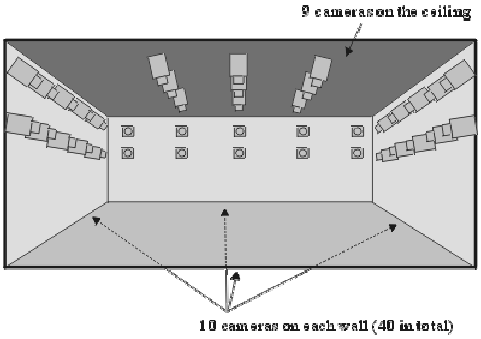
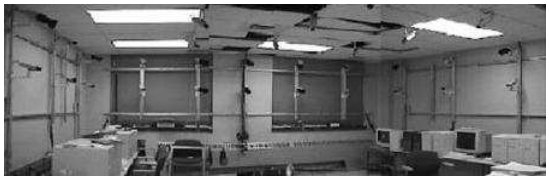
3D Photography

• • •

3D Voxel Model
72 K voxels colored
7.6 M voxels tested
7 min. to compute
on a 250MHz SGI

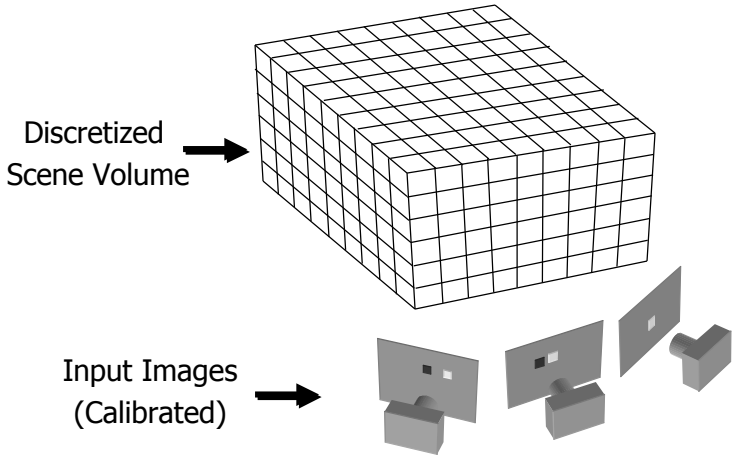
3D Room (Takeo Kanade at CMU)





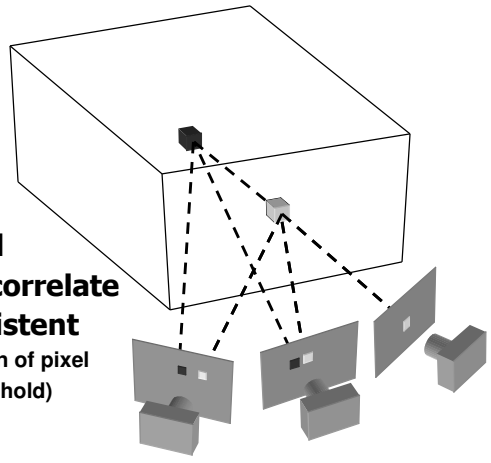
Input
3D
Composite

3D Reconstruction by Voxel Coloring



Goal: **Assign colors to voxels in V *consistent* with images**

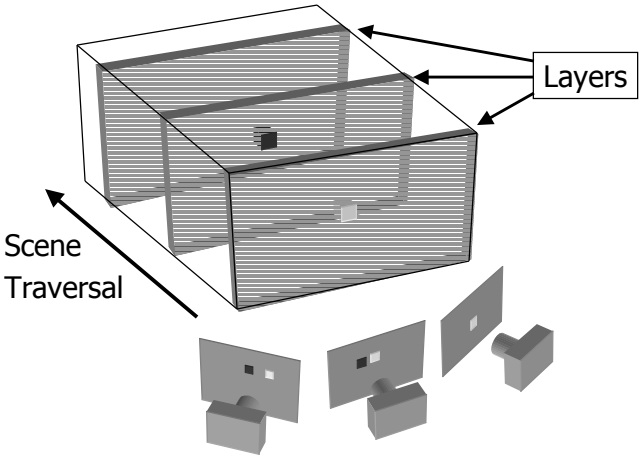
Voxel Coloring Approach



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!



