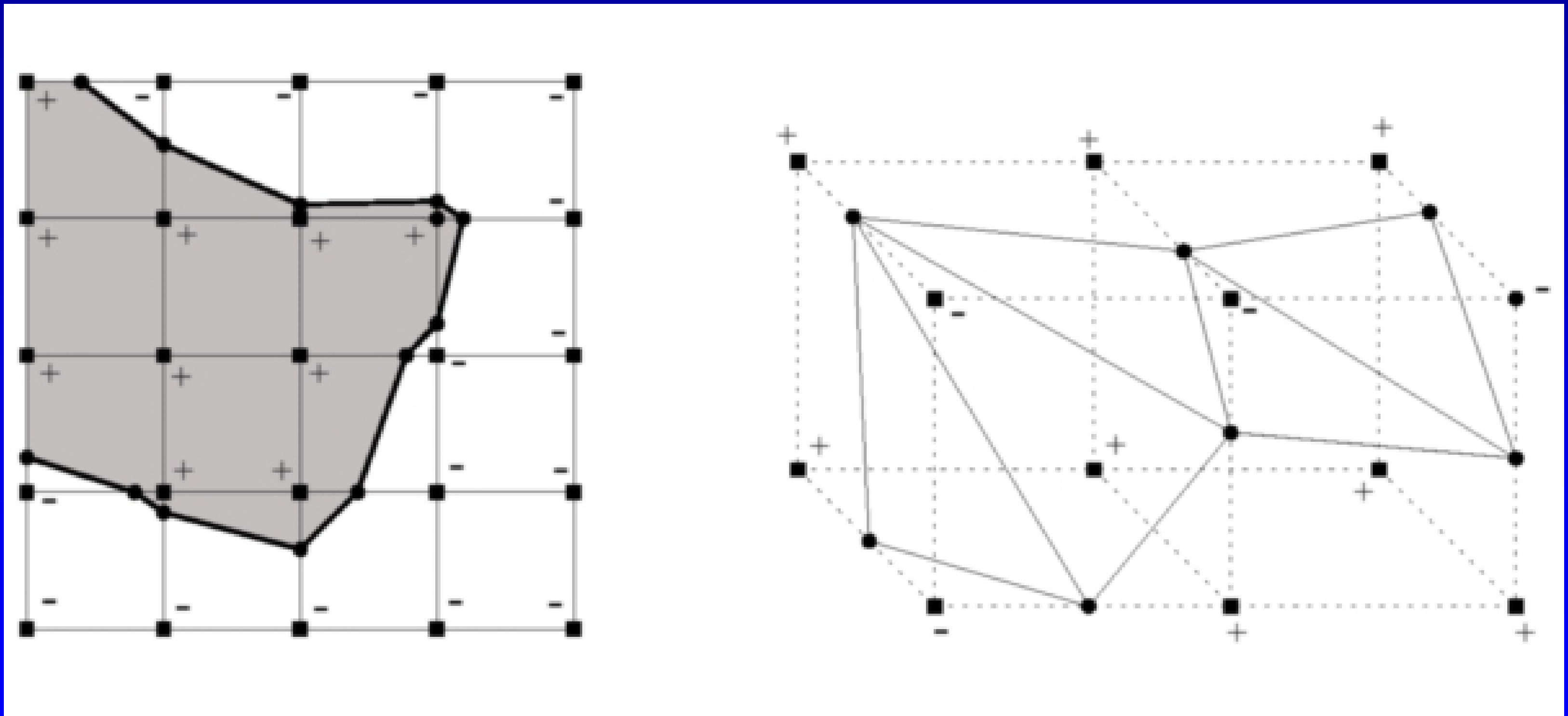
$$E(f) = \sum_{i=1}^{N} \int d_i^2(x, f)\,dx$$

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.

Isosurface Extraction



Hole Filling

The procedure so far will reconstruct a mech from the observed surface. Unseen portions will appear as holes in the reconstruction.

A hole-free, manifold mesh is useful for:

