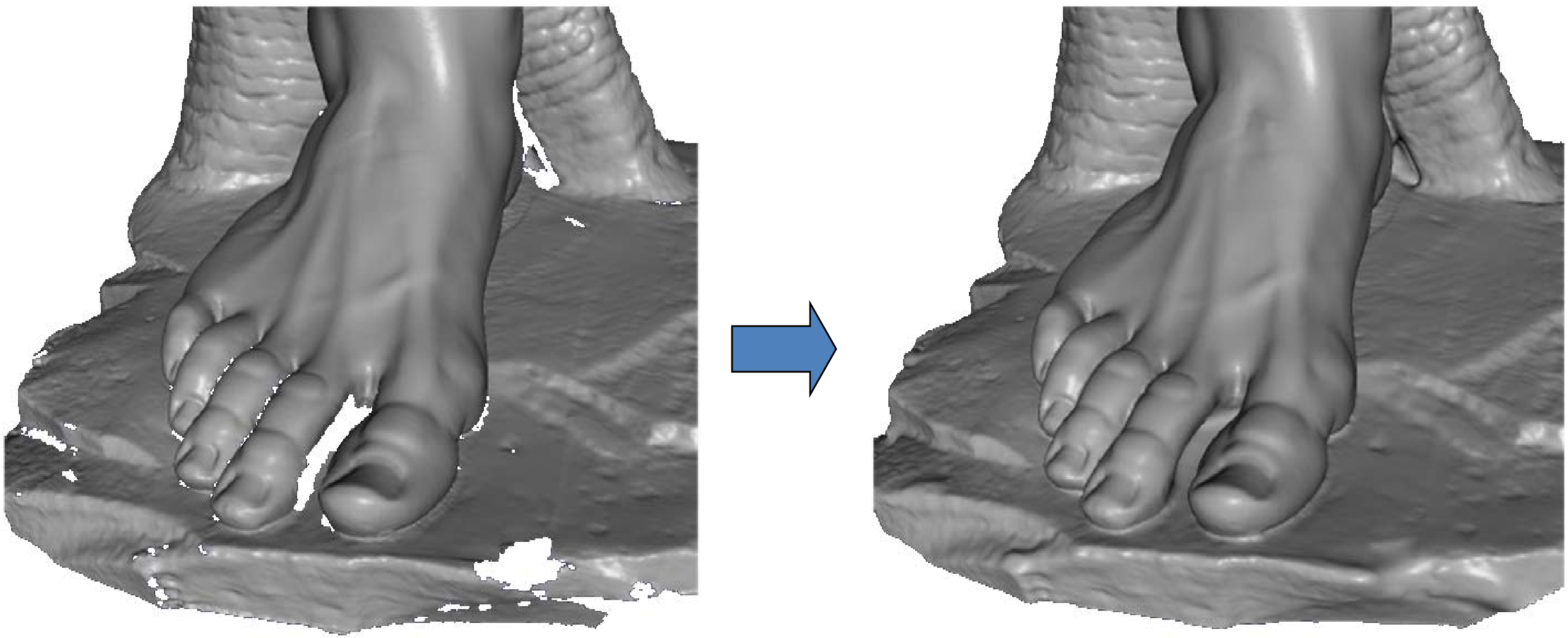
Surface Completion

Ligang Liu
Graphics&Geometric Computing Lab
USTC
http://staff.ustc.edu.cn/~lgliu

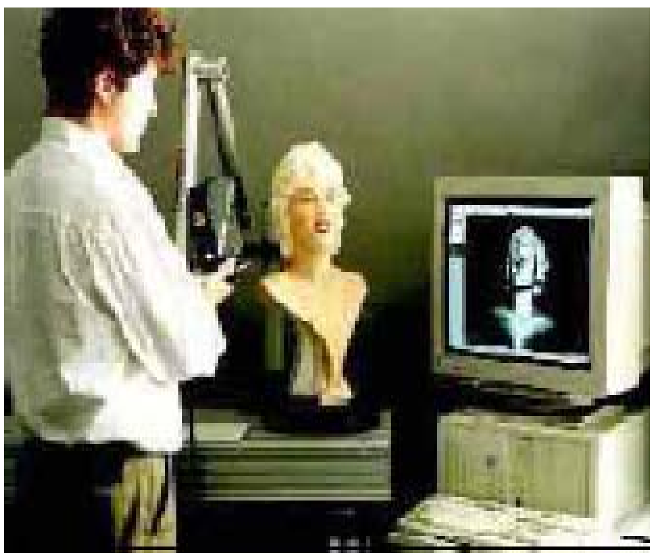
Problem

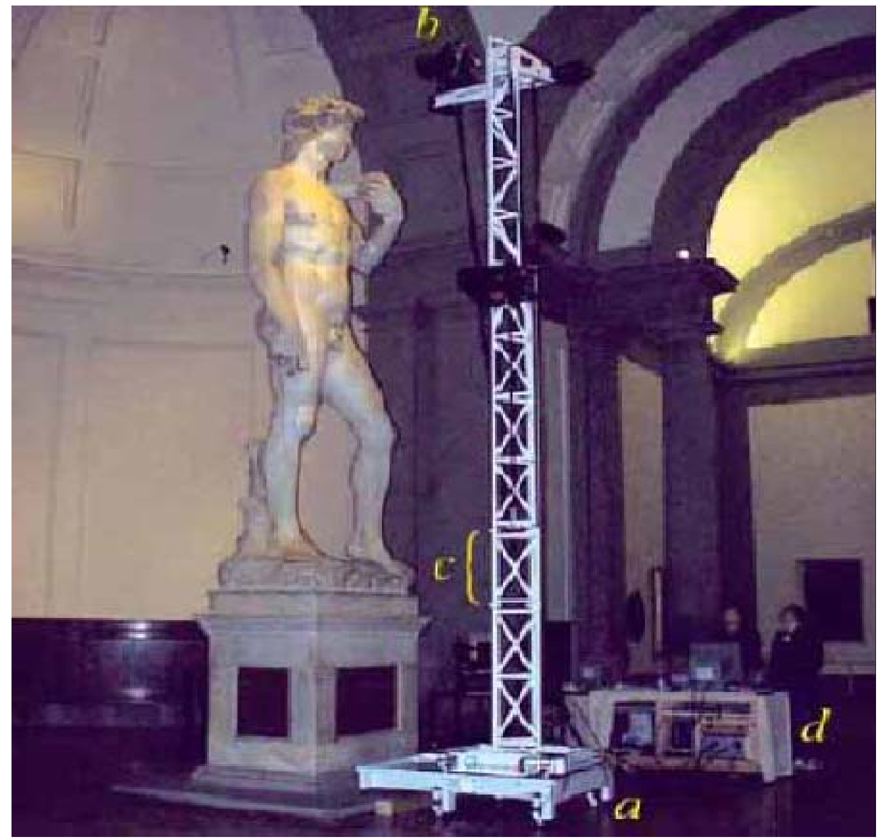
- Filling holes in surface



Background

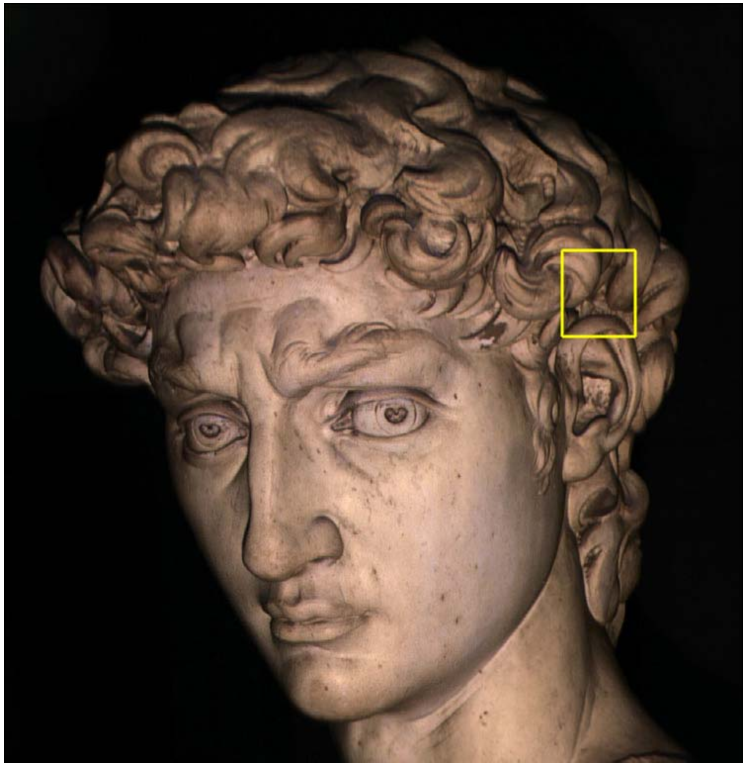
- **Data acquisition**

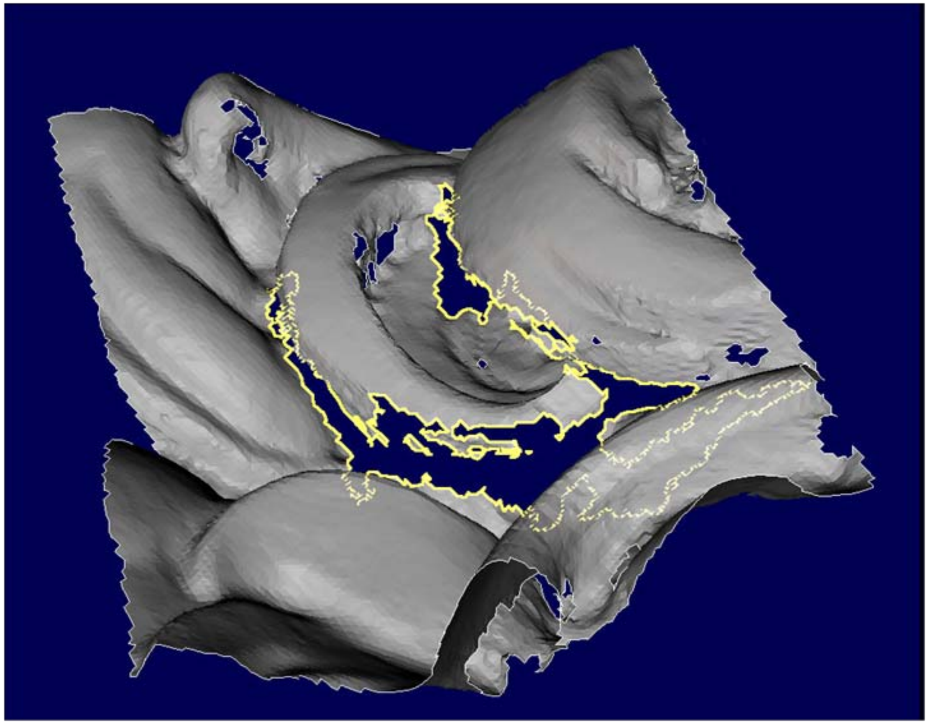




Background

- Surface reconstruction





Surface Completion

- Integrated into surface reconstruction algorithm
- Considered as a post-processing

Other Terminologies

- Surface completion
- Surface inpainting
- Surface repairing
- Surface hole filling
- Surface restoration

Outline

- Image inpainting
- Surface completion
  - Geometric method
  - Volumetric method
  - Texture synthesis based method

1. Image Inpainting

Image Inpainting

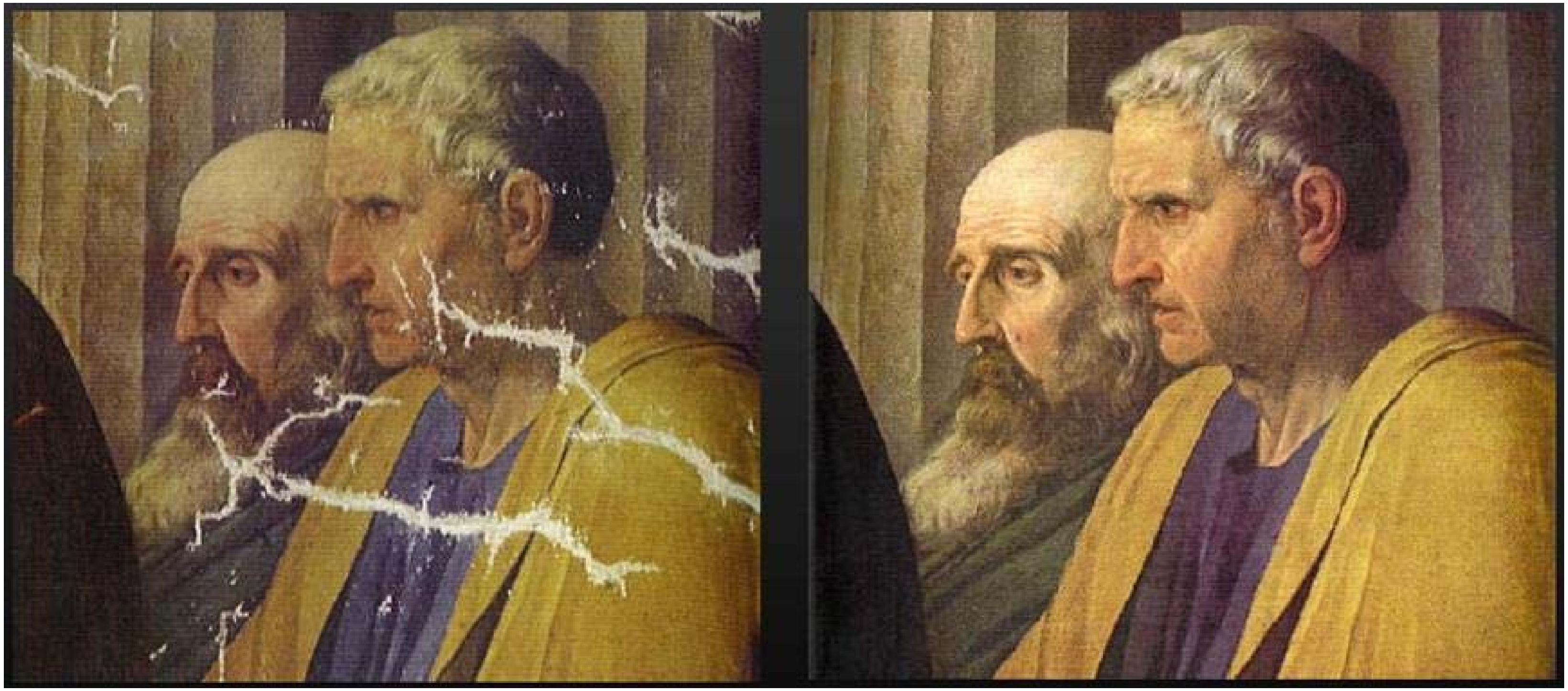
- Objectives
  - Modify the image in a way that is non-detectable by an observer (fill holes in image)
  - Remove objects from the image
- Originated from museum restoration artists
  - Also known as “retouching”
- Less information present within the region to be inpainted

Revised Definition

"Digital Image Inpainting is an iterative method for repairing damaged pictures or removing unnecessary elements from pictures"

"Fast Digital Image Inpainting",
Manuel M. Oliveira, Brian Bowen, Richard McKenna and Yu-Sung Chang

Photo Restoration



"Image Inpainting : An Overview",
Guillermo Sapiro

Object Removal

Related Work: Films

- e.g. Kokaram et al.

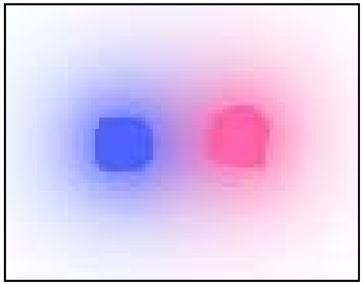
- Doesn't work for stills or static objects

In the Literature

- Image Inpainting
  - Bertalmio and Sapiro , Siggraph 2000
- Level Lines Based Disocclusion
  - Masnou and Morel , ICIP 1998
- Fast Digital Image Inpainting
  - Oliveira et al., ICVIP 2001
- Image Inpainting: An Overview,
  - Sapiro 2002
- Fragment-based Image Completion
  - Drori et al., Siggraph 2003
- Image Completion with Structure Propagation
  - Sun et al., Siggraph 2005

Photoshop

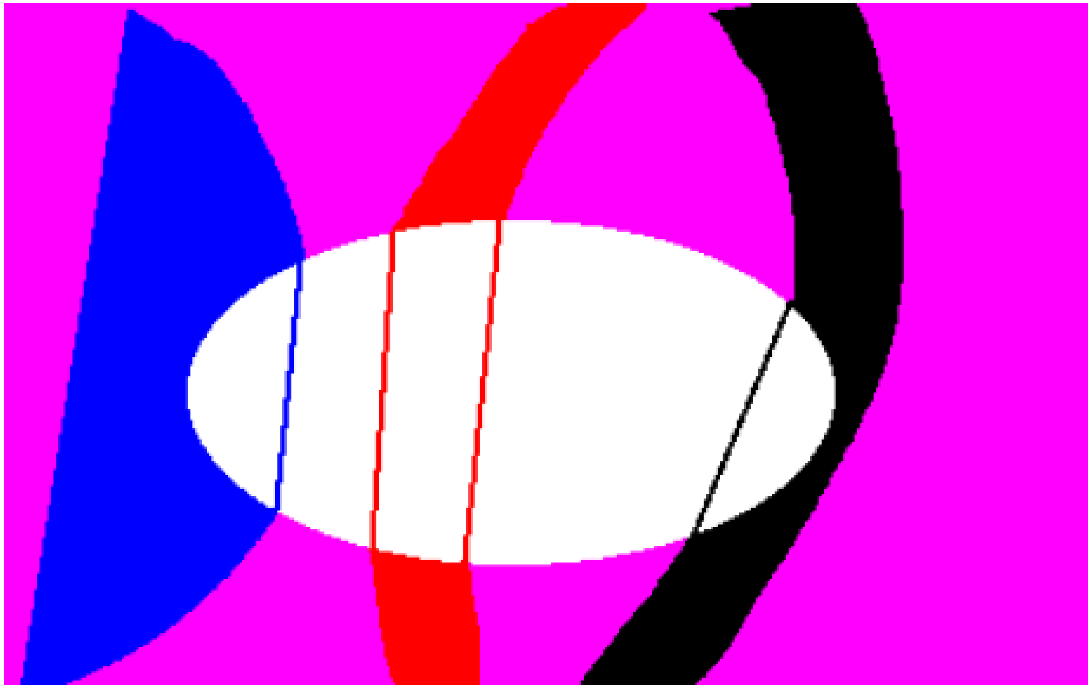
- Photoshop has some utilities for image inpainting
- Diffusion based inpainting
  - ❑ Simplest of all
  - ❑ Colors diffuse into the missing areas of the image
  - ❑ Repeated blurring
  - ❑ Colors of each pixel are averaged with a small portion of the color from the neighboring pixels.



