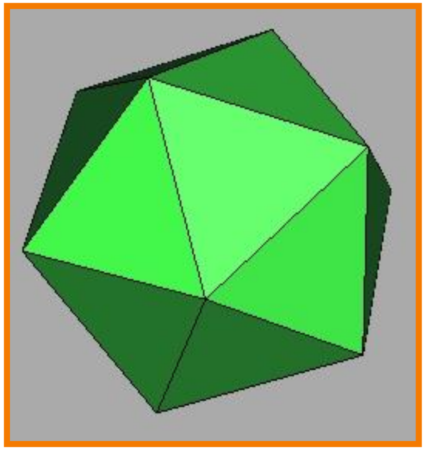
3D Object Representations

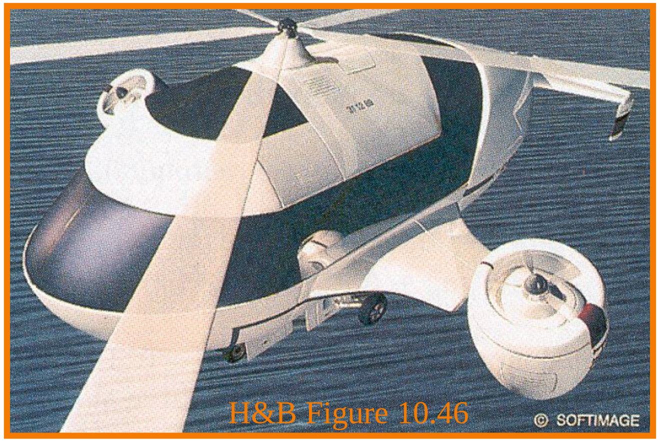
COS 526, Fall 2016

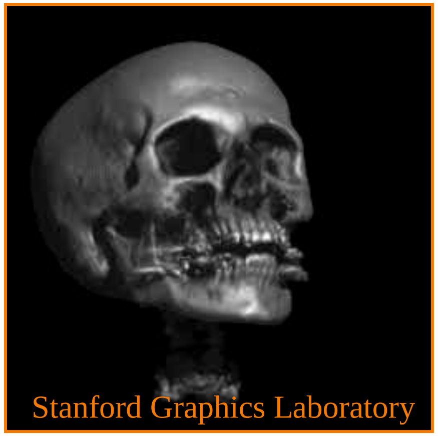
Princeton University

3D Object Representations

- How do we ...
  - Represent 3D objects in a computer?
  - Acquire computer representations of 3D objects?
  - Manipulate computer representations of 3D objects?



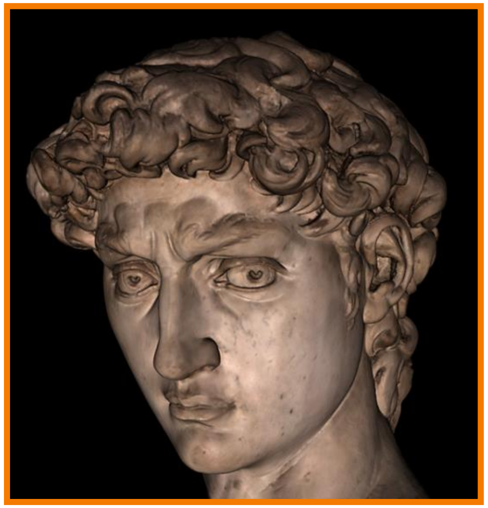




3D Object Representations

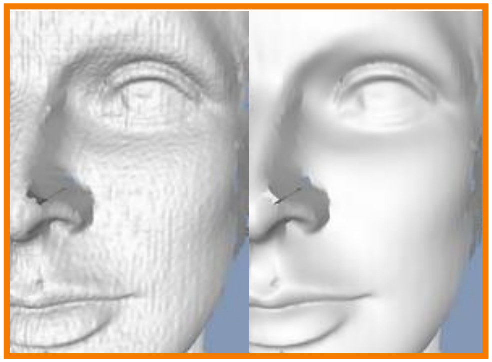
What can we do with a 3D object representation?

- Edit
- Transform
- Smooth
- Render
- Animate
- Morph
- Compress
- Transmit
- Analyze
- etc.

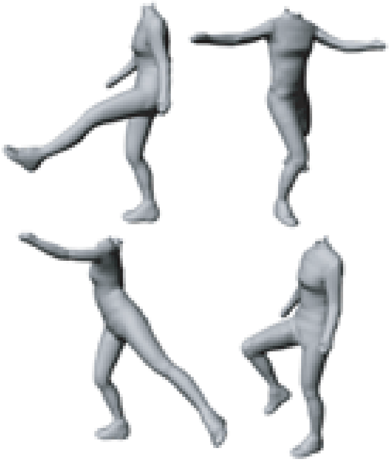


Digital Michelangelo

Pirates of the Caribbean



Thouis “Ray” Jones

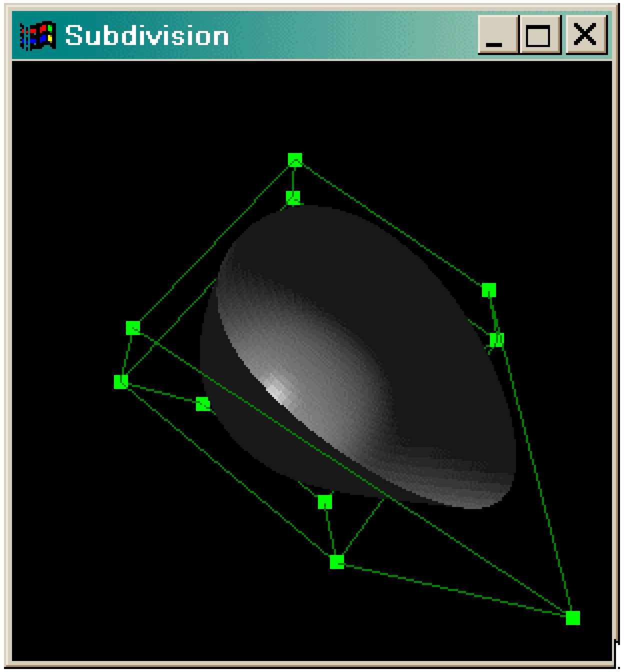


Sand et al.

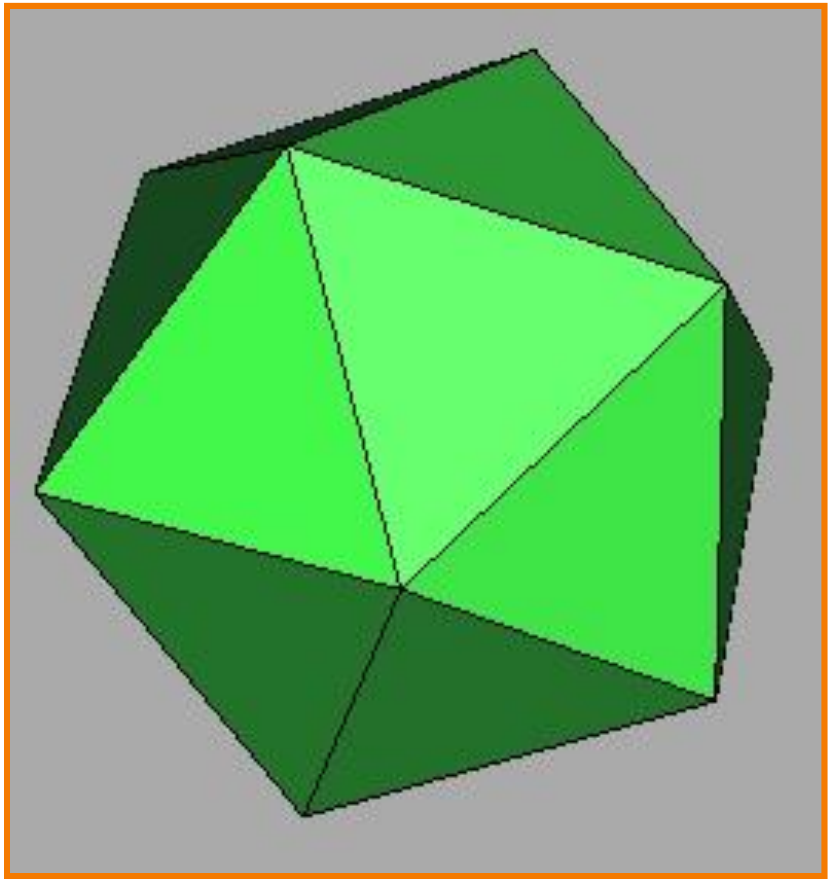
3D Object Representations

Desirable properties depend on intended use

- Easy to acquire
- Accurate
- Concise
- Intuitive editing
- Efficient editing
- Efficient display
- Efficient intersections
- Guaranteed validity
- Guaranteed smoothness
- etc.

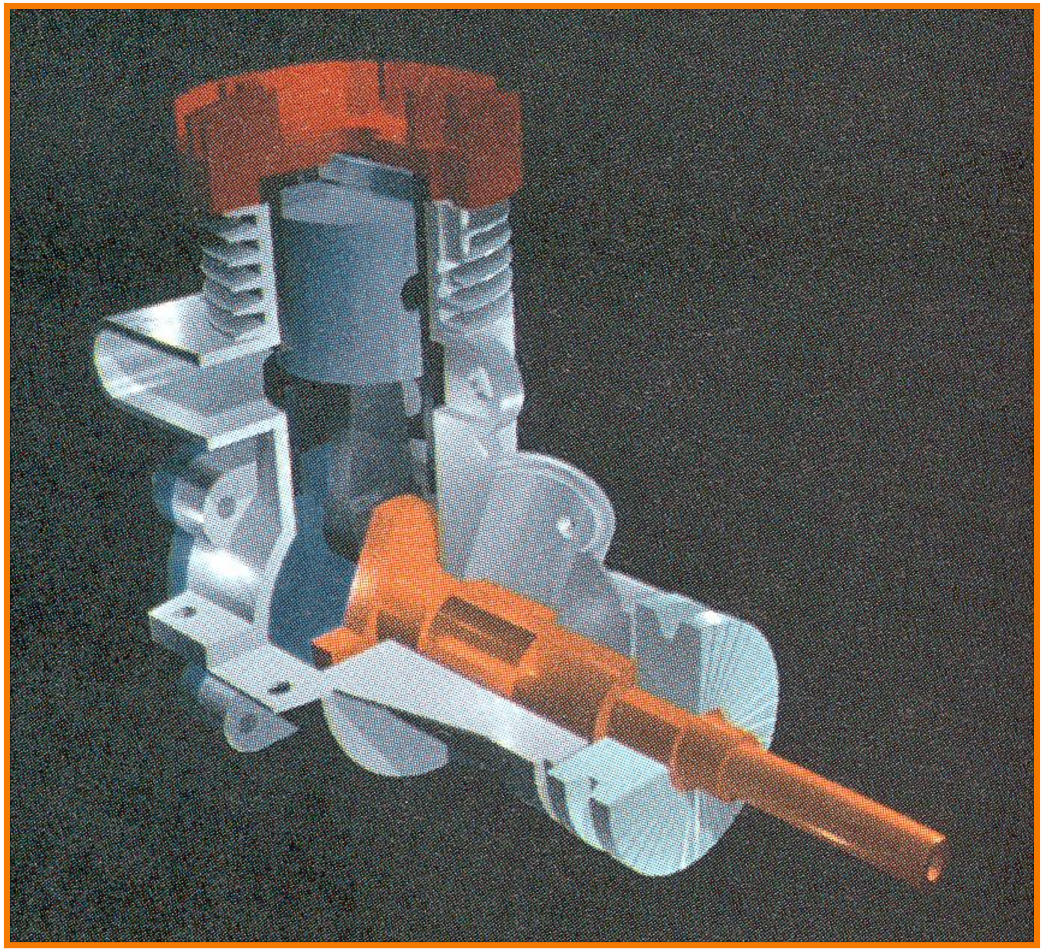


3D Object Representations



How can this object be represented in a computer?

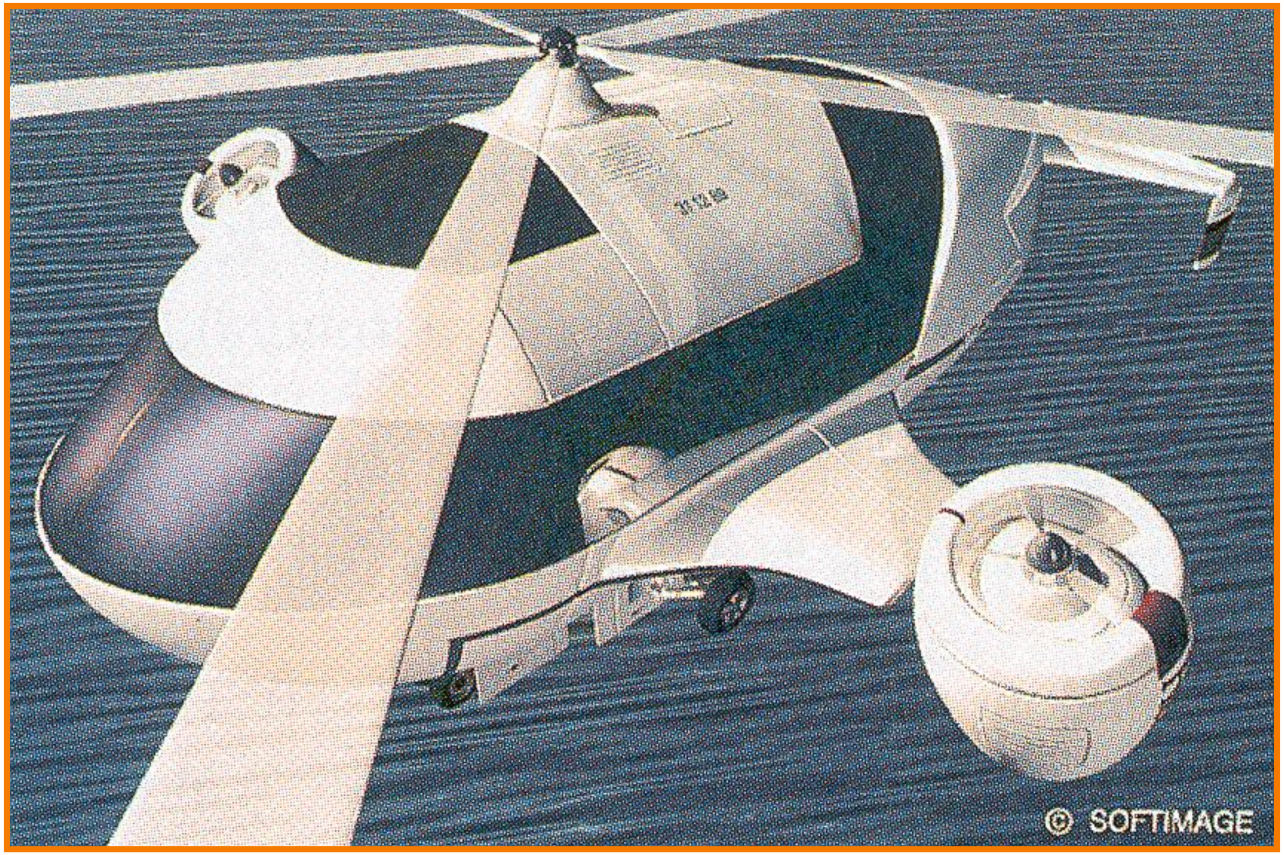
3D Object Representations



H&B Figure 9.9

This one?

3D Object Representations



H&B Figure 10.46

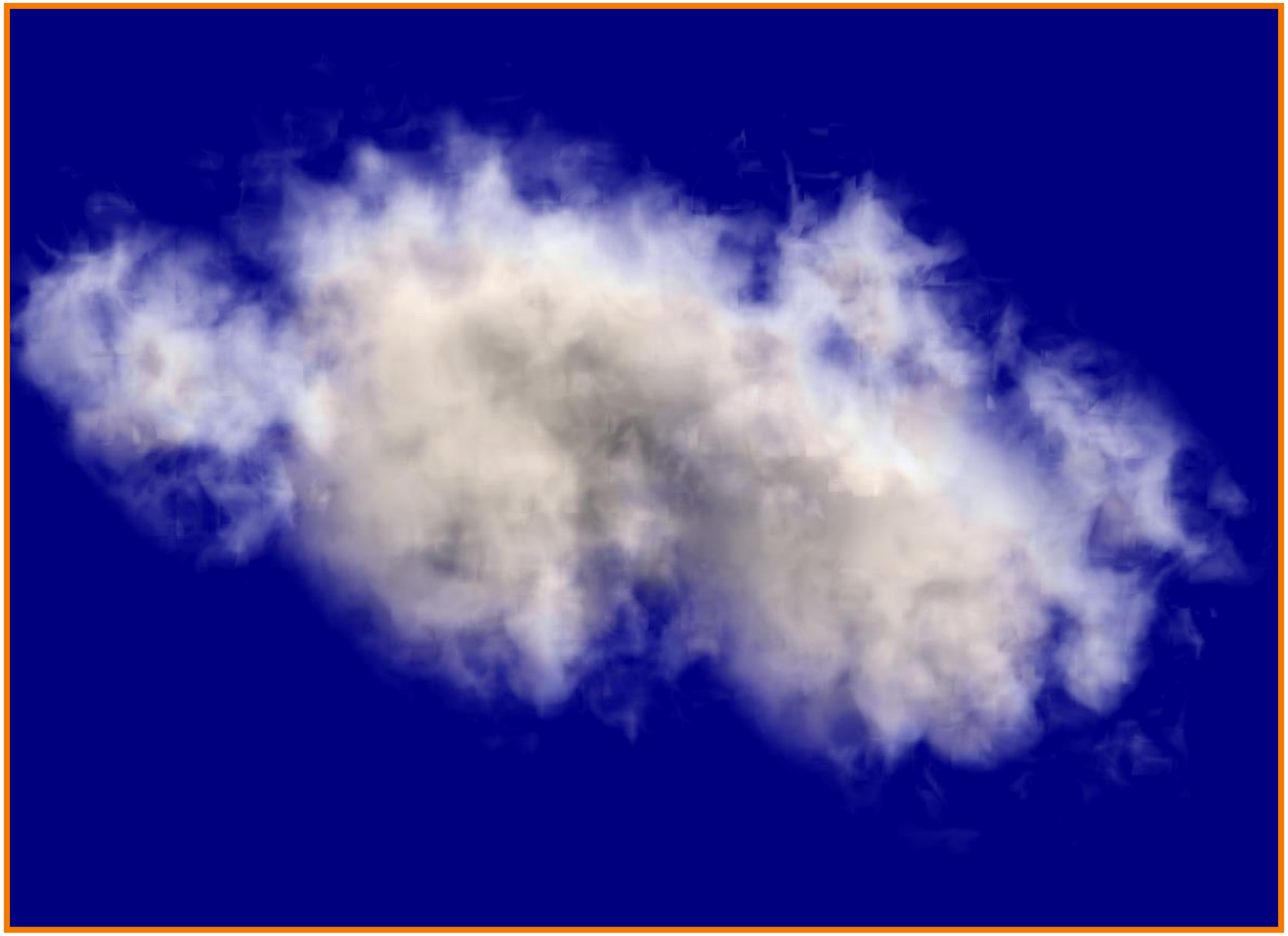
This one?

3D Object Representations

This one?

Stanford Graphics Laboratory

3D Object Representations



This one?

3D Object Representations

- Points
  - Range image
  - Point cloud
- Surfaces
  - Polygonal mesh
  - Subdivision
  - Parametric
  - Implicit
- Solids
  - Voxels
  - BSP tree
  - CSG
  - Sweep
- High-level structures
  - Scene graph
  - Application specific

Equivalence of Representations

- Thesis:
  - Each representation has enough expressive power to model the shape of any geometric object
  - It is possible to perform all geometric operations with any fundamental representation
- Analogous to Turing-equivalence
  - Computers and programming languages are Turing-equivalent, but each has its benefits…

Why Different Representations?