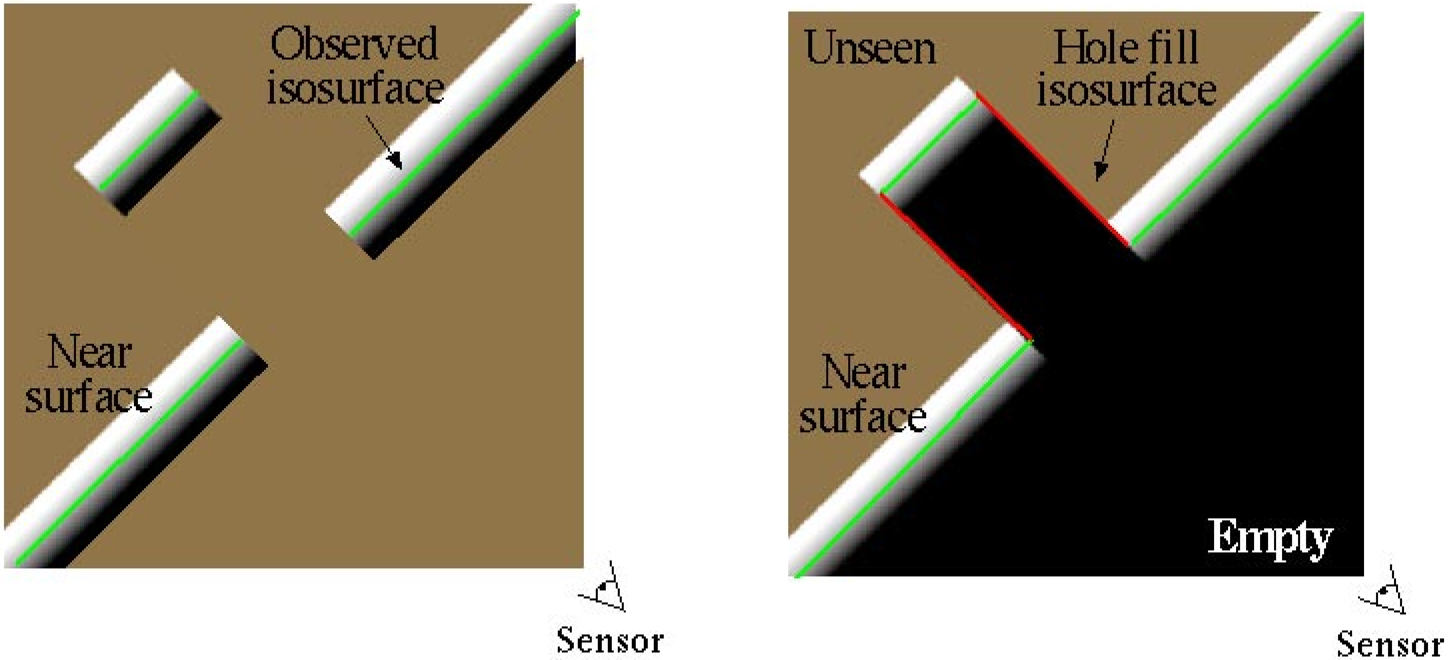
- ***Fitting surfaces to meshes***
- ***Manufacturing models***
- ***Aesthetic rendering***
- ***Conversion into high-level representations?***
- ***Object classification/identification?***