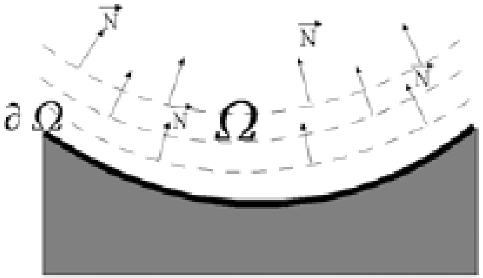
1.1 Level Line Based Method

- Joining with geodesic curves the points of the isophotes (lines of equal gray values) arriving at the boundary of the region to be inpainted
- Drawbacks
  - Inpainted region should have simple topology
  - Angle of level lines is not preserved

Example



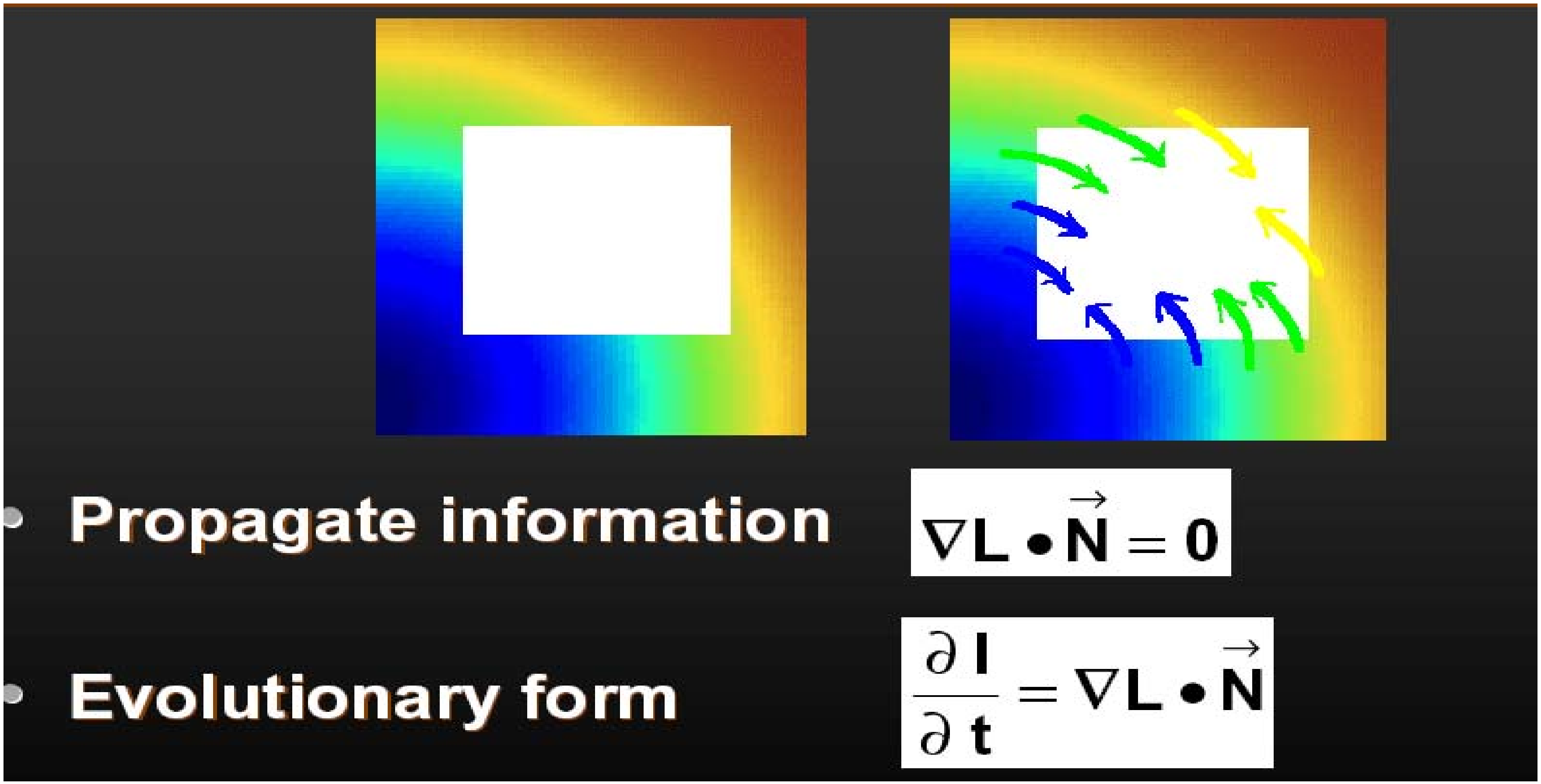
Extension



[Siggraph 2000]

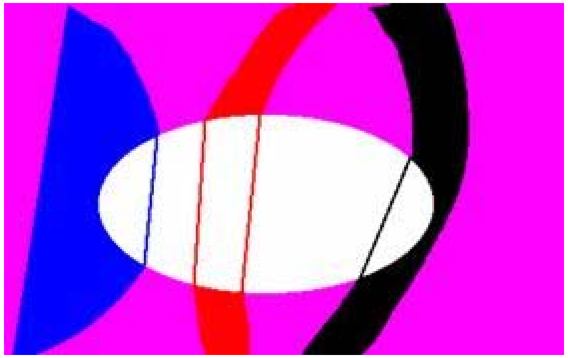
- Apply diffusion to the original image to avoid noise
- Updates to the values of pixels inside the region are made, information propagated in the direction of the isophotes
- After every few iterations, diffusion process is applied
- Propagation of gray values and the isophotes direction is critical
- Color images are considered as a group of 3 images and this technique is applied independently to them

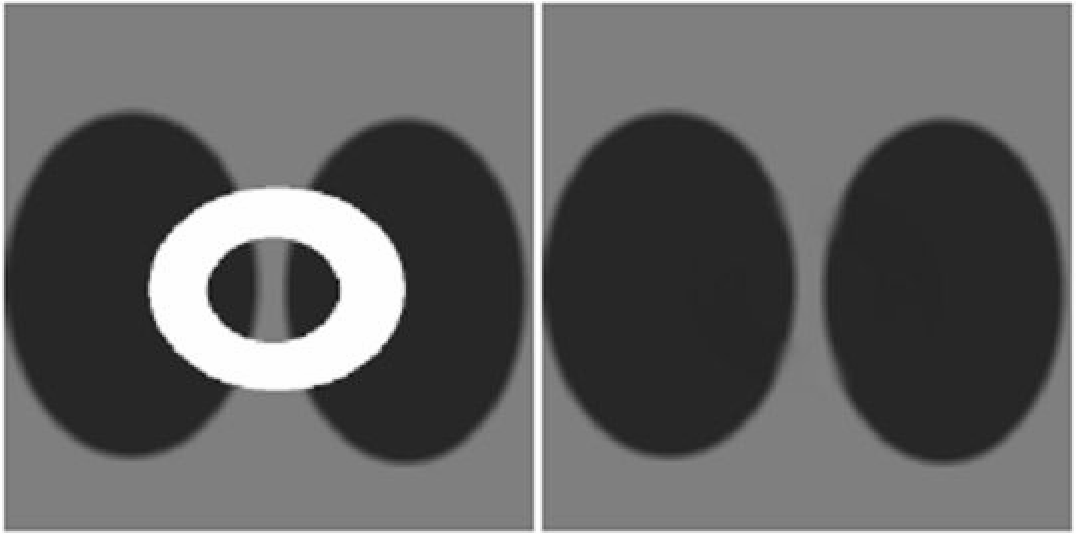
Idea



• Propagate information
$\nabla L \bullet \vec{N} = 0$
• Evolutionary form
$\frac{\partial I}{\partial t} = \nabla L \bullet \vec{N}$

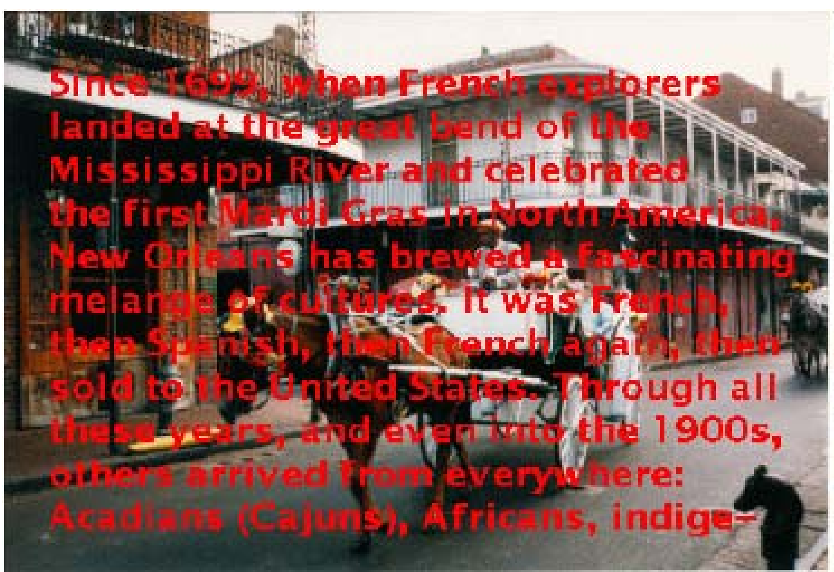
Comparison





Examples

Examples


Since 1699, when French explorers
landed at the great bend of the
Mississippi River and celebrated
the first Mardi Gras in North America,
New Orleans has brewed a fascinating
melange of cultures. It was French,
then Spanish, then French again, then
sold to the United States. Through all
these years, and even into the 1900s,
others arrived from everywhere:
Acadians (Cajuns), Africans, indige-

1.2 Texture Synthesis Based Method

- Use frequency and spatial domain information to fill a given region with a selected texture
- Requires the user to specify which texture to put where
- Will not be preferred when the region to be replaced covers several different structures

Texture Synthesis

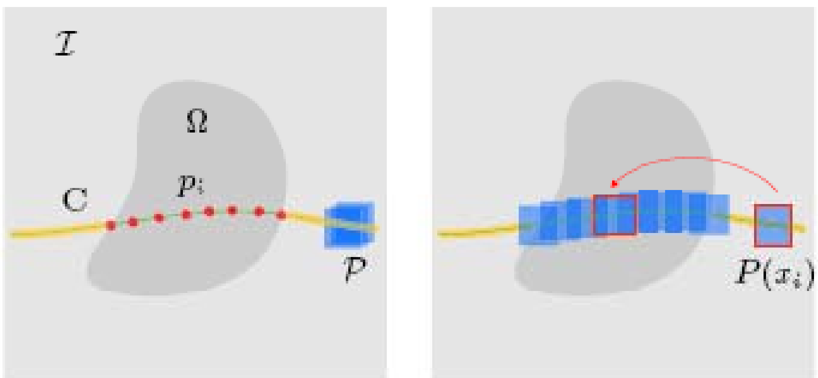
- Hirani, Efros, Heeger, DeBonet, Simoncelli, Zhu, etc.
- Not practical for rich regions
- Not designed for structured regions
- "Copy" information instead of "see and interpolate"

1.3 Structure Propagation

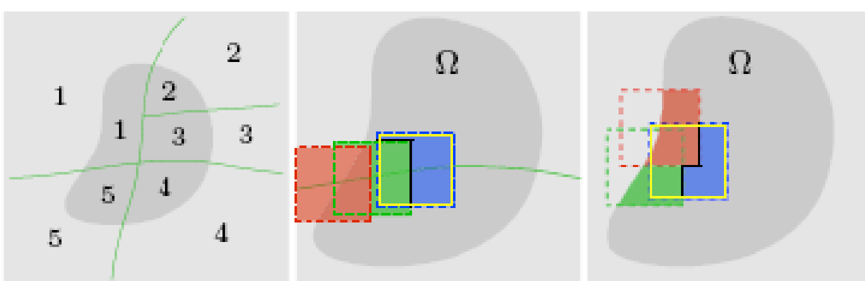
[Siggraph 2005]

- Structure propagation
  - User specified structure curves
- Patch based texture synthesis

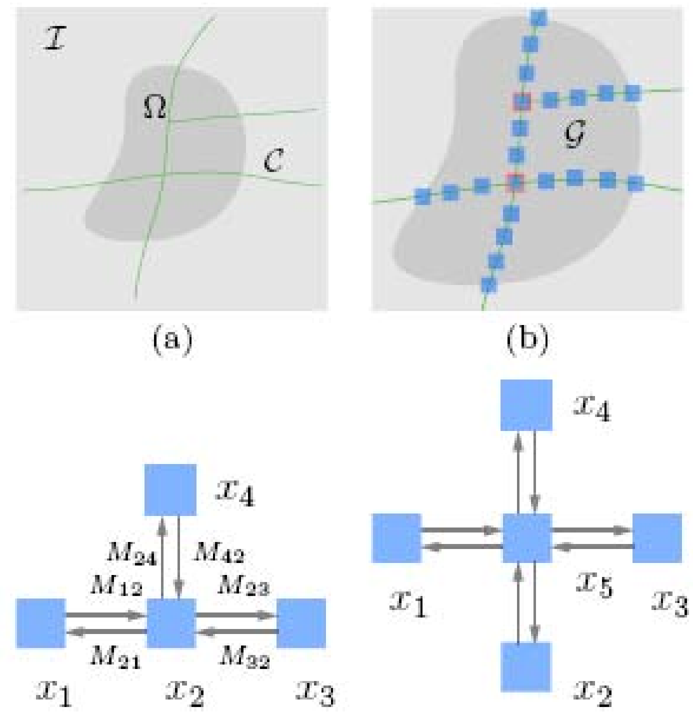
Structure Propagation



1D chain propagation



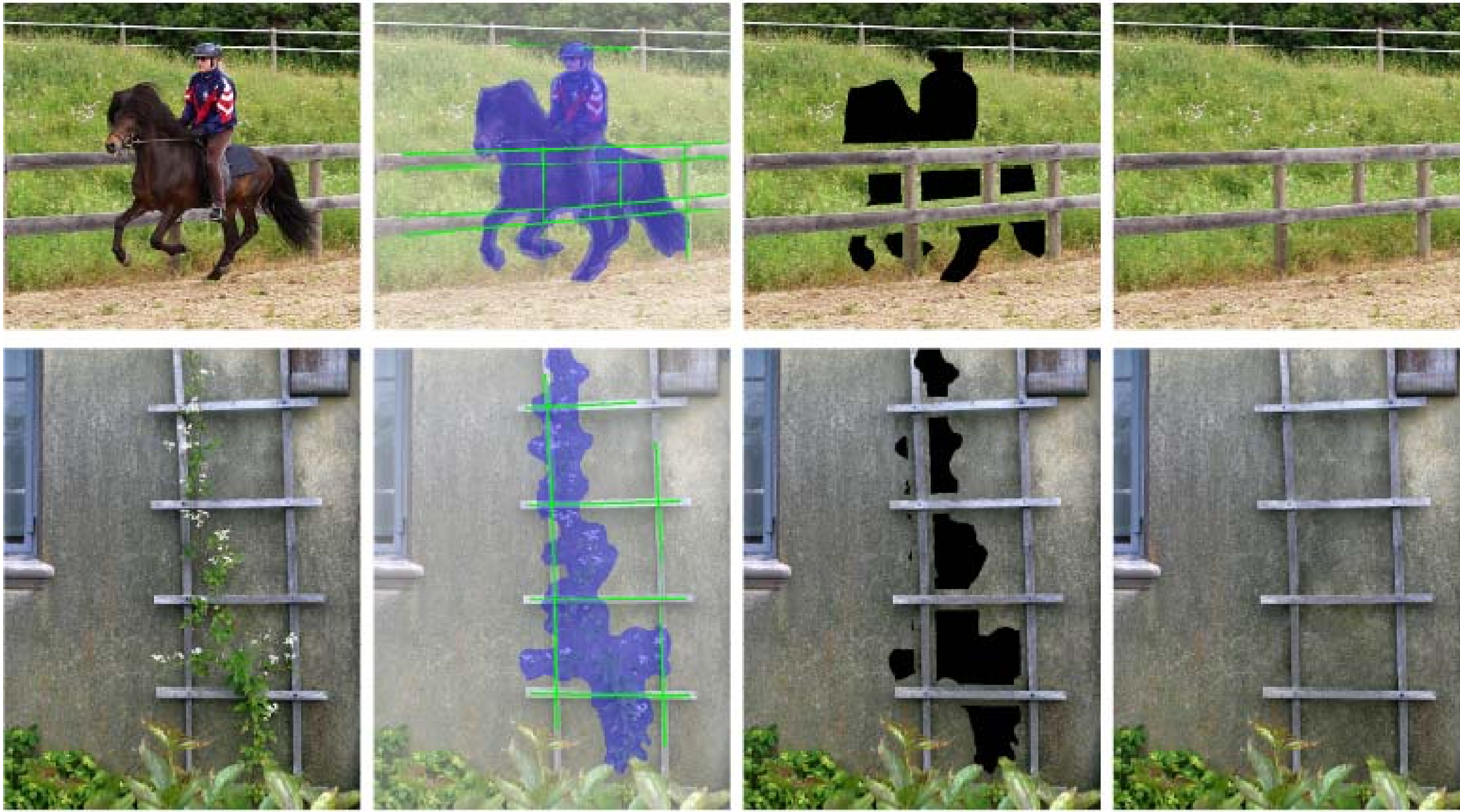
texture propagation



2D graph propagation

Examples

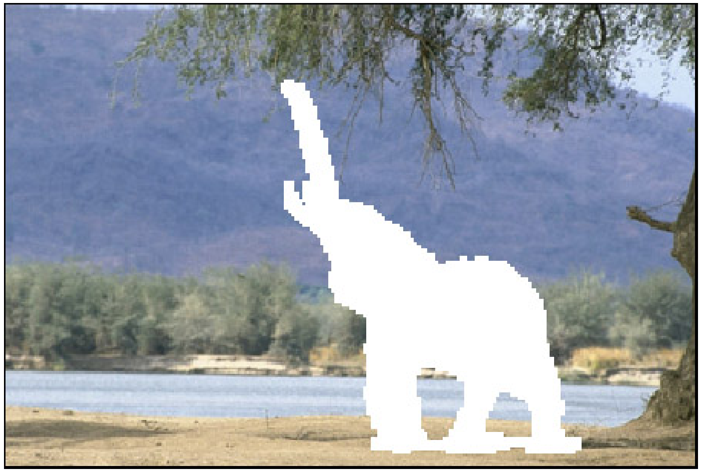
Examples



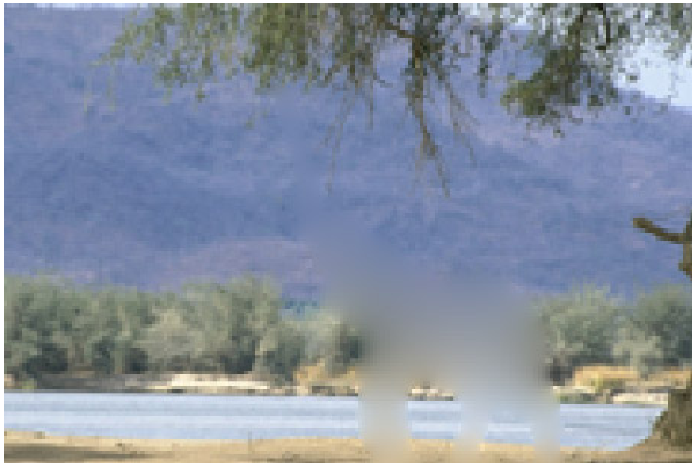
1.4 Fragment-based Method

[Siggraph 2003]

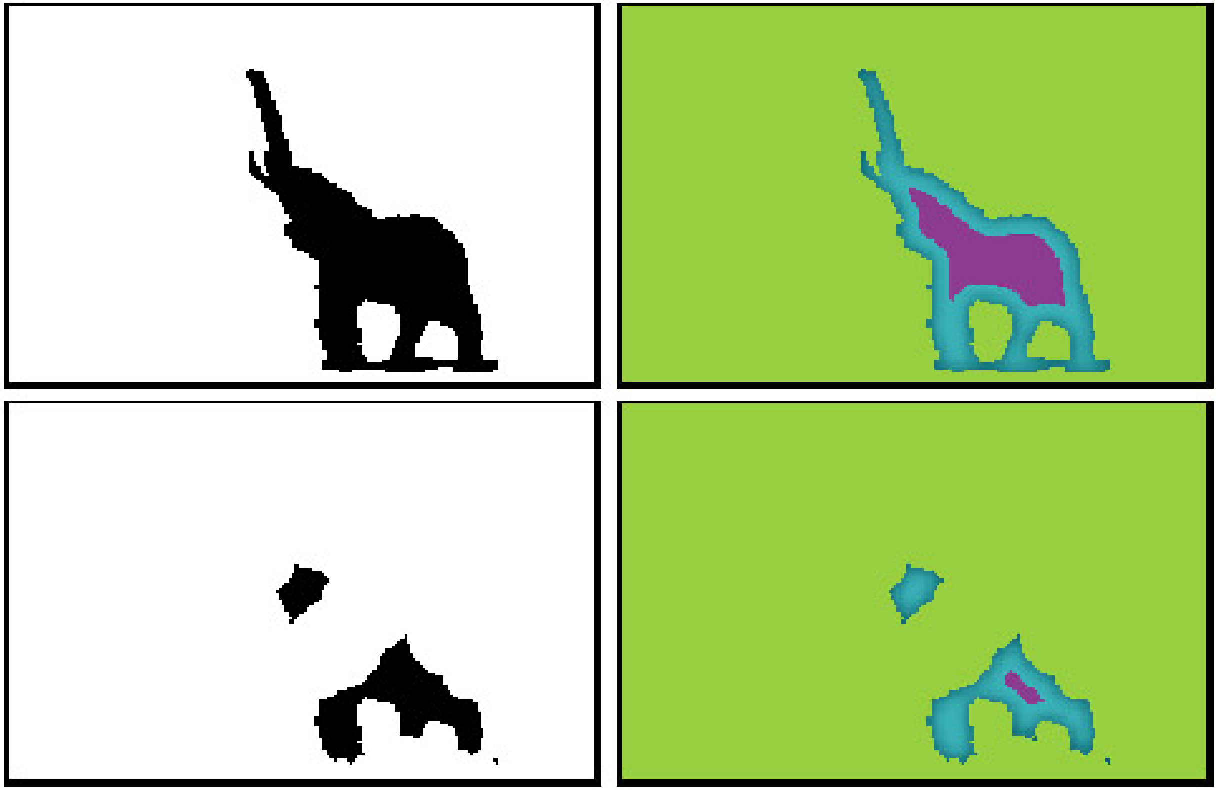
Multiply Image by inverse matte and add matte