Steps

For each plane

- For each voxel v in the plane
  - > Project v to all of the images I_1, I_2, …, I_n
  - > Evaluate “free” pixels to which v projects
    - e.g., standard deviation, other metrics
  - > If error below threshold
    - accept voxel
    - assign average pixel color
    - Mark the pixels as being “covered”
  - > else
    - reject voxel

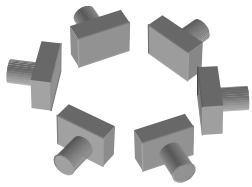
Batch mode

For each plane

- Slide project each of the images I_1, I_2, …, I_n ONTO the plane
  - > Implemented as a texture-map
  - > Produces warped images W_1, W_2, …, W_n
    - a voxel maps to the same pixel in all warped images
- Evaluate consistency of warped images
  - > Standard devation($W_1(u,v)$, $W_2(u,v)$, …, $W_n(u,v)$)
- Mark W_i pixels as being “free” or “covered”
- Mark I_i pixels as being “free” or “covered”
  - > Requires unwarping W_i to I_i

Panoramic Depth Ordering

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



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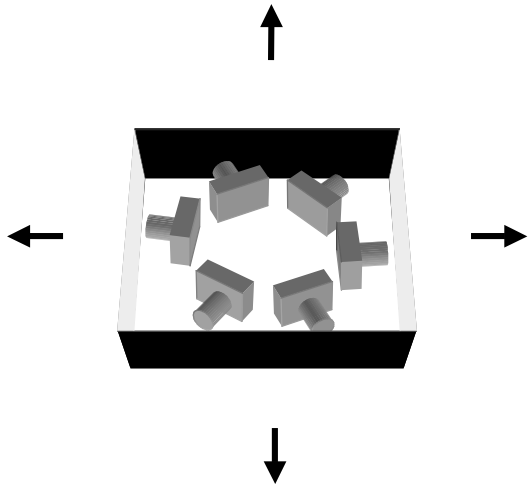
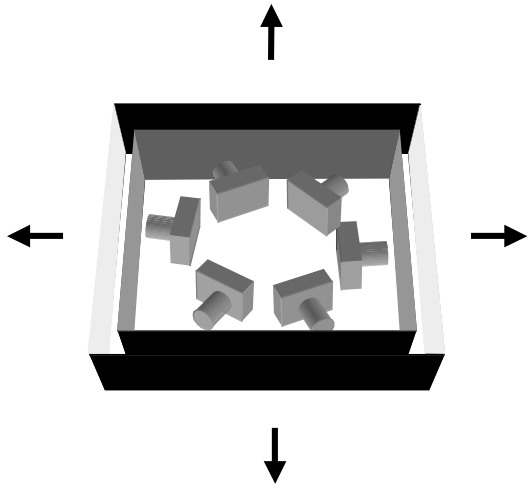


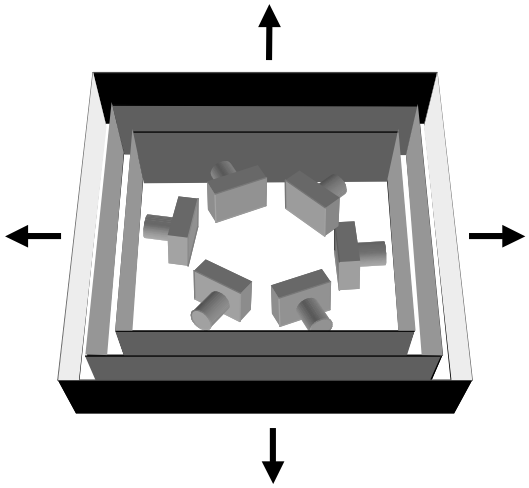
Layers radiate outwards from cameras

Panoramic Layering



Layers radiate outwards from cameras

Panoramic Layering

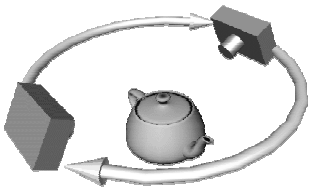


Layers radiate outwards from cameras

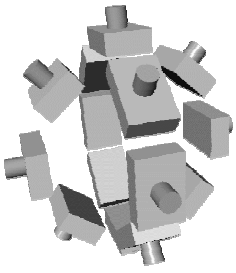
Compatible Camera Configurations

Depth-Order Constraint

- Scene outside convex hull of camera centers

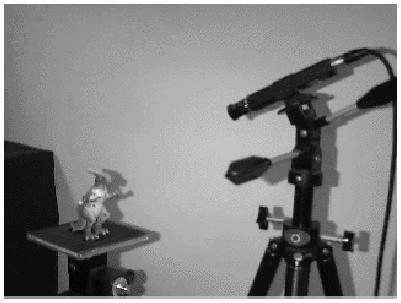


Inward-Looking
cameras above scene

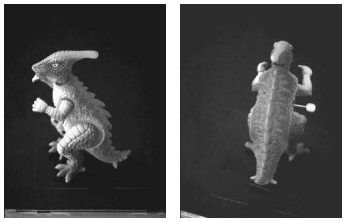


Outward-Looking
cameras inside scene

Calibrated Image Acquisition



Calibrated Turntable
360° rotation (21 images)



Selected Dinosaur Images

Selected Flower Images

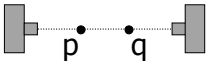
Voxel Coloring Results (Video)

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

Space Carving Algorithm

The Basic Algorithm is Unwieldy

- Complex update procedure

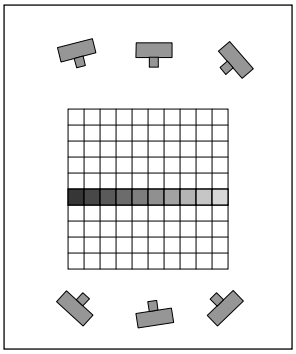
Alternative: Multi-Pass Plane Sweep

- Efficient, can use texture-mapping hardware
- Converges quickly in practice
- Easy to implement

