Volumetric stereo

- Definition
- Shape from Contours
- Shape from Shadows
- Voxel coloring
“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
- Shadows
- Colors
Contours are a rich source of geometric information
**DEFINITION:** projection of the locus of points on the surface which separate the visible and occluded parts on the surface.
Why contours are interesting visual cues?

- Provide information in absence of other visual cues
  - No texture
  - No shading
Why contours are interesting visual cues?

- Relatively easy to detect

Diagram: Camera captures an image of an object, and the contours are easily segmented.
How can we use contours?

- Object
- Visual cone
- Image
- Camera
- Object apparent contour
How can we use contours?

In 2D:

- Camera
- Image
- Object
- Image object’s contour

Visual cone
The views are calibrated
how to perform visual cones intersection?

- decompose visual cone in polygonal surfaces

  (among others: Reed and Allen ‘99)
Using contours/silhouettes in volumetric stereo
also called Space carving

[ Martin and Aggarwal (1983) ]
Computing visual hull in 2D
Computing visual hull in 2D
Computing visual hull in 2D
Computing visual hull in 2D

Consistency:
A voxel must be projected into a silhouette in each image

Visual hull:
an upper bound estimate
Space Carving has complexity \( O(N^3) \)

- Octrees
  (Szeliski ’93)
Complexity reduction: octrees
Complexity reduction: octrees
Subdiving volume in voxels of progressive smaller size
Complexity reduction: octrees
Complexity reduction: 2D example

4 voxels analyzed
Complexity reduction: 2D example

16 voxels analyzed
Complexity reduction: 2D example

52 voxels analyzed
1+ 4 + 16 + 52 + 34x16 = 617 voxels have been analyzed in total (rather than 32x32 = 1024)

16x34 voxels analyzed
Advantages of space carving

- Robust and simple
- No need to solve for correspondences
Limitations of space carving

- Accuracy function of number of views

Not a good estimate

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

- Laurentini (1995)
  Closest approximation
  Conservative

(hyperbolic regions are ok)
Space carving: a classic setup

Object

Turntable

Camera

Courtesy of seitz & dyer
Space carving: a classic setup
Space carving: Experiments

- 24 poses (15°)
- Voxel size = 2mm
Space carving: Experiments

- 24 poses (15°)
- voxel size = 1mm

30 cm
Space carving: Conclusions

- Robust
- Produce conservative estimates
- Concavities can be a problem
- Low-end commercial 3D scanners
Contours in the computer vision literature

Analyzing changes in apparent contours

- Giblin and Weiss (1987)
- Cipolla and Blake (1992)
- Vaillant and Faugeras (1992)
- Ponce ('92), Zheng ('94)
- Furukawa et al. ('05...)

Picture from of Sato & Cipolla
Volumetric stereo

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Self-shadows are visual cues for shape recovery

Self-shadows indicate concavities (no modeled by contours)
Shape from shadow in the literature

- Shafer & Kanade ('83)
- Hatzitheodorou & Kender ('89)
- et al...

- shape as a 2.5D terrain -- i.e. surface modeled as $f(x)$
- accurate shadow detection – i.e. $x_b$ and $x_e$
Shape from shadow in the literature

- Shafer & Kanade ('83)
- Hatzitheodorou & Kender ('89)
- et al...

*shape as a 2.5D terrain — i.e. surface modeled as $f(x)$

Using shadows in volumetric stereo
Shadow Carving

- Robust with respect to shadow estimates
- Object with arbitrary topology (no 2.5D terrains)

Savarese et al ‘01

Self-shadows

Object’s upper bound
Shadow carving: setup

Let’s define a 2D model...
2D slice model

Object

Light

Image

Camera
2D slice model

From 3D to 2D

Object

Image

Light

Object

Image line

Camera

Light
The idea

Object's upper bound

Object

Shadow

Image line

Image shadow

Camera

Light
The idea

Object's upper bound

Image line

Camera

Object

Shadow

Image shadow

Light
The idea

Object's upper bound

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Object's upper bound

Object

Shadow

Image line

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The idea

Object

Object's upper bound

Image line

Image shadow

Camera

Light

- Shadow
The idea

- Object's upper bound
- Image line
- Camera
- Image shadow
- Shadow
- Light

The diagram illustrates the concept of capturing an object's upper bound using an image line from a camera to the light source, which casts a shadow.
The idea

Reconstruction after 3 iterations
What is known?

- Light known
- Camera known
- Object unknown
- Upper bound object estimate
What can we carve?
What can we carve?

- shadow cone
- upper-bound shadow
- light cone
- carvable area
What can we carve?

- shadow cone
- upper-bound shadow
- light cone
- carvable area

The upper-bound estimate is refined
What can we carve?

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

**Proof of correctness**
Algorithm: step $k$

- Image
- Camera
- Light source
- Image line
- Upper-bound from step $k-1$
- Object
- Image shadow
Algorithm: step k

Image

Camera

Light source

Image line

Dual image shadow

Upper-bound from step k-1

Object

Image shadow
Algorithm: step k

Consistency:
A voxel must be projected into both image shadow and dual image shadow
Algorithm: step k

Complexity?

$O(2N^3)$
Shadow carving: the setup

Array of lights

Camera

Object

Turntable
Shadow carving: the setup

Array of lights

Camera

Object

Turntable
Experimental results
Simulating the system with 3D studio Max

- 24 positions
- 4 lights

- 72 positions
- 8 lights
- 24 positions
- 4 lights

- 72 positions
- 8 lights
- 16 positions
- 4 lights
Shadow carving: summary

- Produces a conservative volume estimate
- Accuracy depending on view point and light source number
- Limitations with specular & low albedo regions
Volumetric stereo

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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?
Basic idea
Uniqueness

Multiple consistent scenes
Uniqueness

Multiple consistent scenes
Tractability

- Combinatorial number of possible assignments!
- Exhaustive search not feasible
- Model occlusions!
- Use *visibility constraint*
The algorithm
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
If $\lambda < \text{Thresh} \Rightarrow \text{voxel consistent}$
A critical assumption: Lambertian surfaces

\[ I_1(p) = I_2(p) \]
Non Lambertian surfaces
Experimental results

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

Flower

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

Room + weird people
Voxel coloring: conclusions

Good things:

- model intrinsic scene colors and texture
- no assumptions on scene topology
Voxel coloring: conclusions

Good things:

- model intrinsic scene colors and texture
- no assumptions on scene topology

Limitations:

- Constrained camera positions
- Lambertian assumption
Space carving is a binary voxel coloring.
Shadow carving

no visibility constraint needed
Further contributions

- A Theory of Space Carving
  (Kutulakos & Seitz ‘99)
  - Voxel coloring in more general framework
  - No restrictions on camera position

- Probabilistic Space Carving
  (Broadhurst & Cipolla, ICCV 2001)
  (Bhotika, Kutulakos et. al, ECCV 2002)