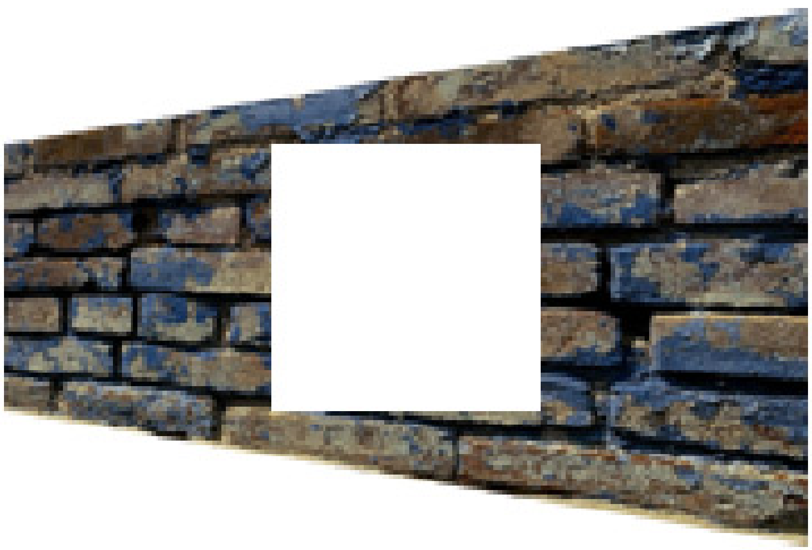
Downsample and upsample with kernel

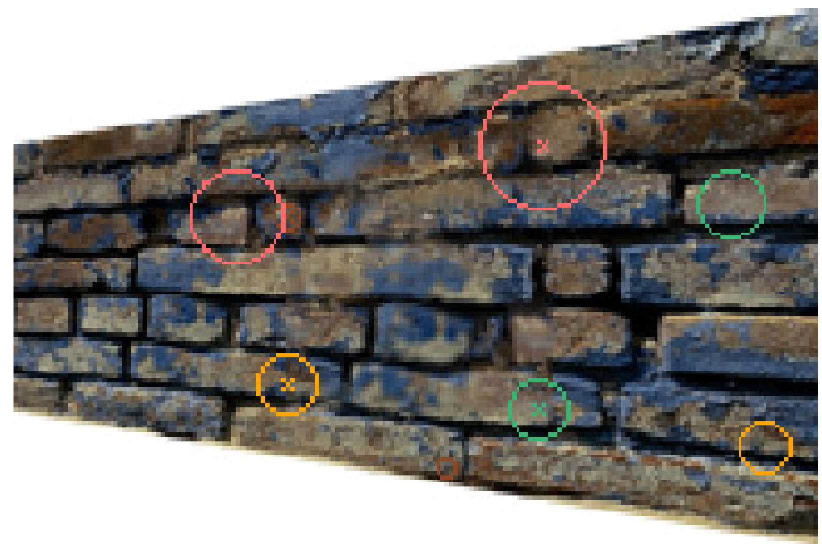


Confidence Map

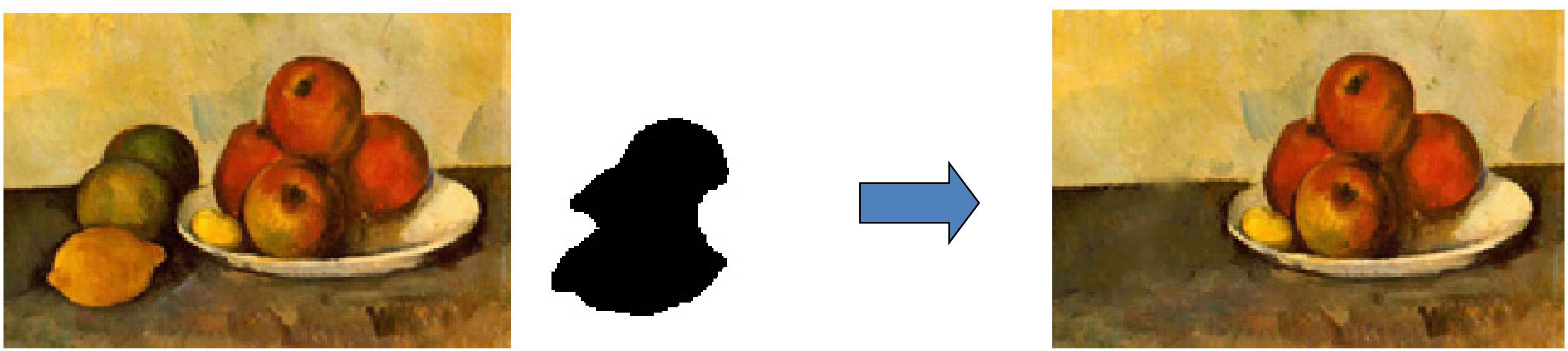


Search

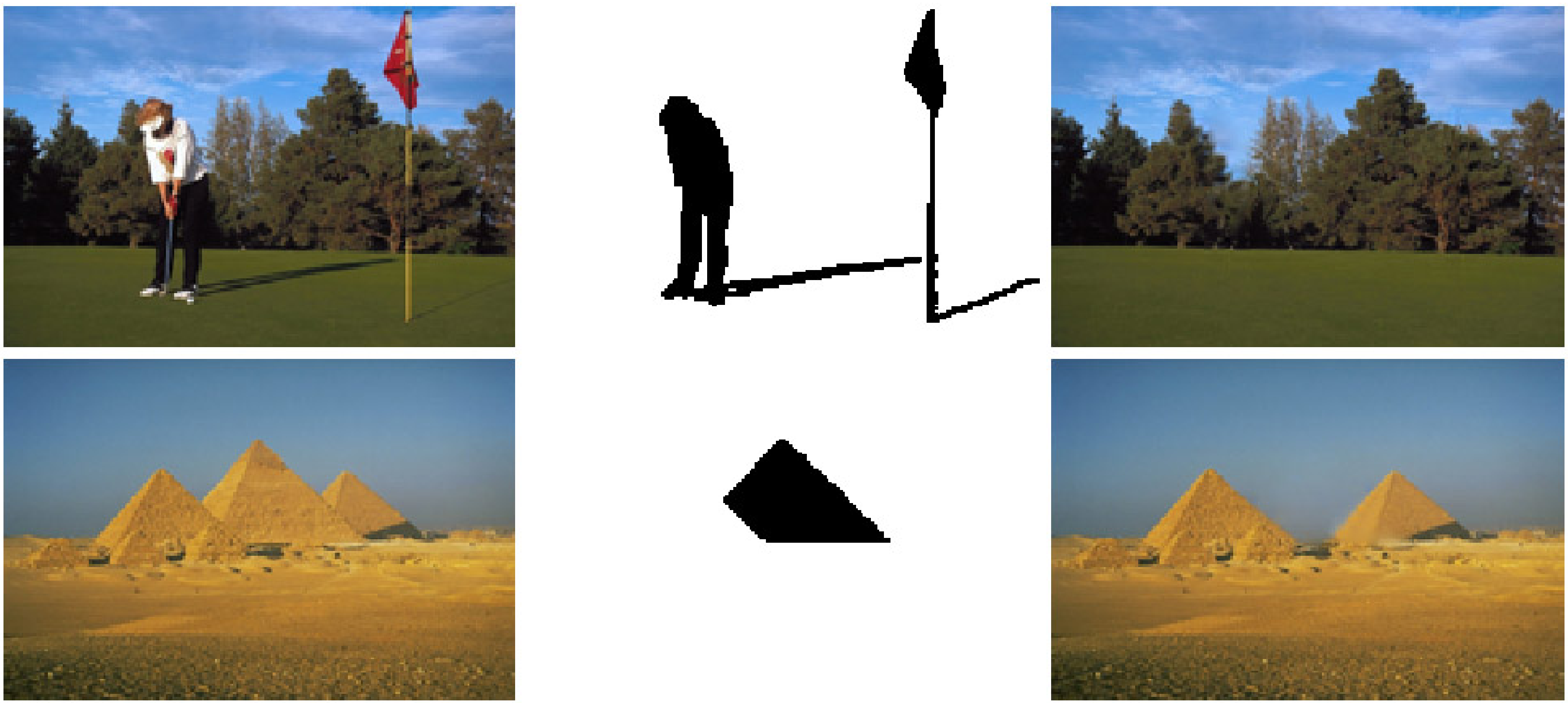




Results



Results



2. Surface Completion

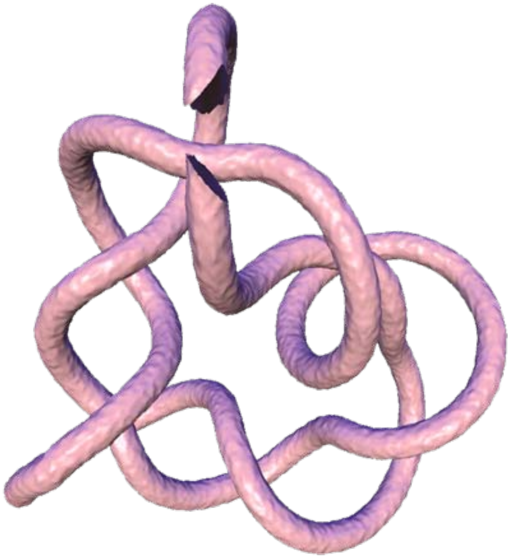
Requirements

- Robustness
  - Producing a watertight surface for any input model
- Efficiency
  - Processing huge models within reasonable time and space
- Accuracy
  - Preserving geometry
  - Boundary condition
  - Context condition

Extend 2D Methods to 3D

- Images
  - A regular spatial structure domain
- Problems in 3D
  - Topology and geometry of missing region
  - Fitting a patch to the boundary of the missing region

- Definition of similarity of shapes
- Definition of a surface patch



Classifications

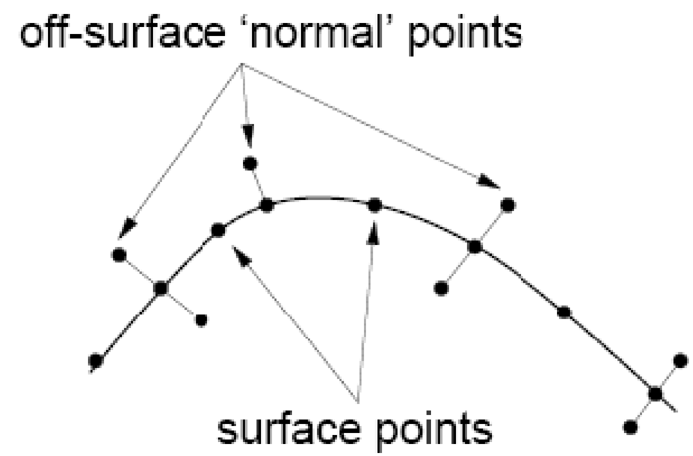
- Geometric method
  - Operate directly on the polygons in the model
- Volumetric method
  - Convert a polygonal model into a volume representation
- Image-based
  - Convert a polygonal model into a geometry image

2.1 Radial Basis Function

[Carr et al., Siggraph 2001]

Signed-distance Function

$$
\begin{array}{lll}
f(x_i, y_i, z_i) = 0, & i = 1, \ldots, n & (\textit{on}\text{-surface points}), \\
f(x_i, y_i, z_i) = d_i \neq 0, & i = n+1, \ldots, N & (\textit{off}\text{-surface points}).
\end{array}
$$



Interpolation Problem

Given: $X = \{x_i\}_{i=1}^{N} \subset \mathbb{R}^3$

and $\{f_i\}_{i=1}^{N} \subset \mathbb{R}$

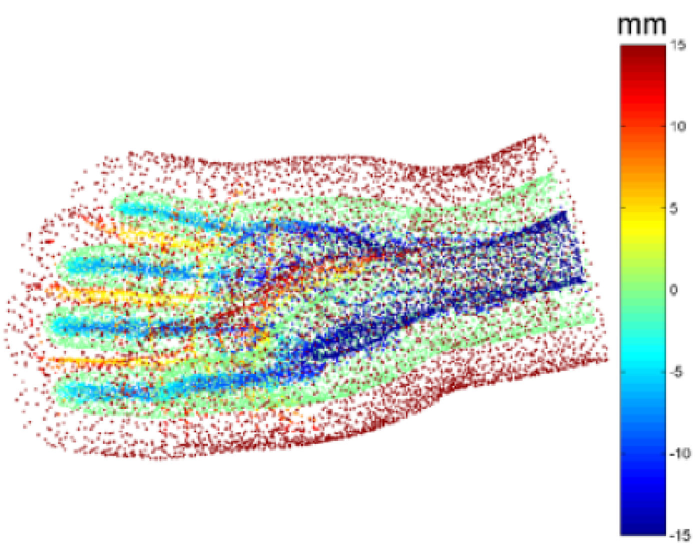
$s : \mathbb{R}^3 \to \mathbb{R}$

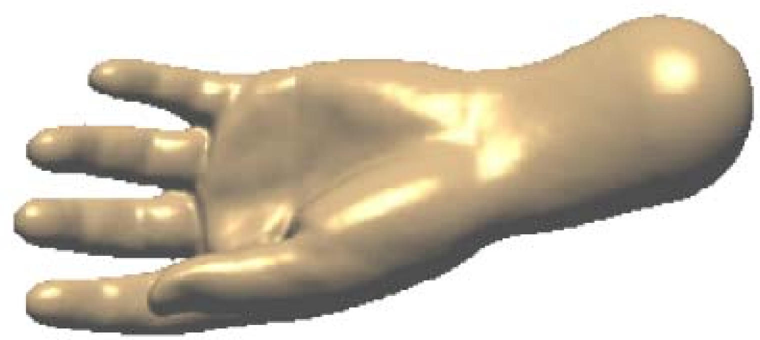
?

$s(x_i) = f_i, \ i = 1, \ldots, N.$

Output:

$\{x \in \mathbb{R}^3 \mid s(x) = 0\}$





Radial Basis Function

- General form

$$s(x) = p(x) + \sum_{i=1}^{N} \lambda_i \phi(|x - x_i|), \quad s \in \mathrm{BL}^{(2)}(\mathbb{R}^3)$$

$p(x)$ is a polynomial of low degree
the basic function ϕ is a real valued function

- e.g.

$$p(\vec{x}) = c_1 + c_2 x + c_3 y + c_4 z,$$
$$\phi(|x_i - x_j|) = |x_i - x_j|,$$

Evaluation

$$s(x) = c_1 + c_2 x + c_3 y + c_4 z + \sum_{i=1}^{N} \lambda_i |x - x_i|,$$

$$s \in \mathrm{BL}^{(2)}(\mathbb{R}^3)$$

$$\sum_{i=1}^{N} \lambda_i = \sum_{i=1}^{N} \lambda_i x_i = \sum_{i=1}^{N} \lambda_i y_i = \sum_{i=1}^{N} \lambda_i z_i = 0.$$

Evaluation

$$\begin{pmatrix} A & P \\ P^{\mathsf{T}} & 0 \end{pmatrix} \begin{pmatrix} \lambda \\ c \end{pmatrix} = \begin{pmatrix} f \\ 0 \end{pmatrix},$$

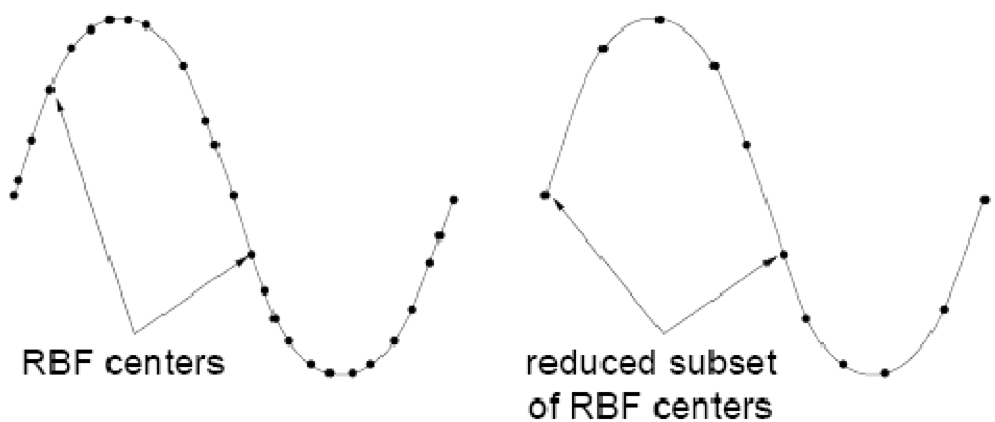
$$A_{i,j} = |x_i - x_j|, \quad i,j = 1,\ldots,N,$$

$$P = (1, x_i, y_i, z_i), \; \lambda = (\lambda_1, \ldots, \lambda_N)^{\mathsf{T}}$$

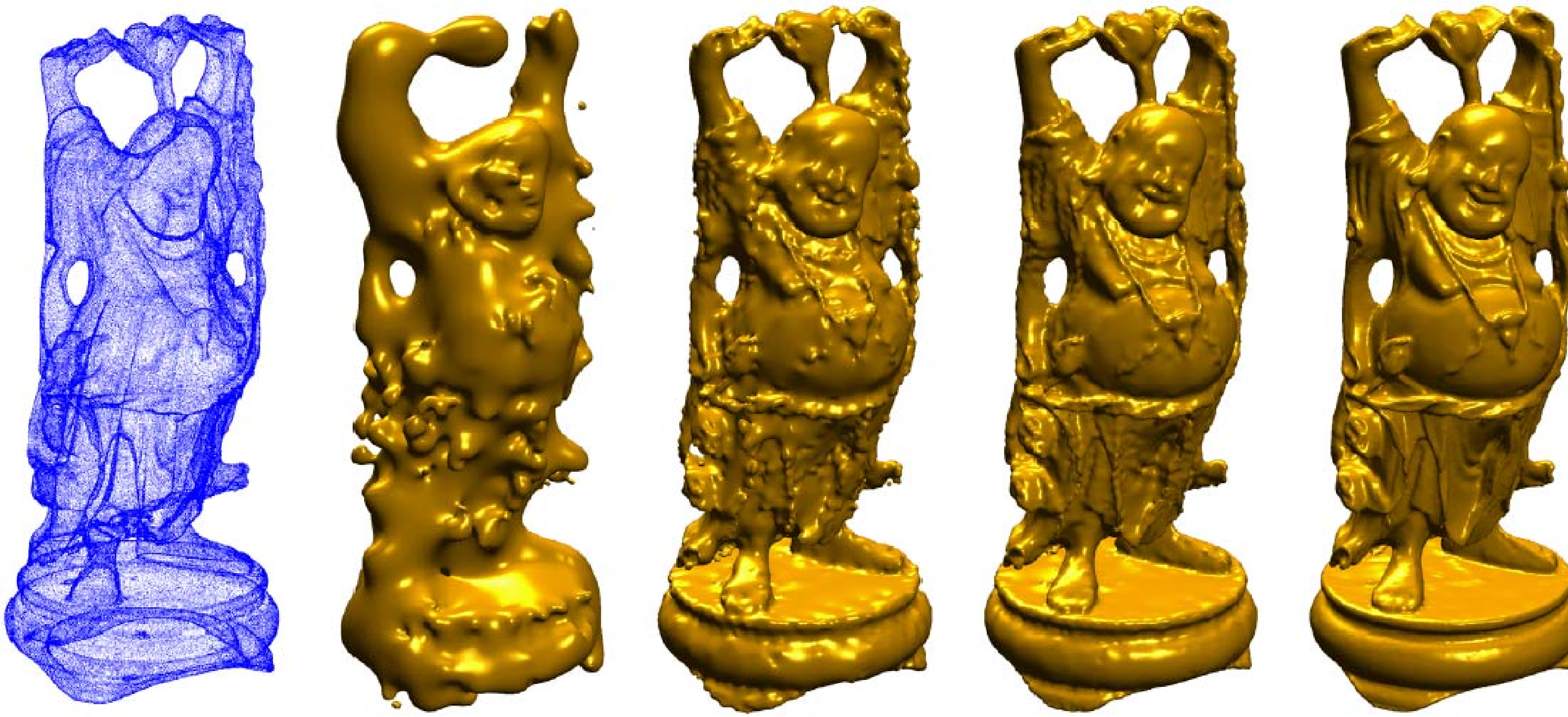
$$c = (c_1, c_2, c_3, c_4)^{\mathsf{T}}.$$

Greedy algorithm

- Procedure
  1. Choose a subset from the interpolation nodes *X* and fit an RBF only to these.
  2. Evaluate the residual, $\varepsilon_i = f_i - s(x_i)$ nodes.
  3. If $\max\{|\varepsilon_i|\} < \textit{fitting accuracy}$ p.
  4. Else append new centers where i ε_i arge.
  5. Re-fit RBF and goto 2.