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*

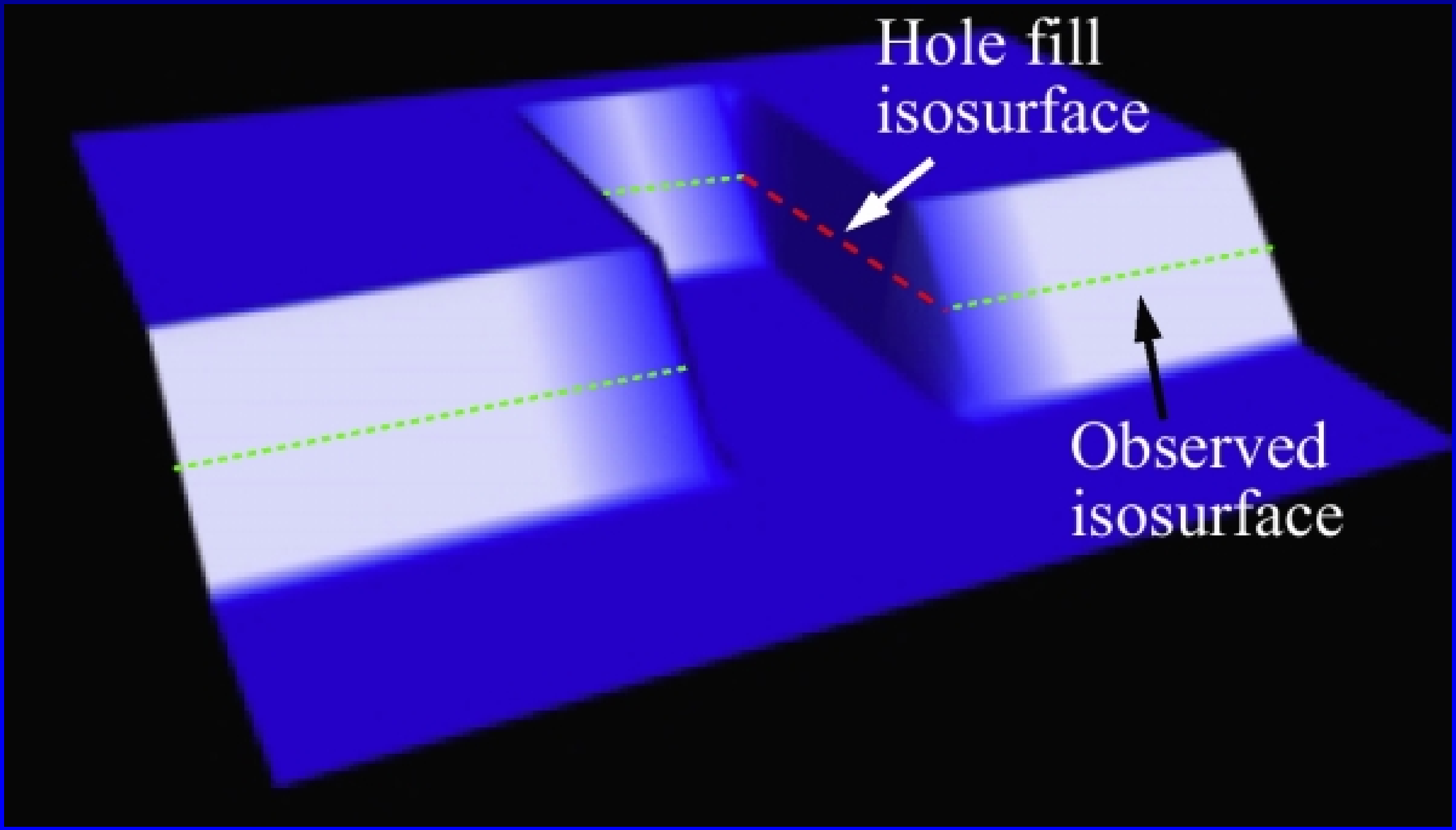
Space carving



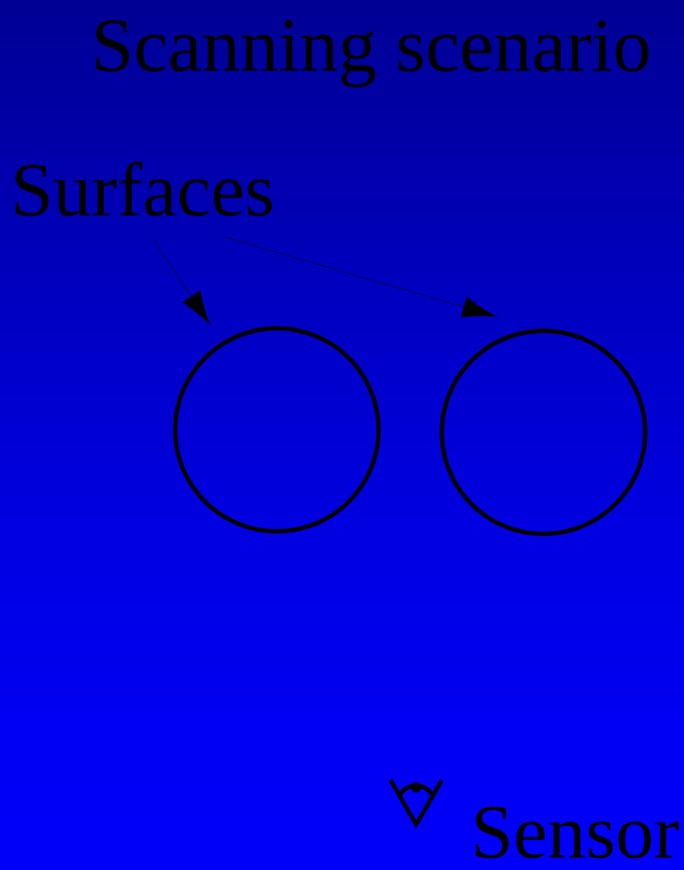
Without space carving