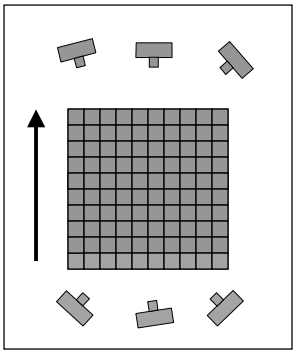
Results Algorithm

Multi-Pass Plane Sweep

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



True Scene



Reconstruction

Multi-Pass Plane Sweep

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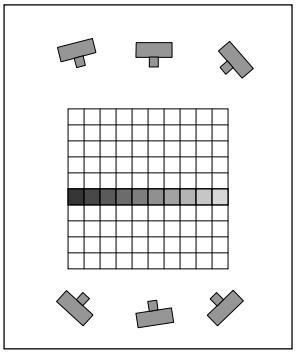

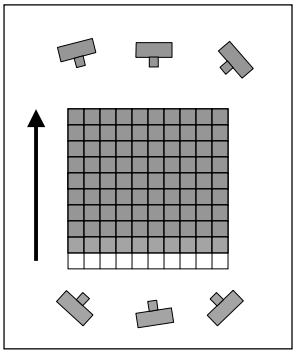

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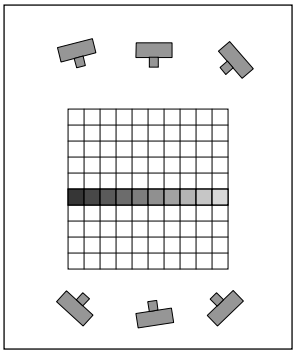

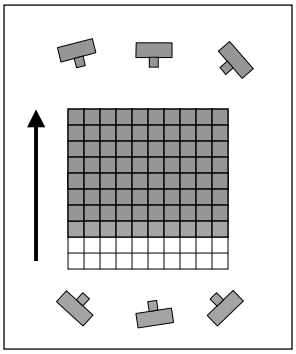

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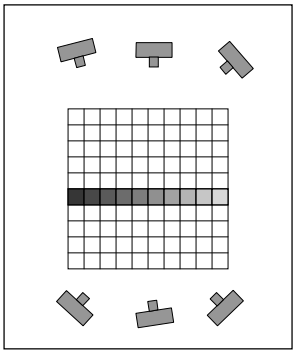

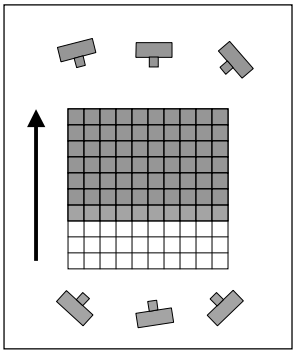

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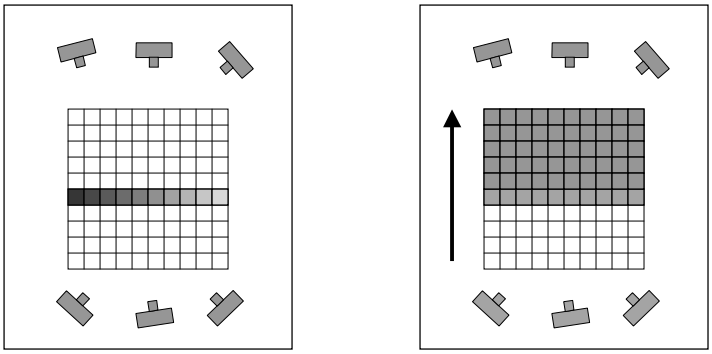

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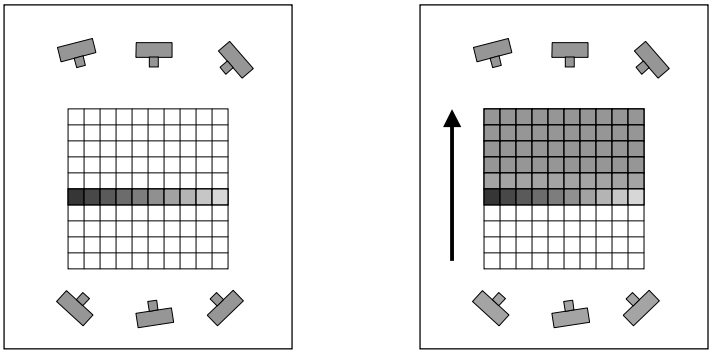

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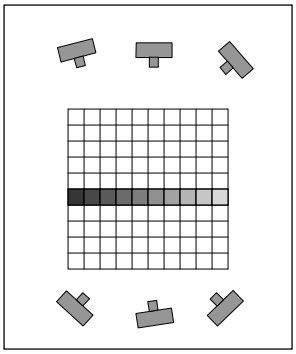