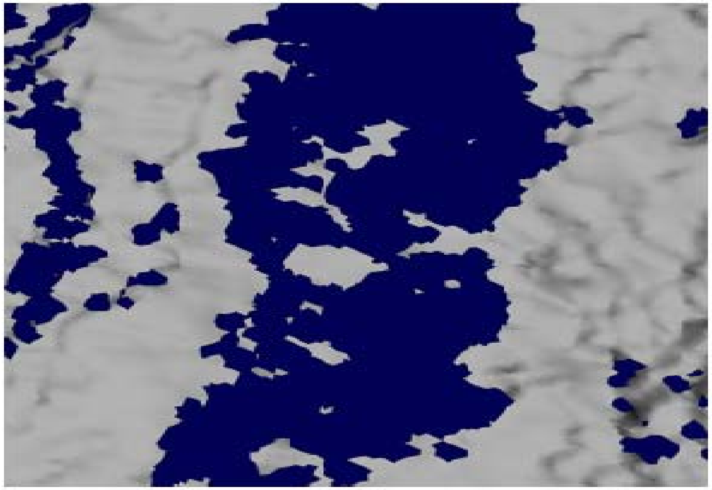


Results



Summary

- Repair holes with arbitrary topology



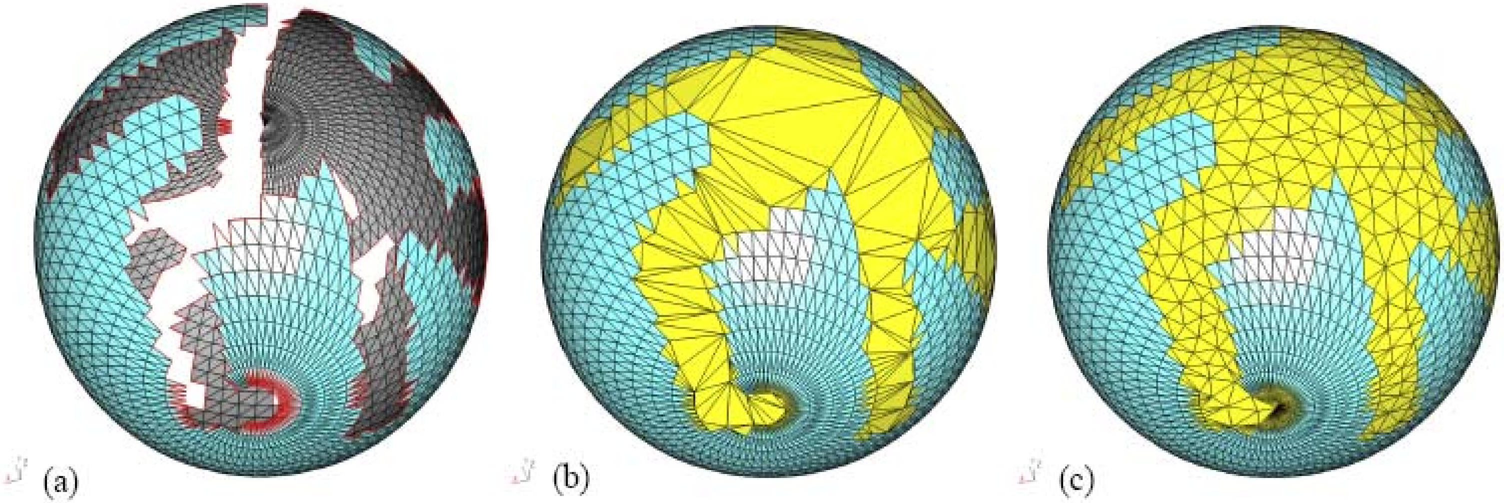
- Holes are smoothly filled
- Approximate original surface

2.2 Filling Holes in Meshes

[Liepa, SGP 2003]

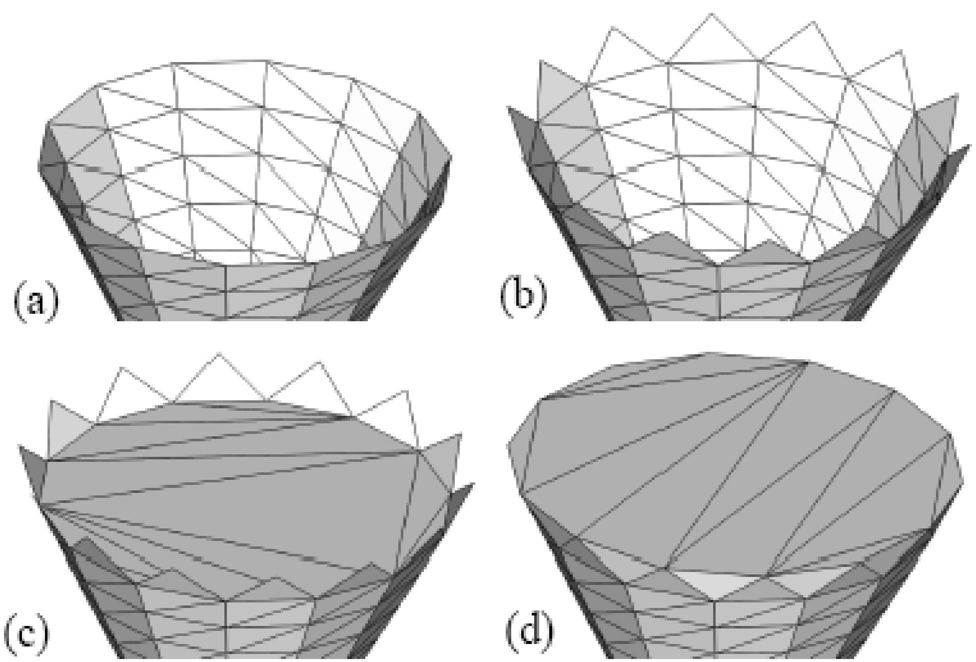
Pipeline

1. Hole identification
2. Hole triangulation
3. Mesh refinement
4. Mesh fairing

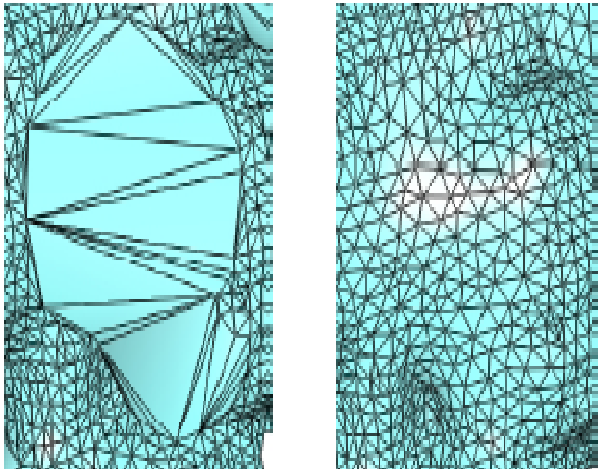


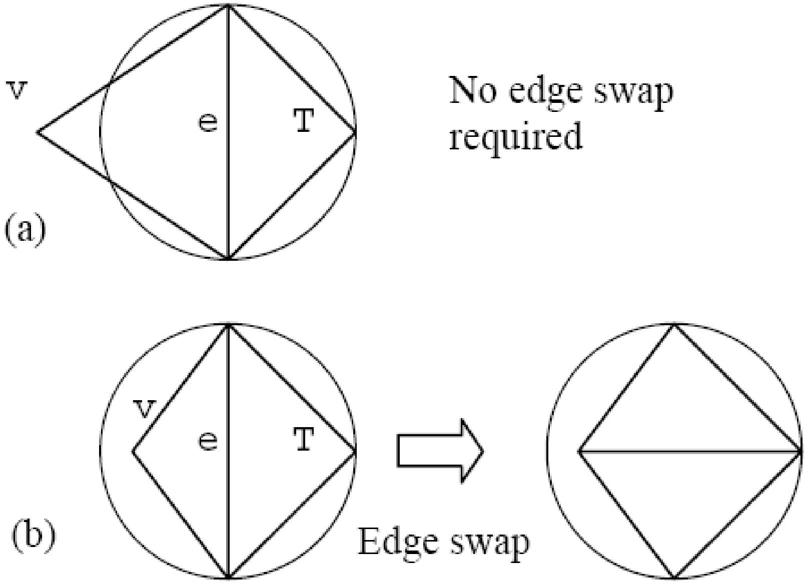
Triangulation of 3D Polygons

- Minimum area triangulation
- Min-max dihedral angel triangulation



Mesh Refinement





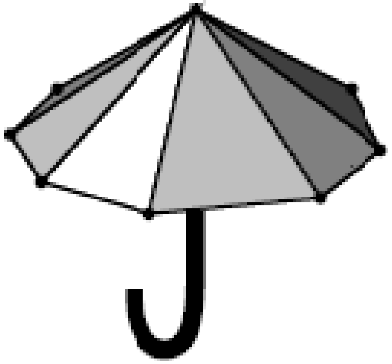
1. Subdivision

2. Edge Relaxation

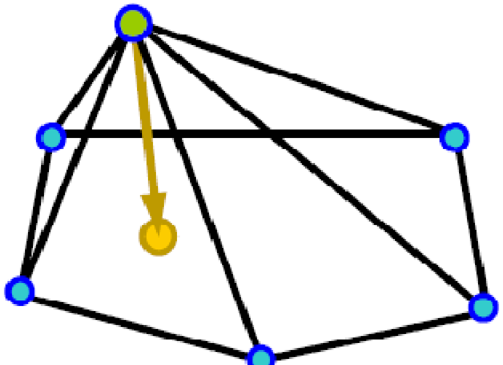
Fairing

- Weighted umbrella-operator

$$\mathrm{U}_{\omega}(v) = -v + \frac{1}{\omega(v)} \sum_i \omega(v, v_i) v_i ,$$



$$v = v + \mathrm{U}_{\omega}(v)$$



- Uniform : $\omega(v_i, v_j) = 1$
- Scale-dependent :

$$\omega(v_i, v_j) = 1 / \left\| v_i - v_j \right\|$$

Summary

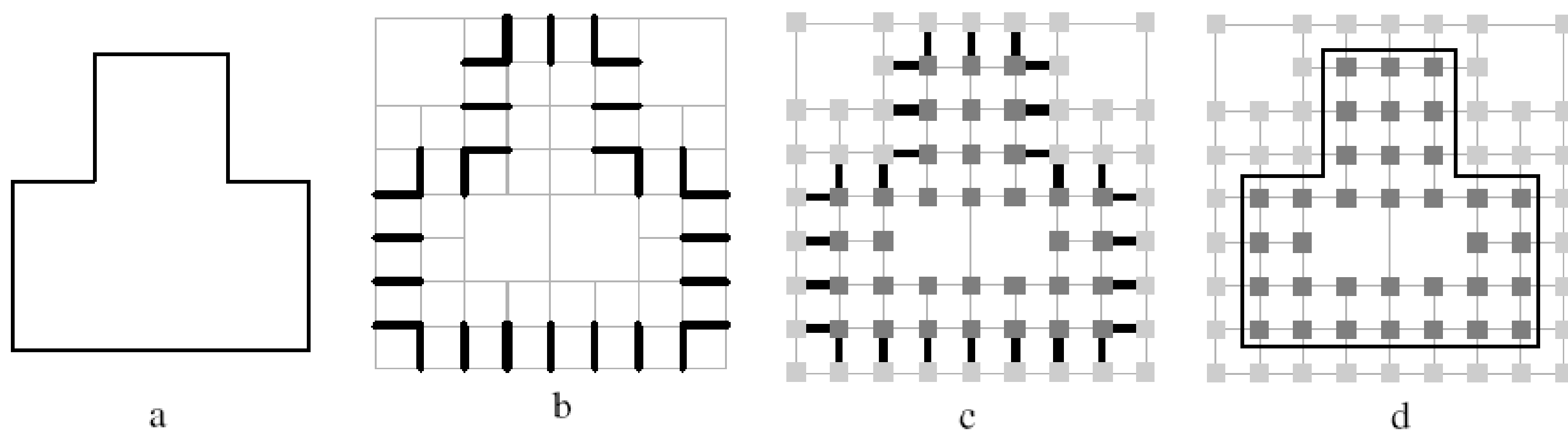
- Easy to implement
- Focus algorithm on holes
- Triangulation may self-intersect
- Can't fill holes with islands
- Fairing weaken original surface feature

2.3 Robust Repair of Polygonal Models

[Ju, Siggraph 2004]