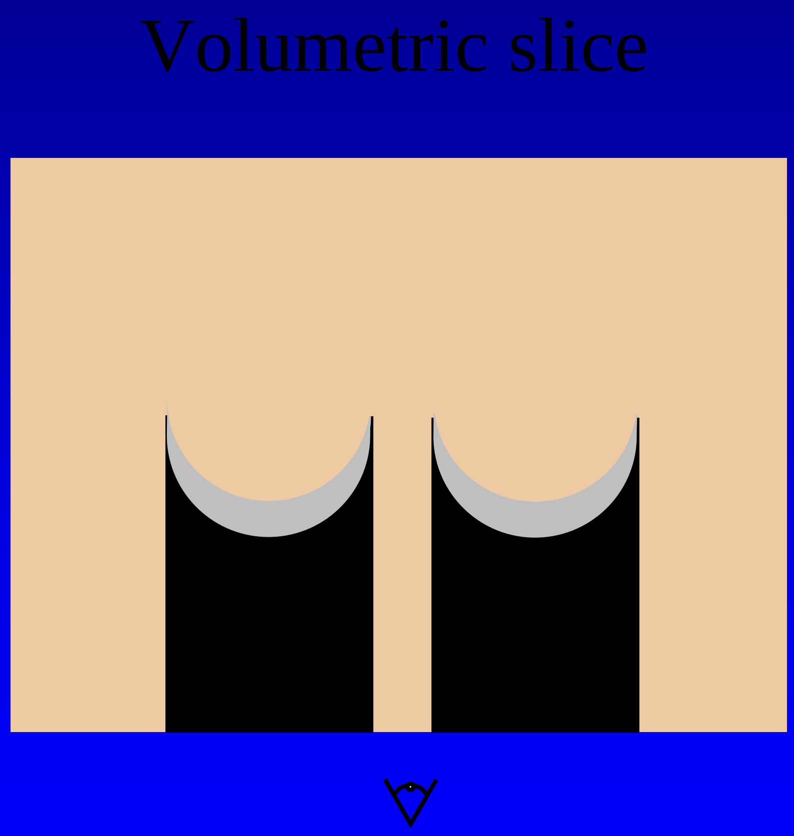
With space carving

Space carving

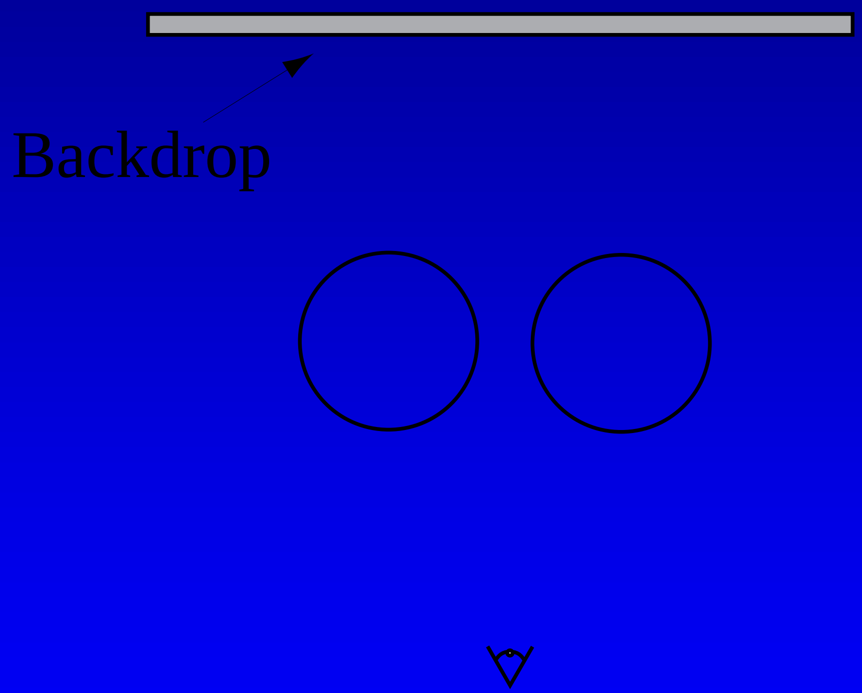


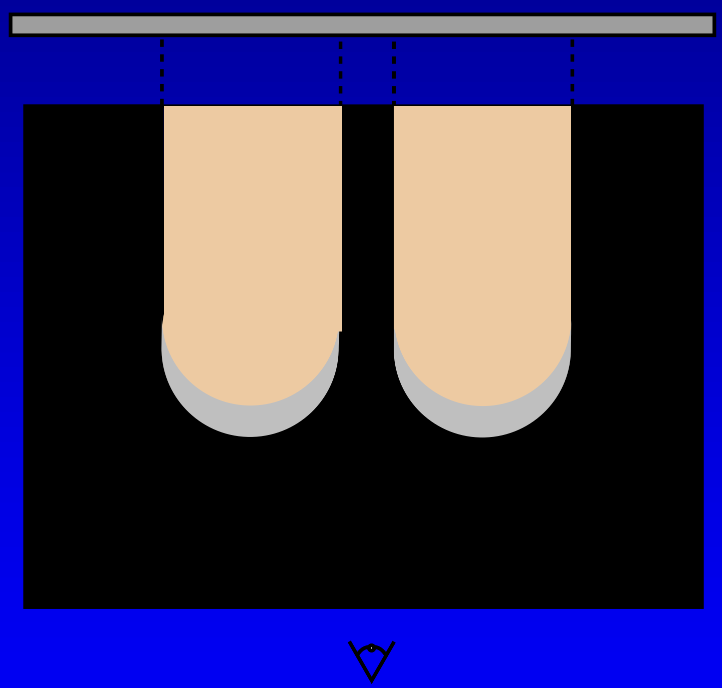
