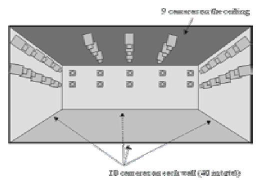
Announcements

- Project 2 winners
- Think about Project 3
- Guest lecture on Monday: Aseem

Multiview stereo

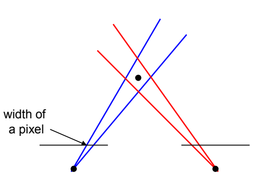



CMU's 3D Room

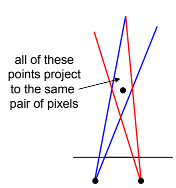
Readings

- S. M. Seitz and C. R. Dyer, Photorealistic Scene Reconstruction by Voxel Coloring, *International Journal of Computer Vision*, 35(2), 1999, pp. 151-173.
  - > http://www.cs.washington.edu/homes/seitz/papers/ijcv99.pdf

Choosing the Baseline



Large Baseline



Small Baseline

What's the optimal baseline?

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

The Effect of Baseline on Depth Estimation

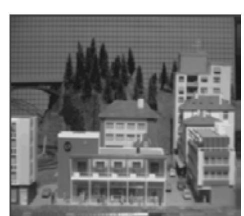
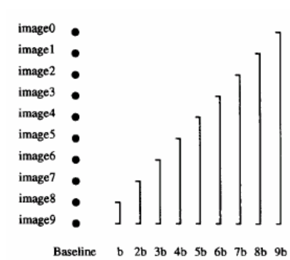
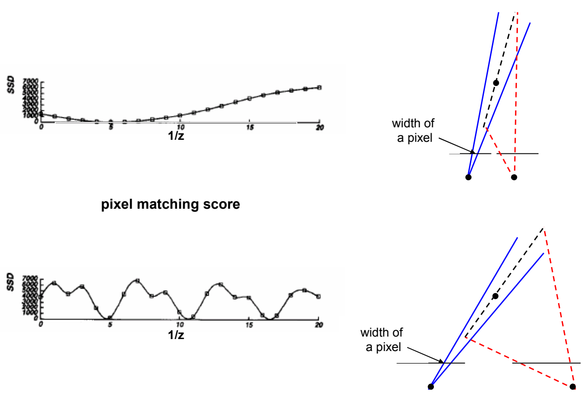
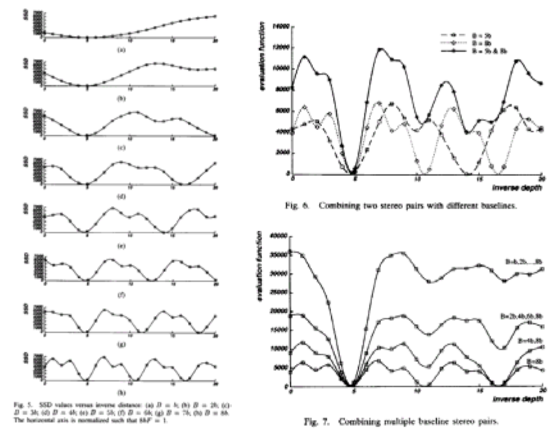


Figure 2: An example scene. The grid pattern in the background has ambiguity of matching.







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!

CMU's 3D Room Video

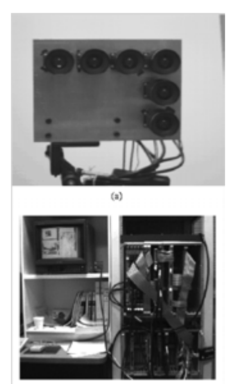
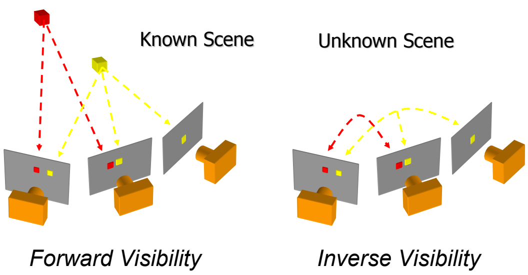


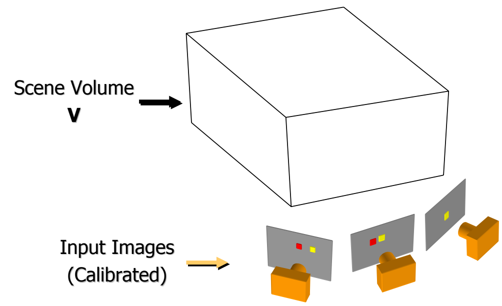
Figure 7: The CMU Video-Rate Stereo Machine Prototype System: (a) camera head; (b) processor boards

The visibility problem

Which points are visible in which images?