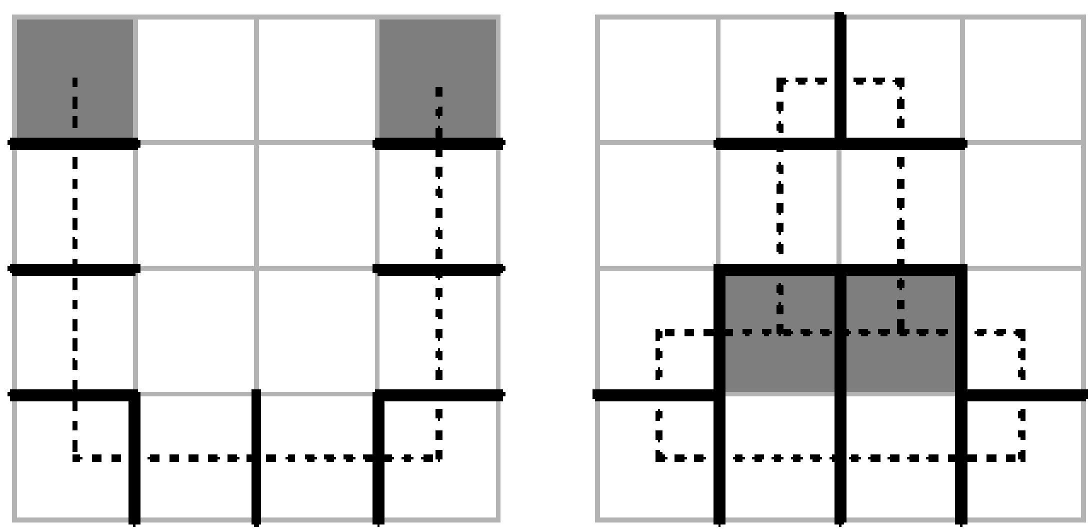
Pipeline

I. Scan-conversion
II. Sign generation
III. Surface reconstruction

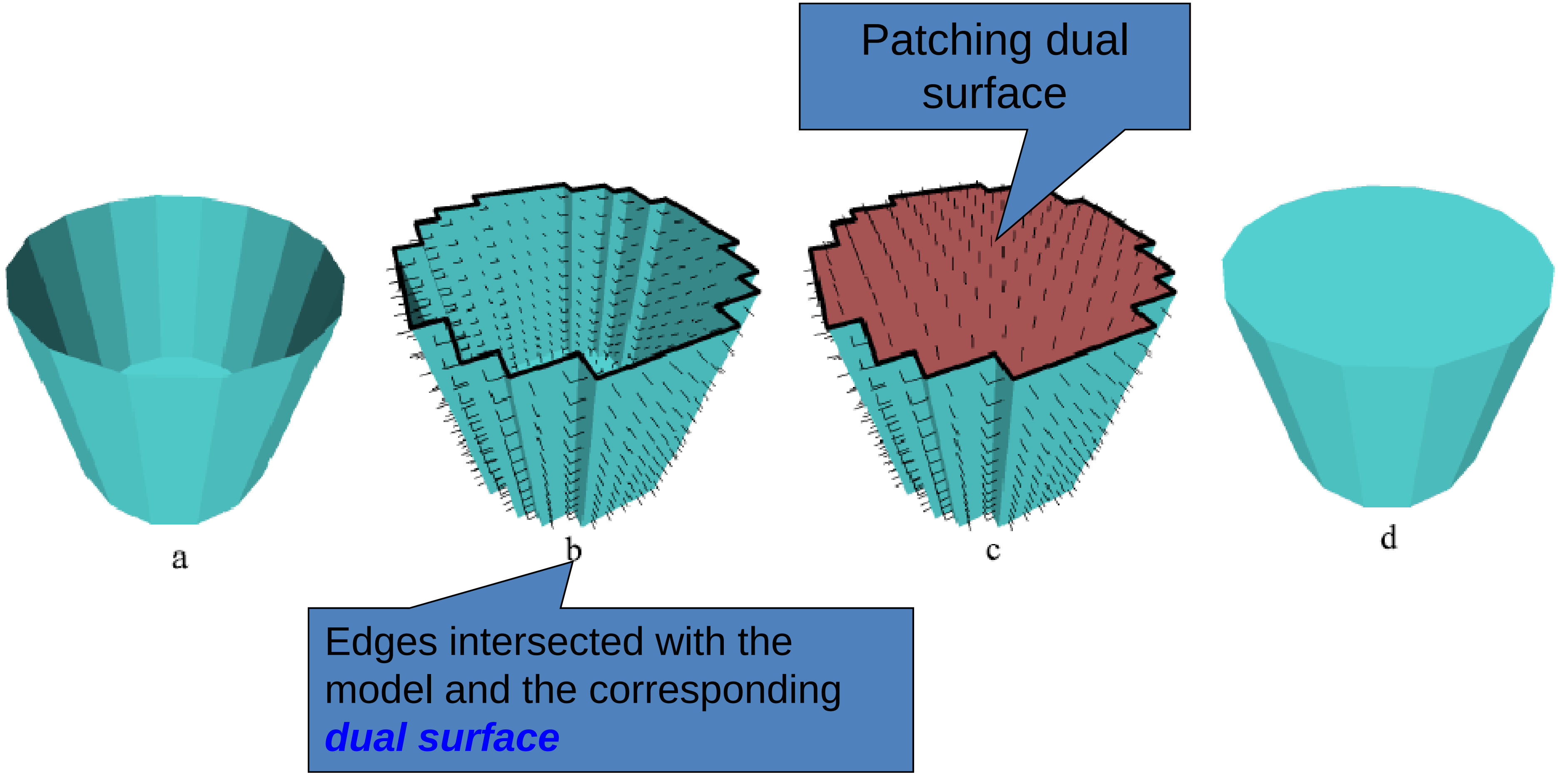


Sign Generation

- Cell faces containing an odd number of intersection edges

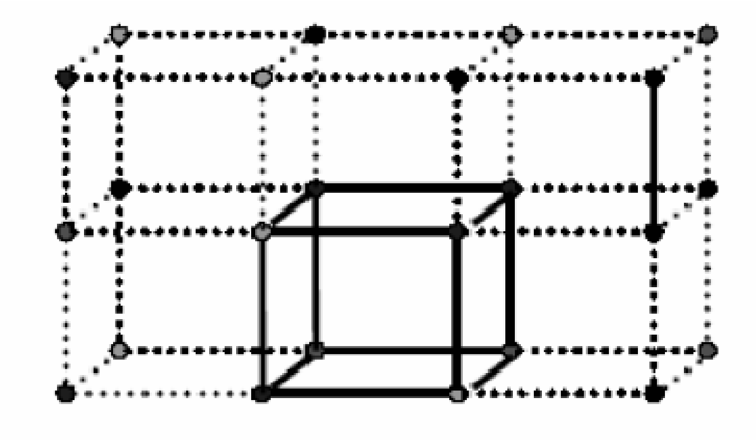


Patch Boundary Circles

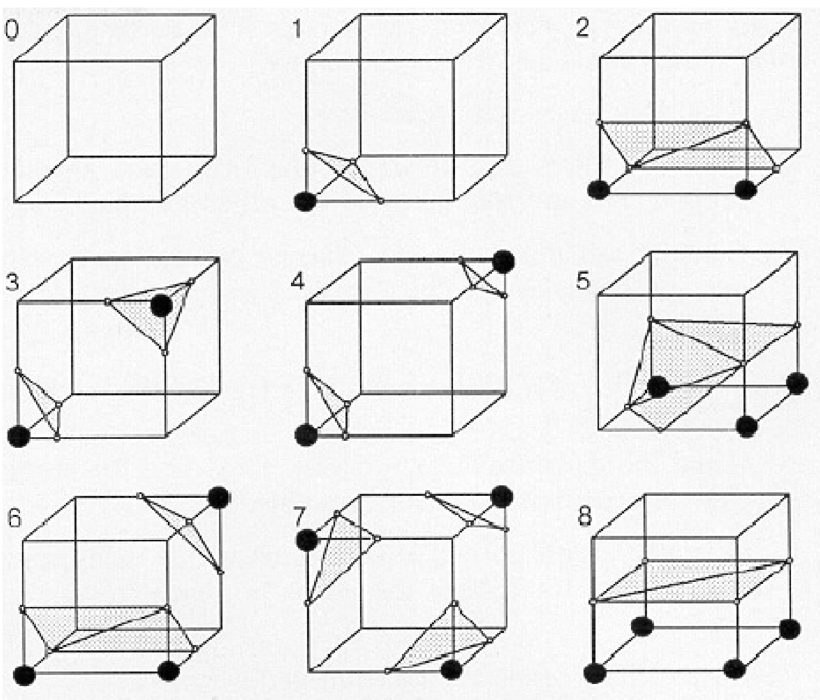


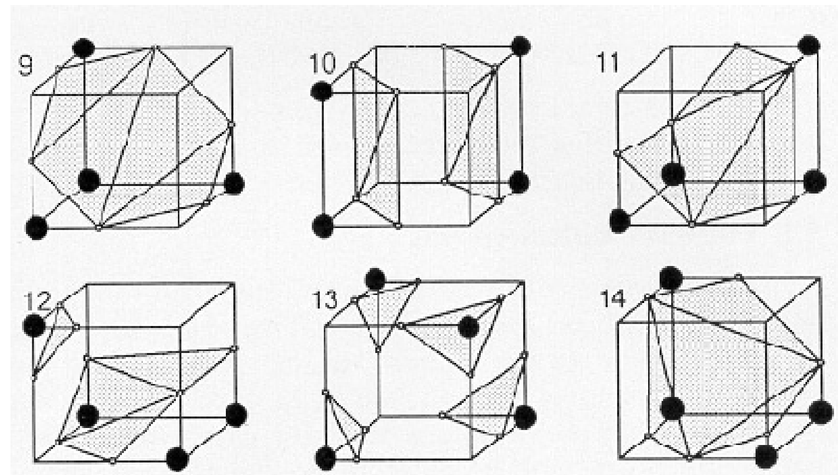
Marching Cubes

- Cube with signs at eight corners

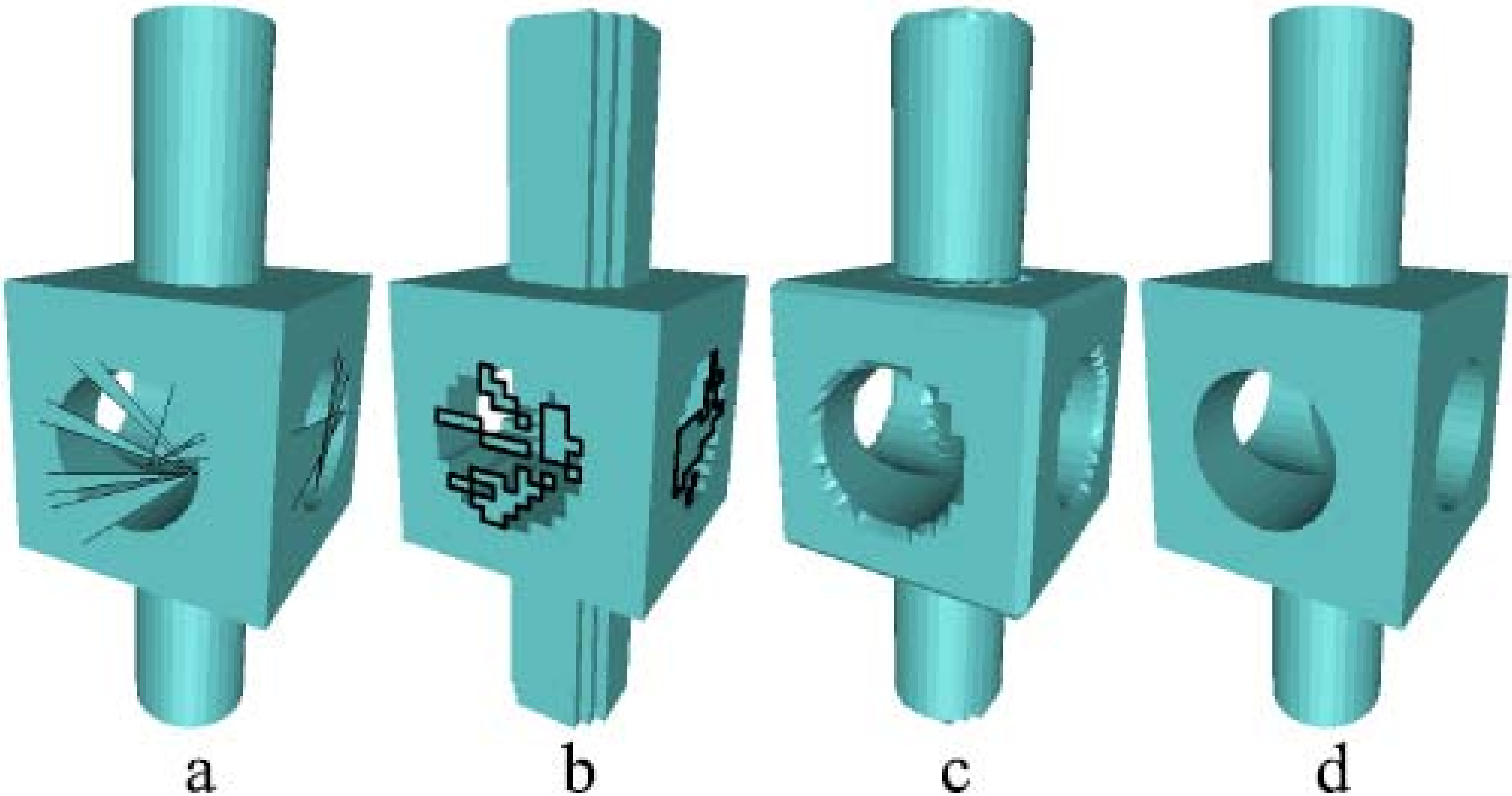


Marching Cubes

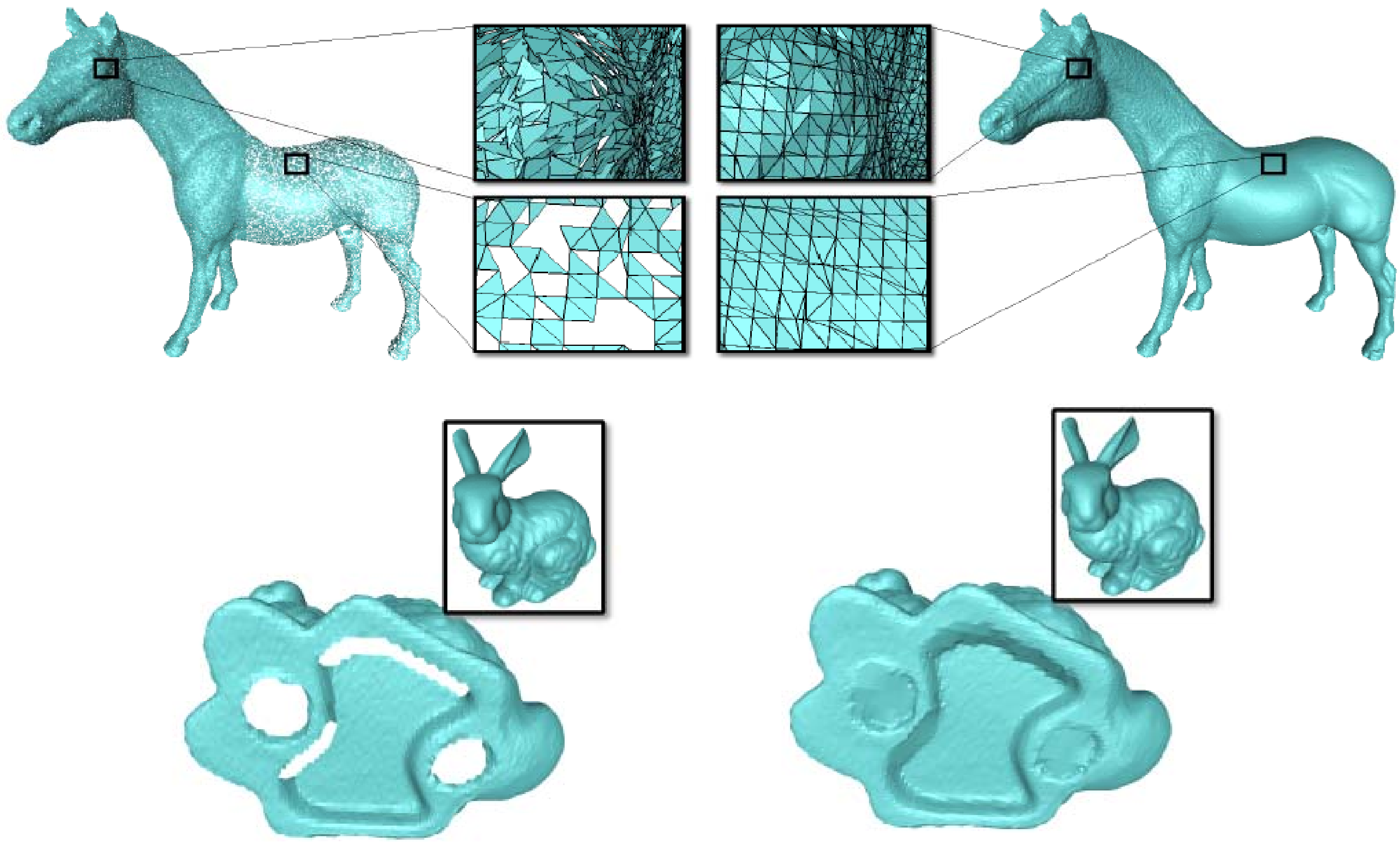




Results



Results



Summary

- Employ a space-efficient octree grid
- Produce closed, manifold surface for any input model

2.4 Context-based Surface Completion

[Sharf et al., Siggraph 2004]

Motivation

Complete the missing region with patches that conform with its context

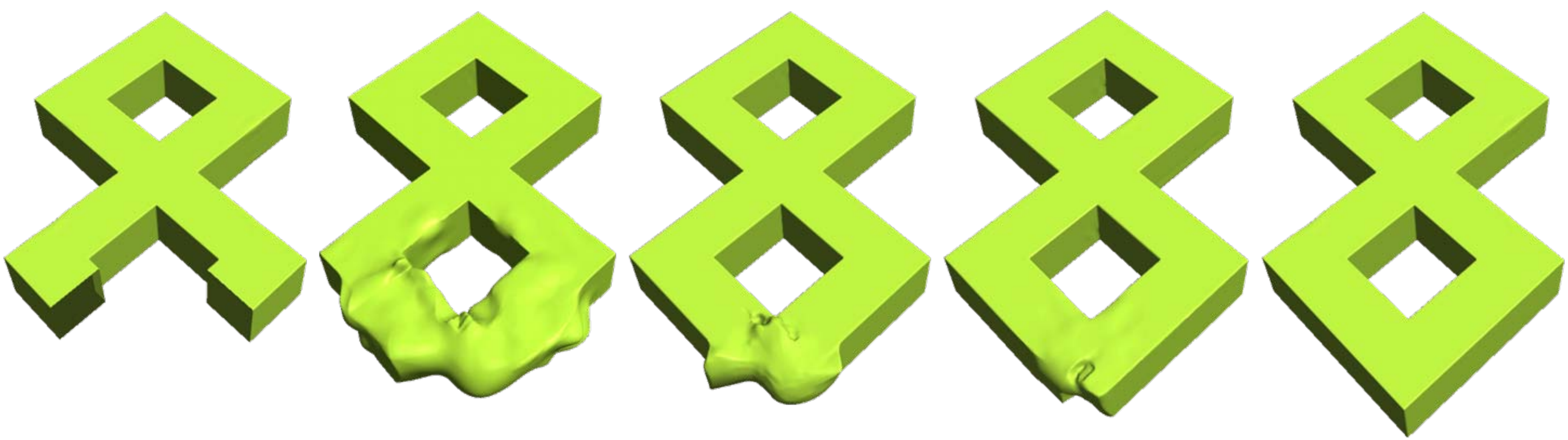
Smooth

Context-based

Method

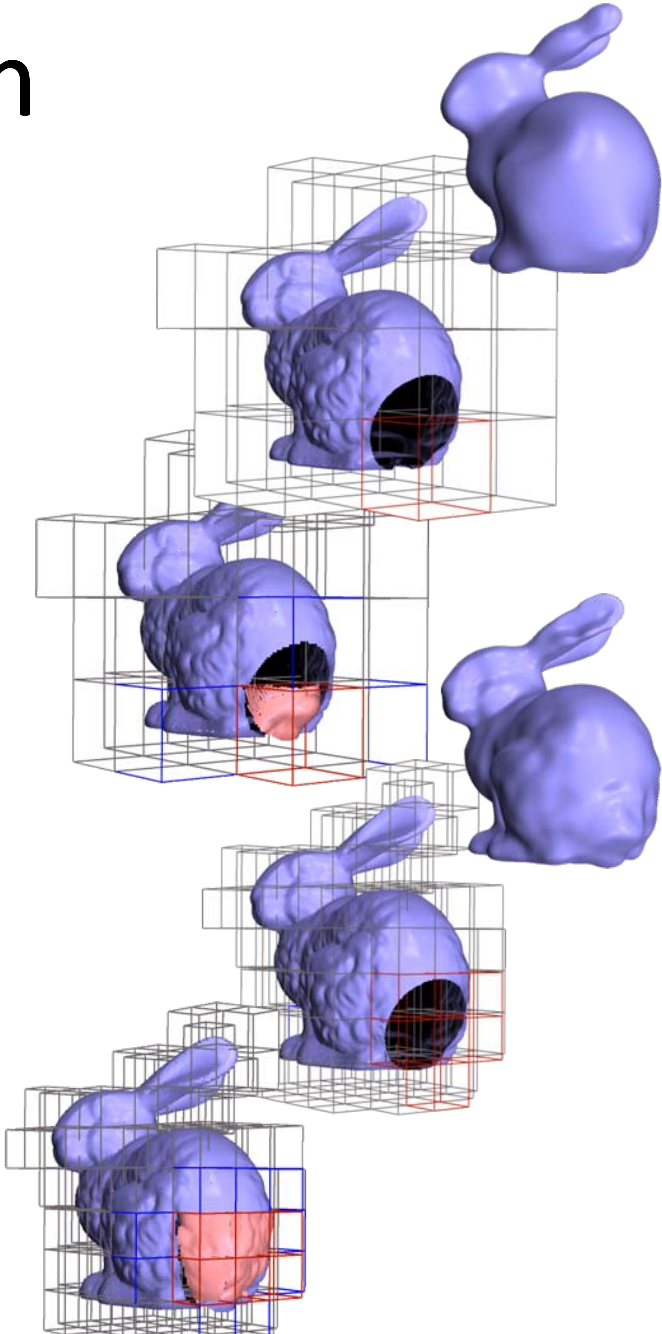
Import patches with matching context from the surface itself :

- Analyze surface characteristics.
- Find best matching patch.
- Fit imported patch to boundary.



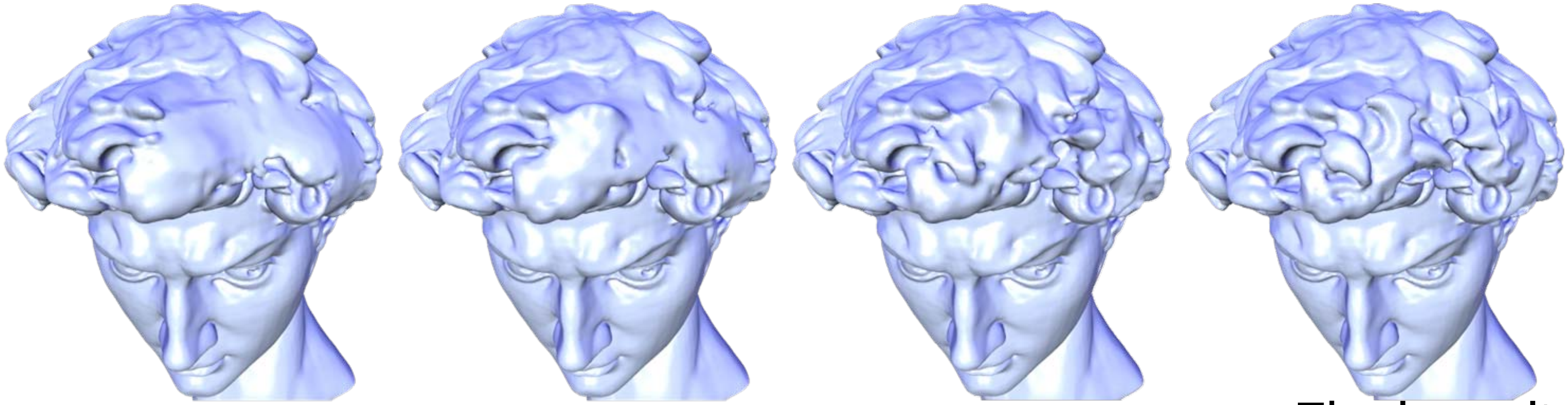
Algorithm

- Create initial spatial subdivision
- For each cell
  - Compute a local shape representation.
  - Compute a shape signature.
- For each empty cell:
  - Find matching nonempty cell *ω'*.
  - Copy patch of *ω'* into *ω*.
- Subdivide cells and repeat
- Until completed region matches its neighborhood



