Multiview stereo

CMU’s 3D Room

Readings (Optional)

Choosing the Baseline

What's the optimal baseline?

- Too small: large depth error
- Too large: difficult search problem

Large Baseline

Small Baseline

all of these points project to the same pair of pixels

width of a pixel
The Effect of Baseline on Depth Estimation

Figure 2: An example scene. The grid pattern in the background has ambiguity of matching.
Fig. 5. SSD values versus inverse distance: (a) \( B = b \); (b) \( B = 2b \); (c) \( B = 3b \); (d) \( B = 4b \); (e) \( B = 5b \); (f) \( B = 6b \); (g) \( B = 7b \); (h) \( B = 8b \). The horizontal axis is normalized such that \( 8bF = 1 \).

Fig. 6. Combining two stereo pairs with different baselines.

Fig. 7. Combining multiple baseline stereo pairs.
Multibaseline Stereo

Basic Approach

• Choose a reference view
• Use your favorite stereo algorithm BUT
  > replace two-view SSD with SSD over all baselines

Limitations

• Must choose a reference view (bad)
• Visibility!
Figure 7: The CMU Video-Rate Stereo Machine Prototype System: (a) camera head; (b) processor boards
The global visibility problem

Which points are visible in which images?

**Known Scene**

**Unknown Scene**

**Forward Visibility**

**Inverse Visibility**
Volumetric stereo

Scene Volume

Goal: Determine occupancy, “color” of points in V

Input Images (Calibrated)
Discrete formulation: Voxel Coloring

Goal: Assign RGBA values to voxels in V photo-consistent with images
Complexity and computability

Discretized Scene Volume

$N^3$ voxels

$C$ colors

All Scenes $\left(C^{N^3}\right)$

Photo-Consistent Scenes

True Scene
Issues

Theoretical Questions
• Identify class of *all* photo-consistent scenes

Practical Questions
• How do we compute photo-consistent models?
Voxel coloring solutions

1. C=2 (shape from silhouettes)
   • Volume intersection [Baumgart 1974]
     > For more info: Rapid octree construction from image sequences. R. Szeliski, CVGIP: Image Understanding, 58(1):23-32, July 1993. (this paper is apparently not available online)

2. C unconstrained, viewpoint constraints
   • Voxel coloring algorithm [Seitz & Dyer 97]

3. General Case
   • Space carving [Kutulakos & Seitz 98]
Reconstruction from Silhouettes ($C = 2$)

Approach:
- *Project* each silhouette
- Intersect projected volumes
Volume intersection

Reconstruction Contains the True Scene

• In the limit (all views) get *visual hull*
  > Complement of all lines that don’t intersect S
Voxel algorithm for volume intersection

- Color voxel black if on silhouette in every image
  - $O(MN^3)$, for $M$ images, $N^3$ voxels
  - Don’t have to search $2^{N^3}$ possible scenes!
Properties of Volume Intersection

Pros

• Easy to implement, fast
• Accelerated via octrees [Szeliski 1993]

Cons

• No concavities
• Reconstruction is not photo-consistent
• Requires identification of silhouettes
Voxel Coloring Solutions

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Voxel Coloring Approach

1. Choose voxel
2. Project and correlate
3. Color if consistent
   (standard deviation of pixel colors below threshold)

Visibility Problem: in which images is each voxel visible?
Depth Ordering: visit occluders first!

Condition: depth order is the same for all input views
Panoramic Depth Ordering

- Cameras oriented in many different directions
- Planar depth ordering does not apply
Panoramic Depth Ordering

Layers radiate outwards from cameras
Panoramic Layering

Layers radiate outwards from cameras
Panoramic Layering

Layers radiate outwards from cameras
Compatible Camera Configurations

Depth-Order Constraint

- Scene outside convex hull of camera centers

**Inward-Looking**
Camera above scene

**Outward-Looking**
Camera inside scene
Calibrated Image Acquisition

Calibrated Turntable

Selected Dinosaur Images

Selected Flower Images
Voxel Coloring Results (Video)

Dinosaur Reconstruction
72 K voxels colored
7.6 M voxels tested
7 min. to compute on a 250MHz SGI