Carving *without* a backdrop



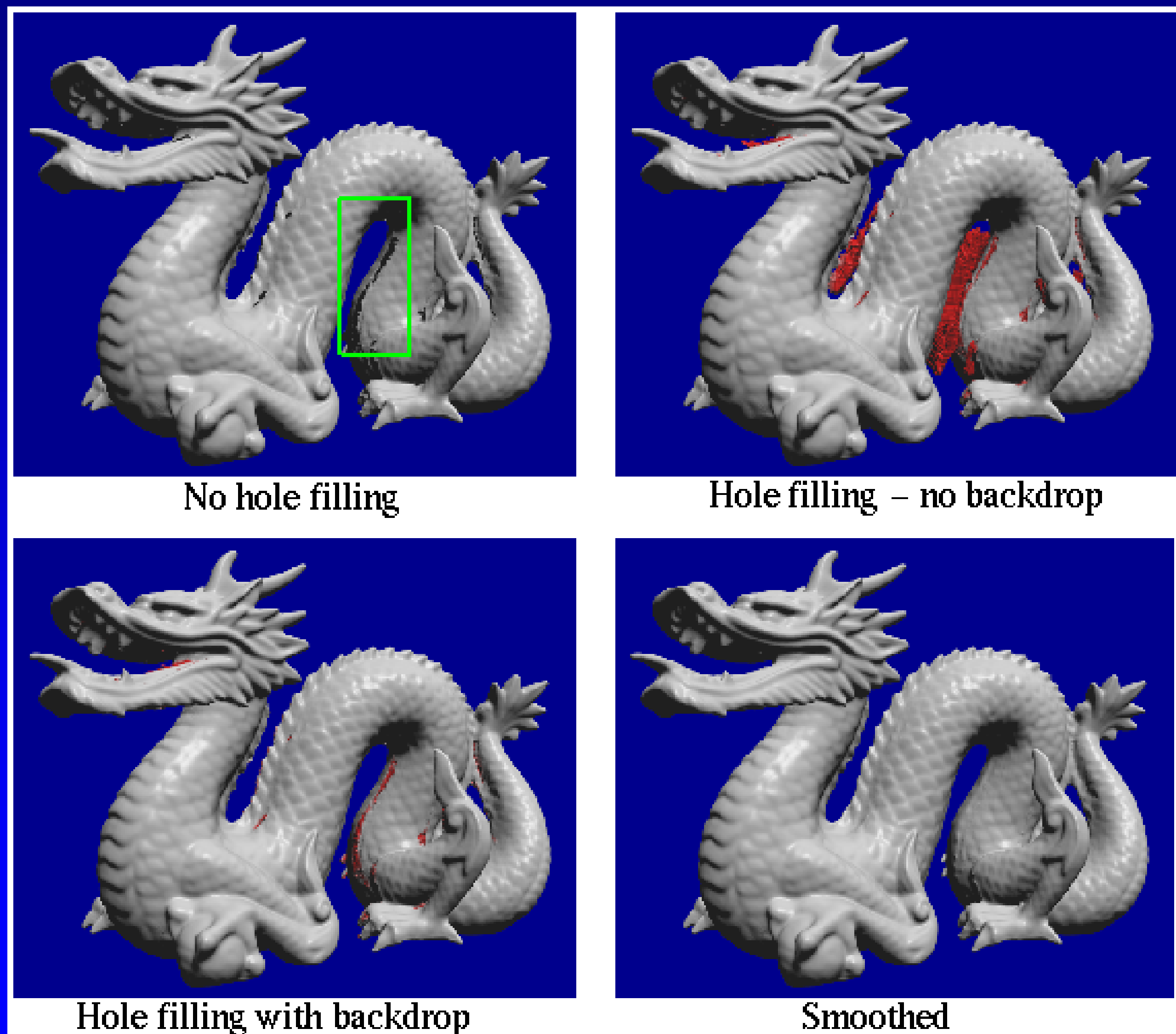


Carving *with* a backdrop

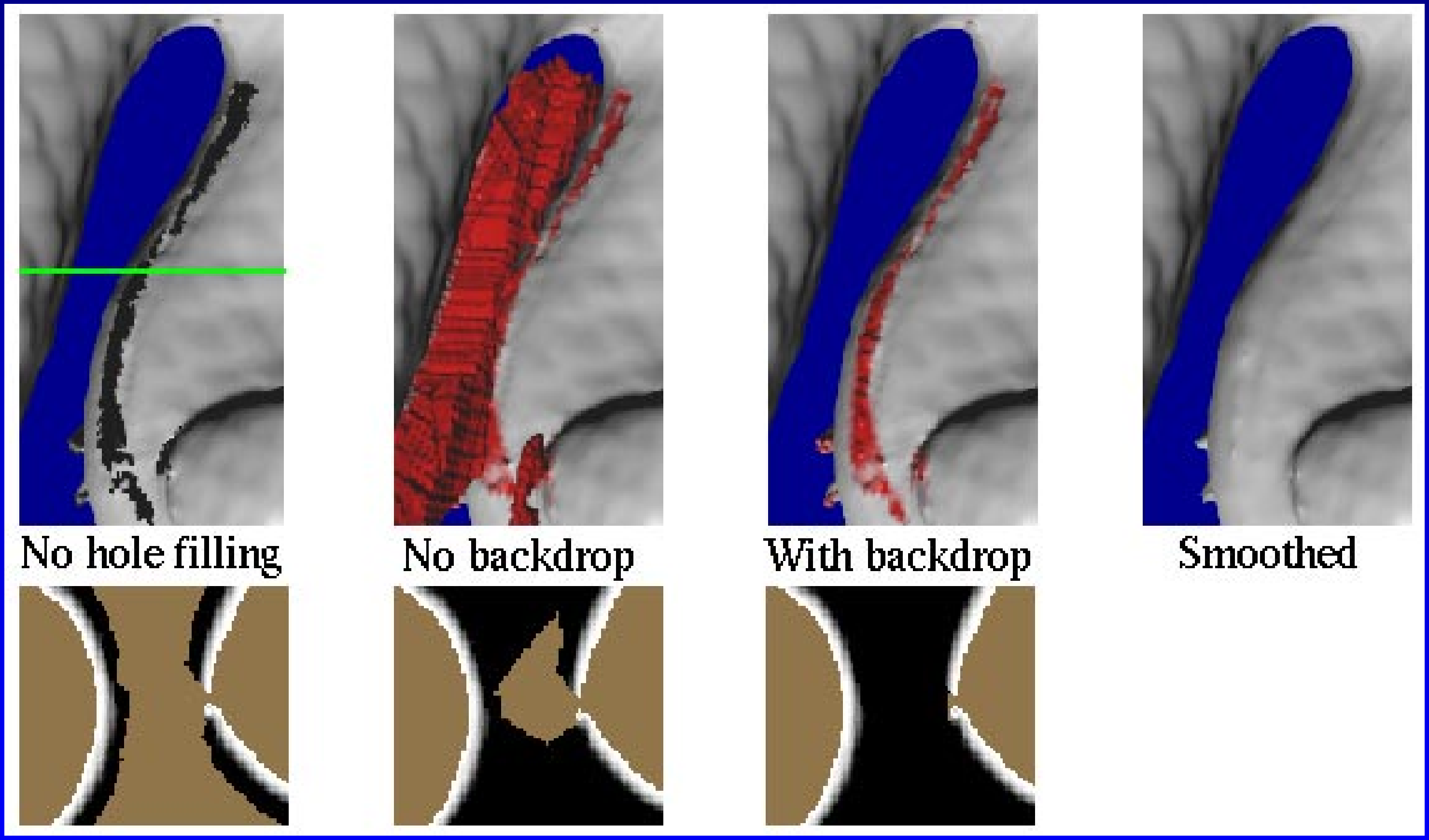




Dragon model