Efficiency for different tasks

- Acquisition
- Rendering
- Manipulation
- Animation
- Analysis

Data structures determine algorithms

Why Different Representations?

- Efficiency
  - Representational complexity (e.g. volume vs. surface)
  - Computational complexity (e.g. $O(n^2)$ vs $O(n^3)$)
  - Space/time trade-offs (e.g. z-buffer)
  - Numerical accuracy/stability (e.g. degree of polynomial)
- Simplicity
  - Ease of acquisition
  - Hardware acceleration
  - Software creation and maintenance
- Usability
  - Designer interface vs. computational engine

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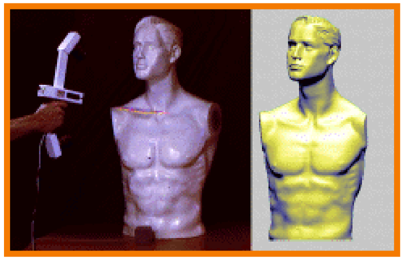
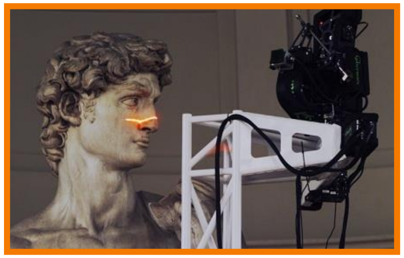
Range Image

Set of 3D points mapping to pixels of depth image

- Can be acquired from range scanner



Cyberware



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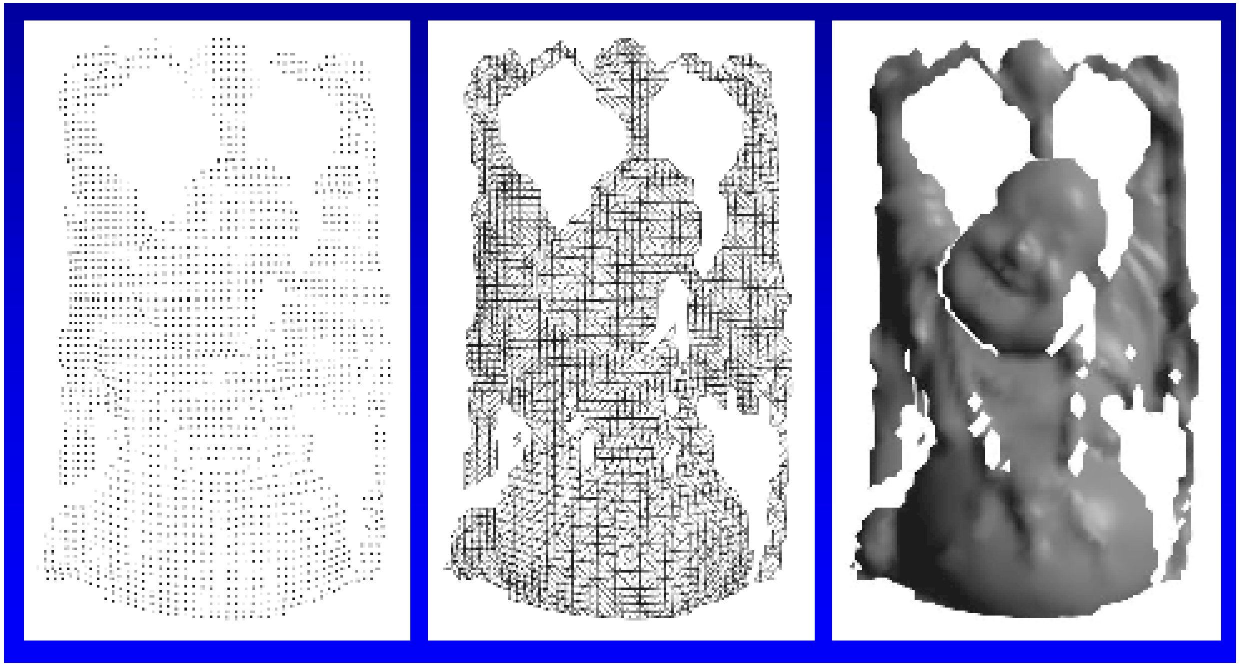

Range Image Tesselation Range Surface

Brian Curless
SIGGRAPH 99
Course #4 Notes

Point Cloud

Unstructured set of 3D point samples

- Acquired from range finder, computer vision, etc

Polhemus

Microscribe-3D

Hoppe

Hoppe

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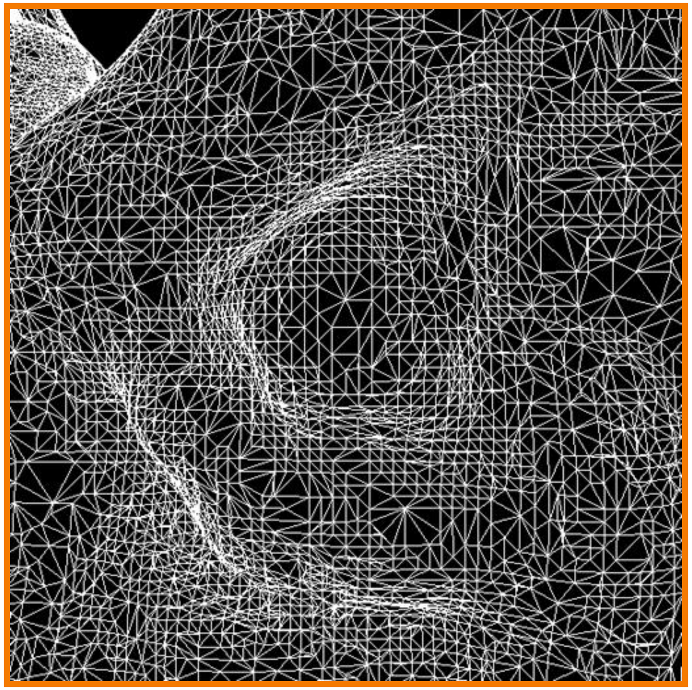
Polygonal Mesh

Connected set of polygons (usually triangles)



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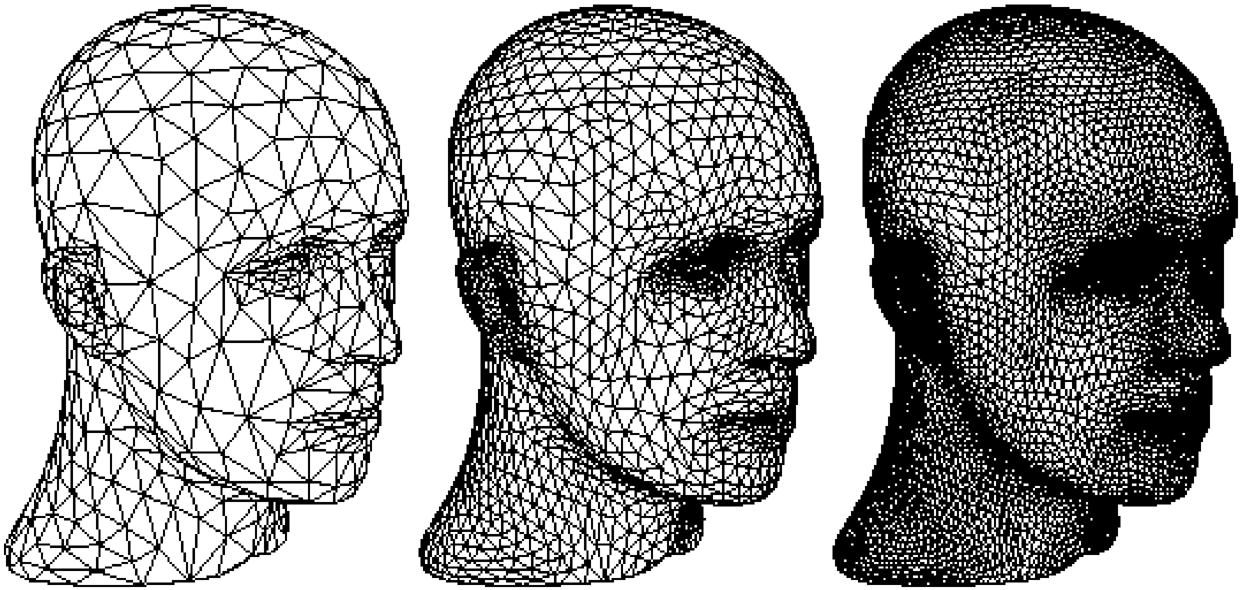
Subdivision Surface

Coarse mesh & subdivision rule

- Smooth surface is limit of sequence of refinements

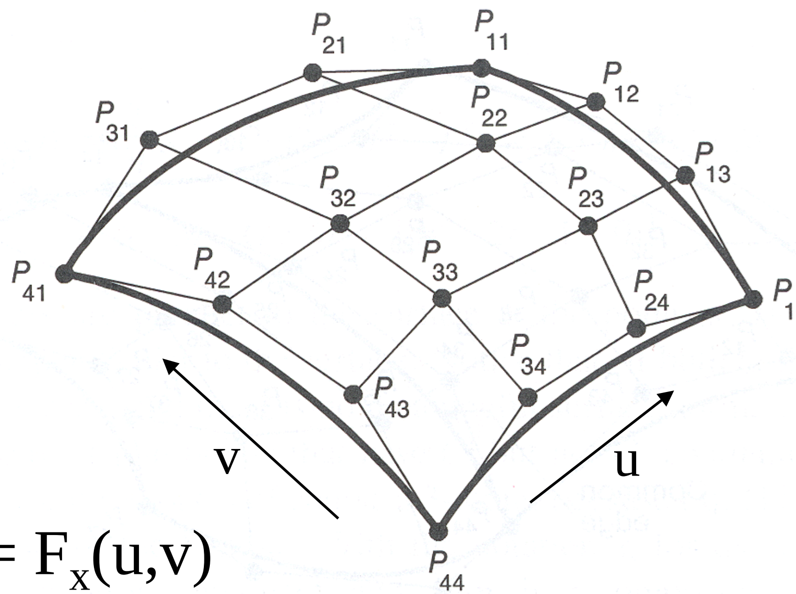


Zorin & Schroeder
SIGGRAPH 99
Course Notes

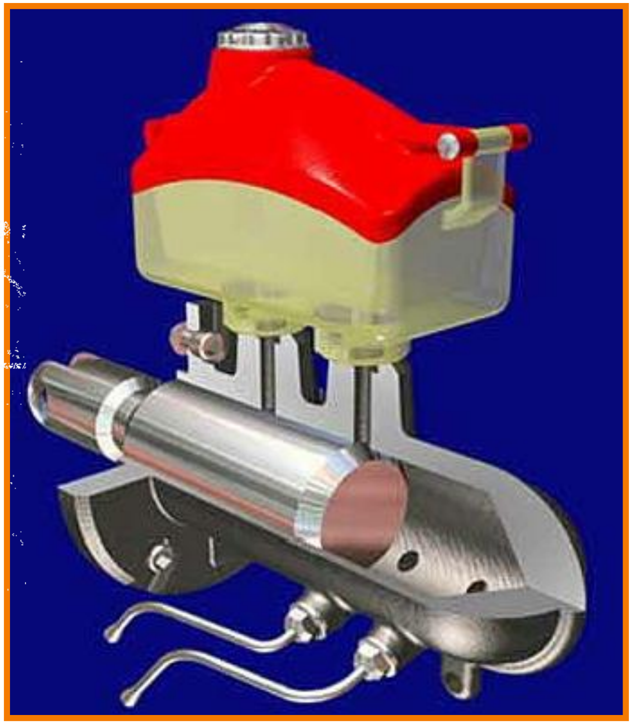
Parametric Surface

Tensor-product spline patches

- Each patch is parametric function
- Careful constraints to maintain continuity



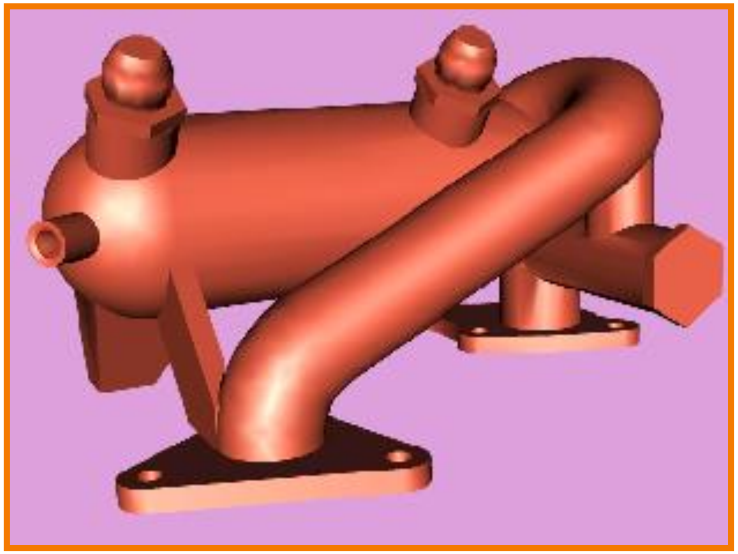
$$x = F_x(u,v)$$
$$y = F_y(u,v)$$
$$z = F_z(u,v)$$



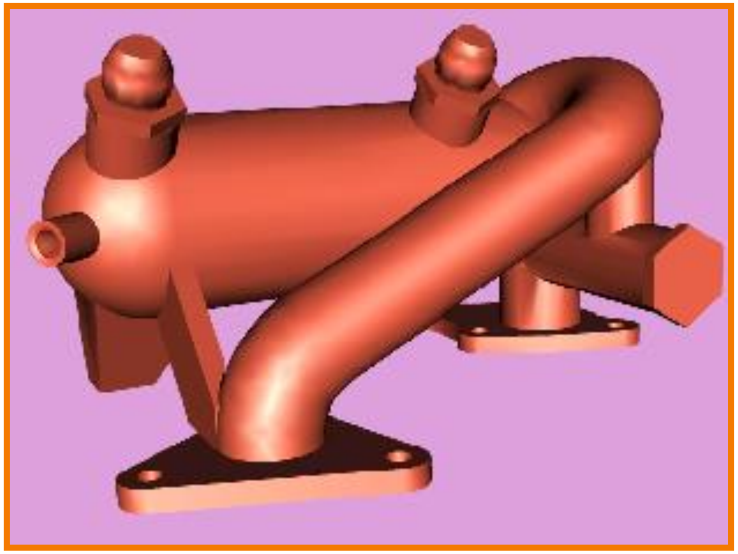
FvDFH Figure 11.44

Implicit Surface

Set of all points satisfying: F(x,y,z) = 0



Polygonal Model



Implicit Model

Bill Lorensen
SIGGRAPH 99
Course #4 Notes

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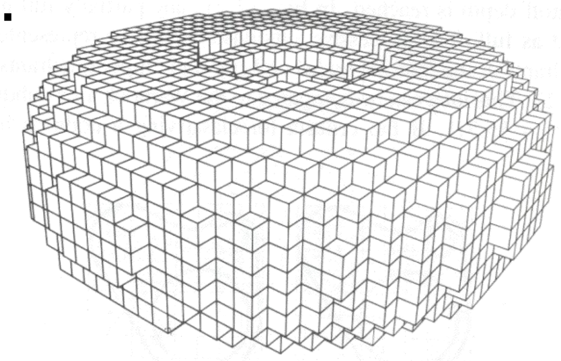
Voxel grid

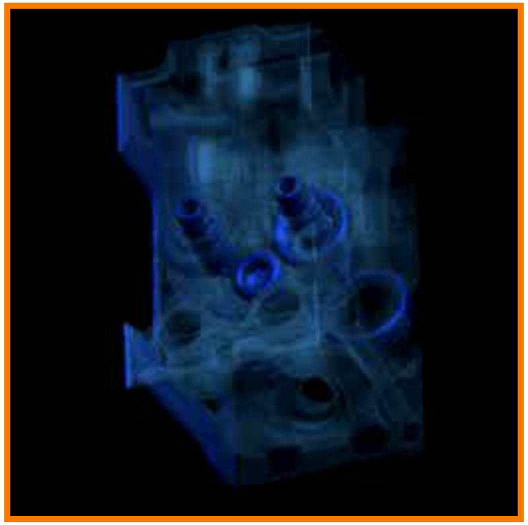
Uniform volumetric grid of samples:

- Occupancy
  (object vs. empty space)
- Density
- Color
- Other function
  (speed, temperature, etc.)

- Often acquired via
  simulation or from
  CAT, MRI, etc.



FvDFH Figure 12.20



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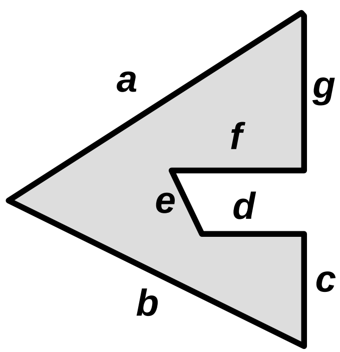
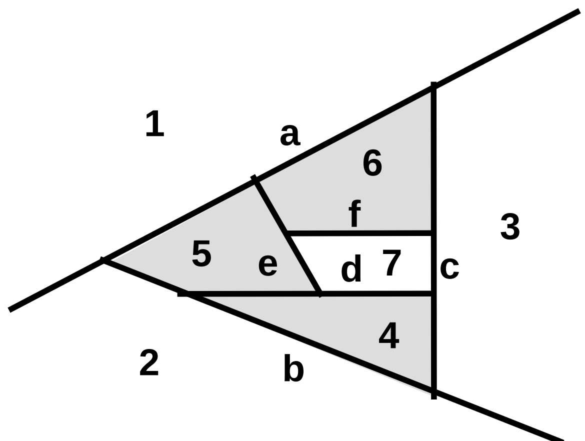
BSP Tree

Hierarchical **Binary** **Space** **Partition** with solid/empty cells labeled

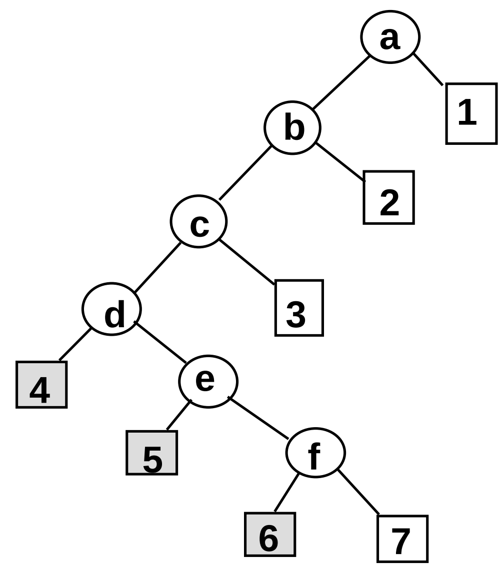
- Constructed from polygonal representations