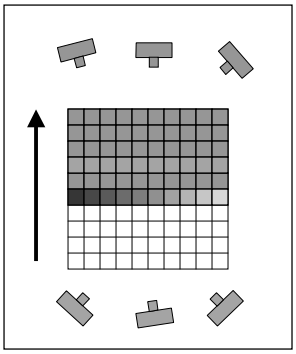

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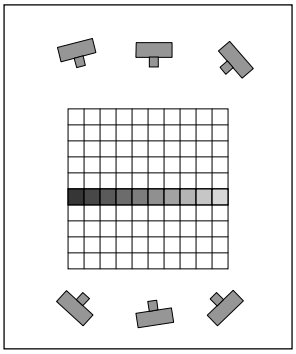

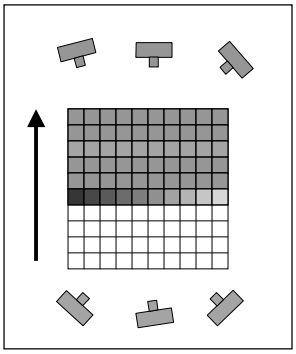

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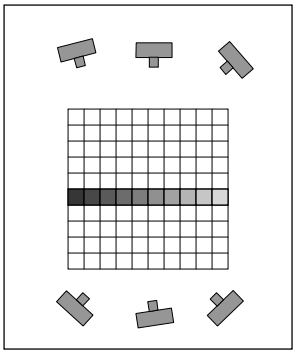

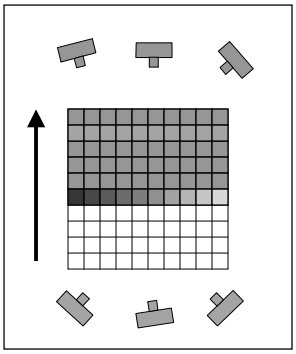

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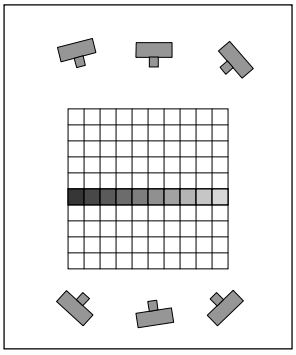

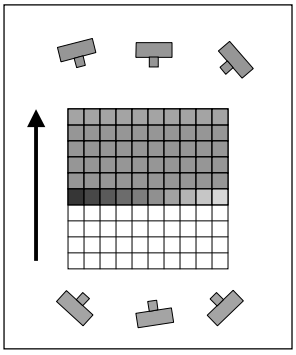

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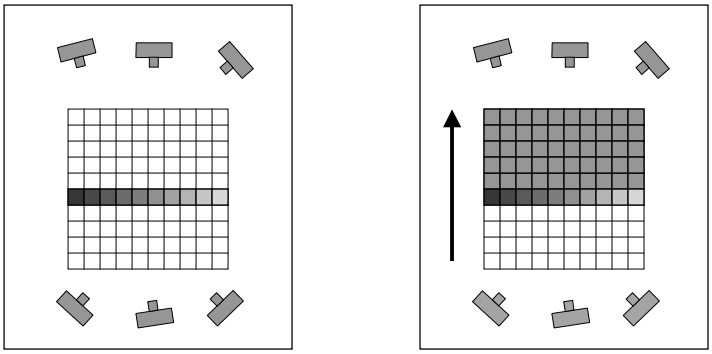

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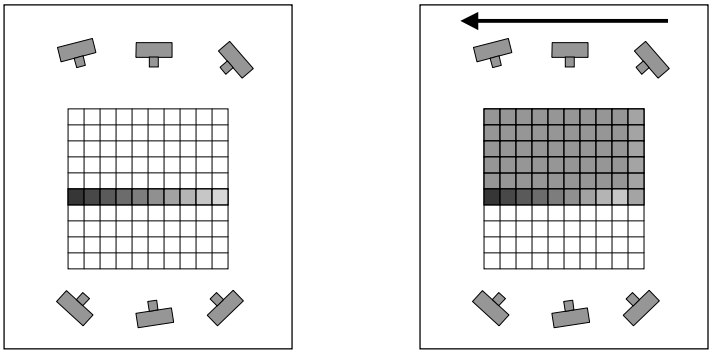

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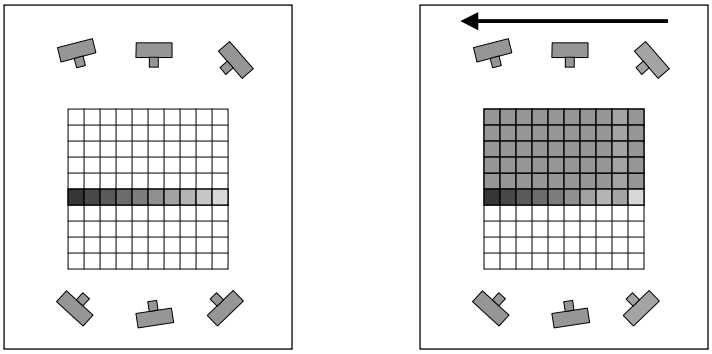