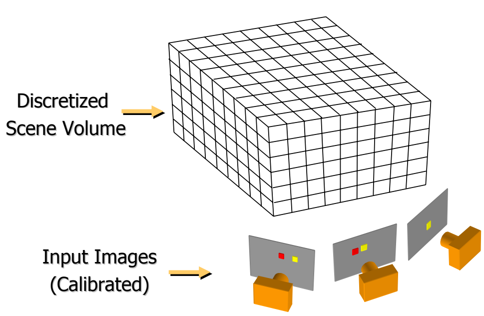


Volumetric stereo



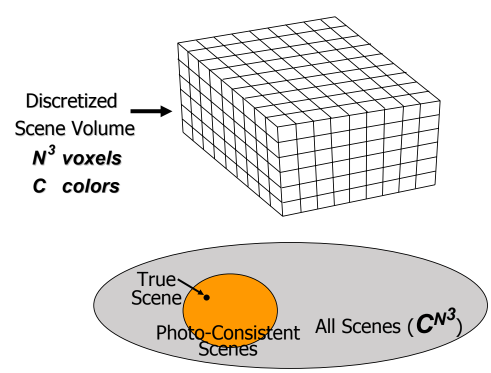
Goal: Determine occupancy, “color” of points in V

Discrete formulation: Voxel Coloring



Goal: Assign RGBA values to voxels in V ***photo-consistent*** **with images**

Complexity and computability



Issues

Theoretical Questions

- Identify class of *all* photo-consistent scenes

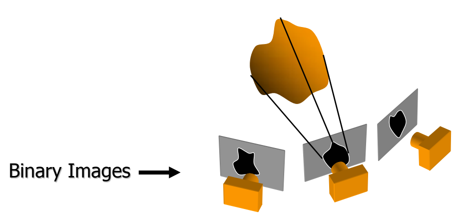
Practical Questions

- 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) or
     > W. Matusik, C. Buehler, R. Raskar, L. McMillan, and S. J. Gortler, *Image-Based Visual Hulls*, SIGGRAPH 2000 (pdf 1.6 MB)
2. C unconstrained, viewpoint constraints
   - Voxel coloring algorithm [Seitz & Dyer 97]
3. General Case
   - Space carving [Kutulakos & Seitz 98]

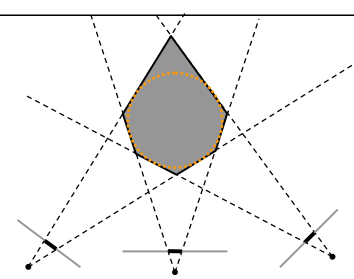
Reconstruction from Silhouettes (C = 2)



Approach:

- *Backproject* each silhouette
- Intersect backprojected volumes

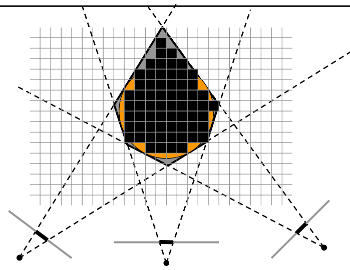
Volume intersection



Reconstruction Contains the True Scene

- But is generally not the same
- 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(?), 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] or interval techniques [Matusik 2000]

Cons

- No concavities
- Reconstruction is not photo-consistent
- Requires identification of silhouettes

Voxel Coloring Solutions

1. C=2 (silhouettes)
   - Volume intersection [Baumgart 1974]
2. C unconstrained, viewpoint constraints
   - Voxel coloring algorithm [Seitz & Dyer 97]
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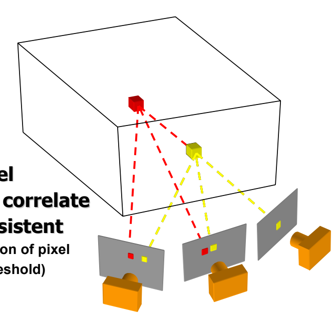
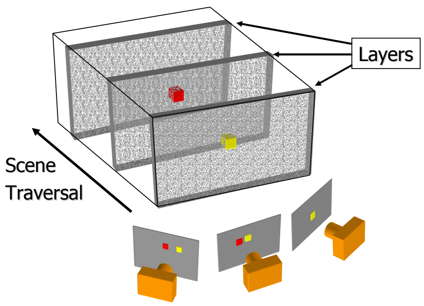
Voxel Coloring Approach



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?