Object



Binary Spatial Partition

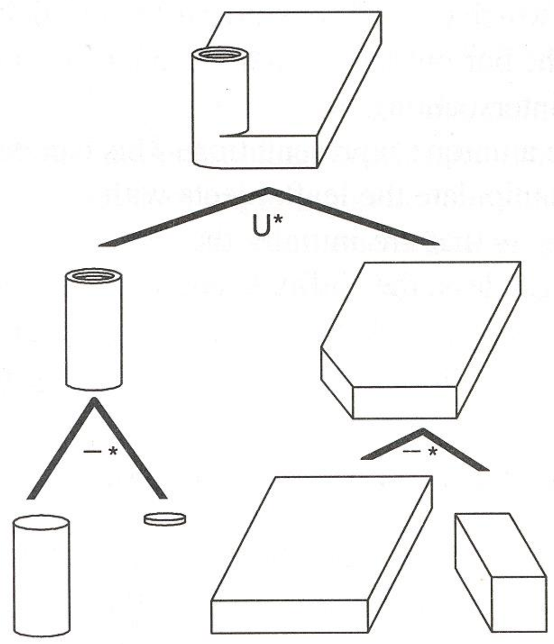


Binary Tree

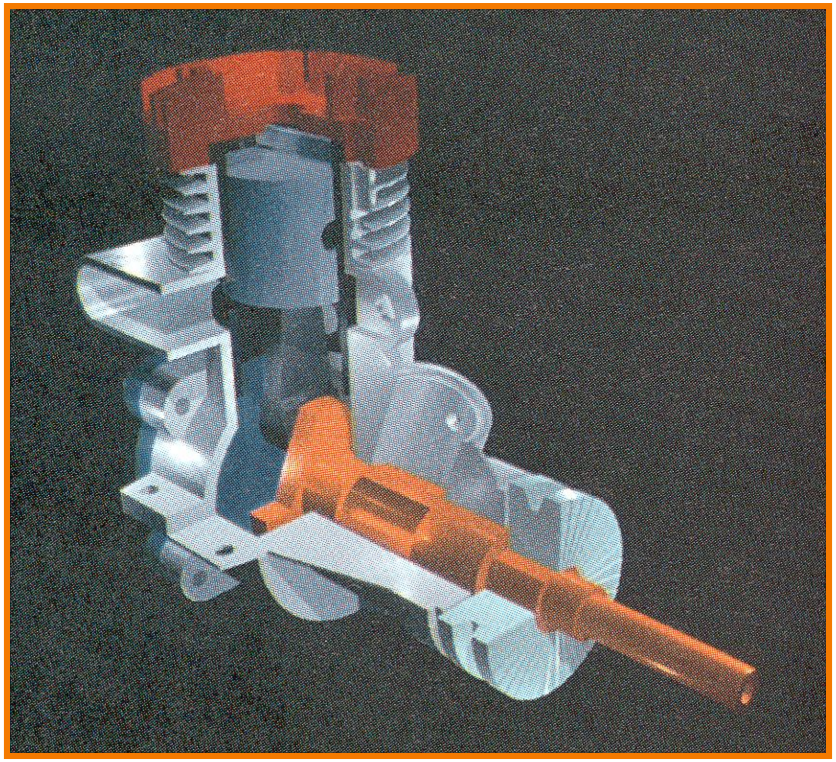
Naylor

CSG

Constructive Solid Geometry: set operations (union, difference, intersection) applied to simple shapes



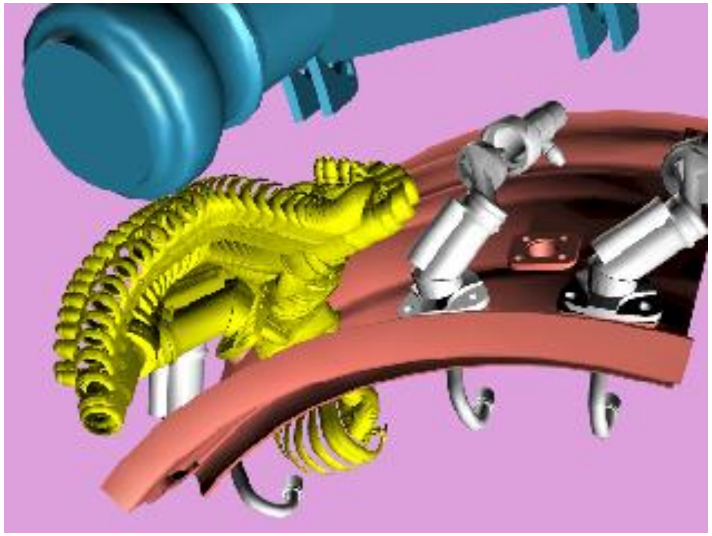
FvDFH Figure 12.27



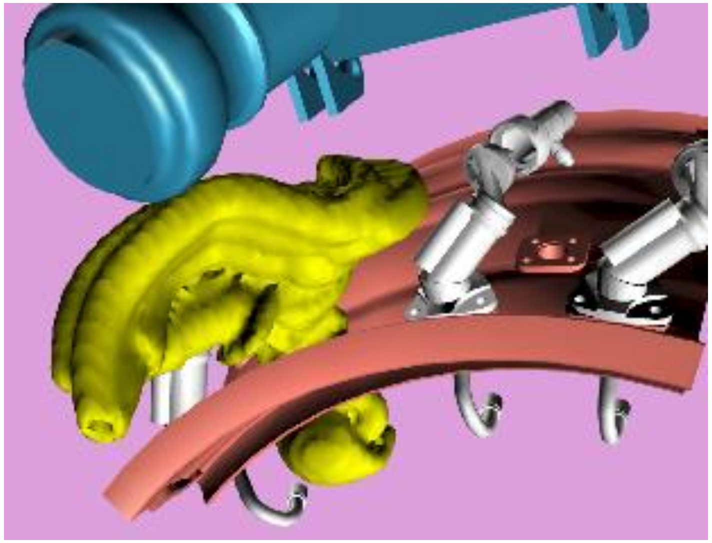
H&B Figure 9.9

Sweep

Solid swept by curve along trajectory



Removal Path



Sweep Model

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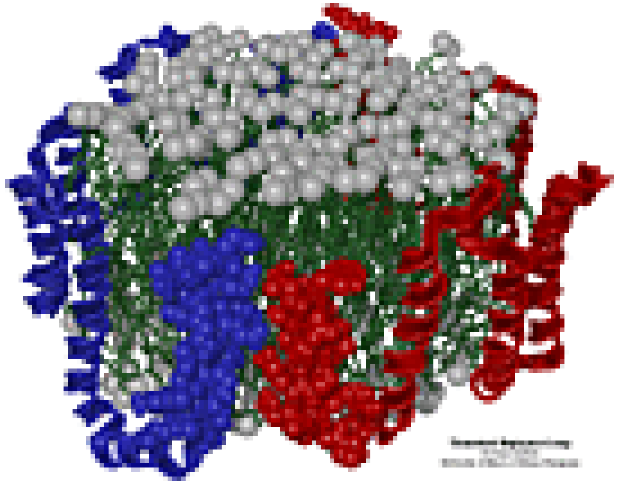
Scene Graph

Union of objects at leaf nodes

Bell Laboratories

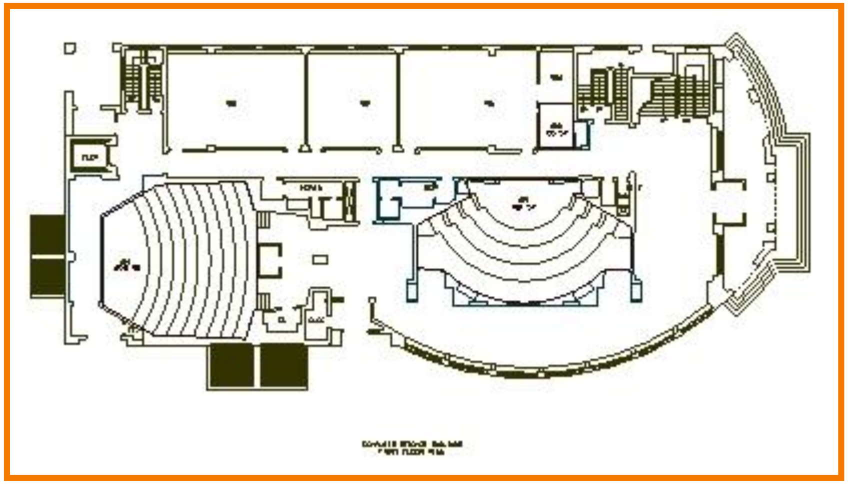
avalon.viewpoint.com

Application Specific



Apo A-1

(Theoretical Biophysics Group,
University of Illinois at Urbana-Champaign)



Architectural Floorplan

(CS Building, Princeton University)

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Point-Based Representations

(with an emphasis on RGB-D scans)

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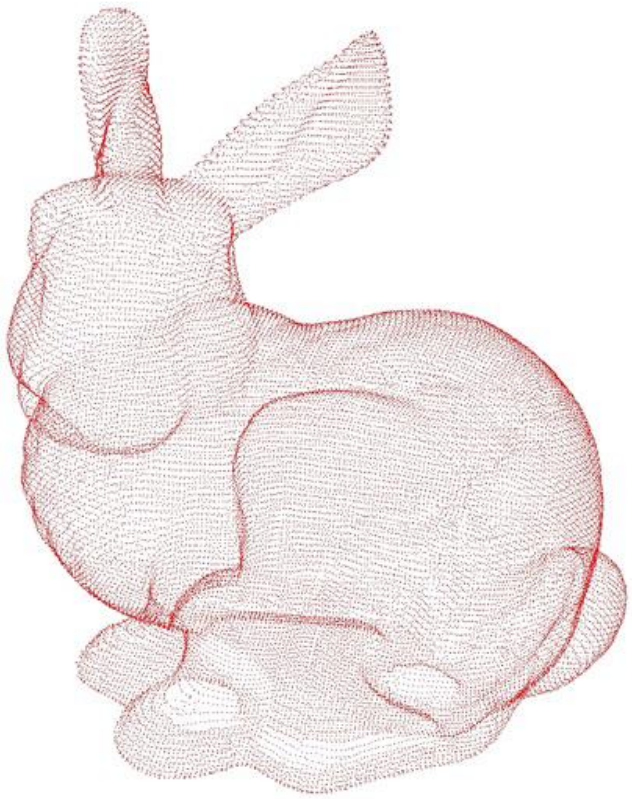
Point Clouds

Represent surface by a set of points

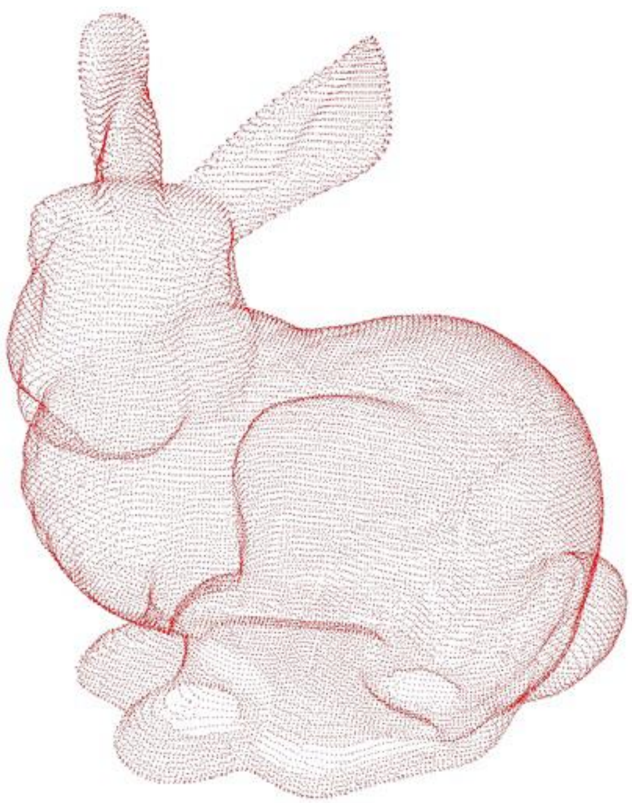
- Each point is represented by (x, y, z) [(r, g, b)]
- No connectivity between points



Point Clouds

Properties?

- Easy to acquire
- Accurate
- Concise
- Intuitive editing
- Efficient editing
- Efficient display
- Efficient intersections
- Guaranteed validity
- Guaranteed smoothness
- etc.



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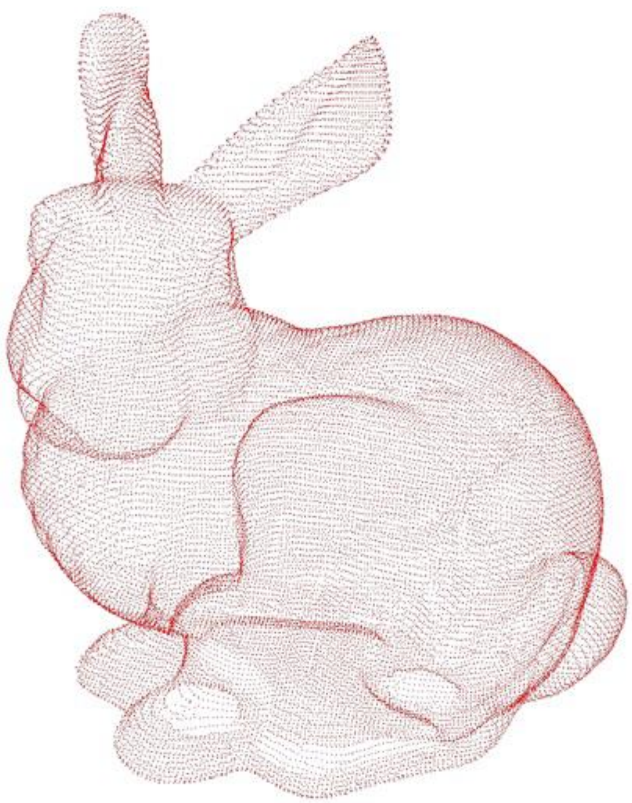


Point Cloud Acquisition

Passive

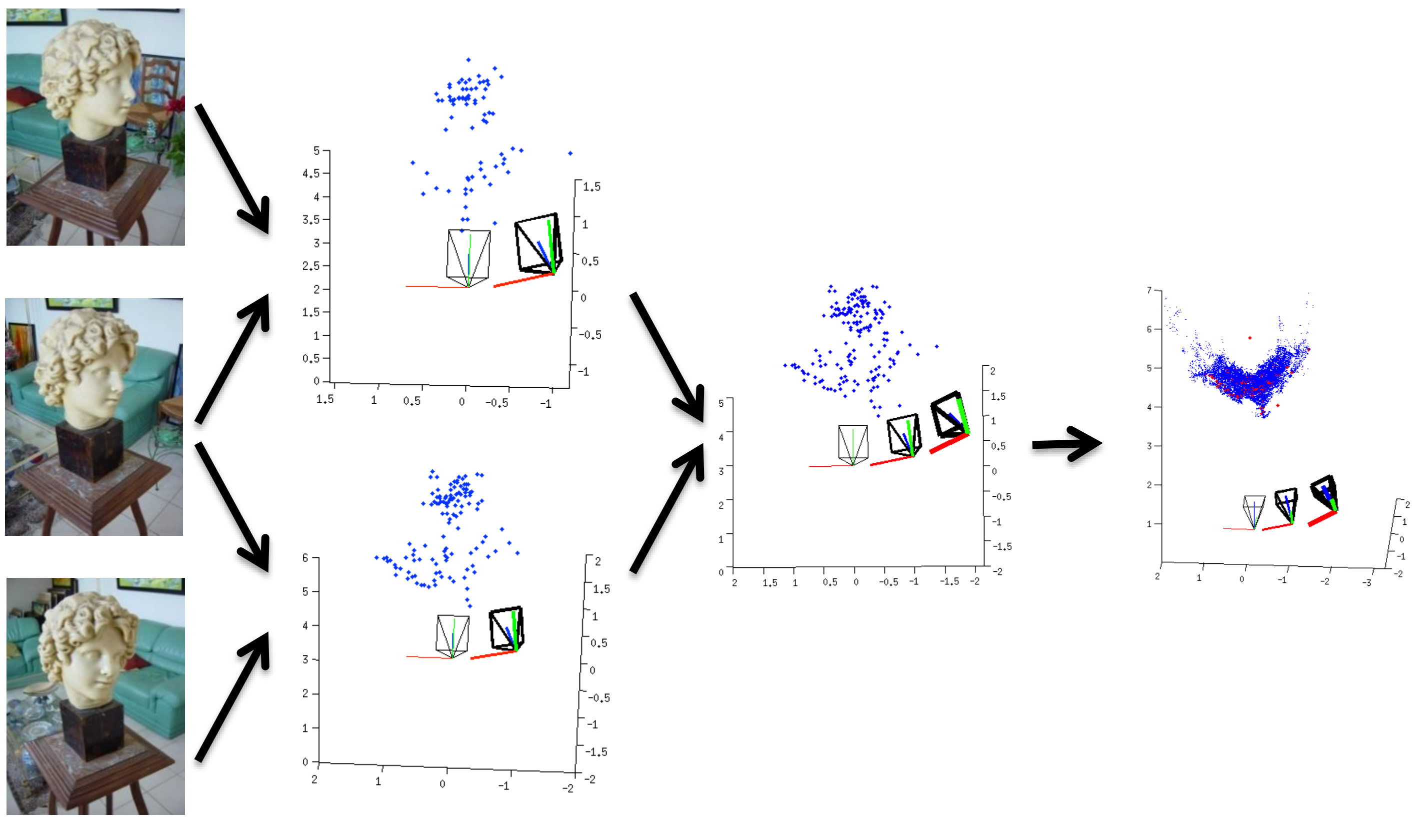
- Structure from motion

Active

- Touch probes
- Reflectance scanning
  - Time of flight
  - Triangulation
    - Laser
    - Structured light

Structure from Motion

Solve for 3D structure of pixel correspondences in multiple images



Structure from Motion (SfM) Multi-view Stereo (MVS)

Structure from Motion

Advantages:

- Has been demonstrated for large photo collections
- Passive

Disadvantages:

- Only works for points where pixel correspondences can be found

Touch Probes

Capture points on object with tracked tip of probe

- Physical contact with the object
- Manual or computer-guided

Touch Probes

Advantages:

- Can be very precise
- Can scan **any** solid surface

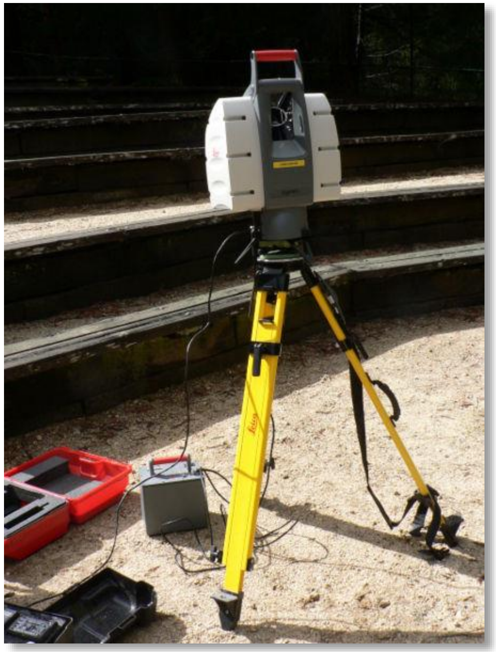
Disadvantages:

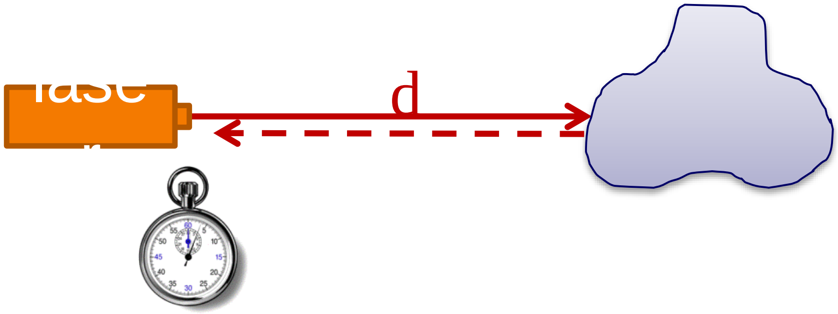
- Slow, small scale
- Can't use on fragile objects