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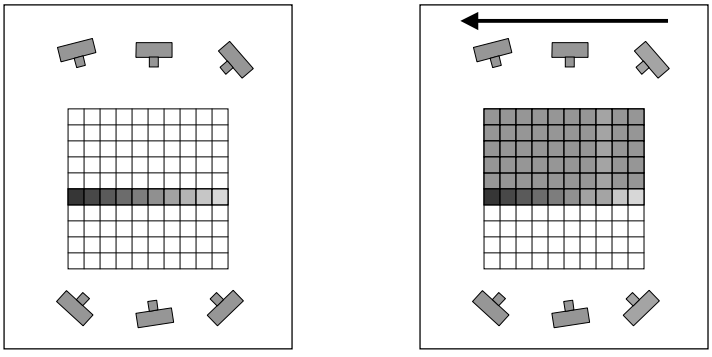

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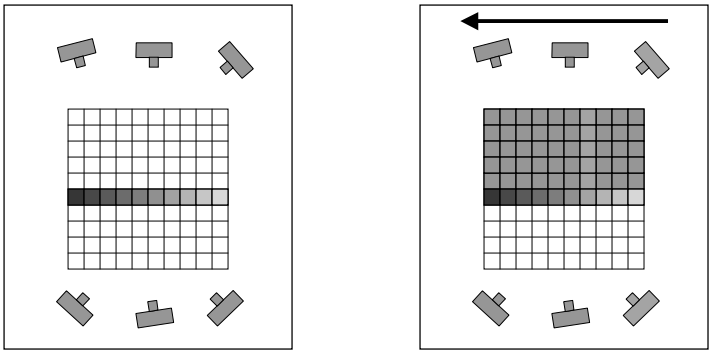

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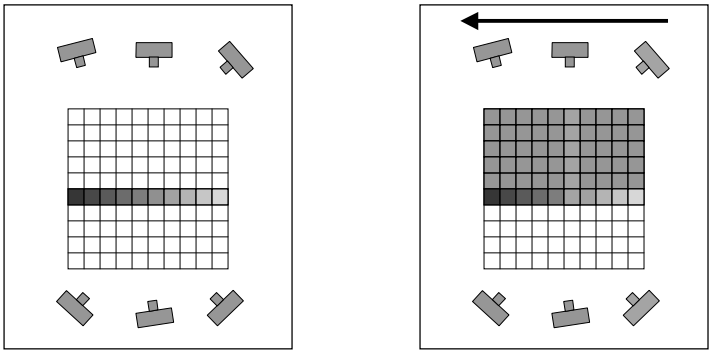

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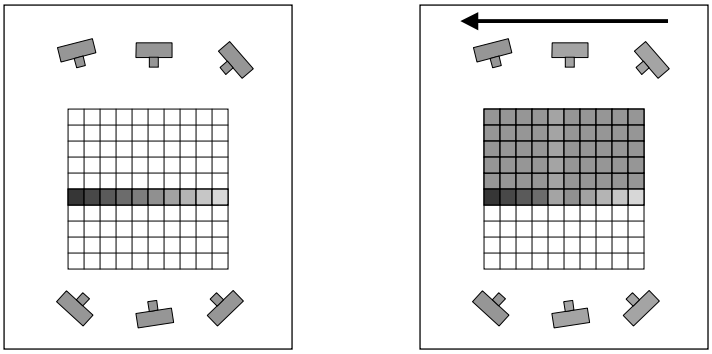

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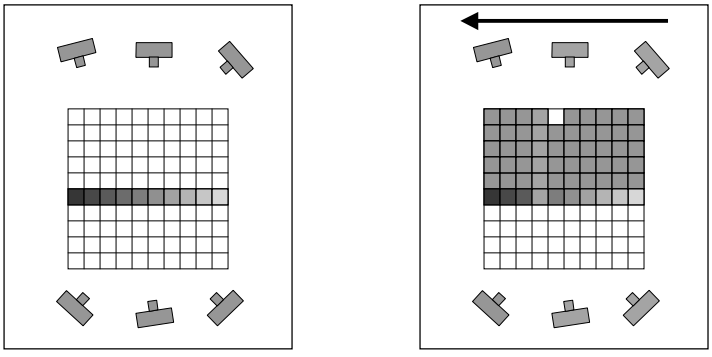

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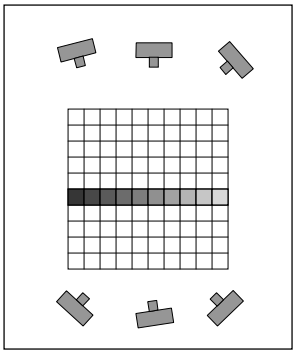

