Lecture 8

Active stereo & Volumetric stereo

• Active stereo
  • Structured lighting
  • Depth sensing

• Volumetric stereo:
  • Space carving
  • Shadow carving
  • Voxel coloring

Reading:

[Szelisky] Chapter 11 “Multi-view stereo”


Traditional stereo

What’s the main problem in traditional stereo? We need to find correspondences!
Active stereo (point)

Replace one of the two cameras by a projector
- Projector geometry calibrated
- What’s the advantage of having the projector?  Correspondence problem solved!

Any limitation??
Active stereo (stripe)

- Projector and camera are parallel
- Correspondence problem is solved!
Calibrating the system

- Use calibration rig to calibrate camera and localize rig in 3D
- Project patterns on rig and calibrate projector
Laser scanning

Digital Michelangelo Project (1990)
http://graphics.stanford.edu/projects/mich/

• Optical triangulation
  - Project a single stripe of laser light
  - Scan it across the surface of the object
  - This is a very precise version of structured light scanning
Laser scanning

The Digital Michelangelo Project, Levoy et al.
Limitations of Laser scanning

• Slow
• Cannot capture deformations in time

Source: S. Seitz
Active stereo (color-coded stripes)

L. Zhang, B. Curless, and S. M. Seitz
2002
S. Rusinkiewicz & Levoy 2002

- Dense reconstruction
- Correspondence problem again
- Get around it by using color codes
Active stereo (color-coded stripes)

Rapid shape acquisition: Projector + stereo cameras

**Active stereo** — depth sensors

- Infrared projector combined with an IR camera
- Captures video data in 3D under any ambient light conditions.

Pattern of projected infrared points to generate a dense 3D image

Depth map

Source: wikipedia
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“Traditional” Stereo

Goal: estimate the position of P given the observation of P from two view points

Assumptions: known camera parameters and position (K, R, T)
Subgoals:
1. Solve the correspondence problem
2. Use corresponding observations to triangulate
Volumetric stereo

1. Hypothesis: pick up a point within the volume
2. Project this point into 2 (or more) images
3. Validation: are the observations consistent?

Assumptions: known camera parameters and position (K, R, T)
Consistency based on cues such as:

- Contours/silhouettes → Space carving
- Shadows → Shadow carving
- Colors → Voxel coloring
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Contours/silhouettes

- Contours are a rich source of geometric information
Apparent Contours

- Projection of the locus of points on the object surface which separate the visible and occluded parts on the surface

[Satoh & Cipolla]
Silhouettes

A silhouette is defined as the area enclosed by the apparent contours.
Detecting silhouettes

Camera → Image → Easy contour segmentation → Object
Detecting silhouettes
How can we use contours?

Silhouette

Camera
Center

Image

Object

Object apparent contour

Visual cone

Camera
How can we use contours?

Silhouette

Camera

Image

Object

Visual cone

Object apparent contour

2D slice:

Camera

Image line

Object’s silhouette

Object
How can we use contours?

- Camera intrinsics are known
- We know location and pose of the camera as it moves around the object

View point 1

View point 2

Object estimate (visual hull)
How to perform visual cones intersection?

- Decompose visual cone in polygonal surfaces (among others: Reed and Allen ‘99)
Space carving

[ Martin and Aggarwal (1983) ]

• Using contours/silhouettes in volumetric stereo, also called **space carving**

![Diagram showing voxel as empty or full](image)
Computing Visual Hull in 2D
Computing Visual Hull in 2D
Computing Visual Hull in 2D
Computing Visual Hull in 2D

Visual hull:
an upper bound estimate

Consistency:
A voxel must be projected into a silhouette in each image
Space carving has complexity $O(N^3)$.

Any suggestion for speeding this process up?

Octrees! (Szeliski ’93)
Complexity Reduction: Octrees
Complexity Reduction: Octrees

- Subdiving volume in sub-volumes of progressive smaller size
Complexity Reduction: Octrees
Complexity Reduction: Octrees
Complexity reduction: 2D example

4 elements analyzed in this step
Complexity reduction: 2D example

16 elements analyzed in this step
Complexity reduction: 2D example
1 + 4 + 16 + 52 + 544 = 617 voxels have been analyzed in total (rather than 32x32 = 1024).

16x34 = 544 voxels are analyzed in this step.