Time of Flight Laser Scanning

Measures the time it takes the laser beam to hit the object and come back

e.g., LIDAR





$d = 0.5\, t \cdot c$

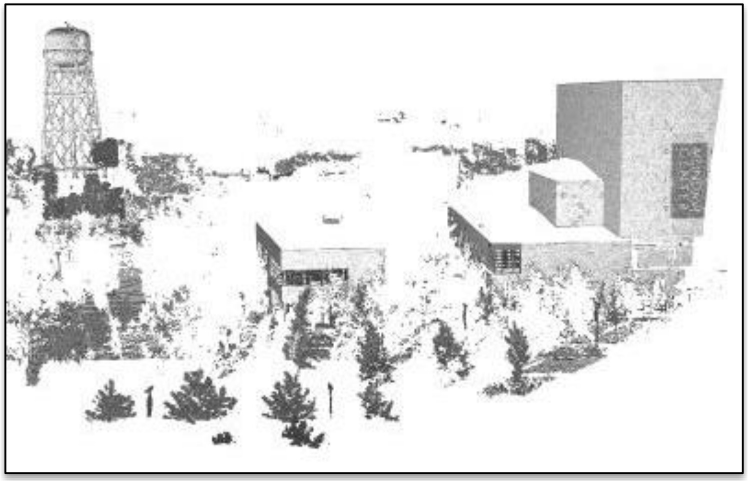
Time of Flight Laser Scanning

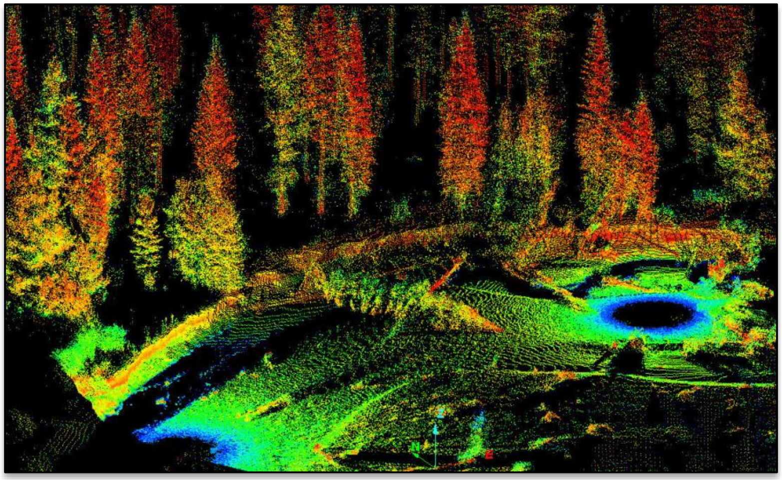
Advantages

- Accommodates large range – up to several miles (suitable for buildings, rocks)

Disadvantages

- Lower accuracy



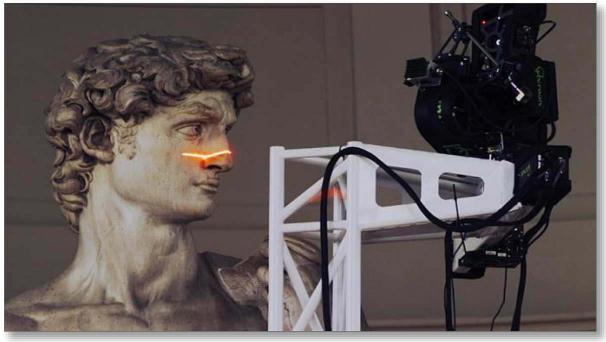


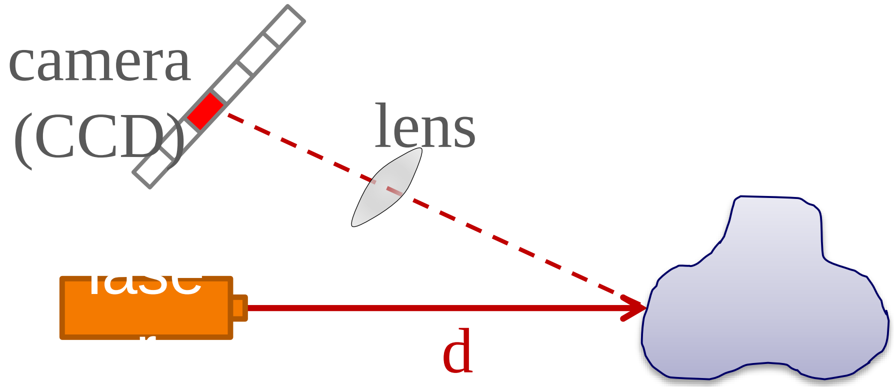
Triangulation Laser Scanning

System includes calibrated laser beam and camera

- Laser dot is photographed

The location of the dot in the image allows triangulation: tells distance to the object





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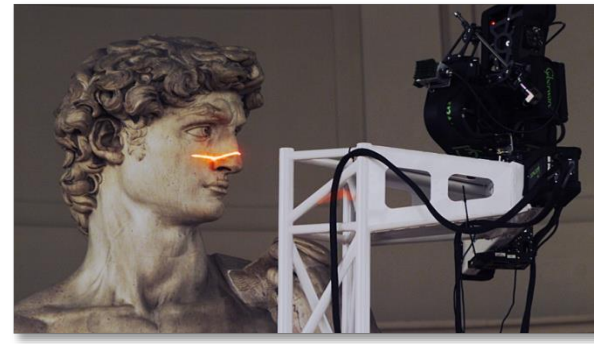

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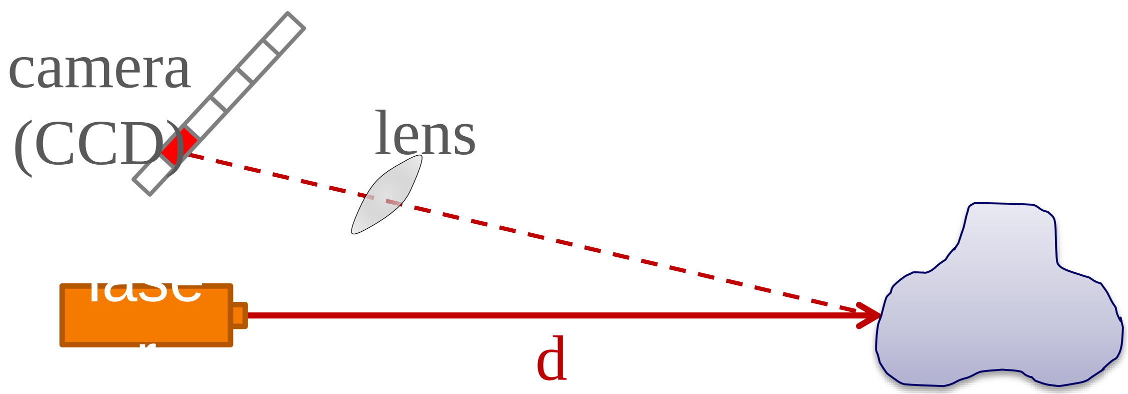
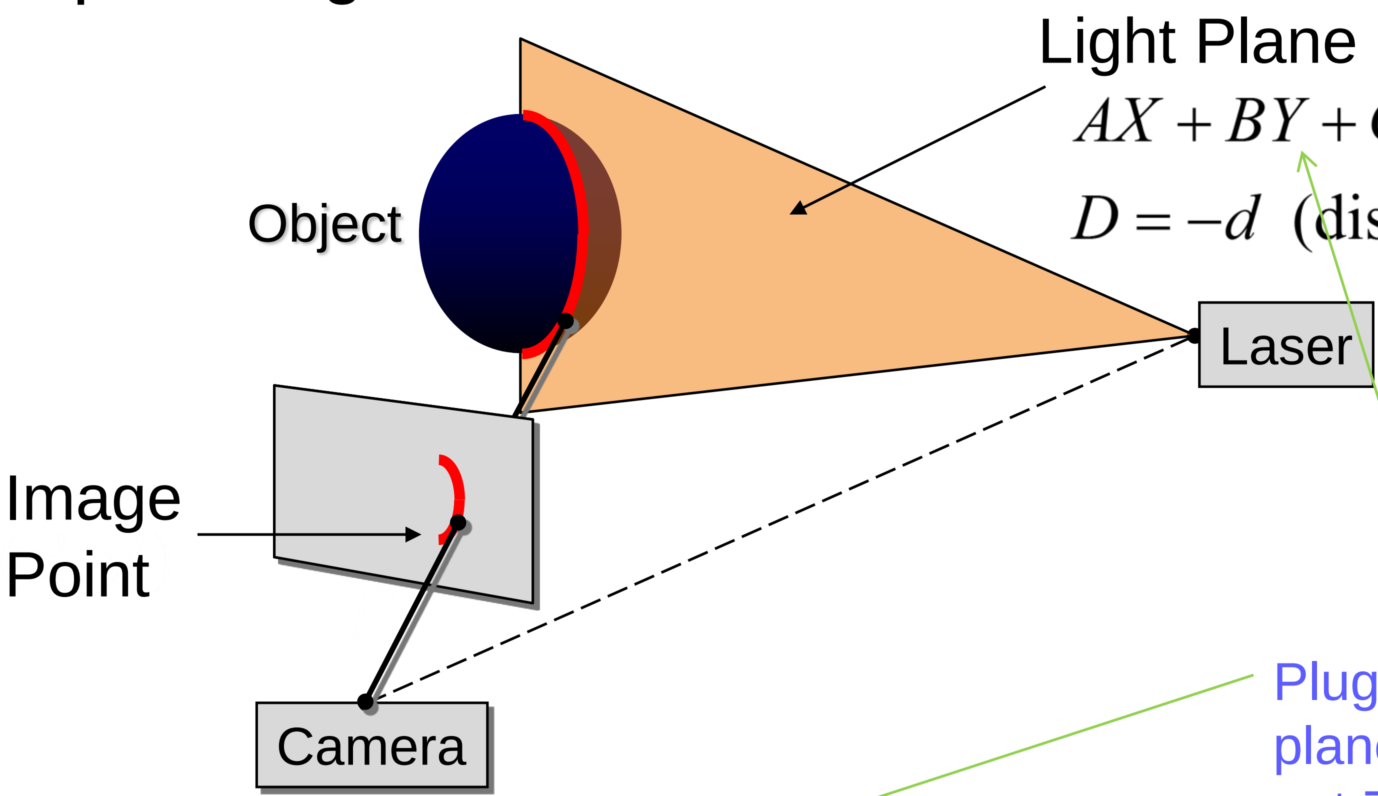


Triangulation Laser Scanning

Stripe triangulation



$$AX + BY + CZ + D = 0$$

$$D = -d \quad \text{(distance)}$$

$$X = x' Z / f' \qquad Y = y' Z / f' \qquad Z = \frac{-Df'}{Ax' + By' + Cf'}$$

Plug X, Y into plane equation to get Z

Courtesy S. Narasimhan, CMU

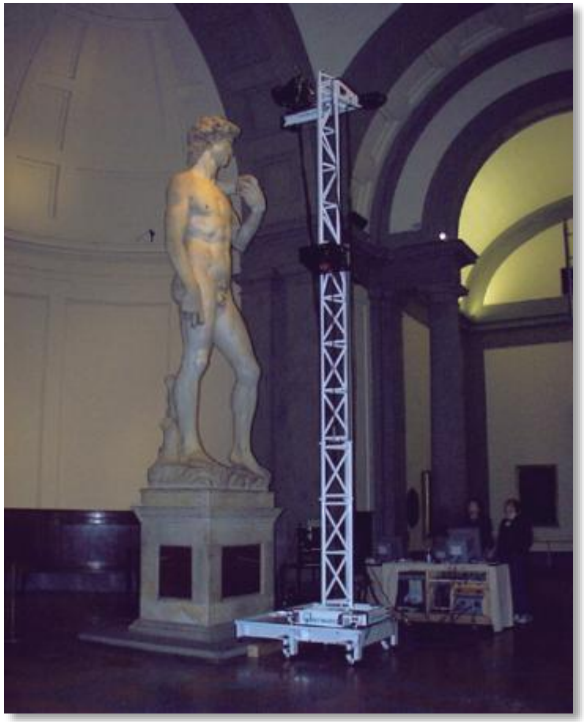
Triangulation Laser Scanning

Advantages

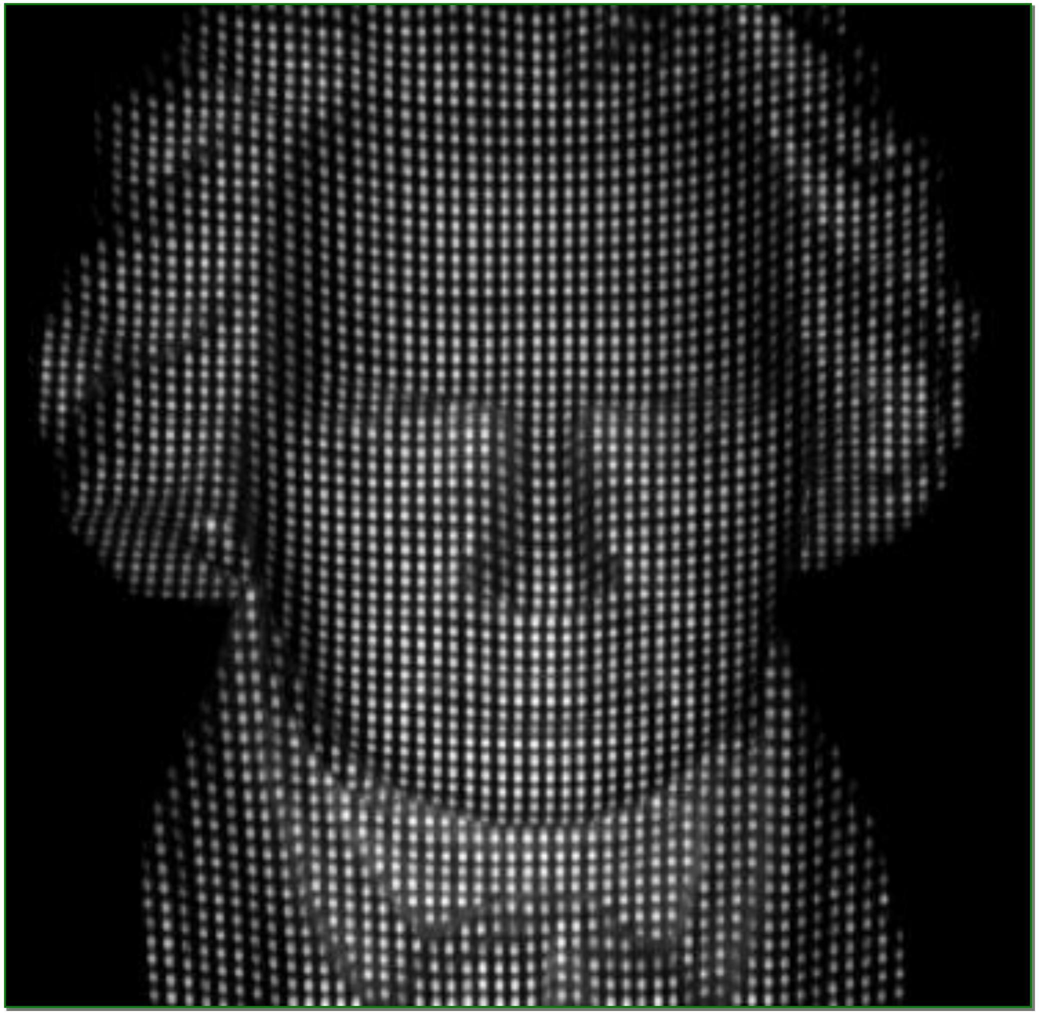
- Very precise (tens of microns)

Disadvantages

- Small distances (meters)
- Inaccessible regions

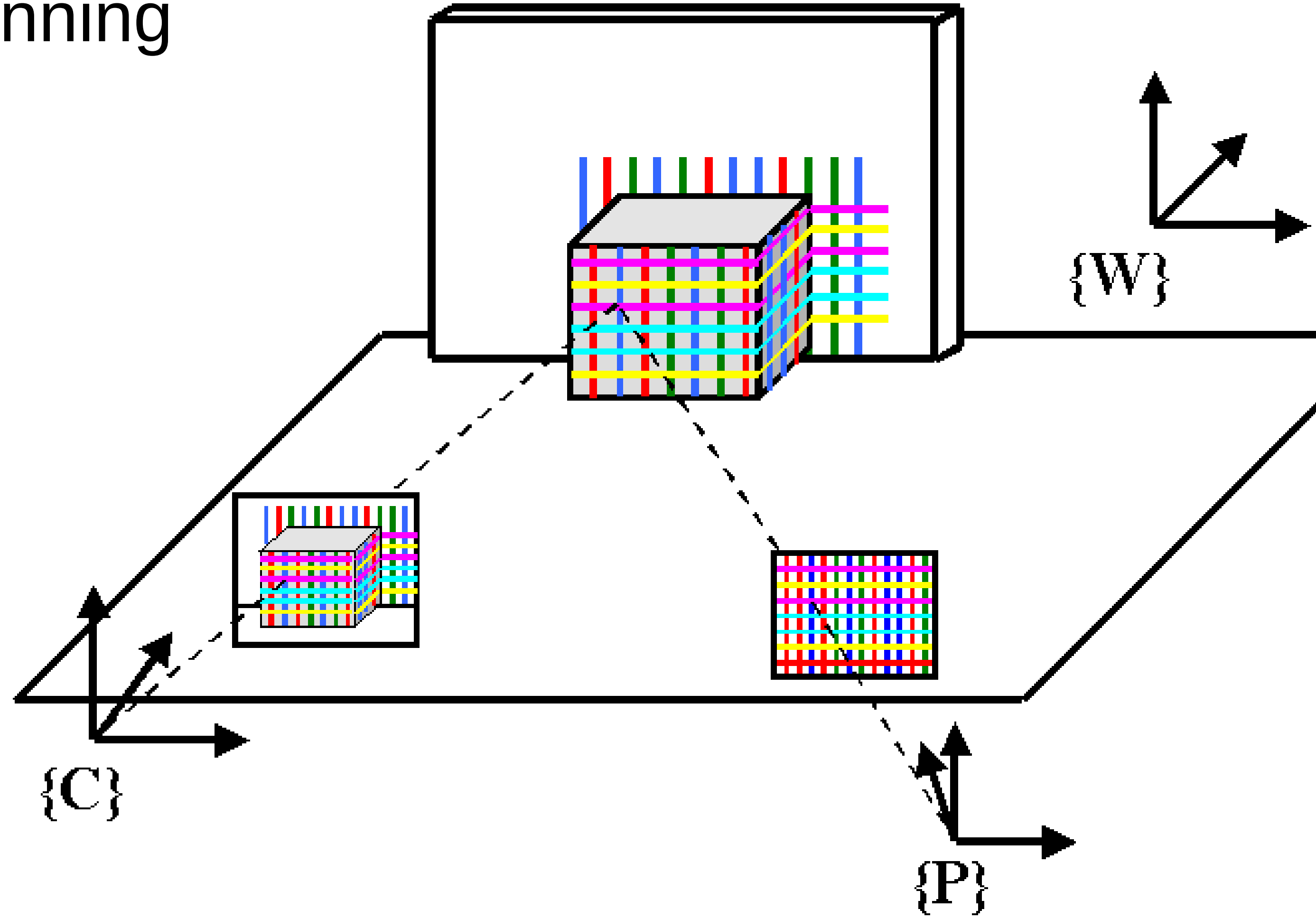


Multi-Stripe Triangulation



Color-Coded Stripe Triangulation

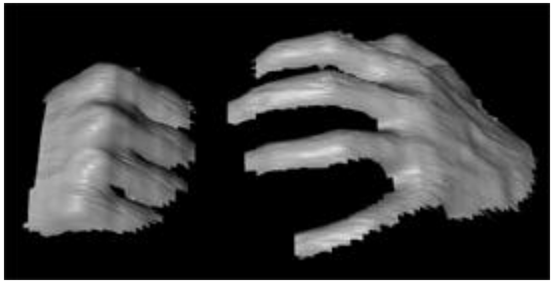
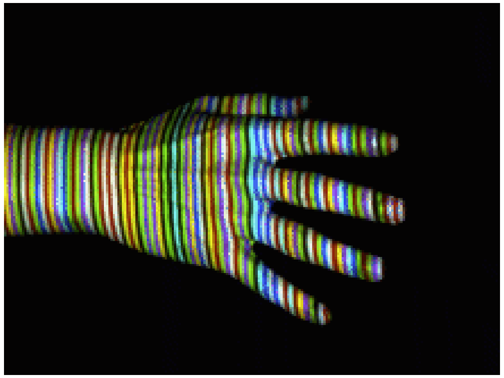
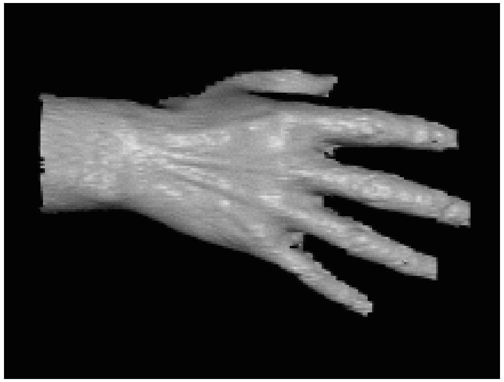
Active
Scanning