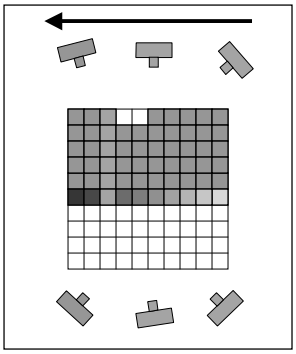

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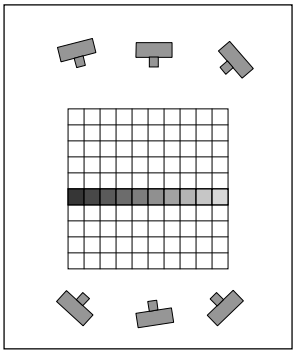

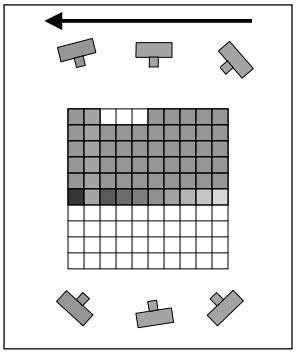

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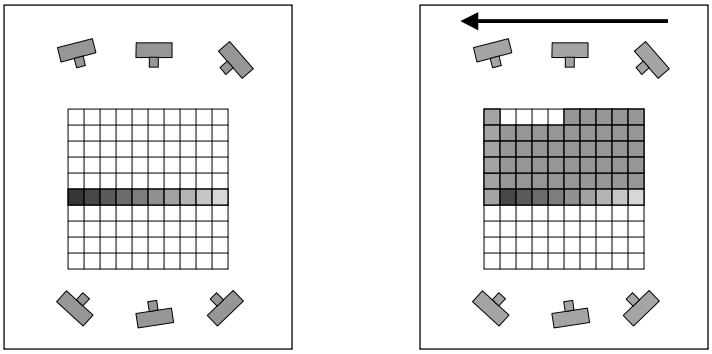

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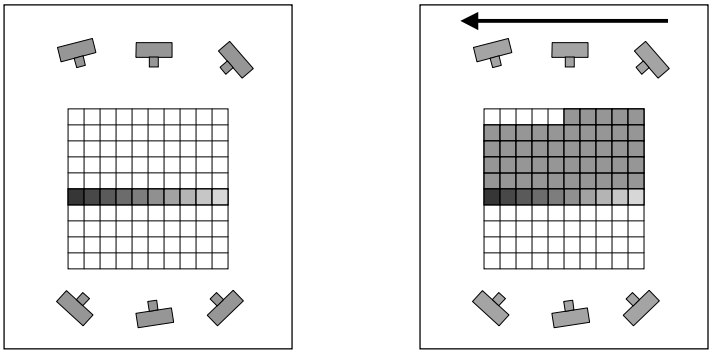
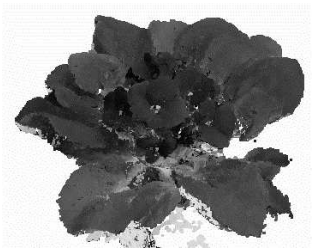


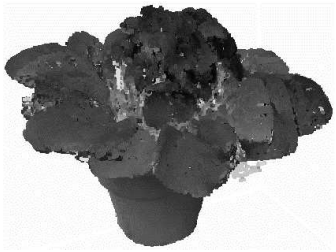
Space Carving Results: African Violet

Input Image (1 of 45)

Reconstruction



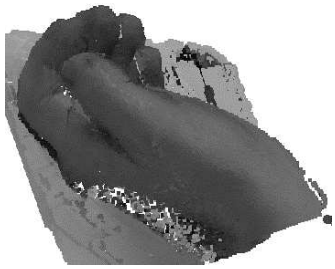
Reconstruction

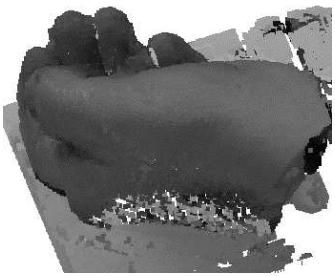


Reconstruction

Space Carving Results: Hand

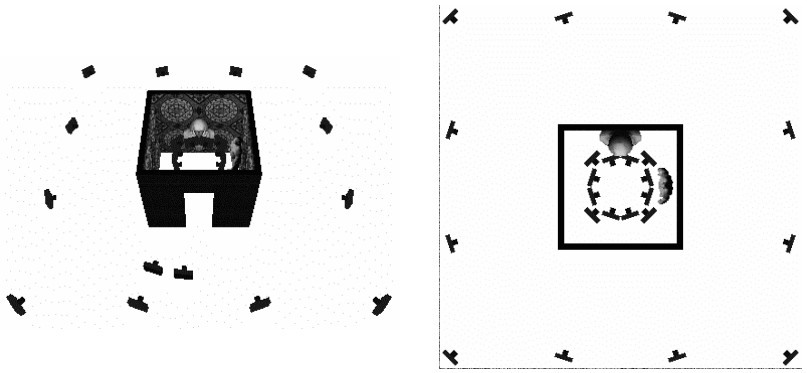
Input Image (1 of 100)