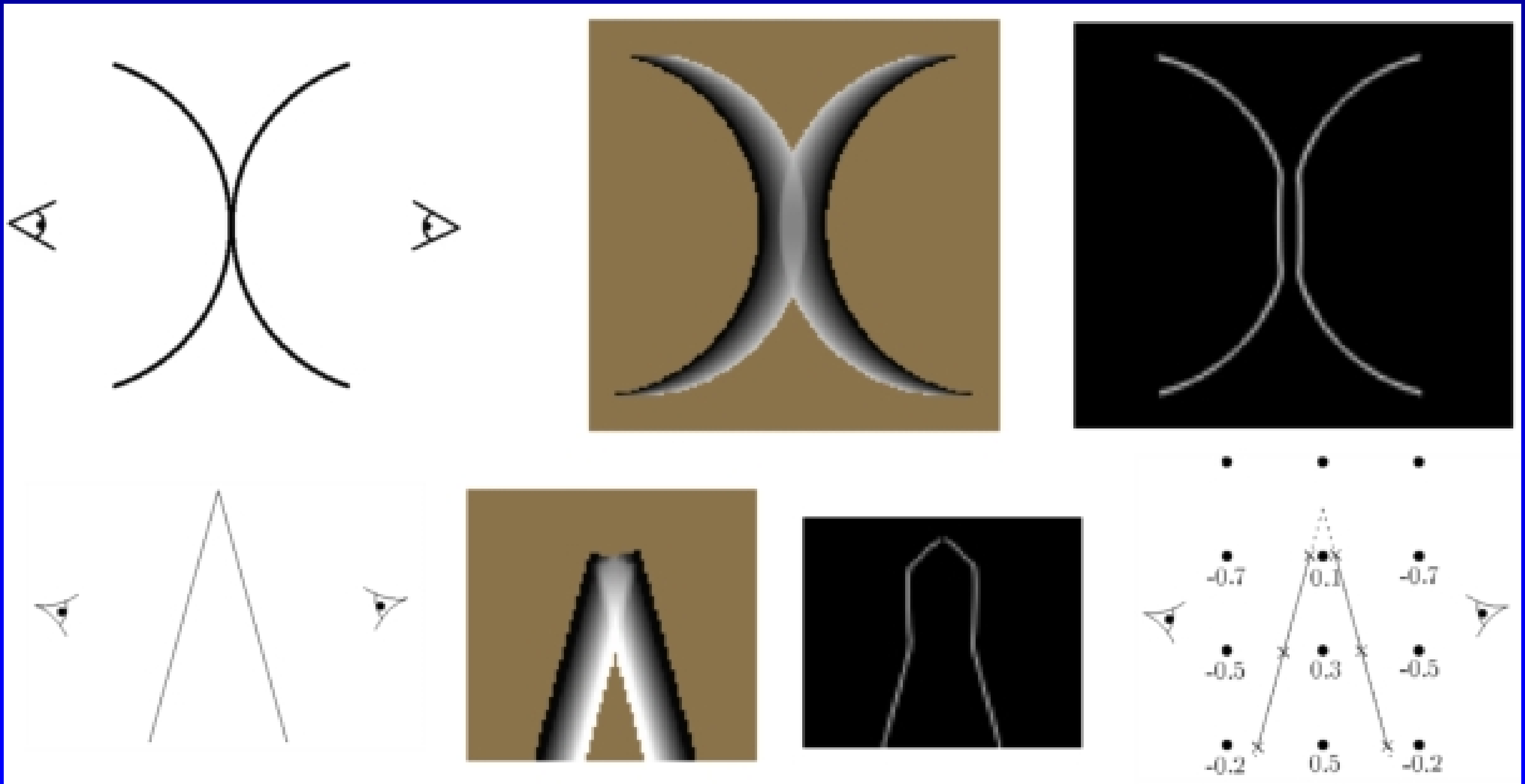


Dragon model

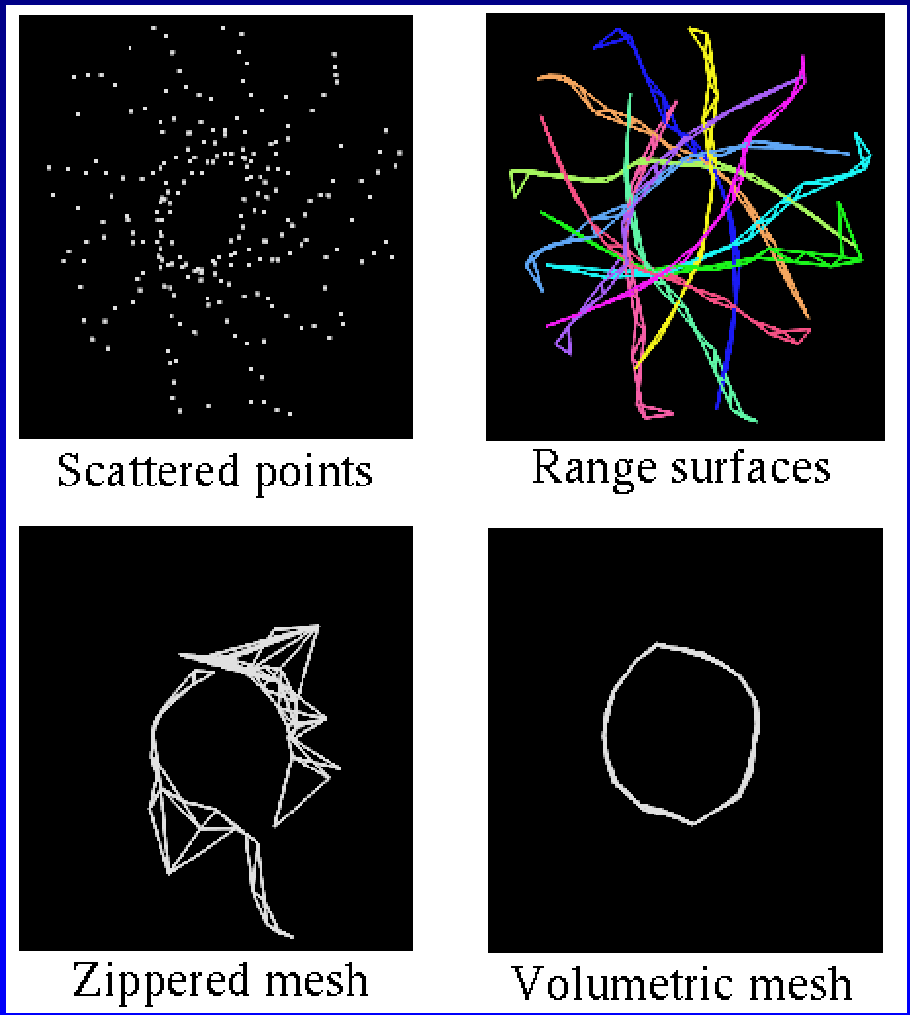


Volumetric approach limitations

Minimum thickness and edge sharpness have limits.