Zhang et al, 3DPVT 2002

Color-Coded Stripe Triangulation

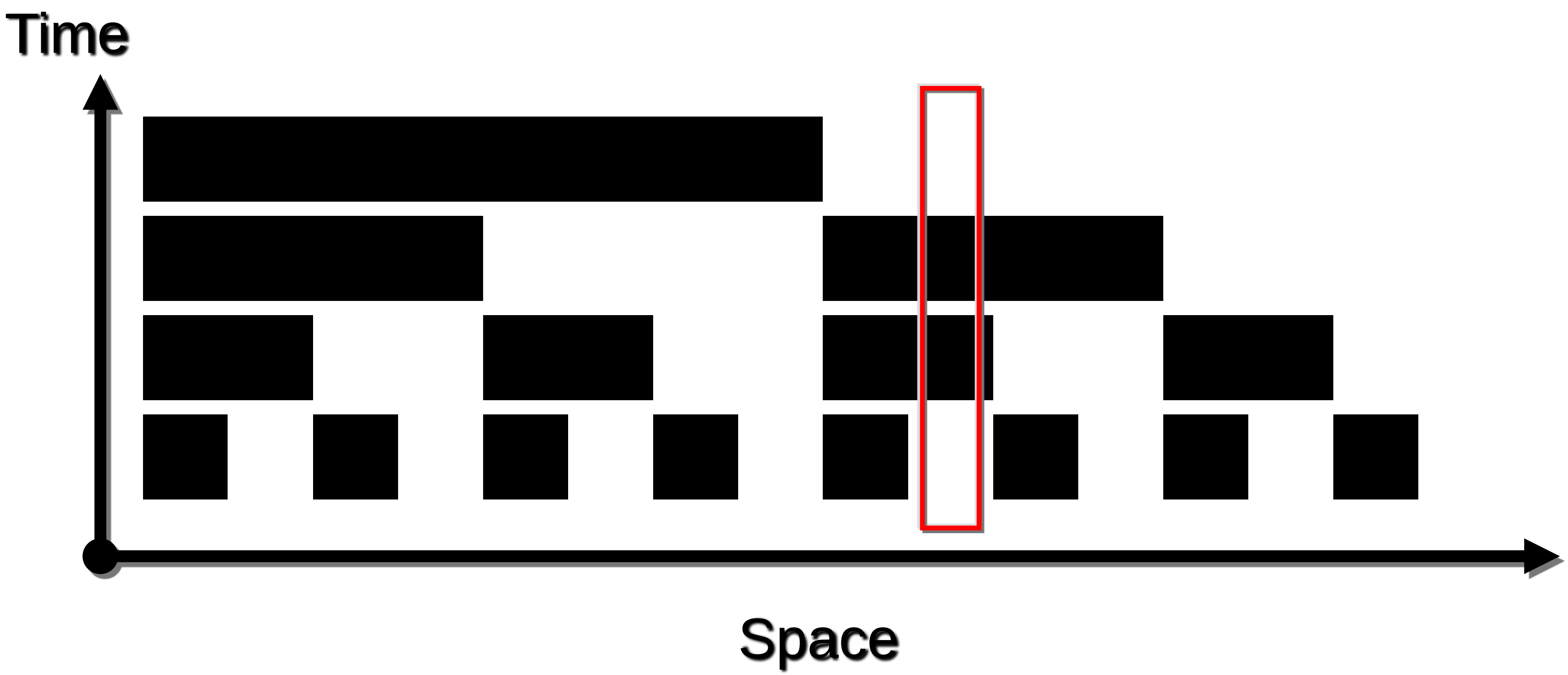


Zhang et al, 3DPVT 2002

Time-Coded Stripe Triangulation

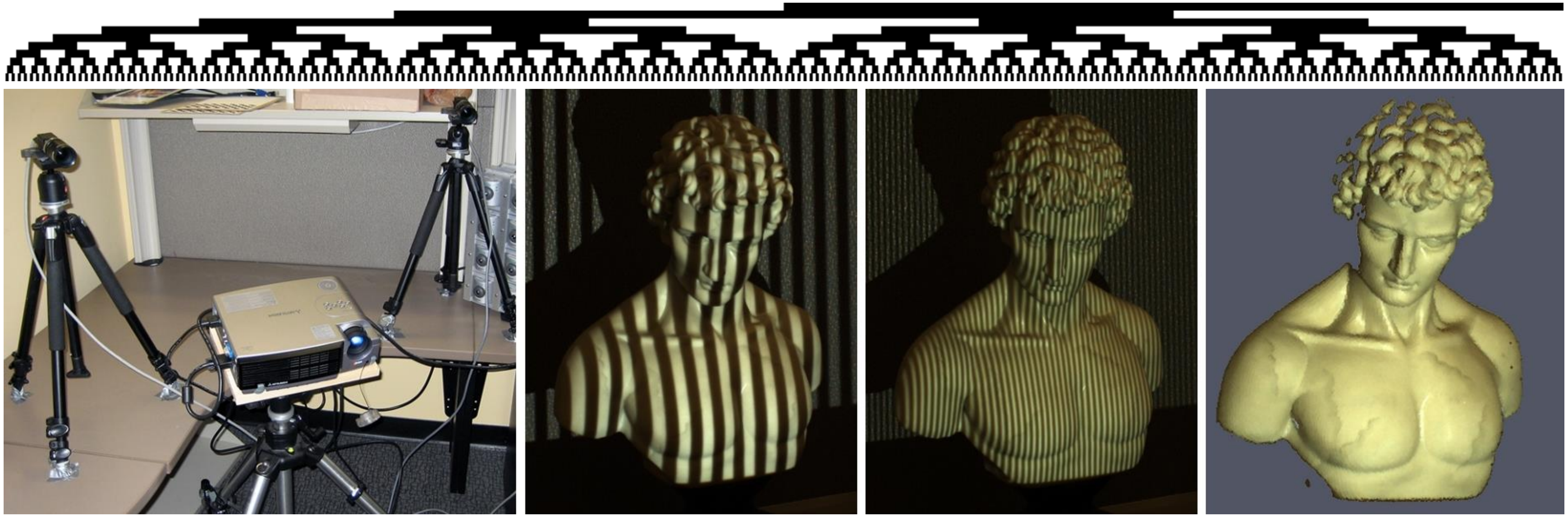
Assign each stripe a unique illumination code over time



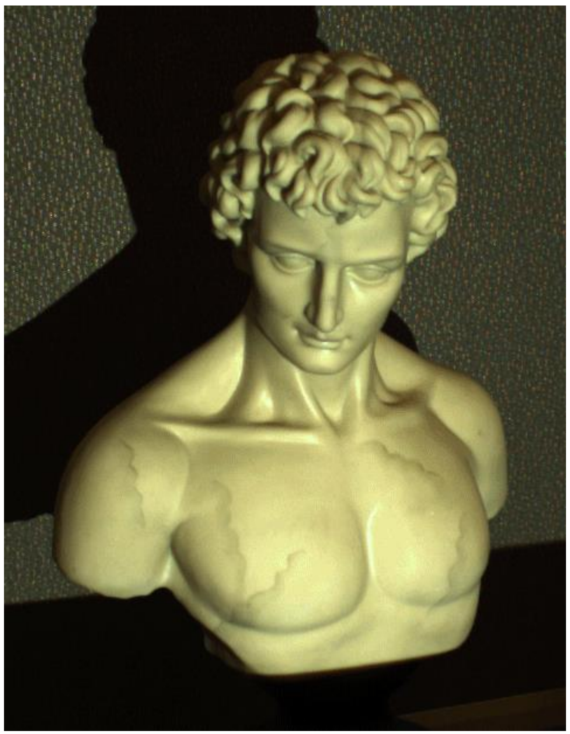
[Posdamer 82]

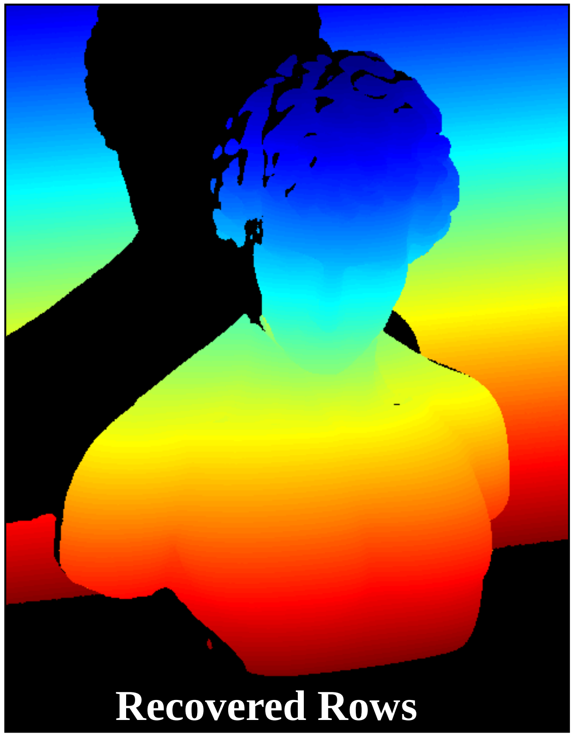
Time-Coded Stripe Triangulation

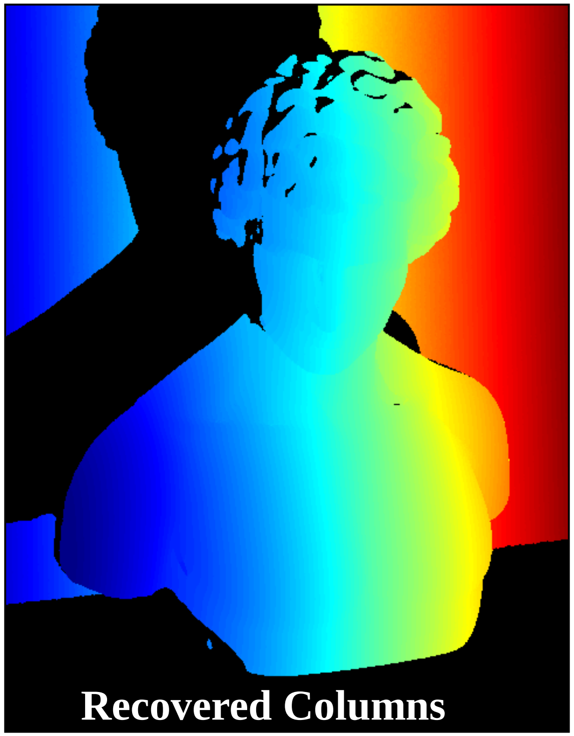
Time-Coded Stripe Triangulation



Time-Coded Stripe Triangulation

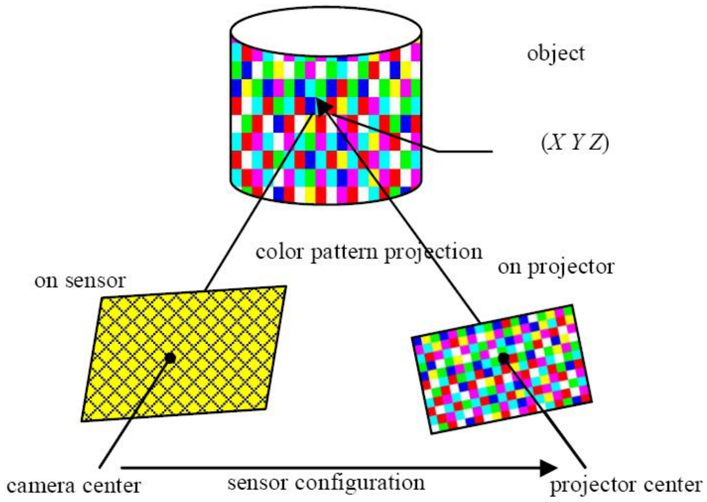




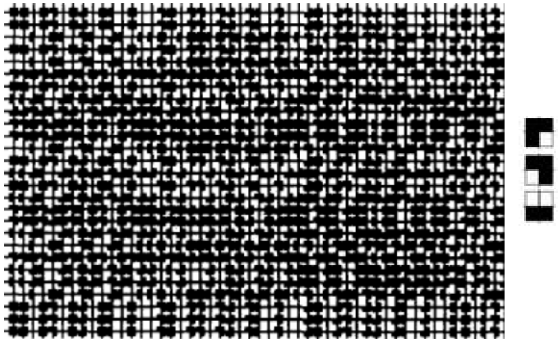


3D Reconstruction using Structured Light [Inokuchi 1984]

Structured Light Patterns

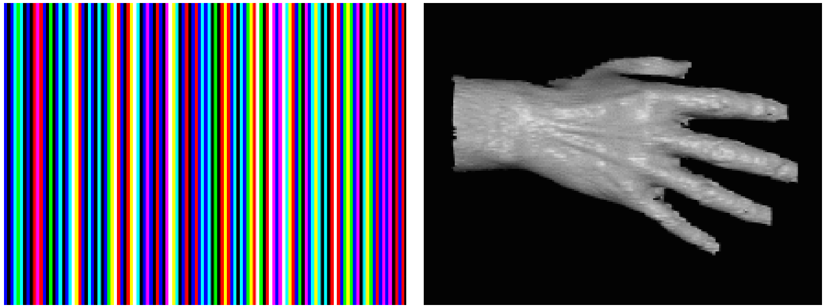


Spatial encoding strategies [Chen et al. 2007]

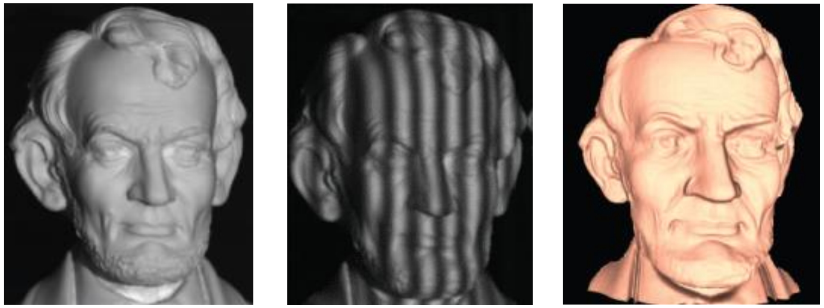


Pseudorandom and M-arrays [Griffin 1992]

“Single-shot” patterns (N-arrays, **grids**, random, etc.)



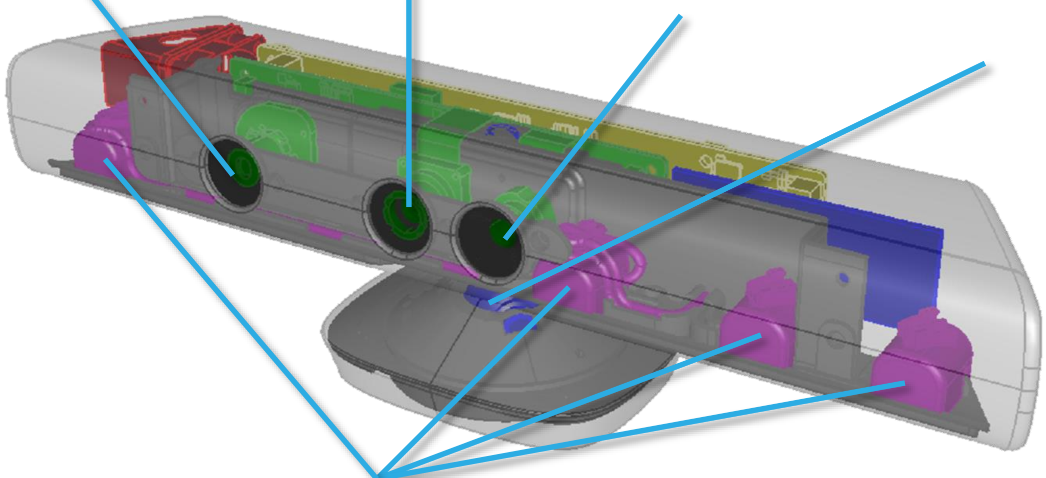
De Bruijn sequences [Zhang et al. 2002]



Phase-shifting [Zhang et al. 2004]

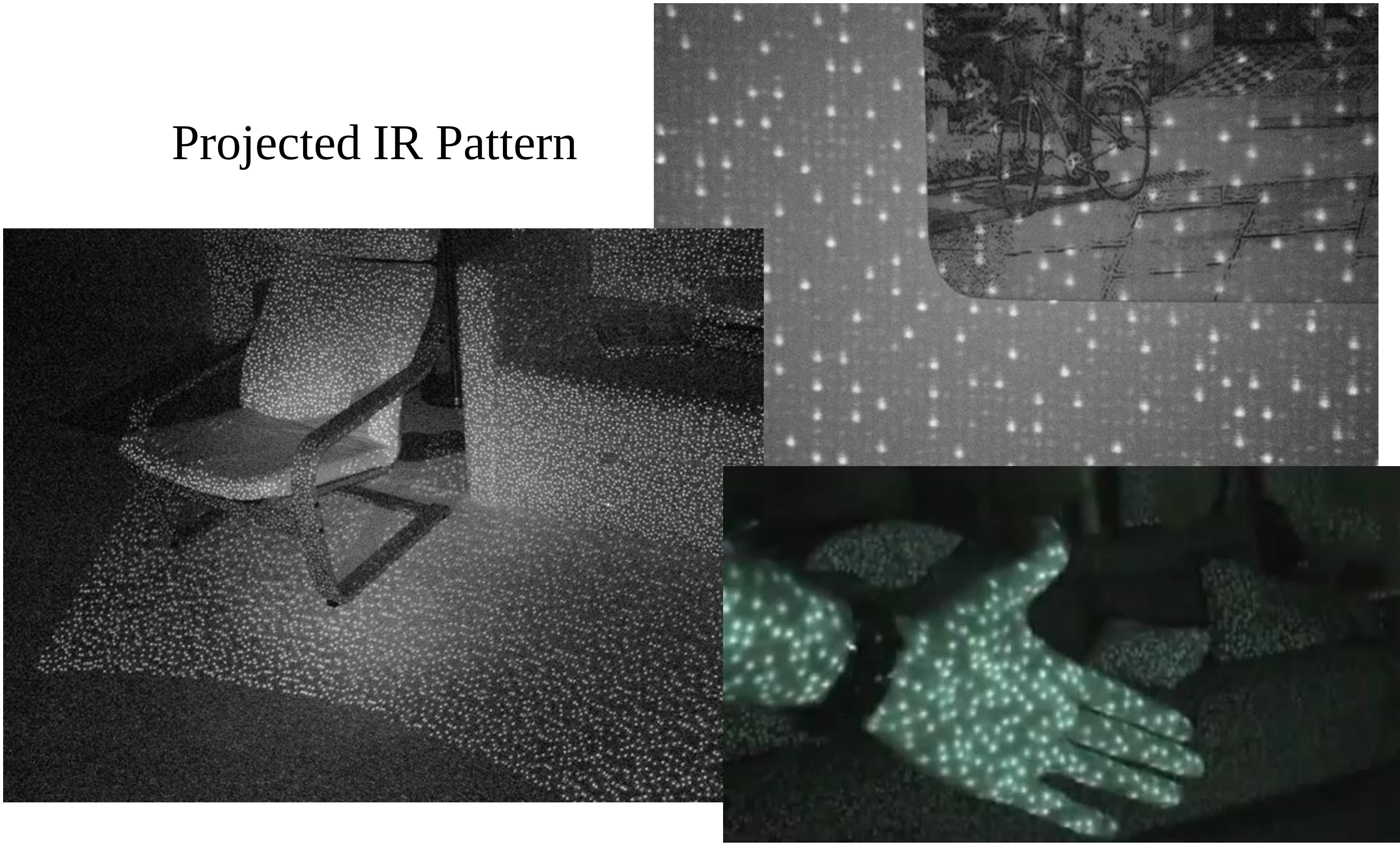
J. Salvi, J. Pagès, and J. Batlle. Pattern Codification Strategies in Structured Light Systems