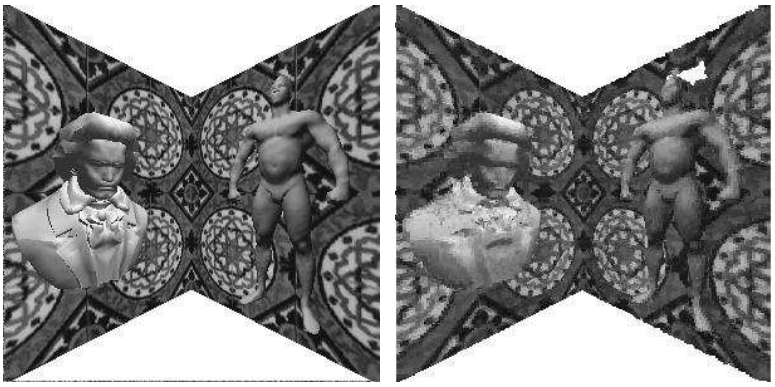
Views of Reconstruction

House Walkthrough



24 rendered input views from inside *and* outside

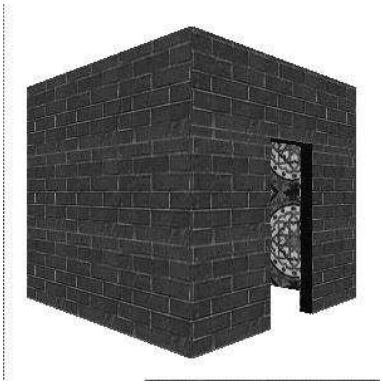
Space Carving Results: House



Input Image
(true scene)

Reconstruction
370,000 voxels

Space Carving Results: House



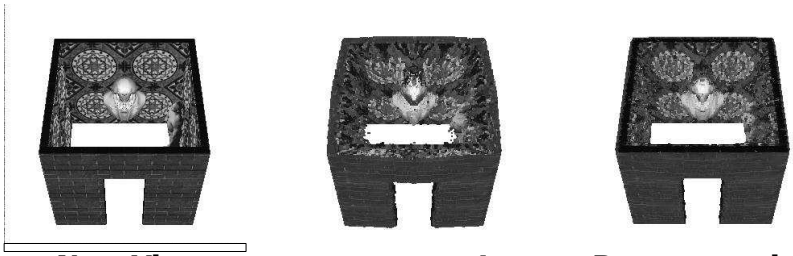
Input Image
(true scene)

Reconstruction
370,000 voxels

Space Carving Results: House

New View (true scene)

Reconstruction

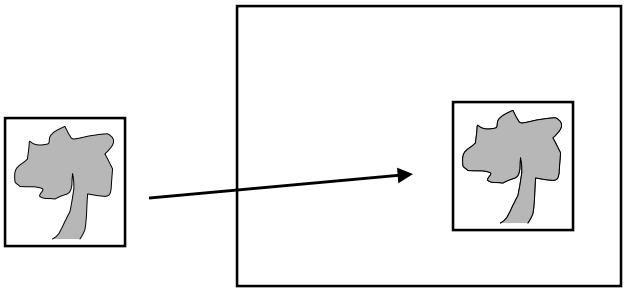


New View
(true scene)

Reconstruction

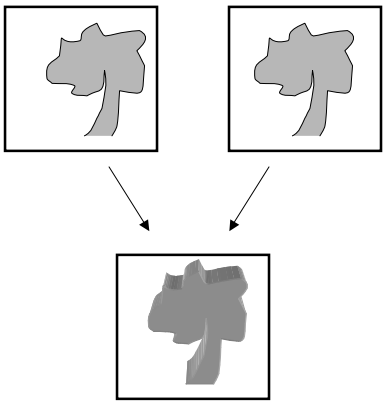
Reconstruction
(with new input view)