52 elements are analyzed in this step.
Advantages of Space carving

• Robust and simple
• No need to solve for correspondences
Limitations of Space carving

- Accuracy function of number of views

What else?
Limitations of Space carving

- Concavities are not modeled

For 3D objects: Are all types of concavities problematic?
Limitations of Space carving

- Concavities are not modeled

(hyperbolic regions are ok)

-- see Laurentini (1995)
Space carving: A Classic Setup

Courtesy of Seitz & Dyer
Space carving: A Classic Setup
Space carving: Experiments

24 poses (15°)
voxel size = 1mm
Space carving: Experiments

24 poses (150°)
voxel size = 2mm
Space carving: Conclusions

- Robust
- Produce conservative estimates
- Concavities can be a problem
- Low-end commercial 3D scanners
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Shape from Shadows

- Self-shadows are visual cues for shape recovery

Self-shadows indicate concavities
(no modeled by contours)
Shadow carving: The Setup

Camera

Array of lights

Object

Turntable
Shadow carving: The Setup

Array of lights

Camera

Object

Turntable
Shadow carving: The Setup

[Savarese et al. '01]
Shadow carving

[Savarese et al. 2001]
Algorithm: Step k

- Image
- Image shadow
- Camera
- Image line
- Light source
- Virtual light image
- Upper-bound from step k-1
- Object
Algorithm: Step k

Theorem: A voxel that projects into an image shadow AND an virtual image shadow cannot belong to the object.
Algorithm: Step k

Properties:

- No further volume can be removed
- Carving process always conservative

Consistency:
In order for a voxel to be removed it must project into both image shadow and virtual image shadow
Algorithm: Step k

Complexity?

$O(2N^3)$
Simulating the System

- 24 positions
- 4 lights

- 72 positions
- 8 lights
Results

- 16 positions
- 4 lights

Space carving

Shadow carving
Results

Space carving

Shadow carving
Shadow carving: Summary

• Produces a conservative volume estimate
• Accuracy depending on view point and light source number
• Limitations with reflective & low albedo regions
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Voxel Coloring

[Seitz & Dyer (’97)]
[R. Collins (Space Sweep, ’96)]

- Color/photo-consistency
- Jointly model structure and appearance
Basic Idea

Is this voxel in or out?
Uniqueness
Uniqueness

- Multiple consistent scenes

How to fix this? Need to use a visibility constraint
Algorithm for enforcing visibility constraints
Algorithm Complexity

- Voxel coloring visits each $N^3$ voxels only once
- Project each voxel into $L$ images

$\Rightarrow O(L \cdot N^3)$

NOTE: not function of the number of colors
A Critical Assumption: Lambertian Surfaces
Non Lambertian Surfaces
Photoconsistency Test

If $C > \lambda$ = threshold $\Rightarrow$ voxel consistent

$$C = \text{corr}(\begin{array}{c} \bullet \bullet \bullet \end{array}, \begin{array}{c} \bullet \bullet \bullet \end{array})$$

$$w = \text{mean}(w)$$

$$w' = \text{mean}(w')$$

$$C = \frac{(w - \bar{w})(w' - \bar{w}')}{\| (w - \bar{w}) \| \| (w' - \bar{w}') \|}$$
Experimental Results

Dinosaur

- 72 k voxels colored
- 7.6 M voxels tested
- 7 min to compute on a 250MHz

Image source: http://www.cs.cmu.edu/~seitz/vcolor.html
Experimental Results

Flower

70 k voxels colored
7.6 M voxels tested
7 min to compute on a 250MHz

Image source: http://www.cs.cmu.edu/~seitz/vcolor.html
Experimental Results

Room + weird people

Image source: http://www.cs.cmu.edu/~seitz/vcolor.html
Voxel Coloring: Conclusions

• Good things
  – Model intrinsic scene colors and texture
  – No assumptions on scene topology

• Limitations:
  – Constrained camera positions
  – Lambertian assumption
Further Contributions

• A Theory of Space carving
  – Voxel coloring in more general framework
  – No restrictions on camera position

• Probabilistic Space carving
  [Broadhurst & Cipolla, ICCV 2001]
  [Bhotika, Kutulakos et. al, ECCV 2002]

• CNN & voxel coloring
  • Incorporate reprojection error in the loss function for estimating object shape
Next lecture...

Fitting and Matching