Structured Light Scanning: Kinect



Structured Light Scanning: Kinect

Projected IR Pattern



Structured Light Scanning: Kinect

Depth Map

RGB Image

Structured Light Scanning: Kinect

http://www.youtube.com/watch?v=uq9SEJxZiUg

Structured Light Scanning

Advantages:

- Very fast – 2D pattern at once

Disadvantages:

- Prone to noise
- Indoor only

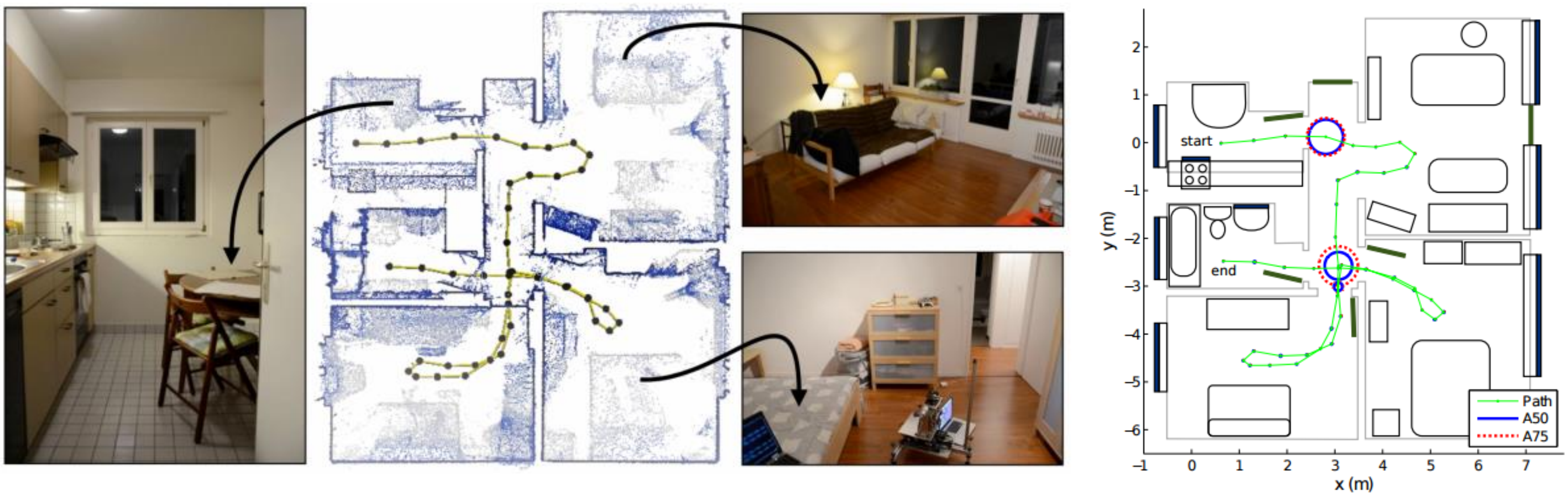
RGB-D Scanning of Static Indoor Environments

RGB-D scanning of indoor places

- Example RGB-D scans

RGB-D scanning of indoor places

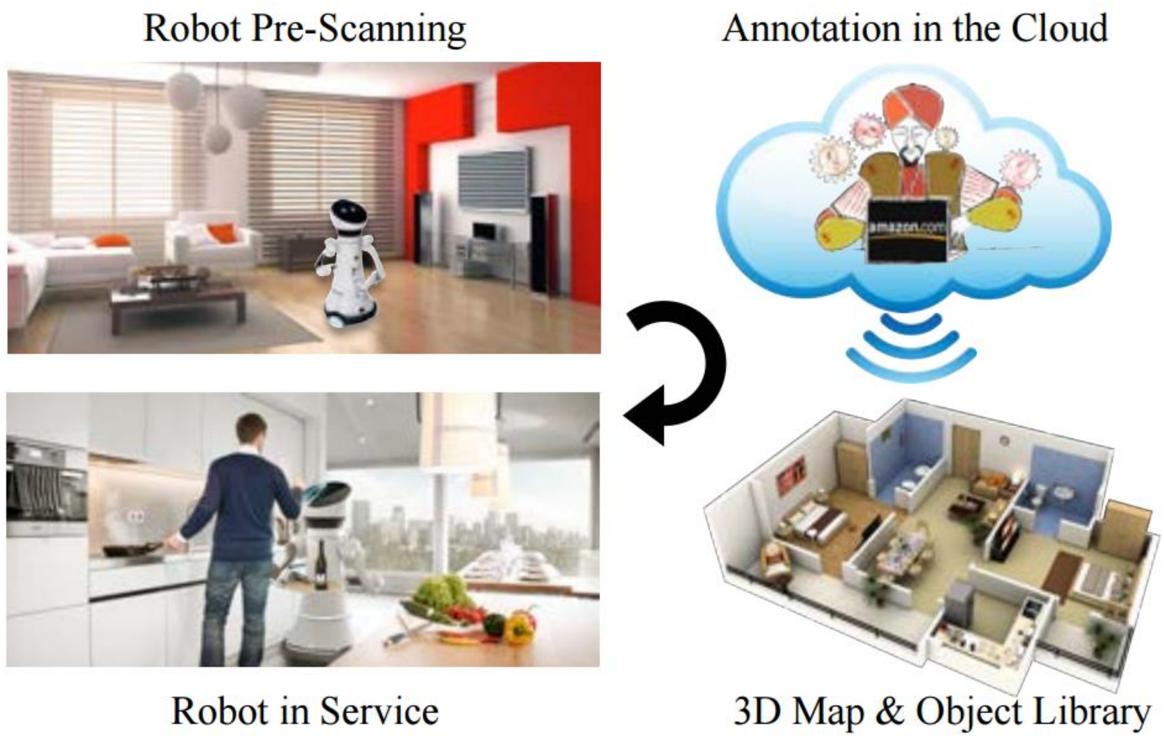
- Motivation: scene modeling and visualization



[Pomerlau et al., 2013]

RGB-D scanning of indoor places

- Applications:
  - Home remodeling
  - Online tourism
  - Virtual worlds
  - Real estate
  - Simulation
  - Forensics
  - Robotics
  - Games
  - etc.



[Song et al., 2015]

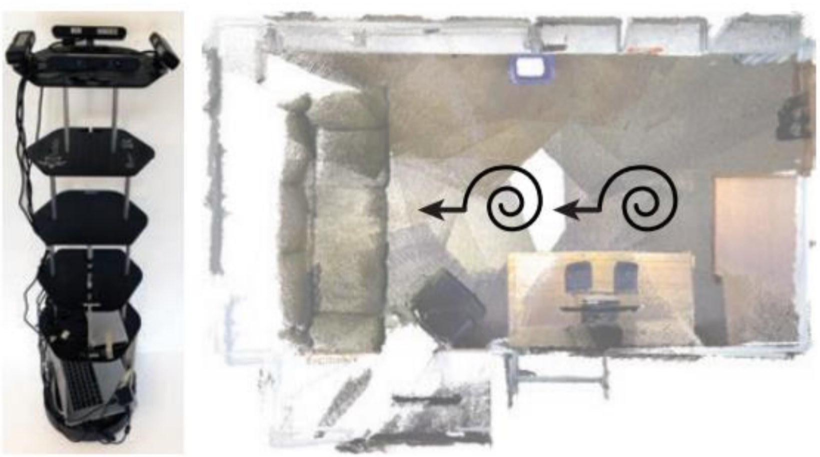
RGB-D scanning of indoor places

- Challenges:
  - Acquisition (scanning process)
  - Registration (camera pose estimation)
  - Surface reconstruction (surface estimation)
  - Surface completion (hole filling)
  - Surface coloring (texture synthesis)
  - Segmentation (object decomposition)
  - Labeling (semantic annotation)
  - Modeling (CAD model extraction)
  - etc.

Acquisition of RGB-D Scans

Tripod (Matterport)

Push Cart (NavVis)



Robot (Princetion Vision Group)

Hand-held (Structure IO, Intel)

Registration of RGB-D Scans

- Goals:
  - Commodity cameras
  - Long RGB-D sequences
  - Large environments
  - Globally consistent
  - Metric accuracy
  - Fast to compute
  - Automatic

RGB-D Registration Techniques

- Real-time:
  - Feature tracking
  - Iterated closest points
  - Volumetric fusion
  - Loop closure search

- Off-line:
  - Pose-graph optimization
  - Robust reconstruction
  - Global ICP

RGB-D Registration Techniques

- Real-time:
  - Feature tracking
  - Iterated closest points
  - Volumetric fusion
  - Loop closure search

Input Image

- Off-line:
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  - Robust reconstruction
  - Global ICP

RGB-D Registration Techniques

- Real-time:
  - ➢ Feature tracking
  - ◦ Iterated closest points
  - ◦ Volumetric fusion
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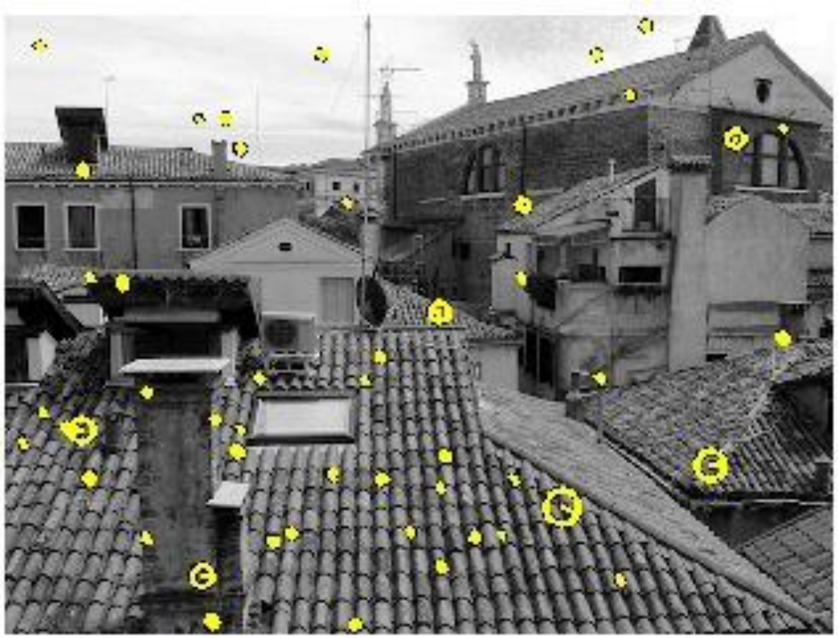


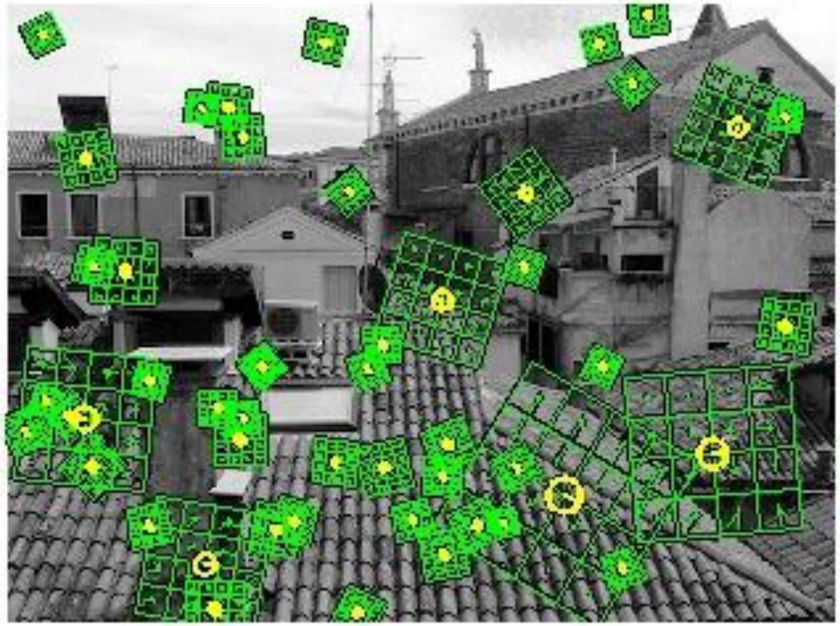
SIFT Keypoints

- Off-line:
  - ◦ Pose-graph optimization
  - ◦ Robust reconstruction
  - ◦ Global ICP

VLFeat

RGB-D Registration Techniques

- Real-time:
  - ➢ Feature tracking
  - ◦ Iterated closest points
  - ◦ Volumetric fusion
  - ◦ Loop closure search



SIFT Descriptors

- Off-line:
  - ◦ Pose-graph optimization
  - ◦ Robust reconstruction
  - ◦ Global ICP

VLFeat

RGB-D Registration Techniques

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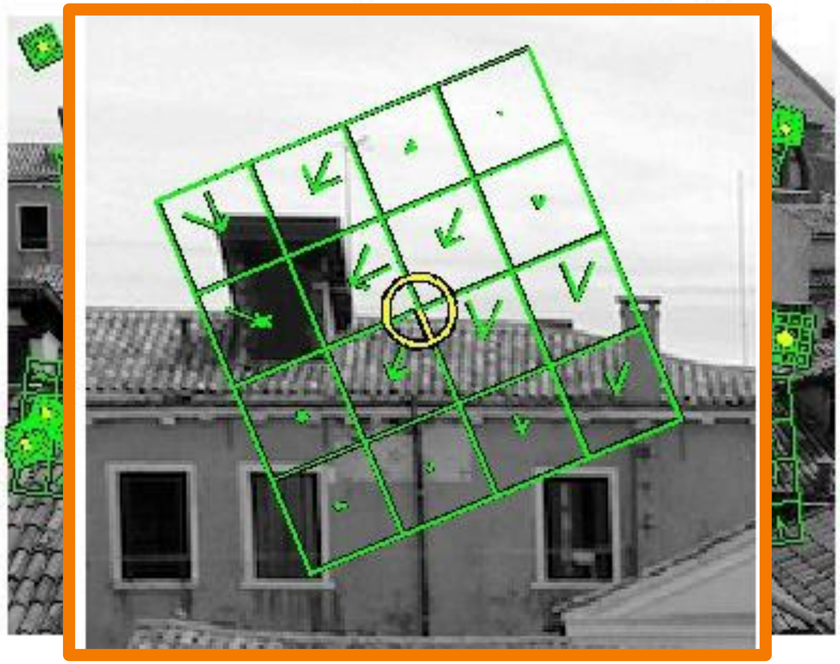

SIFT Descriptors

VLFeat

RGB-D Registration Techniques

- Real-time:
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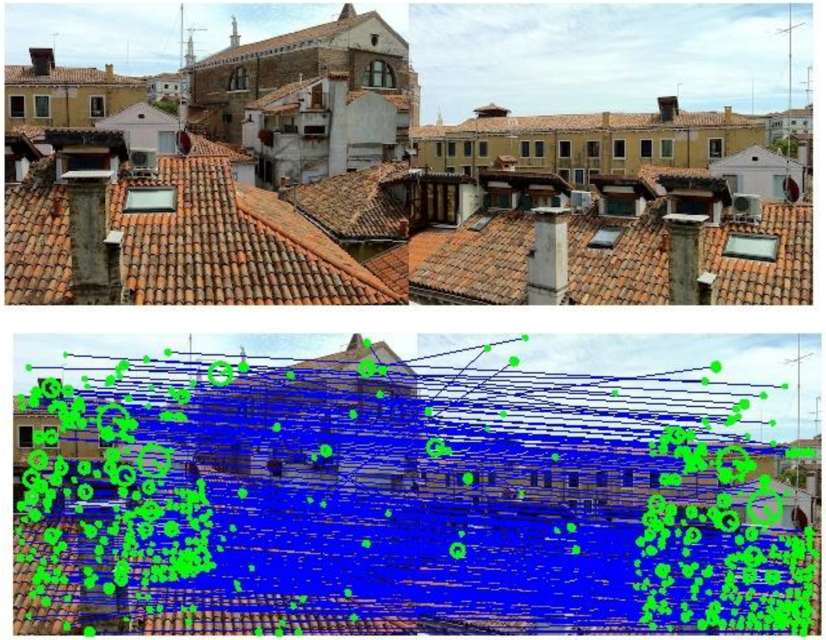

SIFT Keypoint Matches

- Off-line:
  - ◦ Pose-graph optimization
  - ◦ Robust reconstruction
  - ◦ Global ICP

VLFeat

RGB-D Registration Techniques

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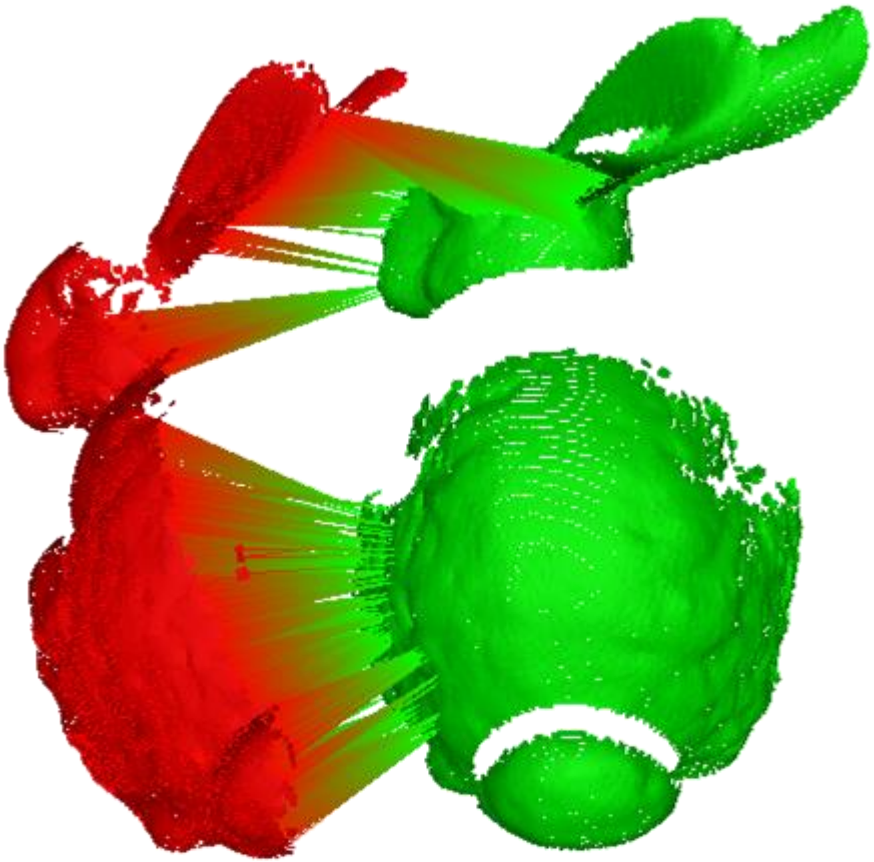