Flower Reconstruction
70 K voxels colored
7.6 M voxels tested
7 min. to compute on a 250MHz SGI
Limitations of Depth Ordering

A view-independent depth order may not exist

Need more powerful general-case algorithms
  • Unconstrained camera positions
  • Unconstrained scene geometry/topology
Voxel Coloring Solutions

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   • Volume intersection [Baumgart 1974]

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Space Carving Algorithm

- Initialize to a volume \( V \) containing the true scene
- Repeat until convergence
  - Choose a voxel on the current surface
  - Project to visible input images
  - Carve if not photo-consistent
  - Repeat until convergence
Convergence

Consistency Property
  • The resulting shape is photo-consistent
    > all inconsistent points are removed

Convergence Property
  • Carving converges to a non-empty shape
    > a point on the true scene is never removed
Visibility lemma

Let \( p \) be a point on \( V \)'s surface, \( \text{Surf}(V) \), and let \( \text{Vis}_V(p) \) be the collection of input images in which \( V \) does not occlude \( p \). If \( V' \), a subset of \( V \), is a shape that also has \( p \) on its surface, \( \text{Vis}_V(p) \) is a subset of \( \text{Vis}_{V'}(p) \).
Non-photo-consistency lemma

Let $p$, which is in $\text{Surf}(V)$, is not photo-consistent with a subset of $\text{Vis}_v(p)$, it is not photo-consistent with the entire $\text{Vis}_v(p)$. 

\[ c_1 \quad c_2 \quad c_3 \quad c_4 \]
The **Photo Hull** *is the UNION of all photo-consistent scenes in V*

- It is a photo-consistent scene reconstruction
- Tightest possible bound on the true scene
Space Carving Algorithm

The Basic Algorithm is Unwieldy

- Complex update procedure

Alternative: Multi-Pass Plane Sweep

- Efficient, can use texture-mapping hardware
- Converges quickly in practice
- Easy to implement
Multi-Pass Plane Sweep

- Sweep plane in each of 6 principle directions
- Consider cameras on only one side of plane
- Repeat until convergence
Multi-Pass Plane Sweep

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Space Carving Results: African Violet

Input Image (1 of 45)

Reconstruction

Reconstruction

Reconstruction

Reconstruction
Space Carving Results: Hand

Input Image (1 of 100)

Views of Reconstruction
House Walkthrough

24 rendered input views from inside and outside
Space Carving Results: House

Input Image (true scene)  Reconstruction 370,000 voxels
Space Carving Results: House

Input Image (true scene)

Reconstruction 370,000 voxels
Space Carving Results:  House

New View (true scene)  Reconstruction

New View (true scene)  Reconstruction  Reconstruction (with new input view)
Other Features

Coarse-to-fine Reconstruction
- Represent scene as octree
- Reconstruct low-res model first, then refine

Hardware-Acceleration
- Use texture-mapping to compute voxel projections
- Process voxels an entire plane at a time

Limitations
- Need to acquire calibrated images
- Restriction to simple radiance models
- Bias toward maximal (fat) reconstructions
- Transparency not supported
Other Approaches

Level-Set Methods  [Faugeras & Keriven 1998]
  • Evolve implicit function by solving PDE’s

Probabilistic Voxel Reconstruction  [DeBonet & Viola 1999],
  [Broadhurst et al. 2001]
  • Solve for voxel uncertainty (also transparency)

Transparency and Matting  [Szeliski & Golland 1998]
  • Compute voxels with alpha-channel

Max Flow/Min Cut  [Roy & Cox 1998]
  • Graph theoretic formulation

Mesh-Based Stereo  [Fua & Leclerc 1995], [Zhang & Seitz 2001]
  • Mesh-based but similar consistency formulation

Virtualized Reality  [Narayan, Rander, Kanade 1998]
  • Perform stereo 3 images at a time, merge results
Bibliography

Volume Intersection


Voxel Coloring and Space Carving

Related References

Summary

Things to take away from this lecture

- Baseline tradeoff
- Multibaseline stereo approach
- Voxel coloring problem
- Volume intersection algorithm
- Voxel coloring algorithm
- Space carving algorithm