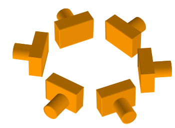
Depth Ordering: visit occluders first!



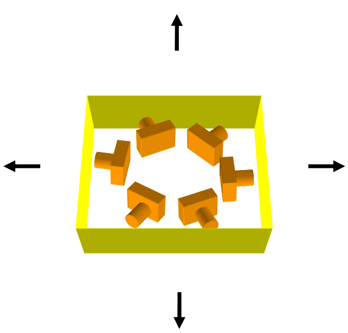
Condition: **depth order is the *same for all input views***

Panoramic Depth Ordering

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

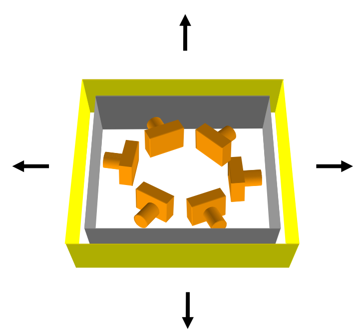


Panoramic Depth Ordering



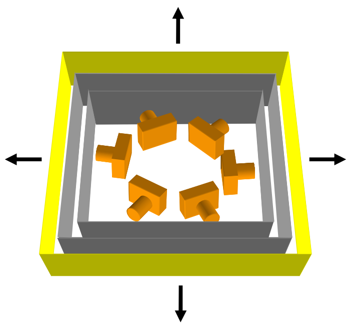
Layers radiate outwards from cameras

Panoramic Layering



Layers radiate outwards from cameras

Panoramic Layering

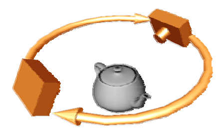


Layers radiate outwards from cameras

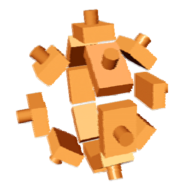
Compatible Camera Configurations

Depth-Order Constraint

- Scene outside convex hull of camera centers

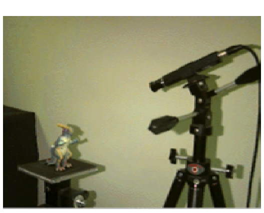


Inward-Looking

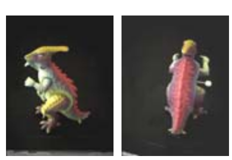


Outward-Looking

Calibrated Image Acquisition



Calibrated Turntable



Selected Dinosaur Images

Selected Flower Images

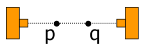
Voxel Coloring Results (Video)

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



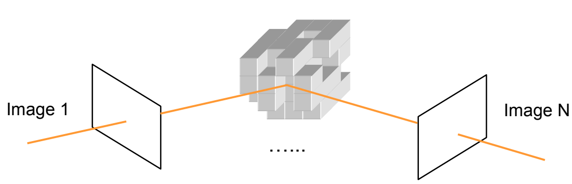
Need more powerful general-case algorithms

- Unconstrained camera positions
- Unconstrained scene geometry/topology

Voxel Coloring Solutions

1. C=2 (silhouettes)
   - Volume intersection [Baumgart 1974]
2. C unconstrained, viewpoint constraints
   - Voxel coloring algorithm [Seitz & Dyer 97]
3. General Case
   - Space carving [Kutulakos & Seitz 98]
     - For more info: http://www.cs.washington.edu/homes/seitz/papers/kutu-ijcv00.pdf

Space Carving Algorithm



Space Carving Algorithm

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

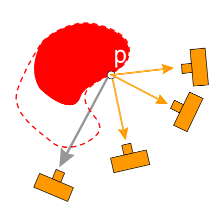
Convergence

Consistency Property

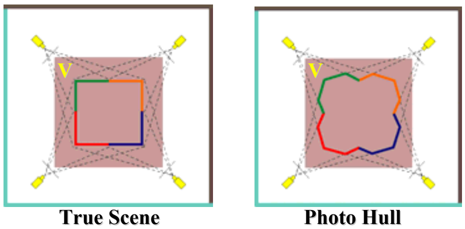
- The resulting shape is photo-consistent
  - all inconsistent points are removed

Convergence Property

- Carving converges to a non-empty shape
  - a point on the true scene is *never* removed

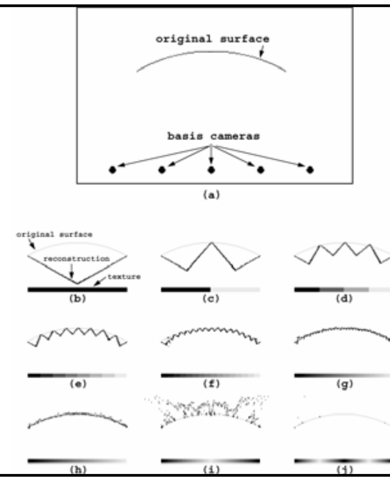


Which shape do you get?