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RGB-D Registration Techniques

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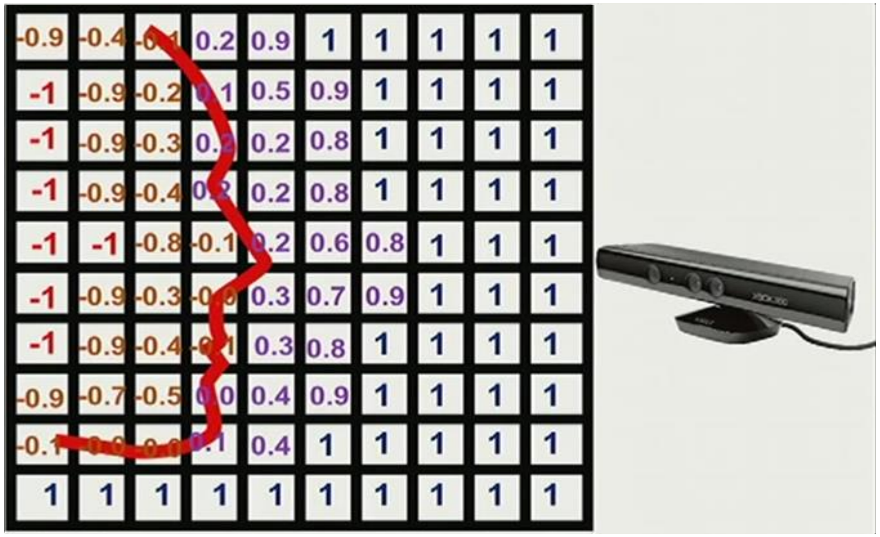

Model previous scans with TSDF
[Newcombe et al., 2011]

- Off-line:
  - Pose-graph optimization
  - Robust reconstruction
  - Global ICP

RGB-D Registration Techniques

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  - Iterated closest points
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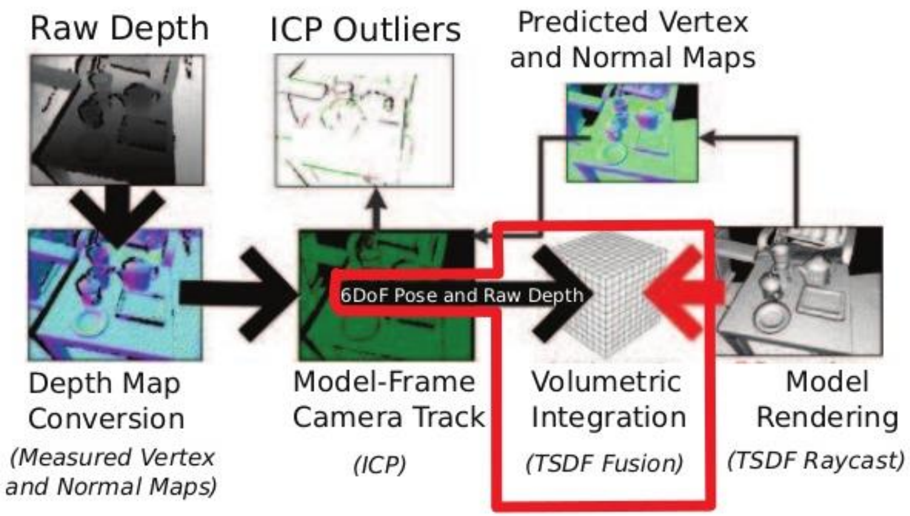

- Off-line:
  - Pose-graph optimization
  - Robust reconstruction
  - Global ICP

Align new scans to TSDF model
[Newcombe et al., 2011]

RGB-D Registration Techniques

- Real-time:
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  - Loop closure search

KinectFusion
[Newcombe et al., 2011]

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RGB-D Registration Techniques

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  - ➢ Volumetric fusion
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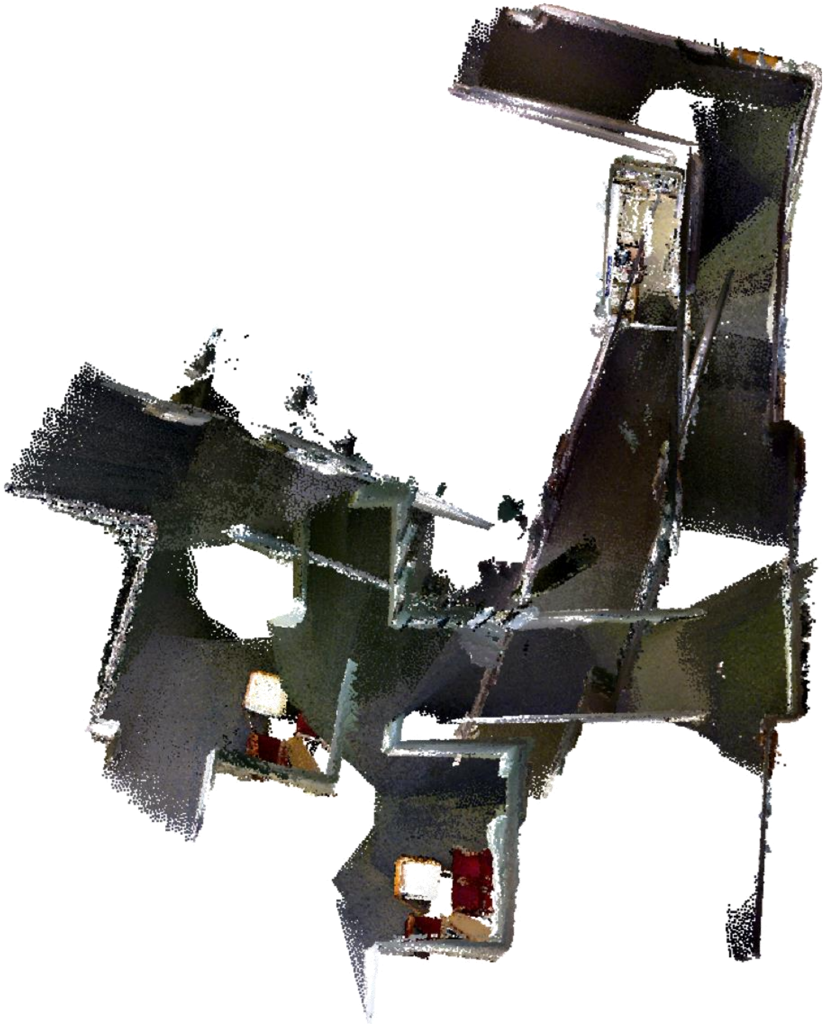

Problems: Drift and Featureless Areas

RGB-D Registration Techniques

- Real-time:
  - Feature tracking
  - Iterated closest points
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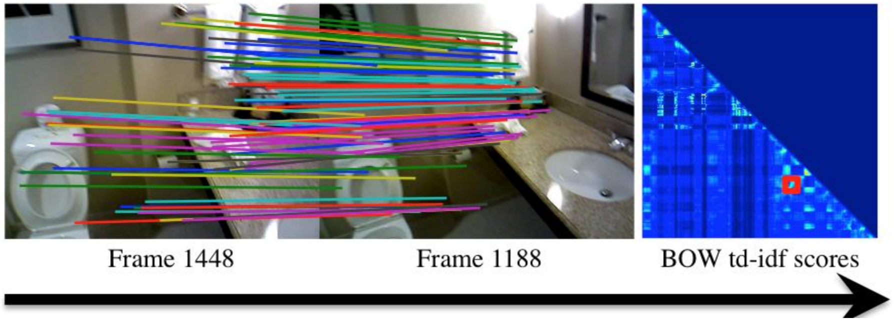
  - ➢ Loop closure search

Loop Closure using BoW



- Off-line:
  - Pose-graph optimization
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SUN3DSfM
[Xiao et al., 2013]

RGB-D Registration Techniques

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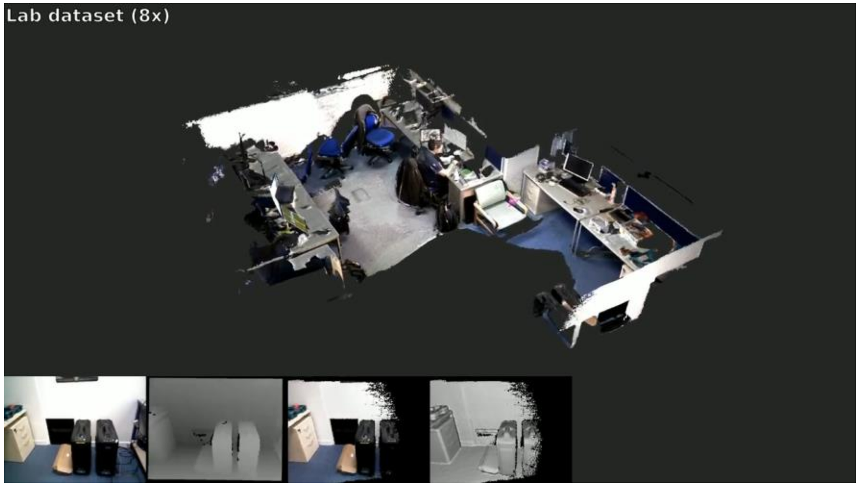

ElasticFusion
[Whelan et al., 2015]

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RGB-D Registration Techniques

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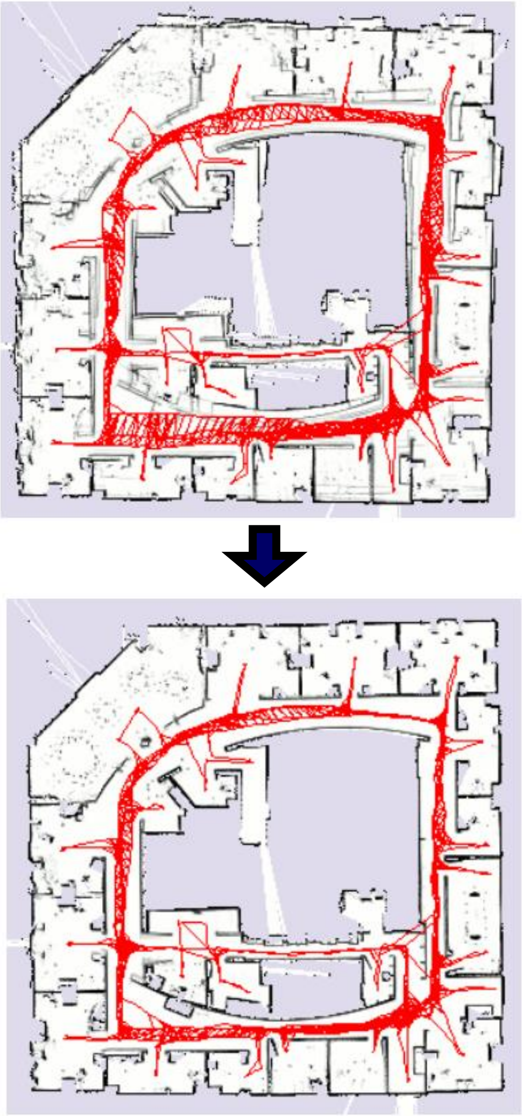

Intel Research Lab in Seattle

RGB-D Registration Techniques

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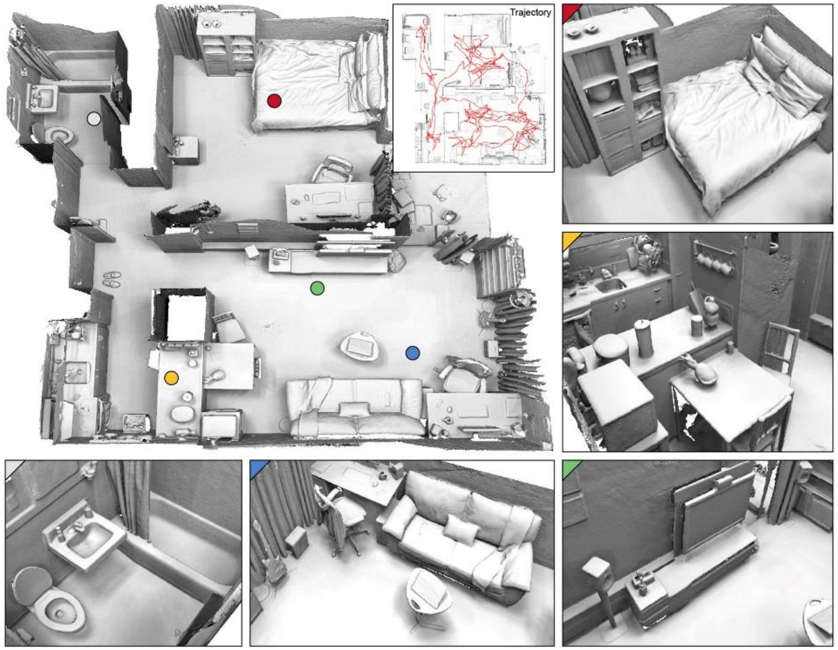
$$
\begin{aligned}
E(\mathbb{T},\mathbb{L}) &= \sum_i f(\mathbf{T}_i,\mathbf{T}_{i+1},\mathbf{R}_i) \\
&+ \sum_{i,j} l_{ij} f(\mathbf{T}_i,\mathbf{T}_j,\mathbf{T}_{ij}) \\
&+ \mu \sum_{i,j} \Psi(l_{ij}).
\end{aligned}
$$



Robust Reconstruction
[Choi et al., 2015]

RGB-D Registration Techniques

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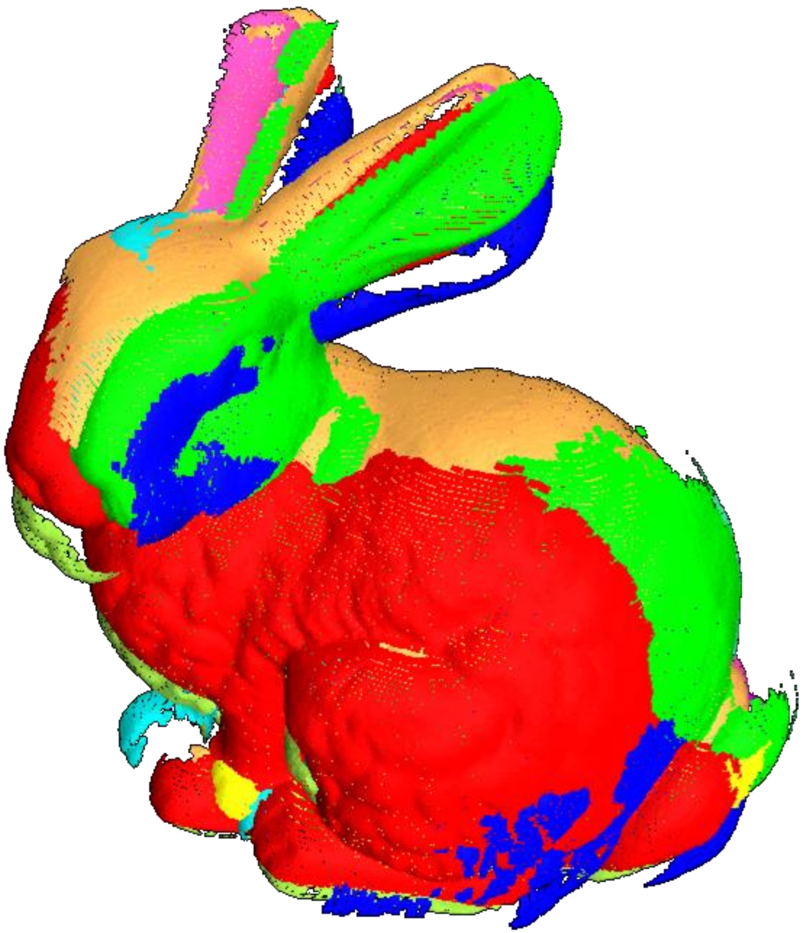

Iterative Closest Points
[Besl, 1992]

RGB-D Registration Techniques

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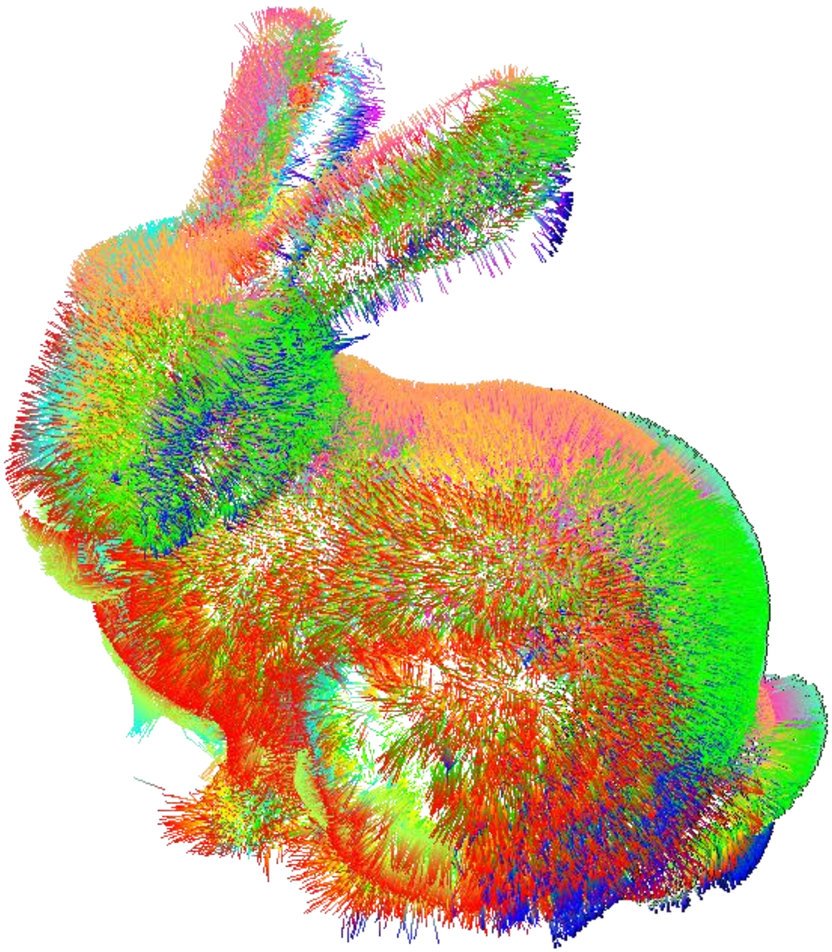