Merging 12 views of a drill bit



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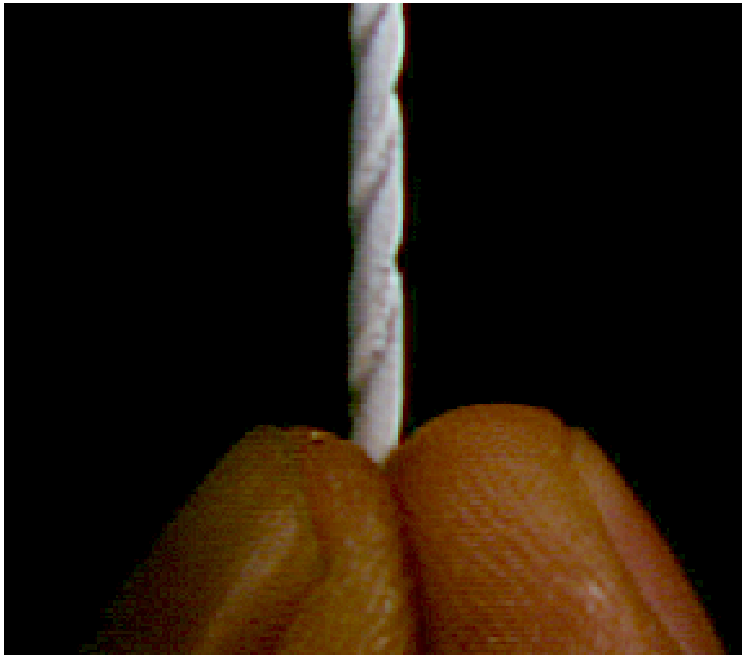
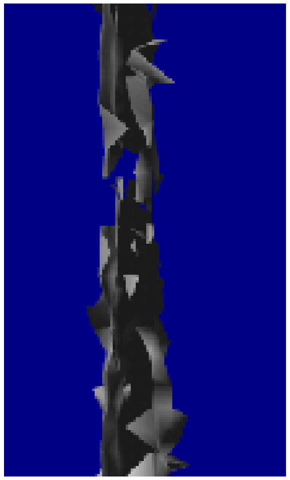
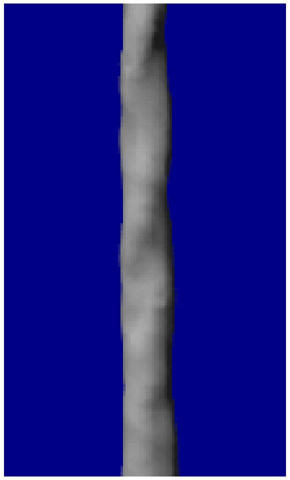