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

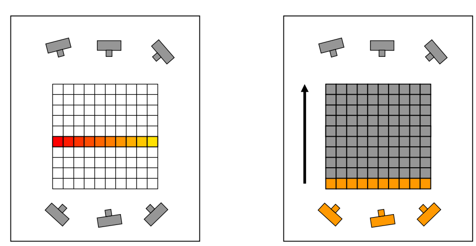
- Complex update procedure

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



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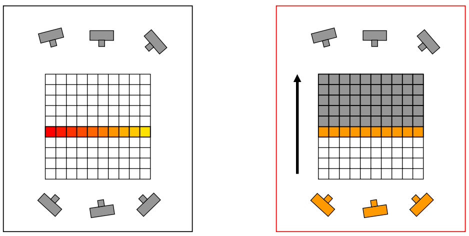

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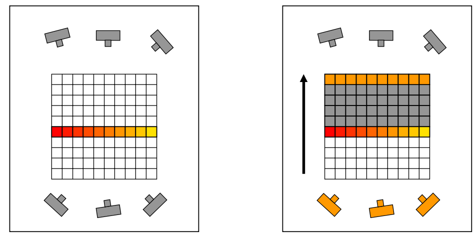

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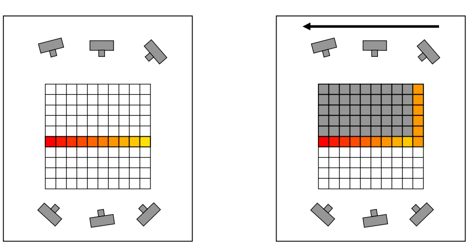

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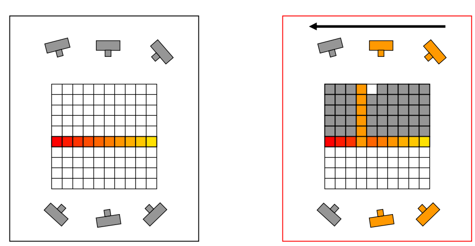

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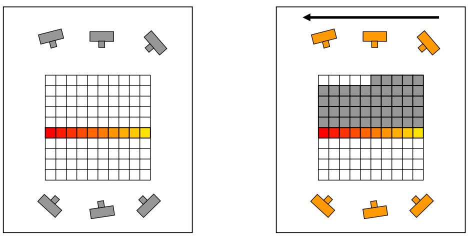


Space Carving Results: African Violet

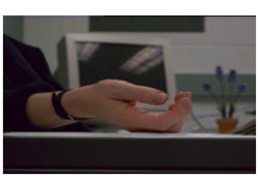
Input Image (1 of 45)

Reconstruction

Reconstruction

Reconstruction

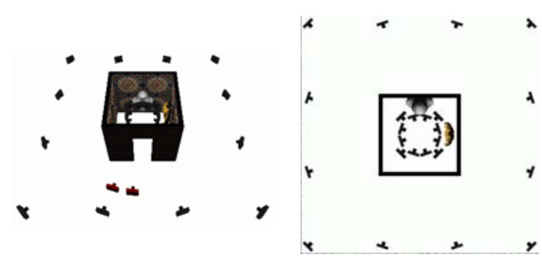
Space Carving Results: Hand



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

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Voxel Coloring and Space Carving

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- Kutulakos & Seitz, "A Theory of Shape by Space Carving", Proc. ICCV, 1998, pp. 307-314.

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- DeBonet & Viola, "Poxels: Probabilistic Voxelized Volume Reconstruction", Proc. Int. Conf. on Computer Vision (ICCV) 1999.
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- Fua & Leclerc, "Object-centered surface reconstruction: Combining multi-image stereo and shading", International Journal of Computer Vision, 16, 1995, pp. 35-56.
- Narayanan, Rander, & Kanade, "Constructing Virtual Worlds Using Dense Stereo", Proc. ICCV, 1998, pp. 3-10.