Completion Process

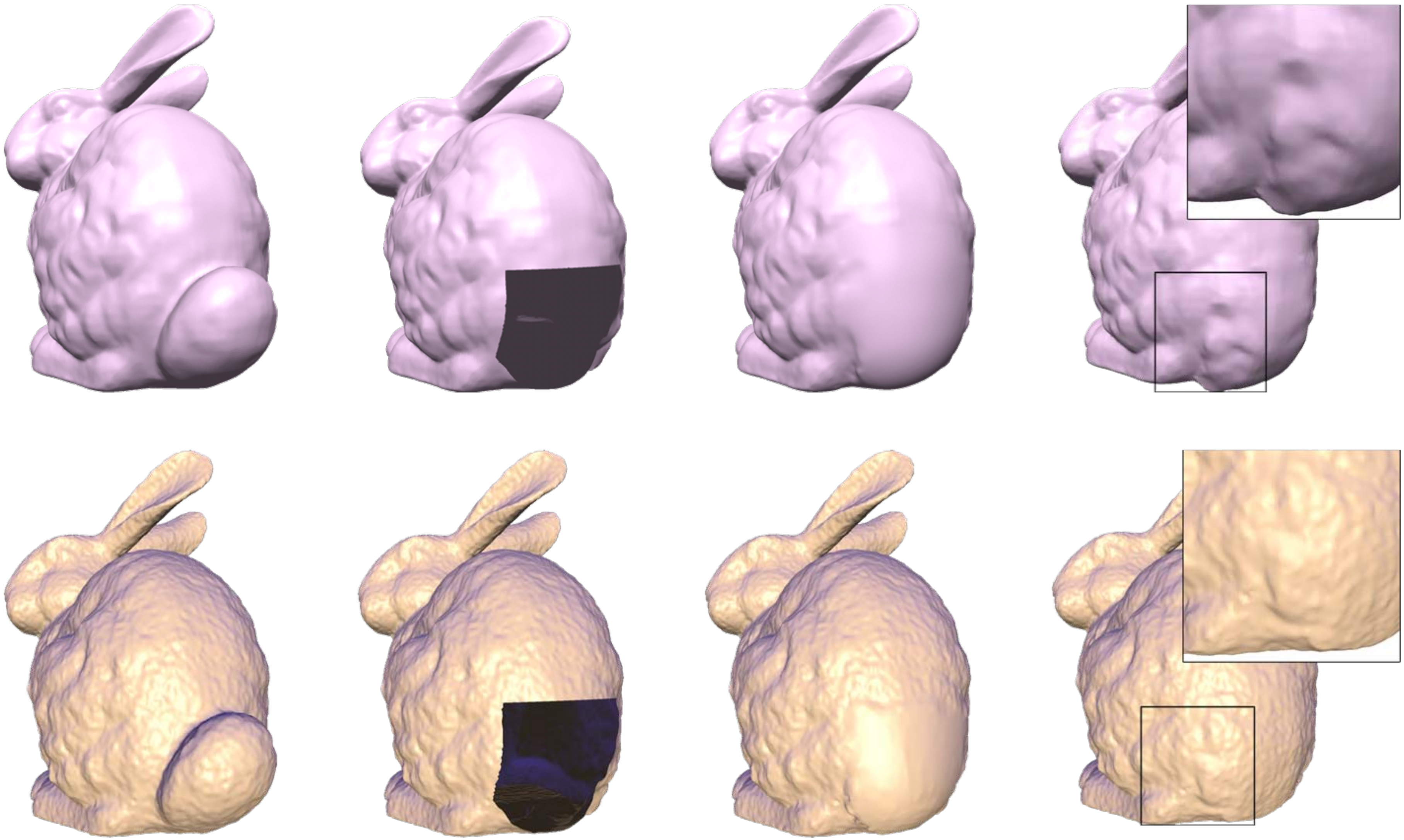
Original



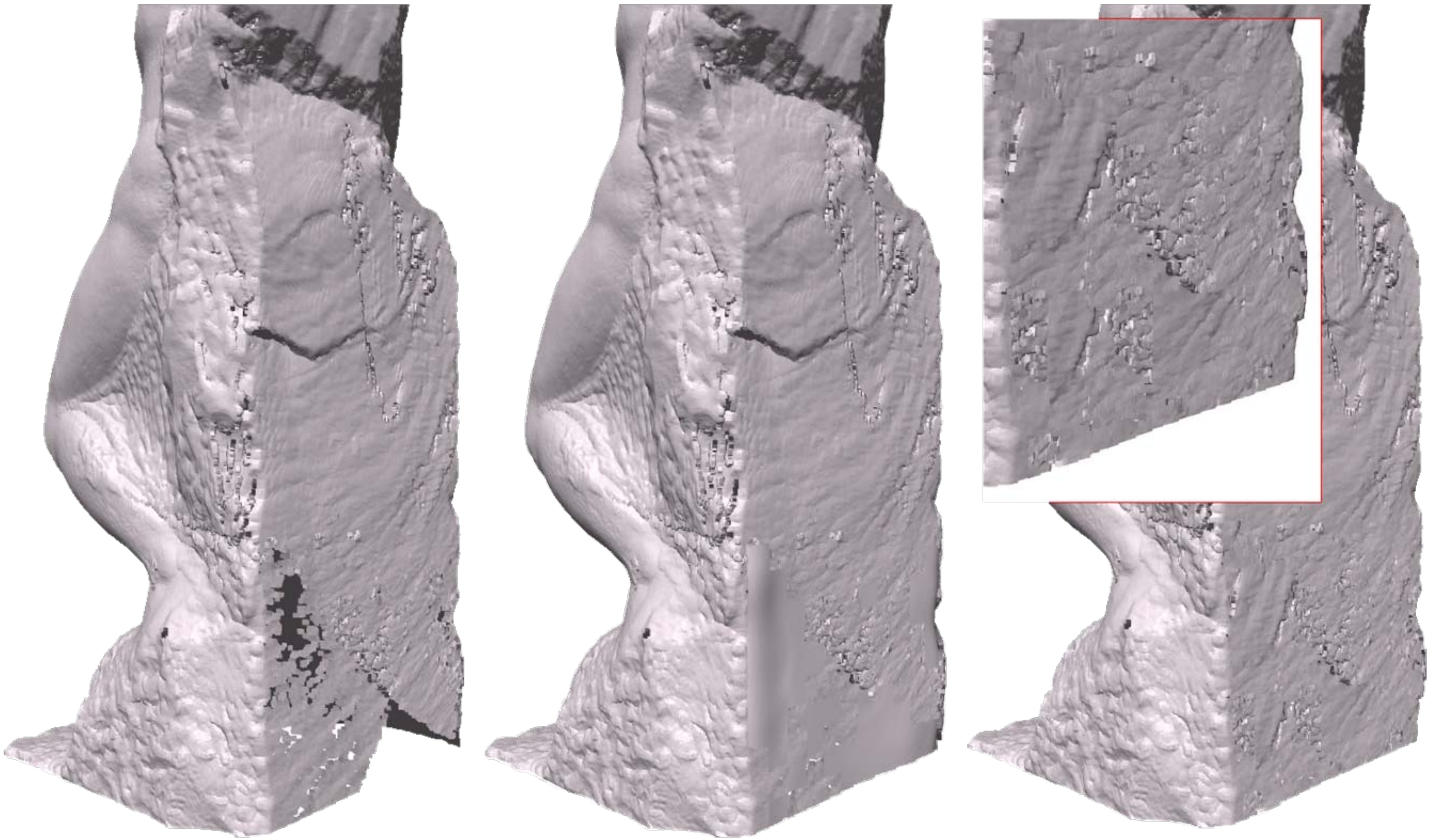
Initial approximation

Final result

Manual Editing of Bunny Model



Scan of "Youth" Statue



Original Smooth Result

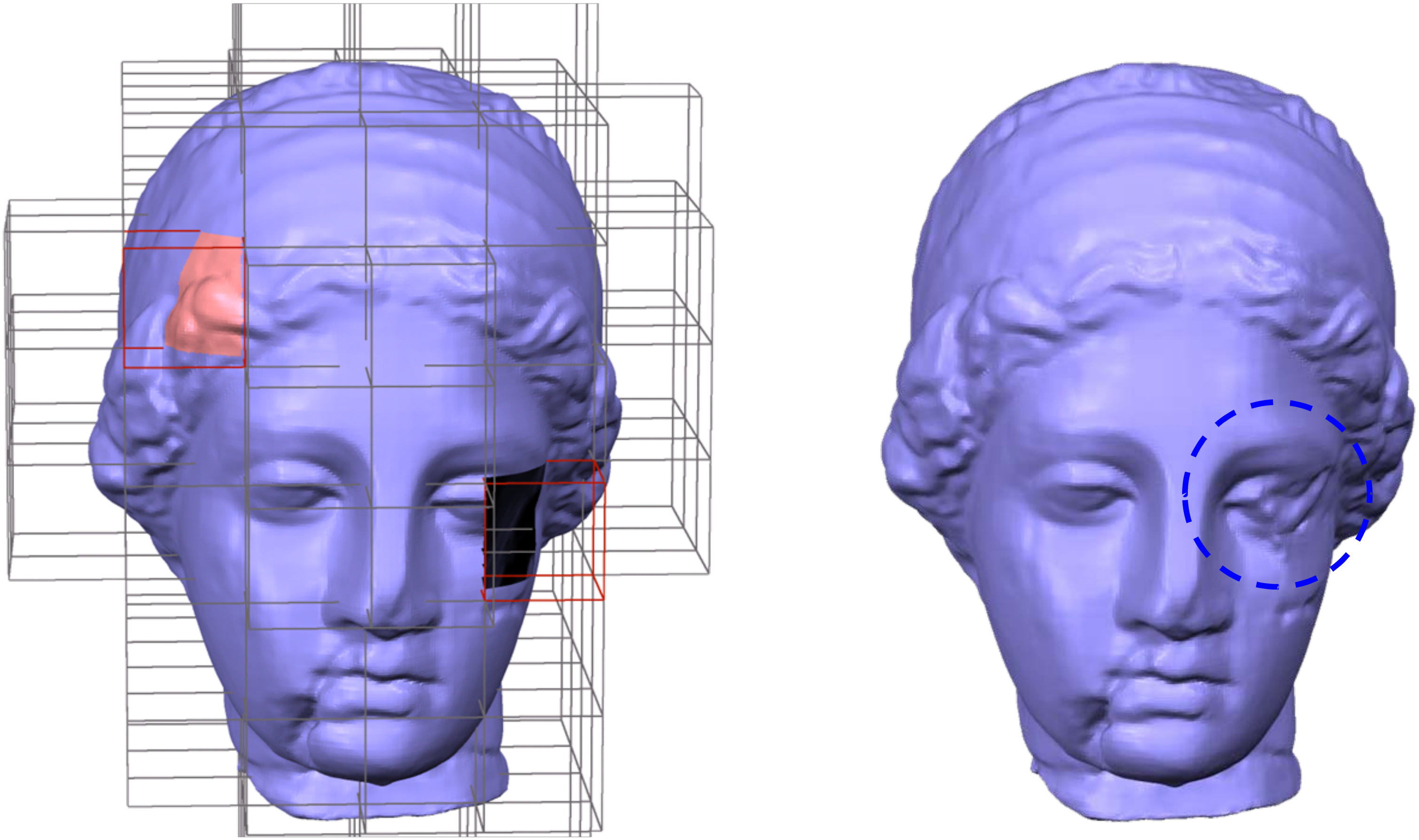
Scan of Human Bone

Original

Smooth

Result

Limitations: Semantics



Summary

- A fully automatic method to complete a missing region in a surface from its context.
  - Completed patches geometrically conform with neighborhood.
  - Incremental scale-space framework for finer approximation of the unknown region.

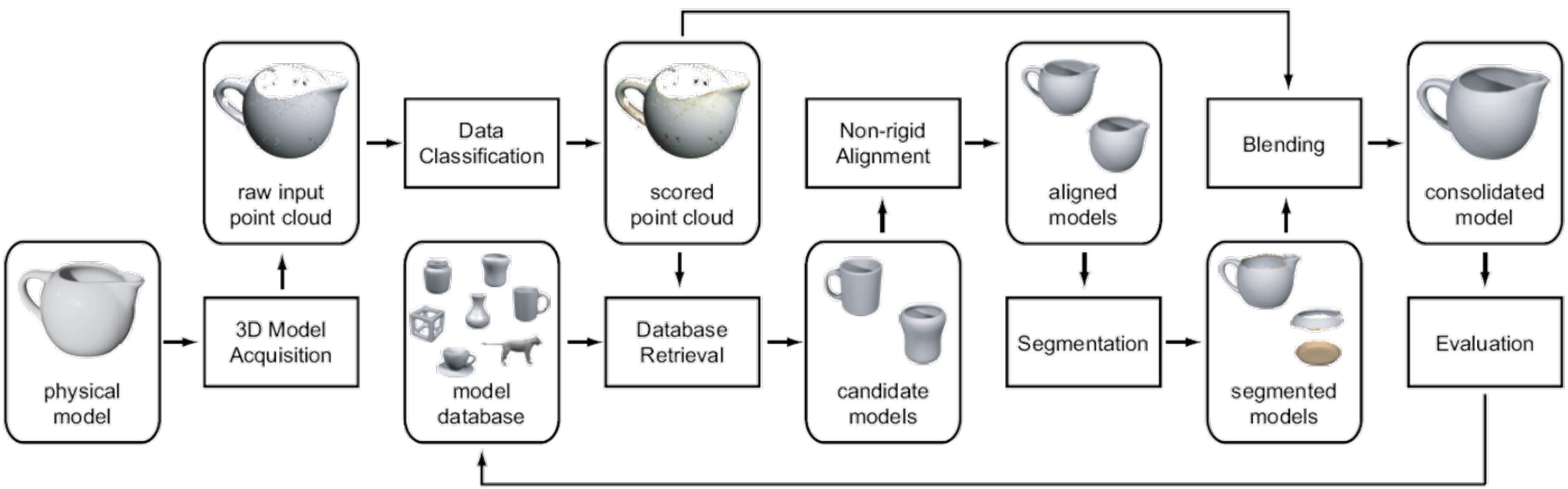
2.5 Example-based Surface Completion

[Pauly et al., SGP 2005]

Solution

- Use ***3D model database*** to provide geometric priors for shape completion
- Apply ***non-rigid transforms*** on the models
  - More deformation $\Rightarrow$ less likely completion
- ***Consistently*** combine geometric information from multiple context models
- Final result comes with ***confidence values***

Shape Completion Pipeline



Data Classification

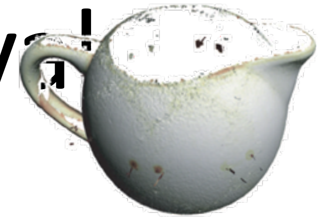
Local analysis

- quality of fit
- uniformity of sample distribution

Scored Point Cloud

- confidence value assigned to each point

Database Retrieval



1.93 1.71 1.46 1.27 1.0

Non-rigid Alignment

Similar to the approaches proposed by:

- Allen, Curless and Popovic, 2003.
- Sumner and Popovic, 2004.

Non-rigid Alignment

Deformation Model

- Piecewise linear.
  Each vertex of the mesh assigned an independent displacement vector.

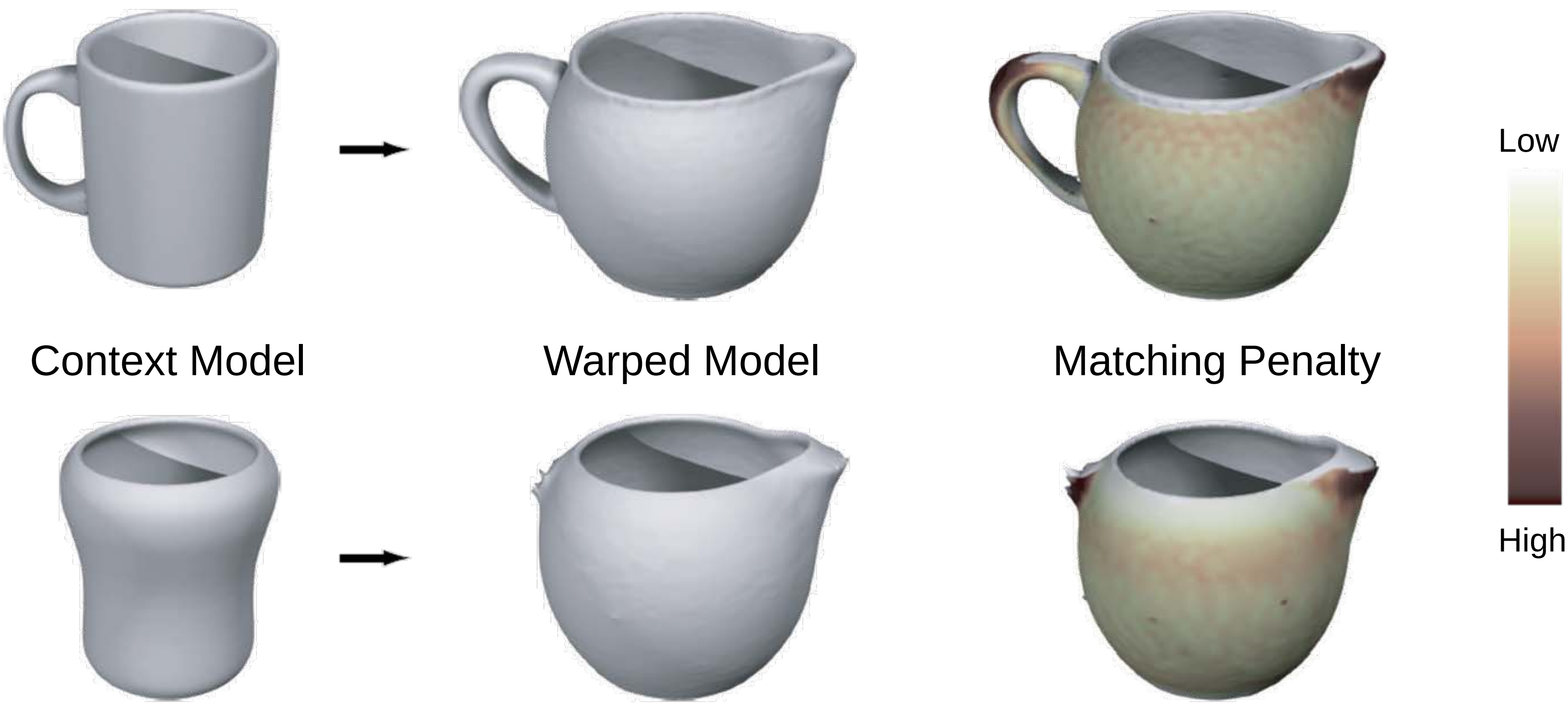
Optimize for smallest ***Shape Matching Penalty***

- Distortion Measure
- Geometric Error

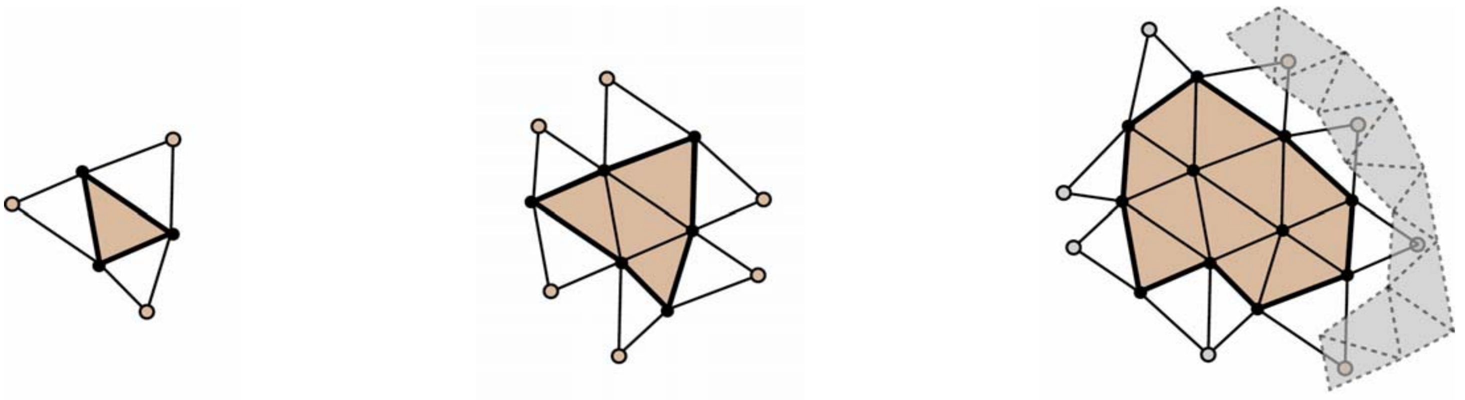
Derived in the continuous setting to allow *consistent comparison* between *different context models.*