Iterative Closest Points
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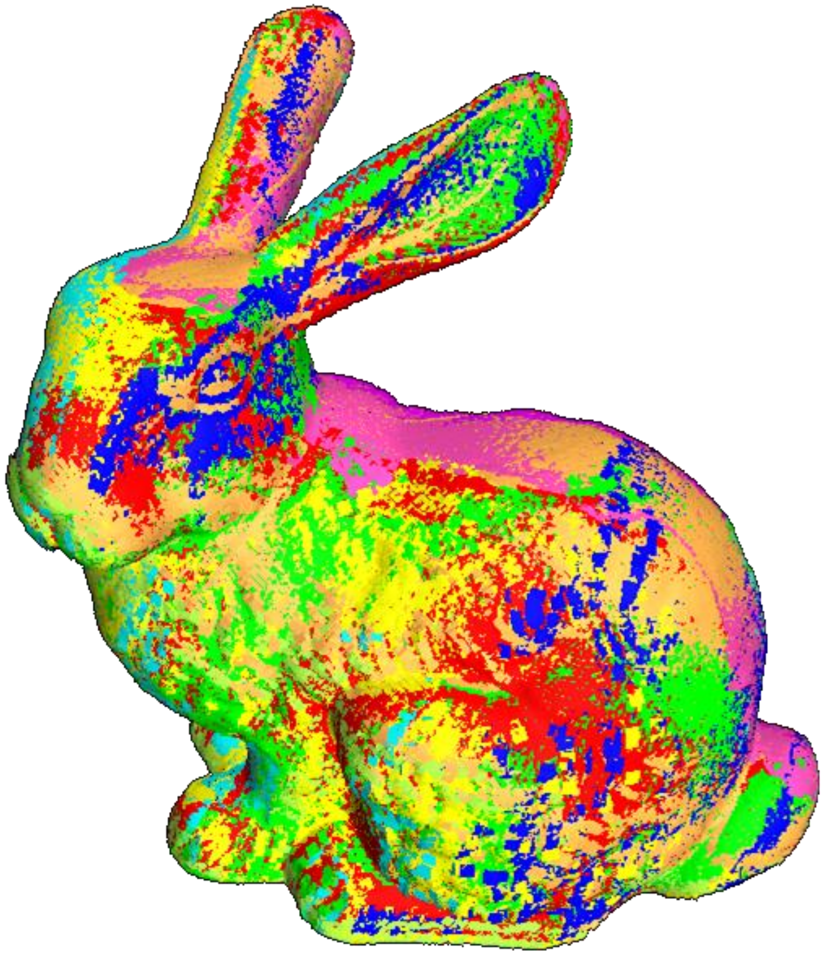
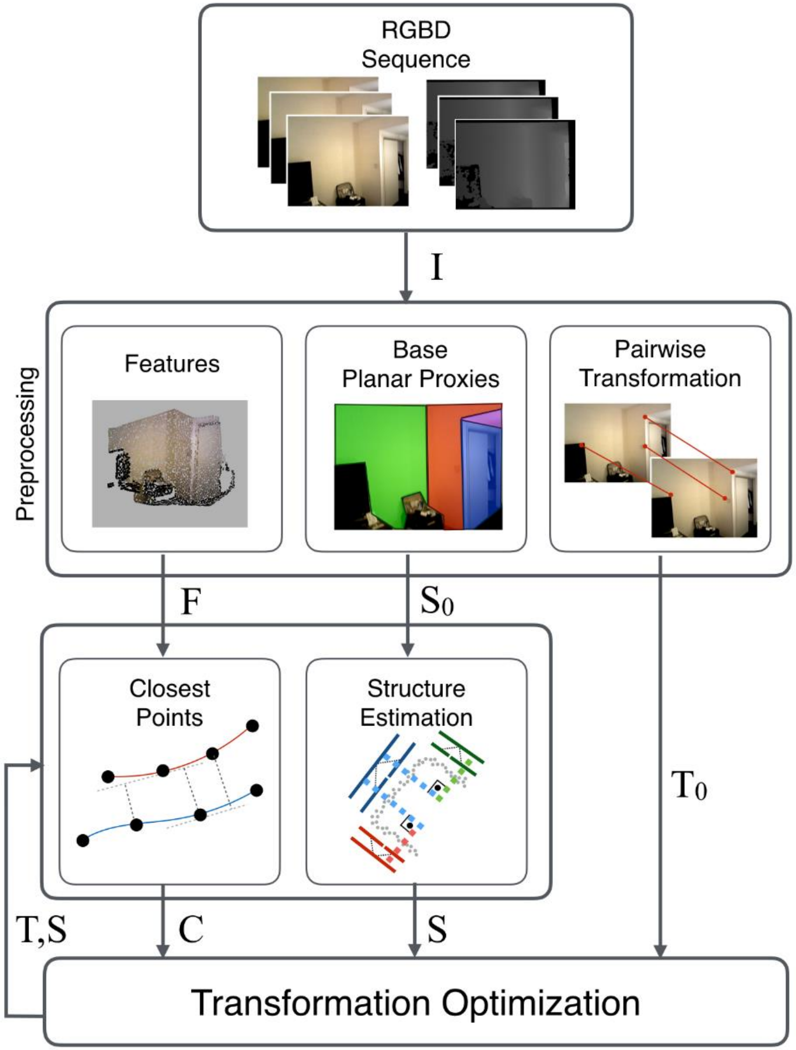


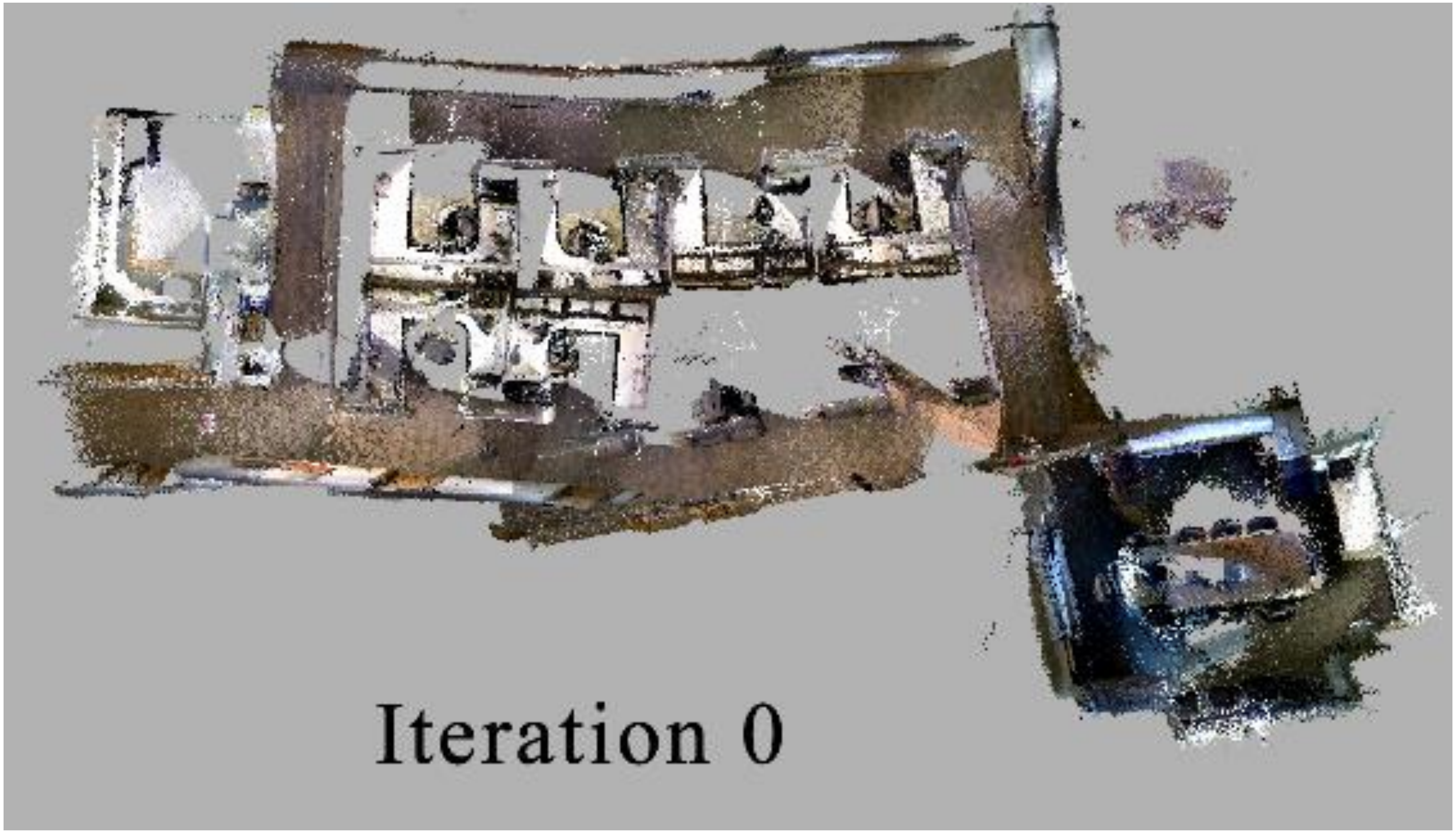
Iterative Closest Points
[Besl, 1992]

Example RGB-D Registration Pipeline



[Halber et al., 2016]

Example RGB-D Registration Pipeline



[Halber et al., 2016]

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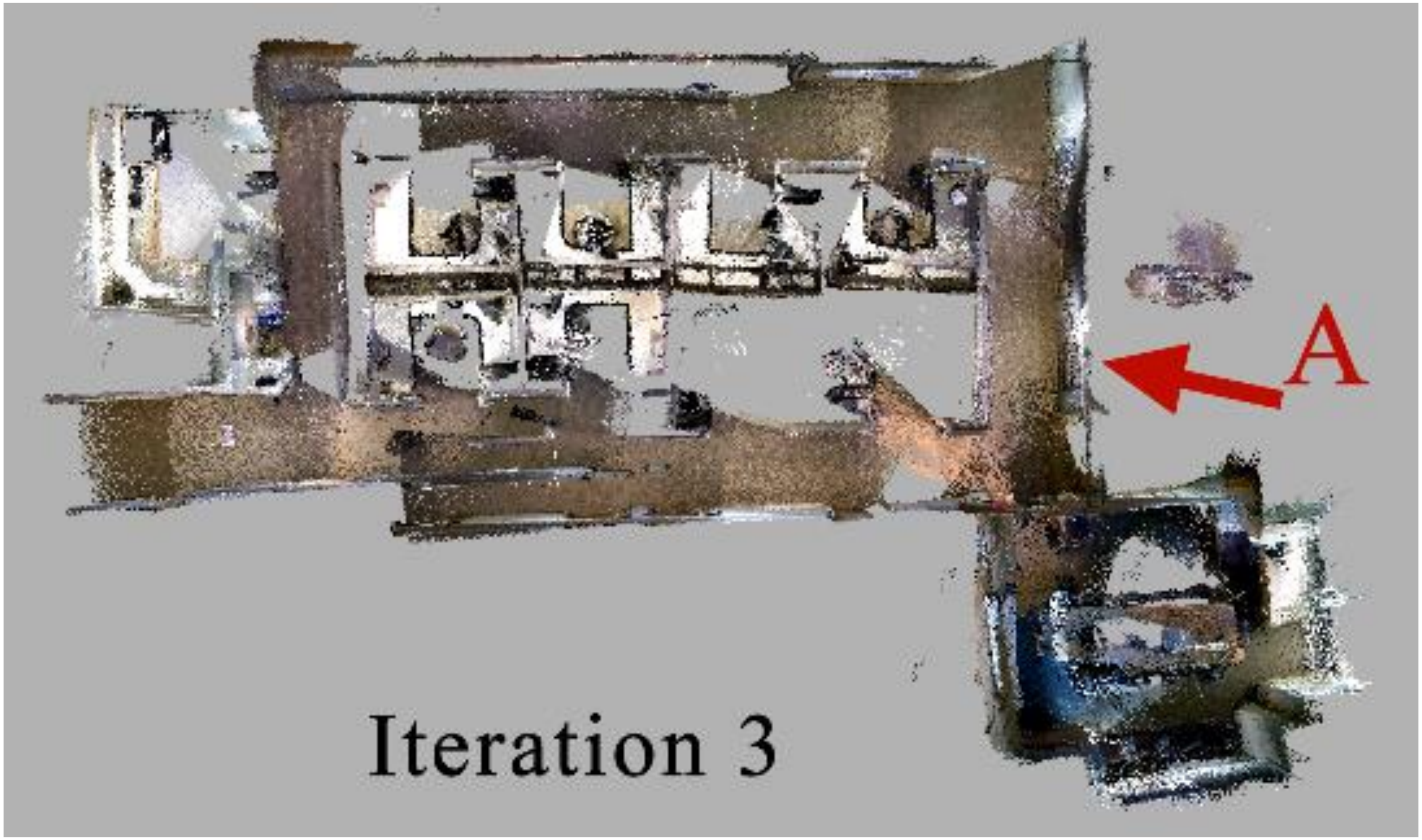

[Halber et al., 2016]

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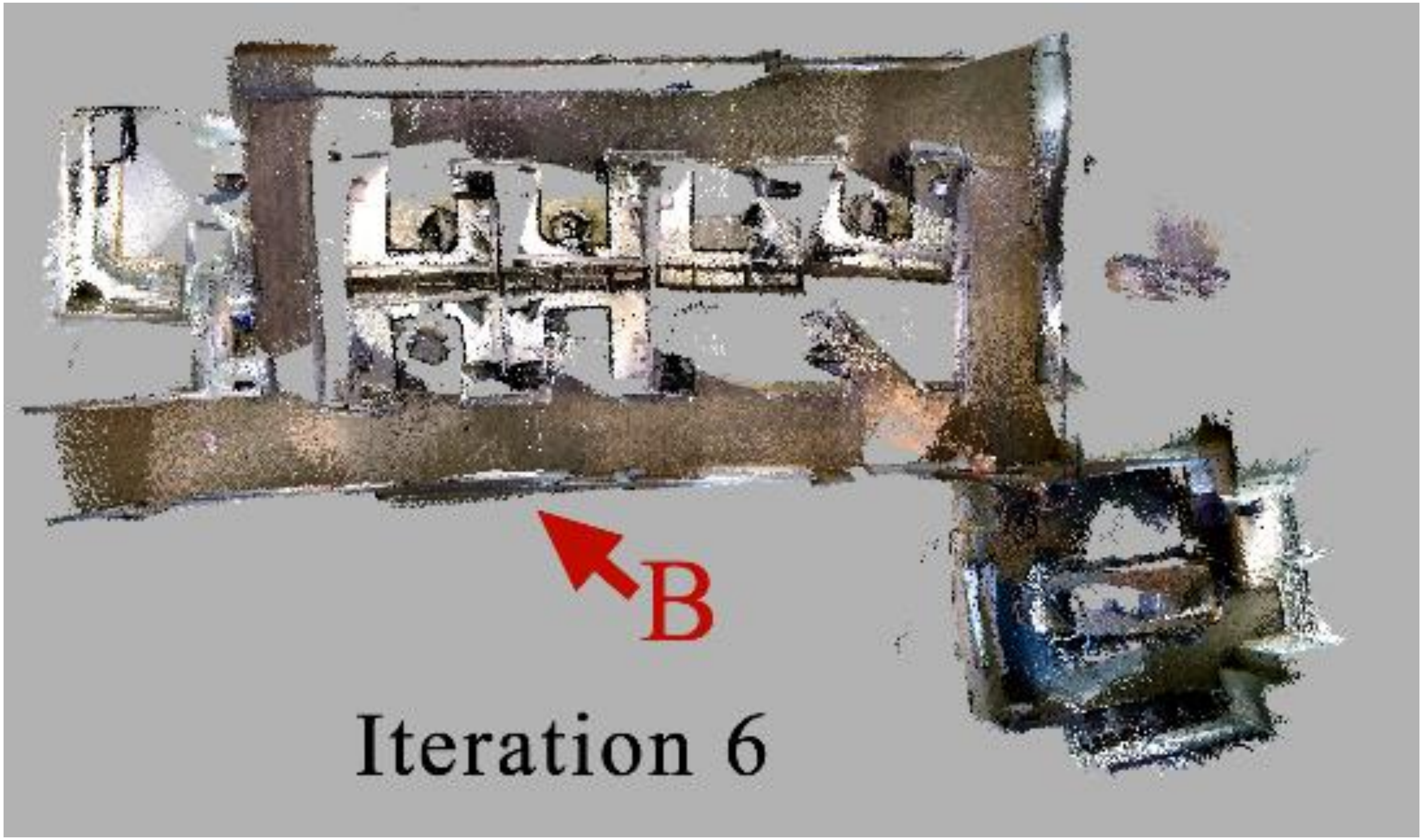

[Halber et al., 2016]

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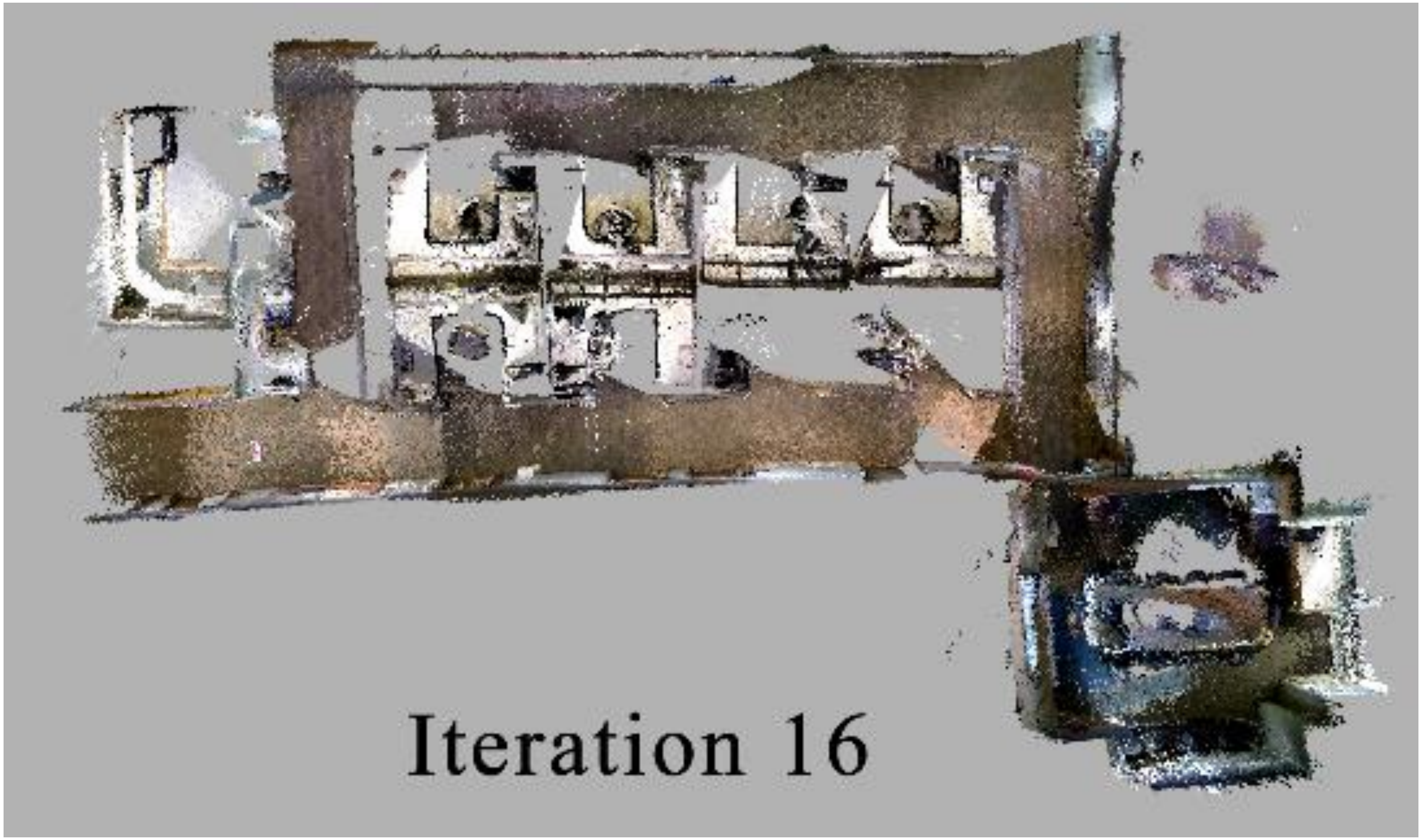

[Halber et al., 2016]

Our Next Class

Field Trip!   Experience scanning 3D environments