Photograph of painted drill bit

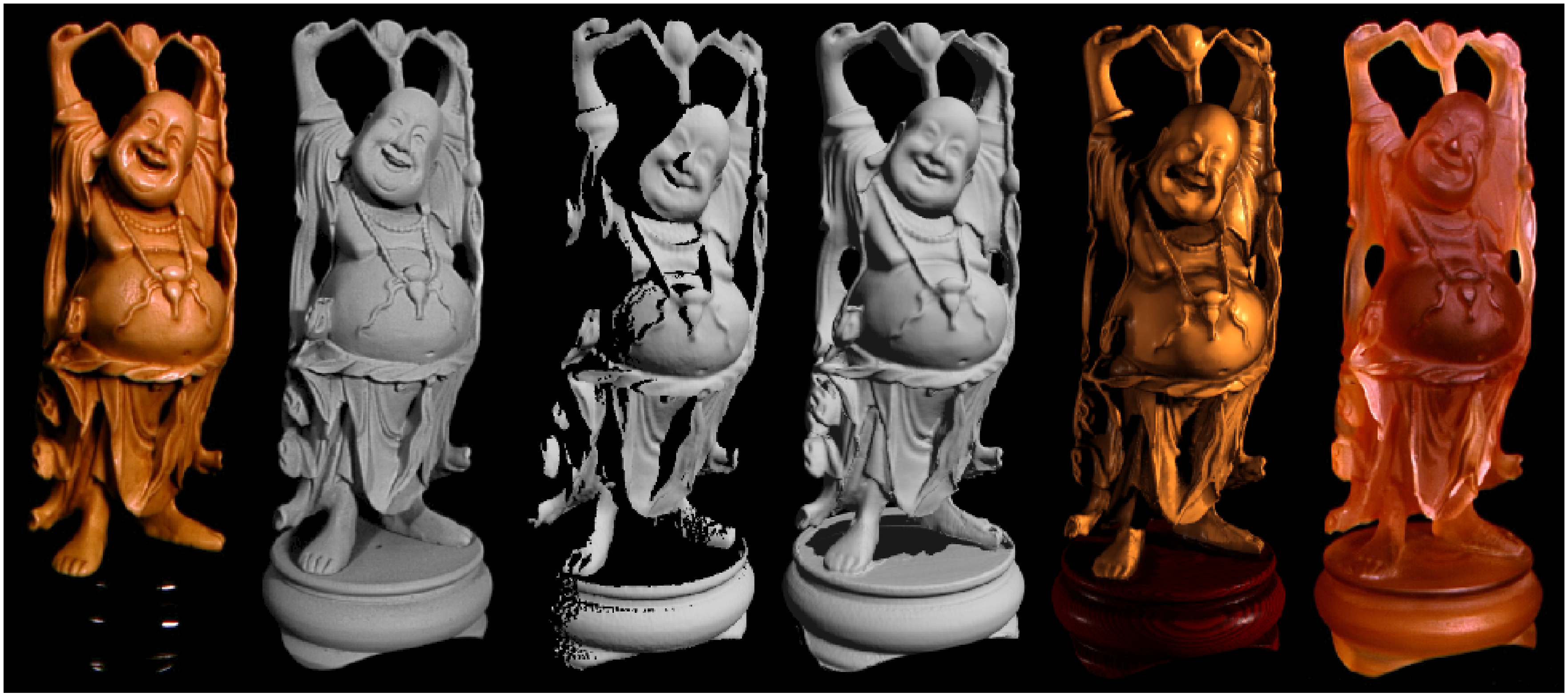


Zippered mesh



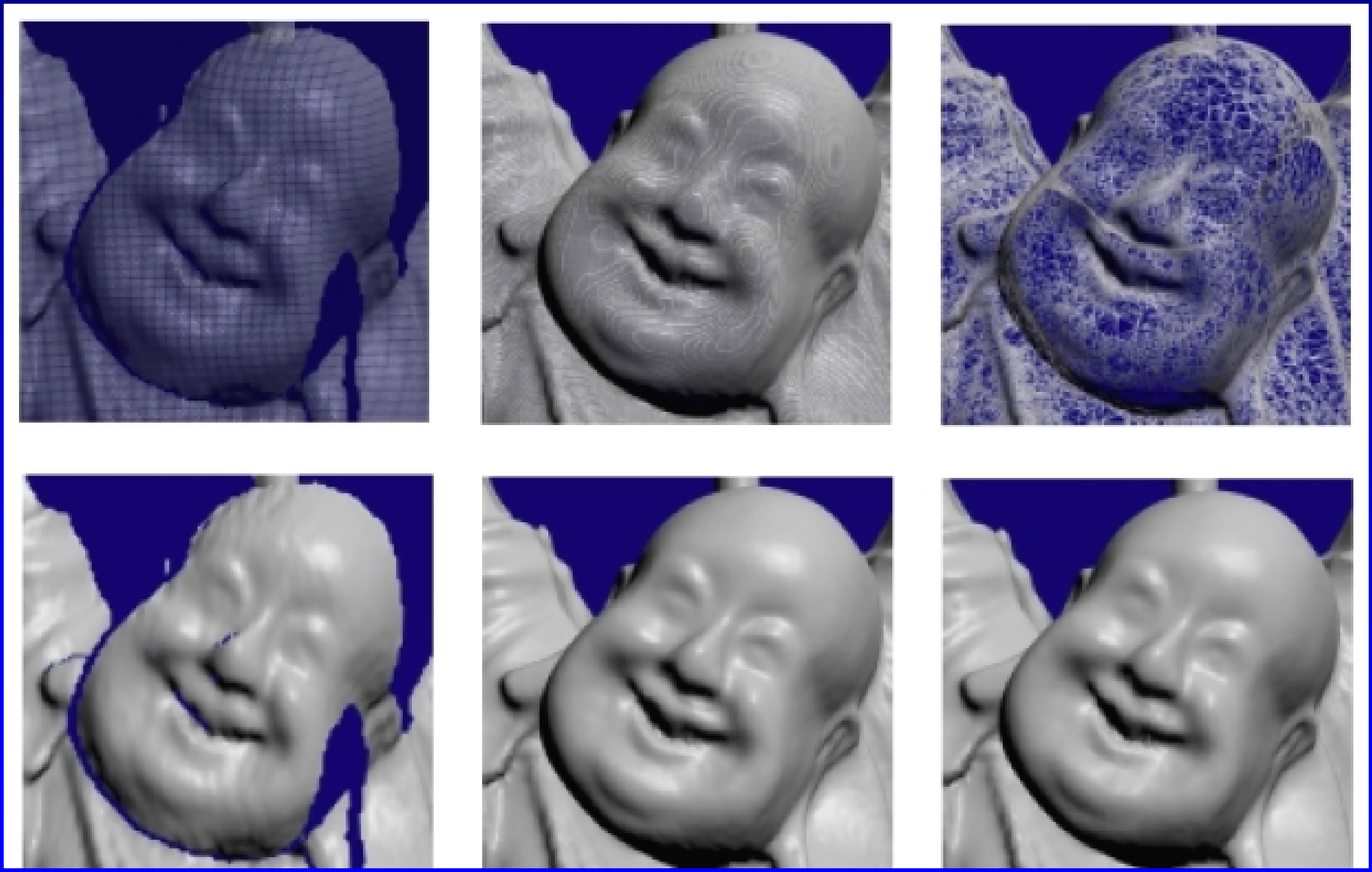
Volumetric mesh

Happy Buddha



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

More Happy Buddha



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Performance Statistics

Model	Scans	Input triangles	Voxel size (mm)	Volume dimensions	Exec. time (min.)	Output triangles	Holes
Dragon	61	15 M	0.35	712x501x322	56	1.7 M	324
Dragon + fill	71	24 M	0.35	712x501x322	257	1.8 M	0
Buddha	48	5 M	0.25	407x957x407	47	2.4 M	670
Buddha + fill	58	9 M	0.25	407x957x407	197	2.6 M	0

Bibliography

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