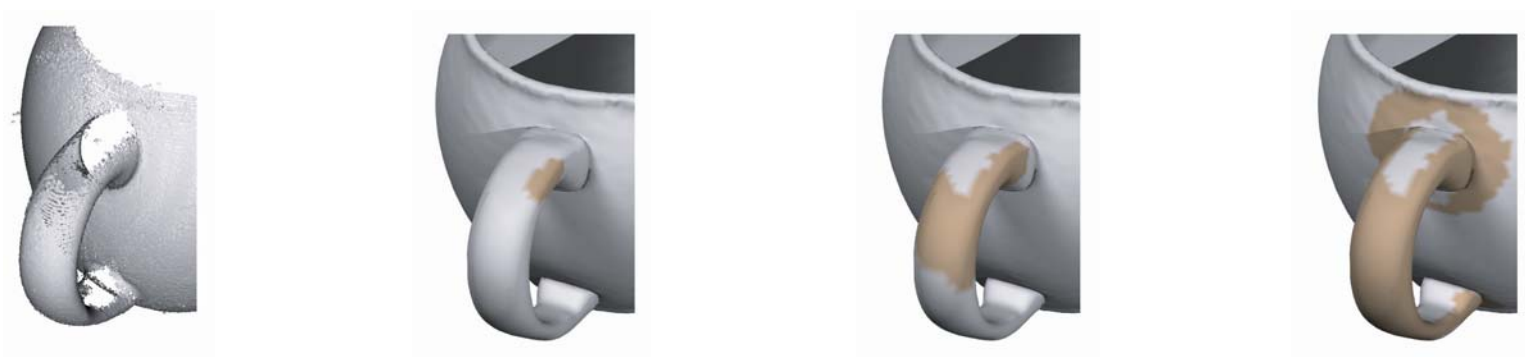
Feature Correspondence

Warped Models



Initial Segmentation

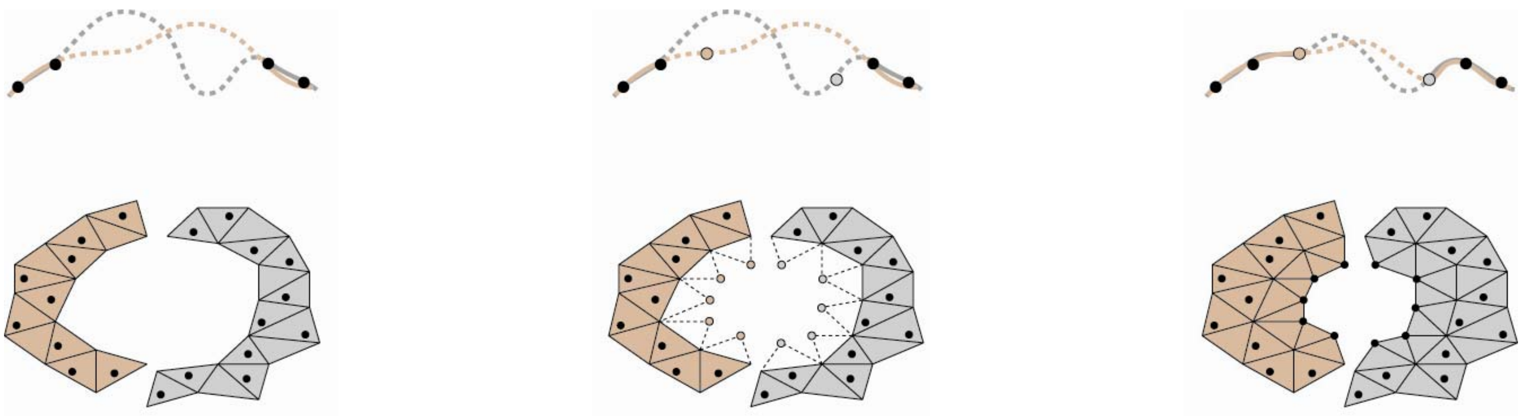




Input Data

Warped Context Model

Patch Growing



Initial Segmentation

Final Segmentation

Result

Giraffe Example

Context Models

Segmentation

Deformed Models

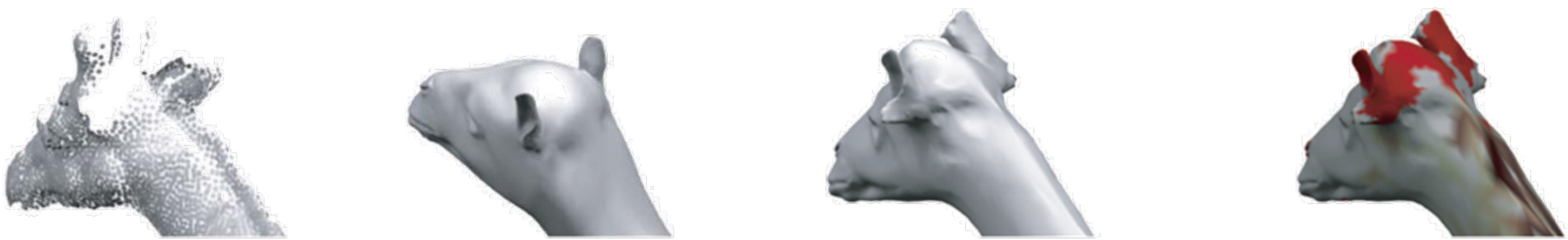
Giraffe Example

Context Models

Deformed Models

Final Model

Evaluation

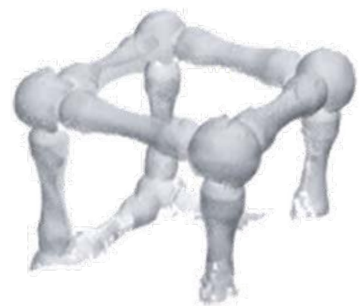


Input Data | Context Model | Final Model | Evaluation

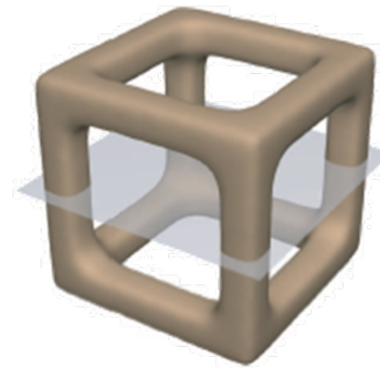
Enriching the Database

Additional Constraints

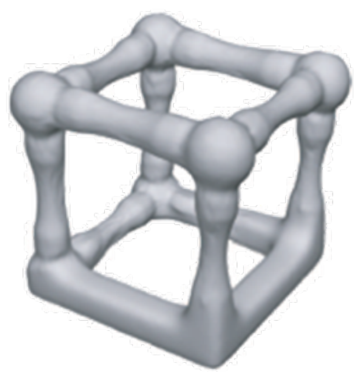
Physical Model



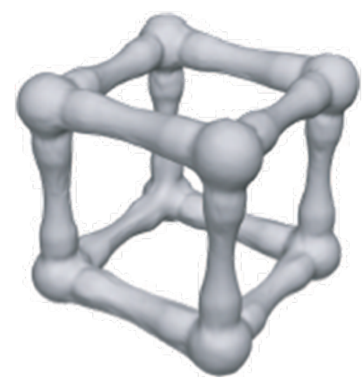
Acquired Data



Context Model



No Constraints



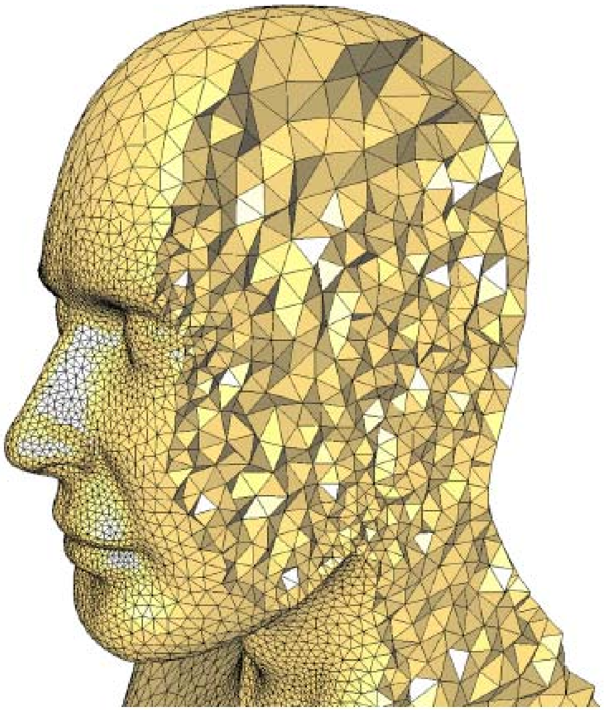
Symmetry Constraints

2.6 Atomic Volumes for Mesh Completion

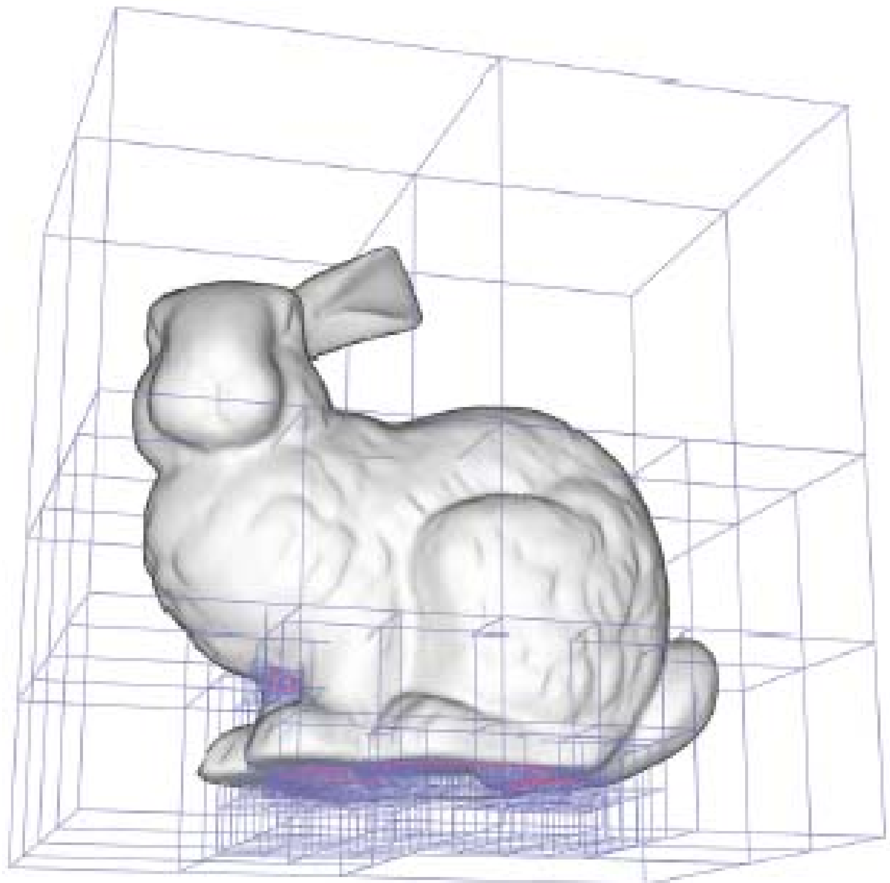
[Podolak and Rusinkiewicz, SGP 2005]

Atomic Volumes

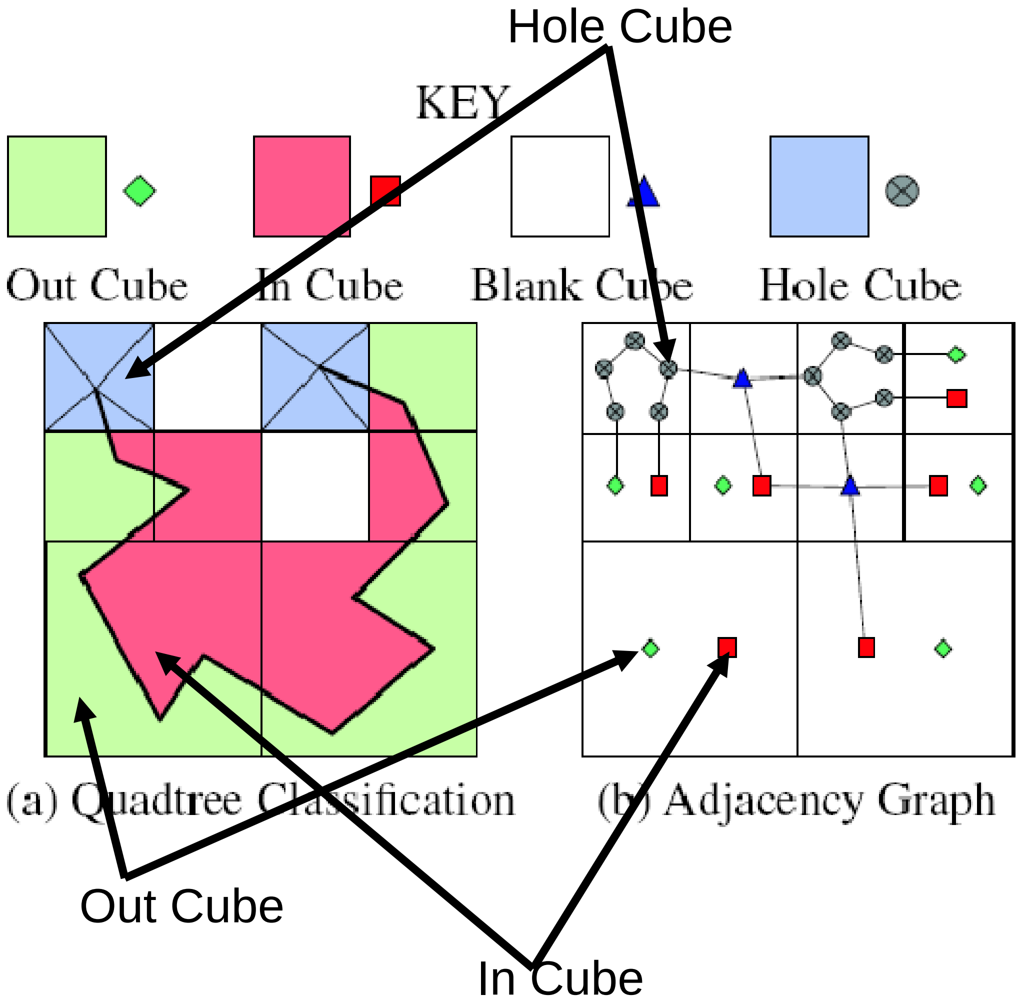
- A volume is *atomic* if it doesn't intersect the polygons of the mesh.



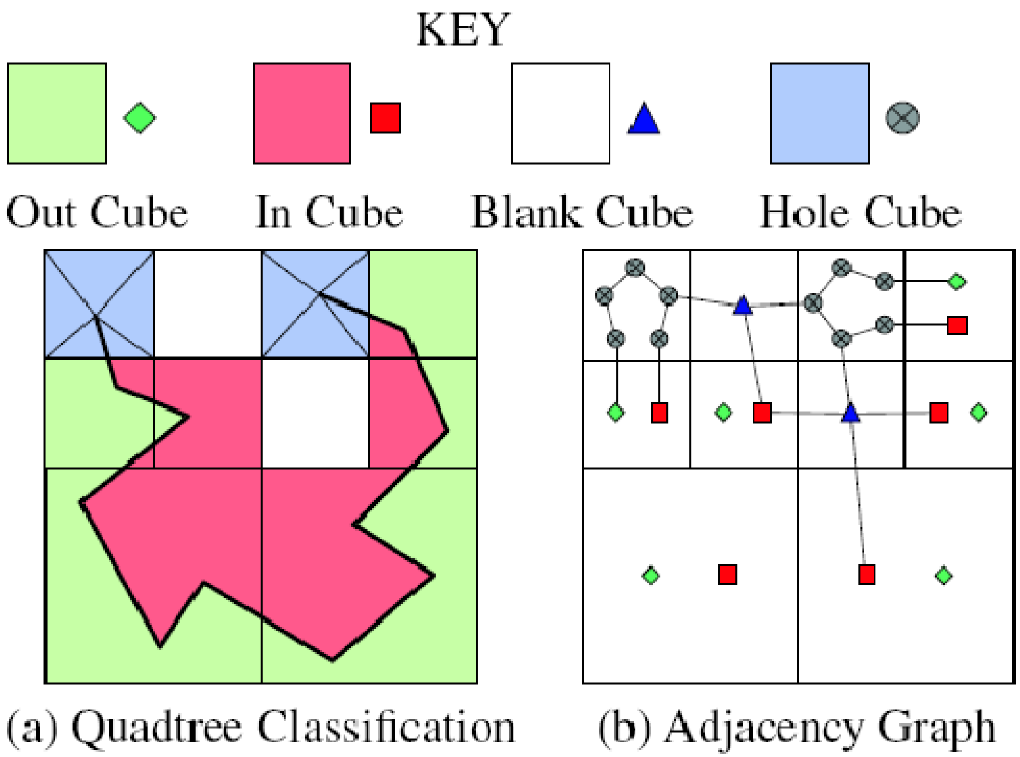
Spatial Partitioning



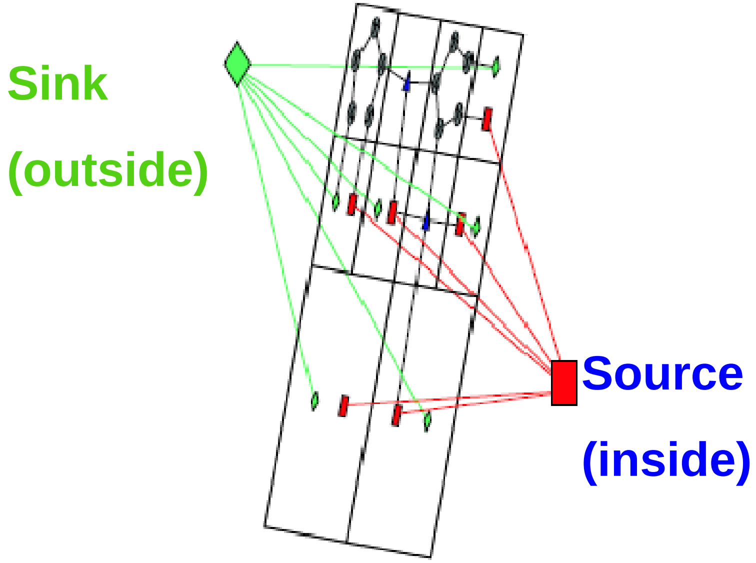
Pipeline


Hole Cube
KEY
Out Cube
In Cube
Blank Cube
Hole Cube
(a) Quadtree Classification
(b) Adjacency Graph
Out Cube
In Cube

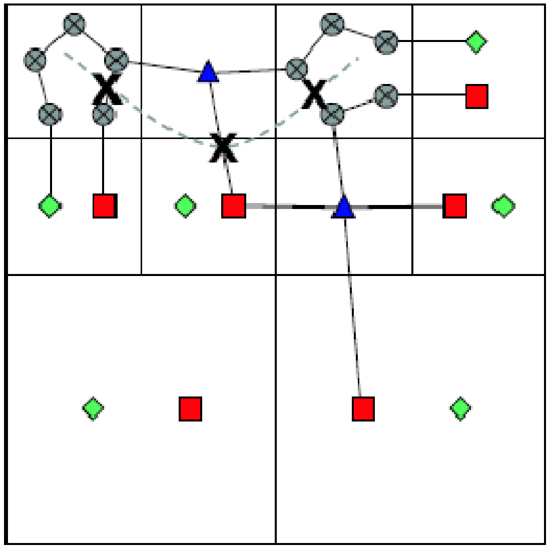
Pipeline


KEY
Out Cube
In Cube
Blank Cube
Hole Cube
(a) Quadtree Classification
(b) Adjacency Graph

Pipeline

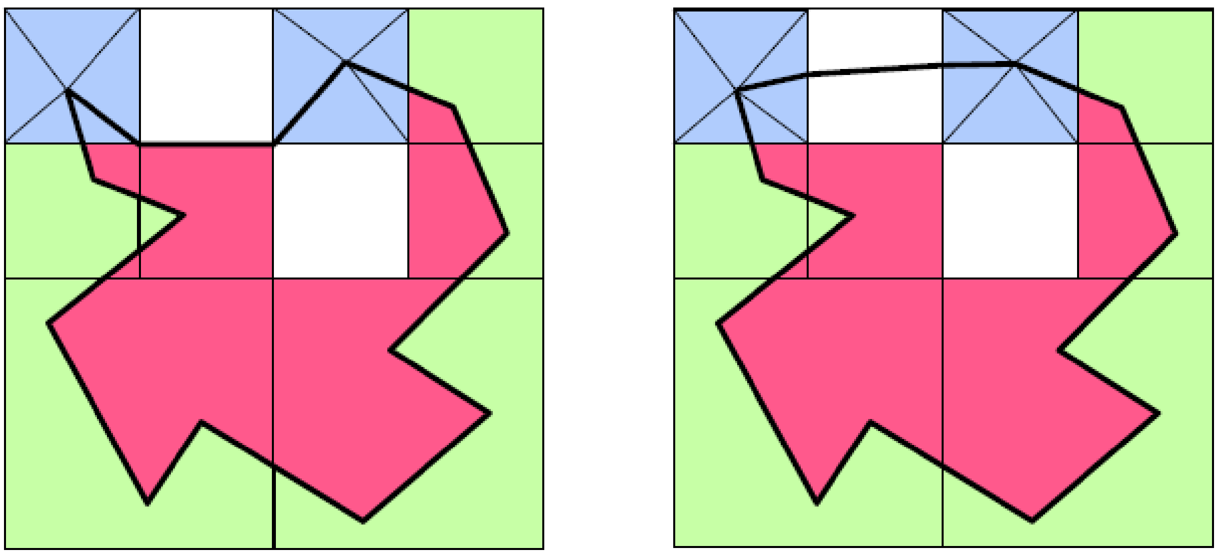


(c) Constraint Edges



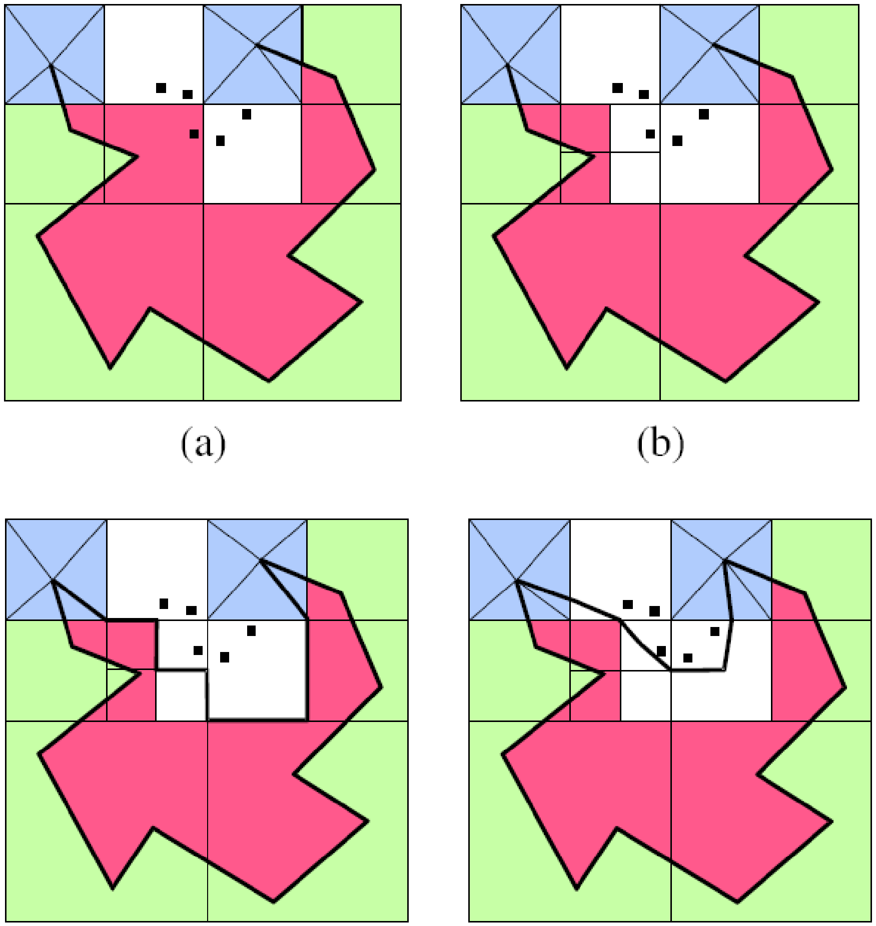
(d) Min Cut

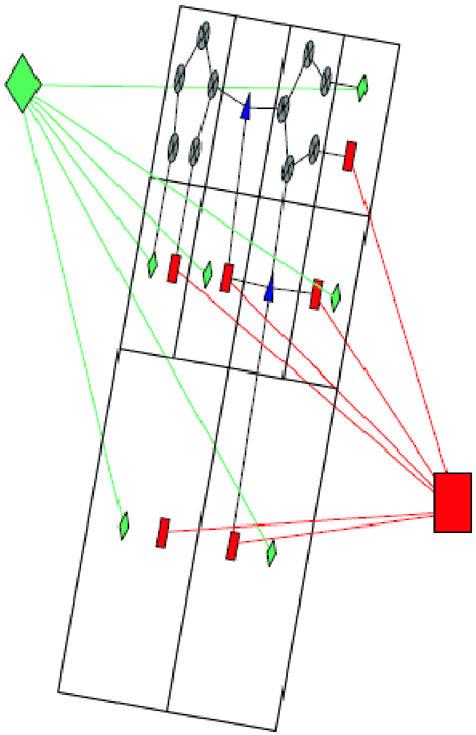
Pipeline



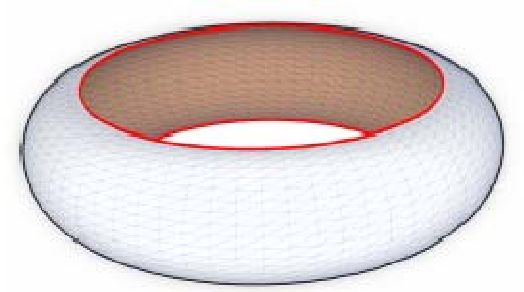
(e) Adding Faces (f) Smoothing

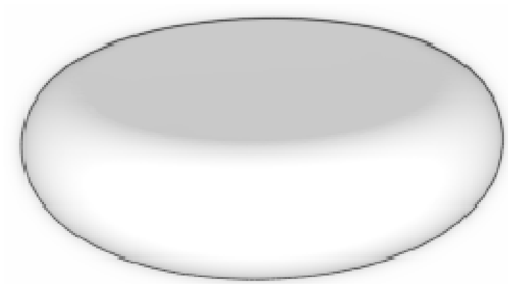
User Constraints

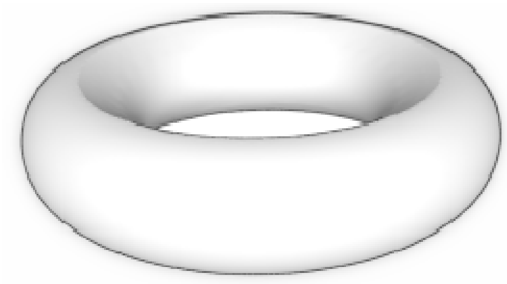

(a) (b) (c) (d)


