Reconstruction

CSE 576
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3d model

- “Digital copy” of real object
- Allows us to
  - Inspect details of object
  - Measure properties
  - Reproduce in different material

- Many applications
  - Cultural heritage preservation
  - Computer games and movies
  - City modelling
  - E-commerce
Applications: cultural heritage

SCULPTEUR European project
Applications: art

Block Works Precipitate III 2004
*Mild steel blocks* 80 x 46 x 66 cm

Domain Series Domain VIII Crouching
1999 *Mild steel bar* 81 x 59 x 63 cm
Applications: structure engineering

BODY / SPACE / FRAME, Antony Gormley, Lelystad, Holland
Applications: art
Applications: computer games
Applications: 3D indexation
Applications: archaeology

- “forma urbis romae” project

**Fragments of the City: Stanford’s Digital Forma Urbis Romae Project**
David Koller, Jennifer Trimble, Tina Najbjerg, Natasha Gelfand, Marc Levoy

Applications: large scale modelling

[Pollefeys08]

[Furukawa10]

[Goesele07]

[Corneilis08]
Scanning technologies

- Laser scanner, coordinate measuring machine
  - Very accurate
  - Very Expensive
  - Complicated to use

Minolta

Contura CMM
Applications: 3D Scanning

Scanning Michelangelo’s “The David”

- The Digital Michelangelo Project
- 2 BILLION polygons, accuracy to .29mm
The Digital Michelangelo Project, Levoy et al.
3d shape from photographs

“Estimate a 3d shape that would generate the input photographs given the same material, viewpoints and illumination”
3D shape from photographs

“Estimate a 3d shape that would generate the input photographs given the same material, viewpoints and illumination”
3d shape from photographs

Appearance strongly depends on the material and lighting

rigid

textureless

textured

deforming
3d shape from photographs

Appearance strongly depends on the material and lighting

No single algorithm exists dealing with any type of scene
3d shape from photographs

Photograph based 3d reconstruction is:

✓ practical
✓ fast
✓ non-intrusive
✓ low cost
✓ Easily deployable outdoors
✗ “low” accuracy
✗ Results depend on material properties
Reconstruction

- Generic problem formulation: given several images of the same object or scene, compute a representation of its 3D shape
Reconstruction

- Generic problem formulation: given several images of the same object or scene, compute a representation of its 3D shape
  - “Images of the same object or scene”
    - Arbitrary number of images (from two to thousands)
    - Arbitrary camera positions (camera network or video sequence)
    - Calibration may be initially unknown
  - “Representation of 3D shape”
    - Depth maps
    - Meshes
    - Point clouds
    - Patch clouds
    - Volumetric models
    - Layered models
Multiple-baseline stereo

Plane Sweep Stereo

- Choose a reference view
- Sweep family of planes at different depths with respect to the reference camera

Each plane defines a homography warping each input image into the reference view

Reconstruction from Silhouettes

- The case of binary images: a voxel is photo-consistent if it lies inside the object’s silhouette in all views.
Use silhouettes

Can be computed robustly
Can be computed efficiently
Reconstruction from Silhouettes

- The case of binary images: a voxel is photo-consistent if it lies inside the object’s silhouette in all views.

Finding the silhouette-consistent shape (*visual hull*):

- 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
Voxel algorithm for volume intersection

Color voxel black if on silhouette in every image
Volumetric Stereo / Voxel Coloring

Goal: Assign RGB values to voxels in V \textit{photo-consistent} with images
Photo-consistency of a 3d point
Photo-consistency of a 3d point

Non photo-consistent point

$\neq$
Photo-consistency of a 3d patch
Measuring photo-consistency

• Equivalent statements
  • voxel \( v \) is photo-consistent
  • image content is (nearly) identical for all projections of \( v \)
  • any pair of projections of \( v \) matches well

• Examples:

\[
\Phi(v) = f \left( \frac{1}{K} \sum_{j=1}^{K} (c_j - c_{\text{mean}})^2 \right)
\]

(variance of average colour \( c_j \) over all \( K \) visible images [Seitz&Kutulakos])

\[
\Phi(v) = \frac{2}{K(K+1)} \sum_{i=1}^{K} \sum_{j=i+1}^{K} \text{NCC}(p_i, p_j)
\]

(average normalised cross-correlation over all pairs of visible images [Vogiatzis et al.])
Challenges of photo-consistency

- Camera visibility

- Failure of comparison metric
  - repeated texture
  - lack of texture
  - specularities
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

*cameras above scene*

Outward-Looking

*cameras 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
Space Carving

Space Carving Algorithm

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

K. N. Kutulakos and S. M. Seitz, A Theory of Shape by Space Carving, ICCV 1999
Space Carving Results: African Violet

Input Image (1 of 45)

Reconstruction

Reconstruction

Reconstruction

Source: S. Seitz
Space Carving Results: Hand

Input Image
(1 of 100)

Views of Reconstruction
Carved visual hulls

- The visual hull is a good starting point for optimizing photo-consistency
  - Easy to compute
  - Tight outer boundary of the object
  - Parts of the visual hull (rims) already lie on the surface and are already photo-consistent

Yasutaka Furukawa and Jean Ponce, Carved Visual Hulls for Image-Based Modeling, ECCV 2006.
Carved visual hulls

1. Compute visual hull
2. Use dynamic programming to find rims (photo-consistent parts of visual hull)
3. Carve the visual hull to optimize photo-consistency keeping the rims fixed

Yasutaka Furukawa and Jean Ponce,
Carved Visual Hulls for Image-Based Modeling, ECCV 2006.
Stereo from community photo collections

- Up to now, we’ve always assumed that camera calibration is known
- For photos taken from the Internet, we need *structure from motion* techniques to reconstruct both camera positions and 3D points
Stereo from community photo collections

Comparison: 90% of points within 0.128 m of laser scan (building height 51m)

M. Goesele, N. Snavely, B. Curless, H. Hoppe, S. Seitz, 
Multi-View Stereo for Community Photo Collections, ICCV 2007
Scanning technologies

Structured light

[Zhang02]
Kinect: Structured infrared light

PrimeSense Patents

FIG. 2
The Kinect uses infrared laser light, with a speckle pattern

Shpunt et al, PrimeSense patent application
US 2008/0106746
KinectFusion: Real-time 3D Reconstruction and Interaction Using a Moving Depth Camera*

SIGGRAPH Talks 2011

KinectFusion: Real-Time Dynamic 3D Surface Reconstruction and Interaction

Shahram Izadi 1, Richard Newcombe 2, David Kim 1,3, Otmar Hilliges 1, David Molyneaux 1,4, Pushmeet Kohli 1, Jamie Shotton 1, Steve Hodges 1, Dustin Freeman 5, Andrew Davison 2, Andrew Fitzgibbon 1

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