Image Registration



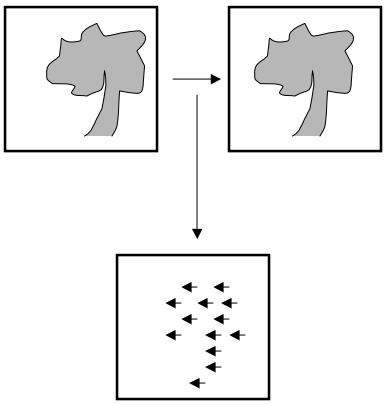
Applications

Stereo



Applications

Stereo
Optical flow



Applications

Stereo
Optical flow
Image mosaics

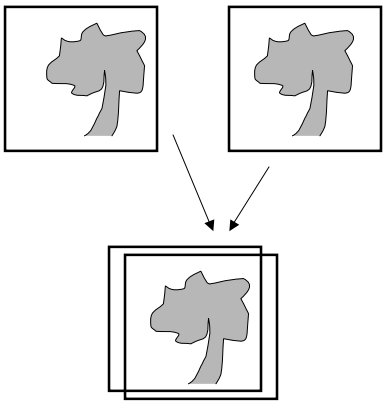
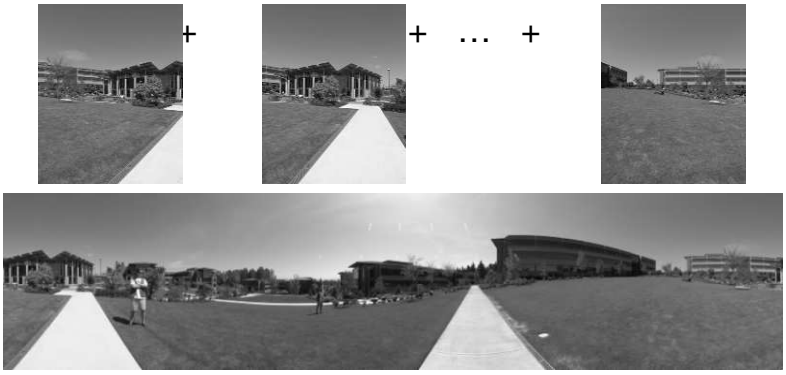


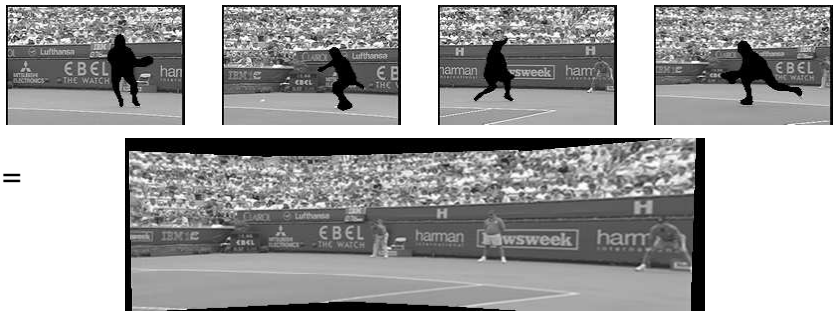
Image Mosaics (stitching)

Blend together several overlapping images into one seamless *mosaic* (composite)



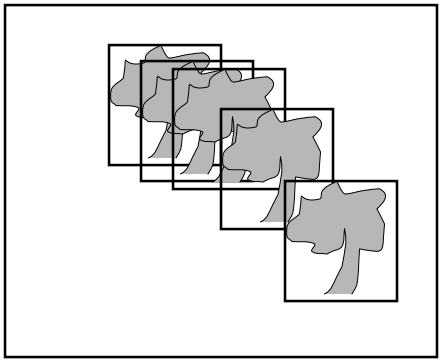
Mosaics for Video Coding

Convert masked images into a background sprite for content-based coding



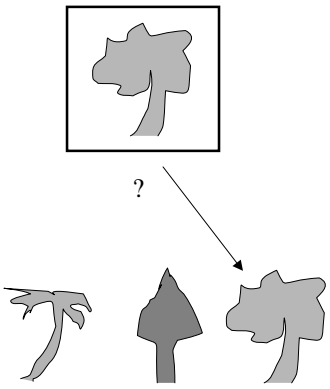
Applications

Stereo
Optical flow
Image mosaics
Tracking



Applications

Stereo
Optical flow
Image mosaics
Tracking
Recognition



Brightness Constraint

Brightness Constancy Equation:

$$J(x, y) \approx I(x + u(x, y), y + v(x, y))$$

Or, better still, Minimize :

$$E(u, v) = (J(x, y) - I(x + u, y + v))^2$$

Linearizing (assuming small *(u,v)*):

$$J(x, y) \approx I(x, y) + I_x(x, y) \cdot u(x, y) + I_y(x, y) \cdot v(x, y)$$

Optical Flow Constraint

$$E(u, v) = (I_x \cdot u + I_y \cdot v + I_t)^2$$

Minimizing:

$$\frac{\partial E}{du} = \frac{\partial E}{dv} = 0$$
$$I_x(I_x u + I_y v + I_t) = 0$$
$$I_y(I_x u + I_y v + I_t) = 0$$

In general $I_x, I_y \neq 0$

Hence, $I_x \cdot u + I_y \cdot v + I_t \approx 0$

The gradient constraint – *only one constraint for each pixel*

Patch Translation

Assume same velocity for all pixels within an image patch

$$E(u,v) = \sum_{x,y \in \Omega} \left(I_x(x,y)u + I_y(x,y)v + I_t \right)^2$$

Minimizing

$$\begin{bmatrix} \sum I_x^2 & \sum I_x I_y \\ \sum I_x I_y & \sum I_y^2 \end{bmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = -\begin{pmatrix} \sum I_x I_t \\ \sum I_y I_t \end{pmatrix}$$

$$\left(\sum \nabla I \nabla I^T \right) \vec{U} = -\sum \nabla I I_t$$