Constraint Edges

Results







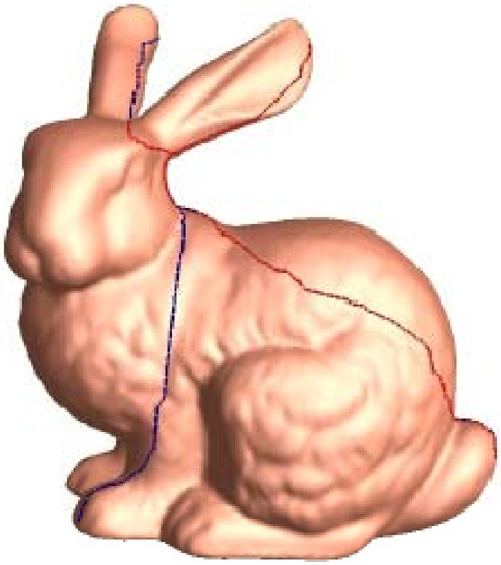
Summary

- Avoid changing, approximating or re-sampling the original mesh data
- Incorporate user constraints
- Can’t process holes with islands

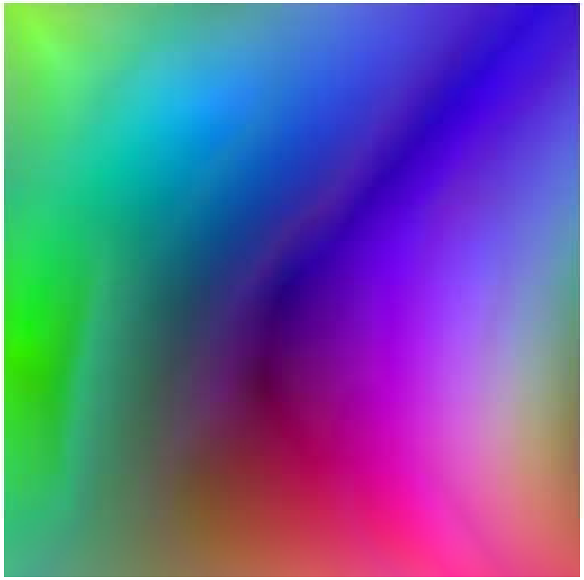
2.7 Geometry Completion by Texture Synthesis

[Nguyen et al., PG 2005]

Geometry Image

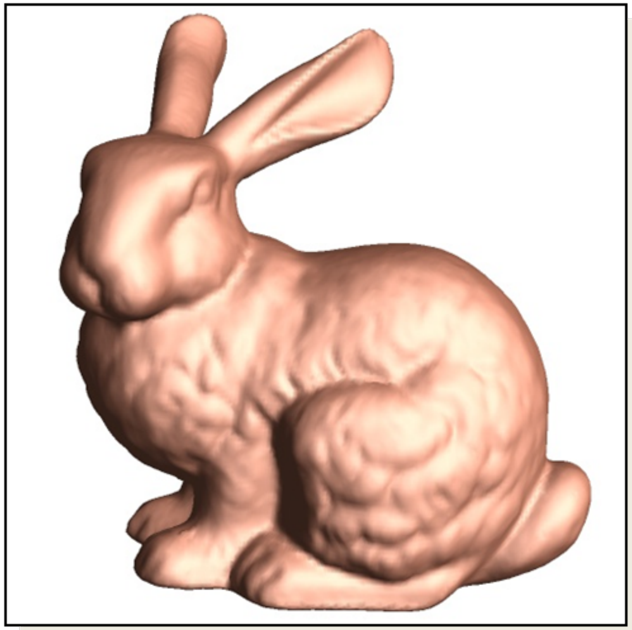


(a) Original mesh with cut

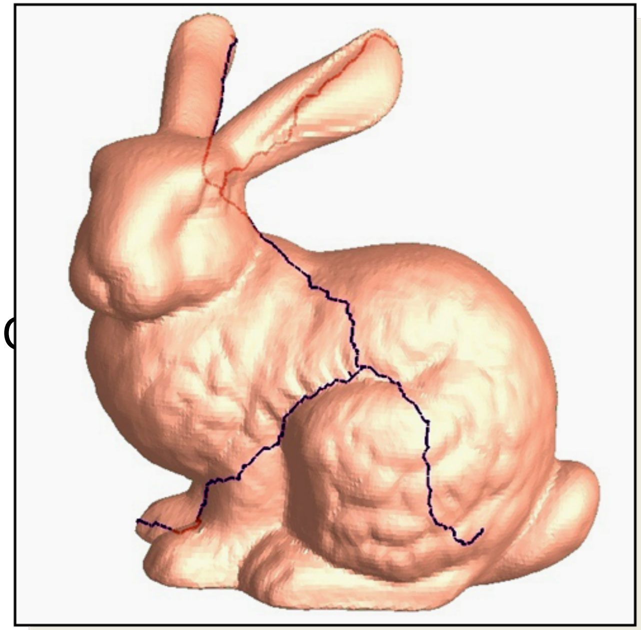


(b) Geometry image 257×257

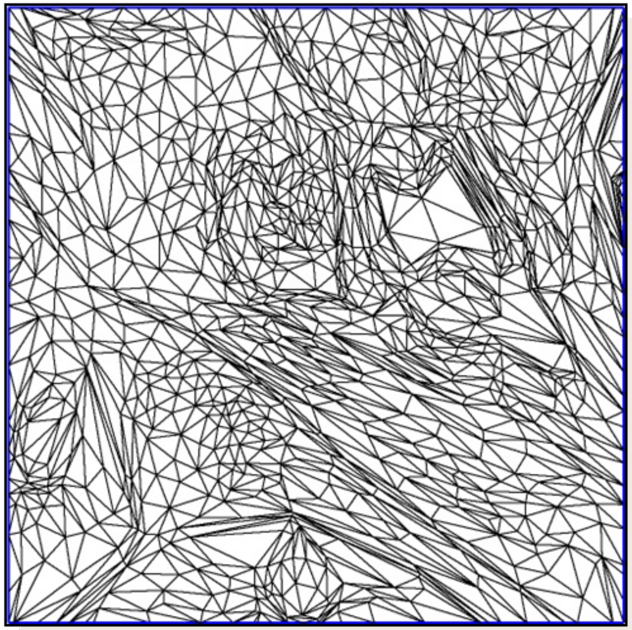
Basic idea



cut

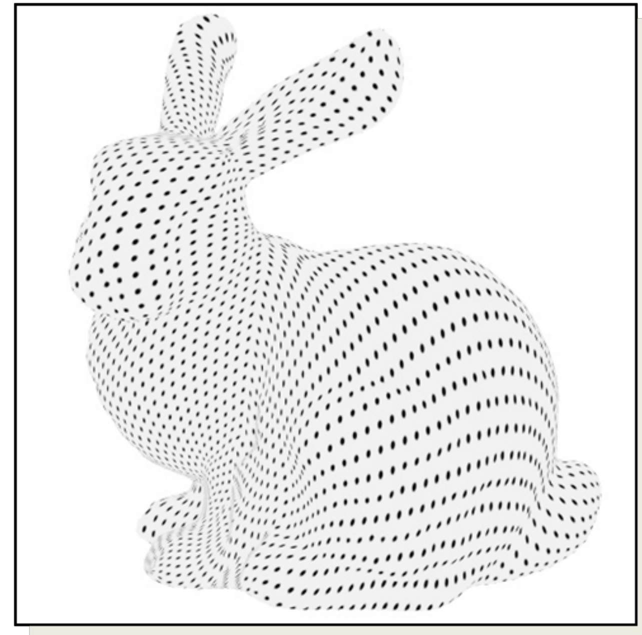


parametrize

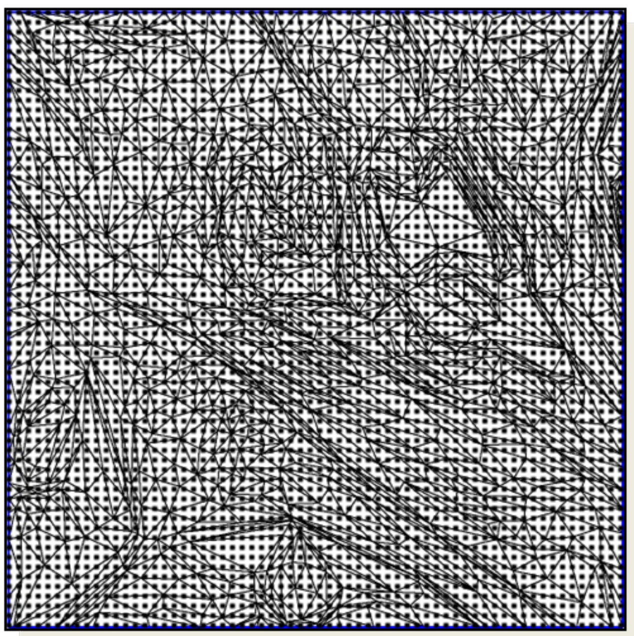


Basic idea

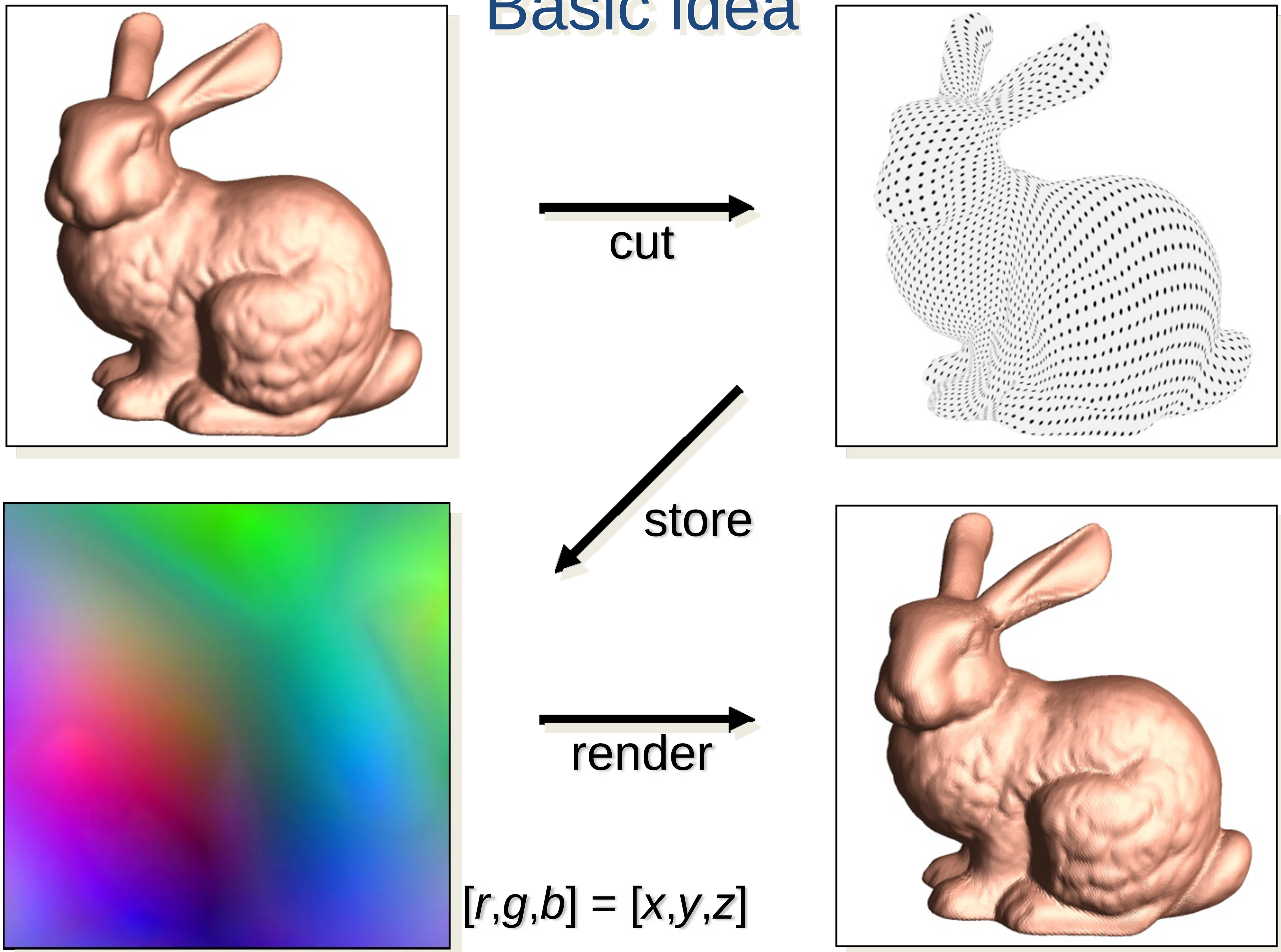
cut

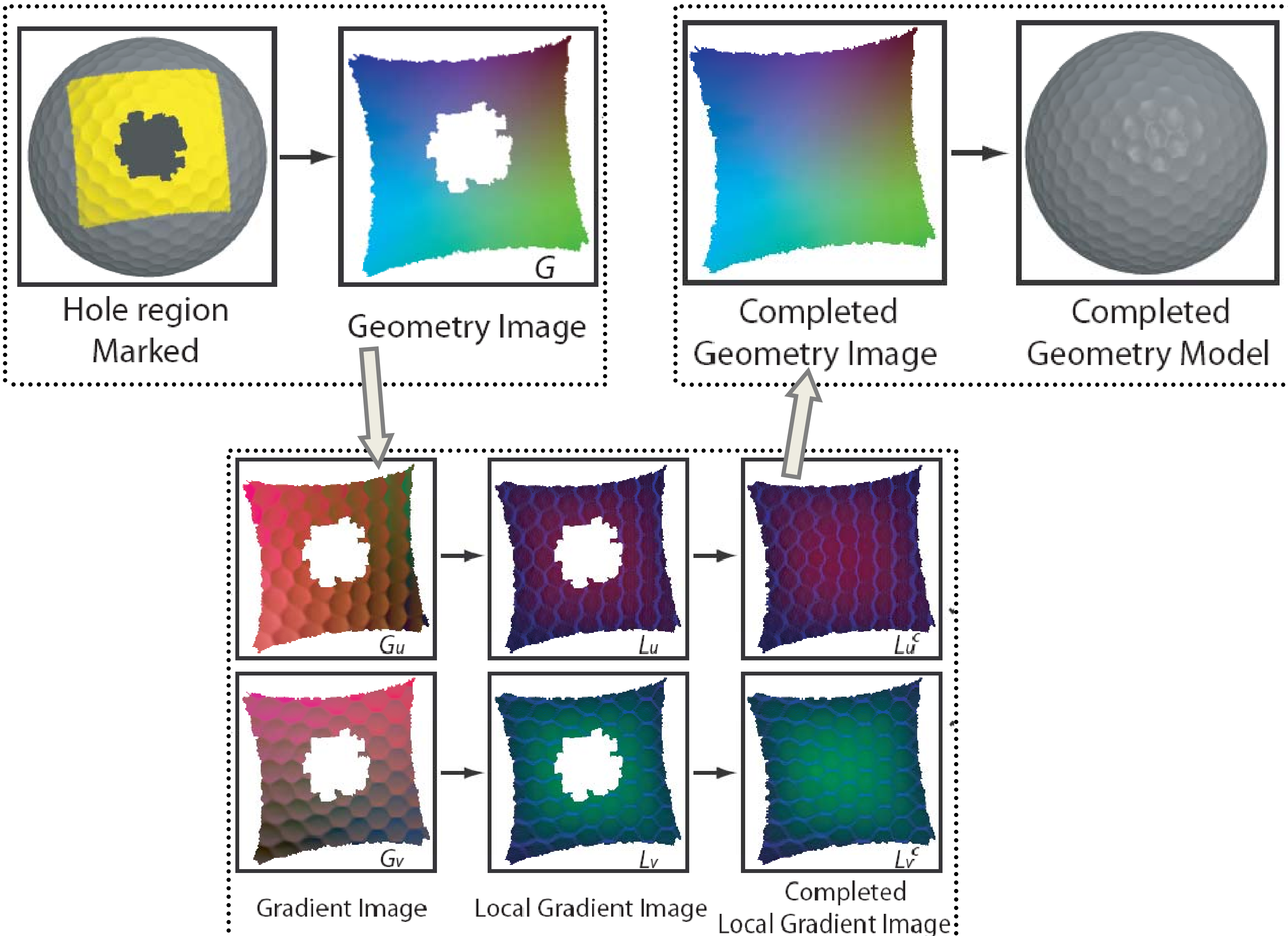


sample



Basic idea

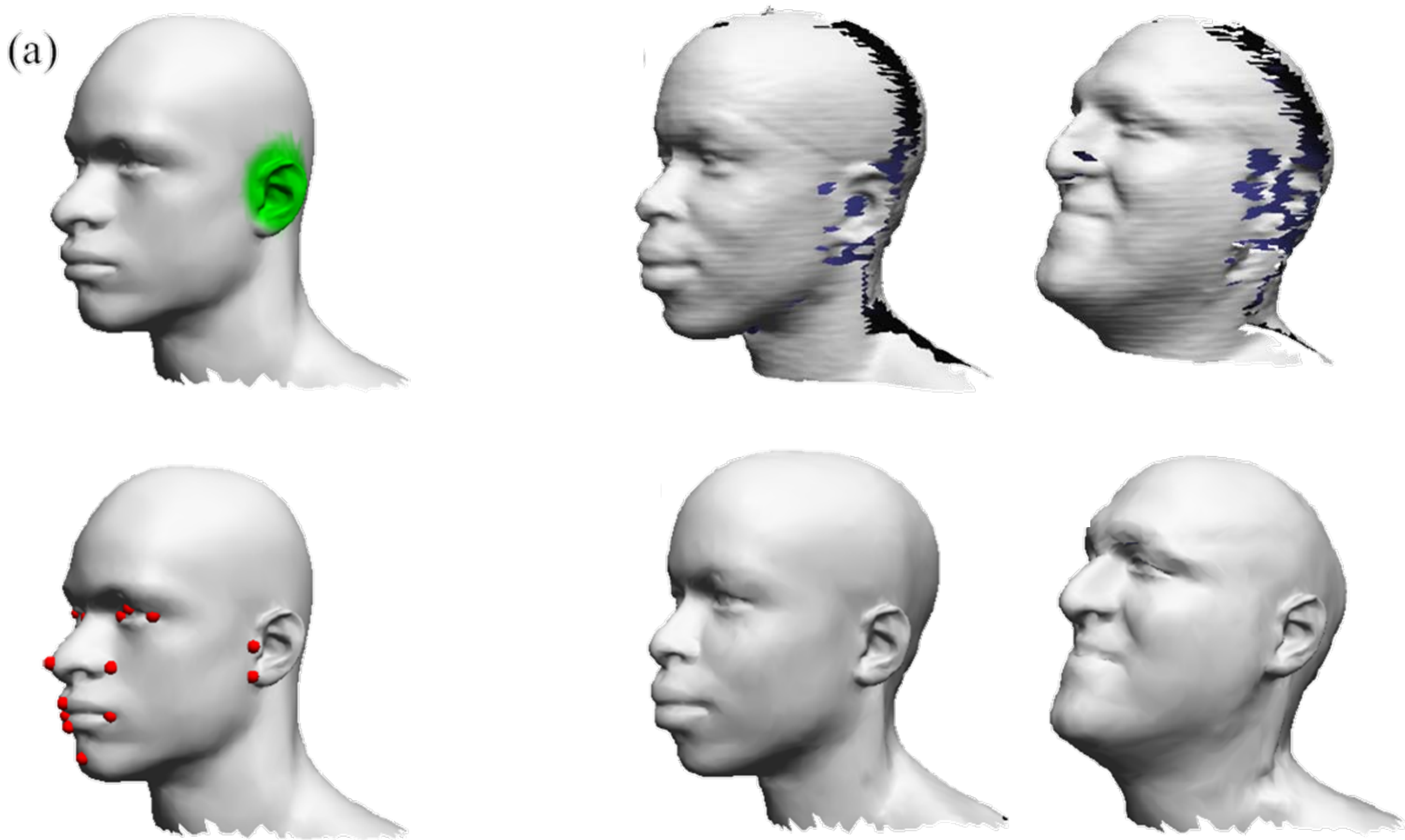



Hole region
Marked
G
Geometry Image
Completed
Geometry Image
Completed
Geometry Model
Gu
Lu
Lu^c
Gv
Lv
Lv^c
Gradient Image
Local Gradient Image
Completed
Local Gradient Image

2.8 Others

Template based Solution

(Allen, Curless, Popovic, 2003; Kraevoy and Sheffer, 2005)



Discussion