Space carving
Shadow Carving
Voxel coloring

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A Tutorial in 3D photography
First International Symposium on
3D Data Processing
Visualization and Transmission
Padua, Italy - June 18 2002

Image object’s contours
(apparent contours)
(kiloholes)

Object
Image

Image object’s contour

Camera

Why contours are interesting visual cues?

🔹 We humans use this information a lot

🔹 Continuous contours yield dense information
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

Contours in the computer vision literature

**APPROACH 1:** analyze changes in contour for small object rotation/translation

- Giblin and Weiss (1987)
- Cipolla and Blake (1992)
- Vaillant and Faugeras (1992)
- Zheng('94), Ponce ('92), etc...

How contours have been used in the computer vision literature?

**APPROACH 2:** Space Carving
Space carving in 2D

The views are calibrated

View point 1

Object estimate according to 2 view points

View point 2

Space Carving:
how to perform the visual cones intersection?

- Discretize the volume in voxels
  (first: Martin and Aggarwal ’83)

- Using polygonal surfaces
  (among others: Reed and Allen ’99)
Discretizing the working volume in sub-volumes

Visual cones intersection
Space Carving has complexity $O(N^3)$

**Advantages of space carving**
- Robust and simple
- Cope with Occlusions
- Wide changes in view points

**Limitations of space carving**
- Need multiple views
- Not a good estimate

**Limitations of space carving**
- Some concavities are not modeled
- Laurentini (1995)
- Conservative

**Octrees (Szeliski '93)**
Space carving: Setup

Object
Camera
Turntable

Space carving: Experiments

The pot
The tape

Note: Hyperbolic region

Space carving: Experiments

Space carving: Conclusions

- Robust
- Produce conservative estimates
- Concavities can be masked
- Low-end commercial 3D scanners
Beyond space carving

- Shadow carving (2000)
- Voxel coloring (1997)
- and, of course, many others....

Self-shadows indicate concavities

The setup

Camera
Image
Epipolar plane
Light
The shadow carving procedure

- Camera known
- Light known
- Object unknown

Upper bound known:
- From space carving
- As a priori estimate

- Shadow cone
- Upper bound surface shadow
- Light cone
- Carvable area
The shadow carving procedure

- An amount of volume has been removed from the concavity.

- As the light source moves, new carvable areas are removed.

The shadow carving procedure

- Reconstruction after 2 iterations.

- As the light source moves, new carvable areas are removed.

The shadow carving: proof of correctness

- The carvable area is always outside the actual object.

- As the light source moves, new carvable areas are removed.
The shadow carving: proof of correctness

- The carvable area is always outside the actual object
- The carvable area well defined with:
  - Occlusions

The shadow carving: proof of correctness

- The carvable area is always outside the actual object
- The carvable well defined with:
  - Occlusions
  - Low albedo regions

Shadow Carving: how to perform the cones intersection?

**AGAIN:**

- Discretize the volume in voxels
- Using polygonal surfaces

Experimental results

The cube
Experimental results

The cube

Experimental results

The thing

Experimental results

The thing

Shadow carving: conclusions

Good things:

- Produce a conservative volume estimate
- Robust with respect to shadow estimates
- General: Voxels approach
- Polygonal surfaces
Shadow carving: conclusions

Good things:
- Still produce a conservative volume estimate
- Robust with respect shadow estimates
- General
- Voxels approach
- Polygonal surfaces

Bad things:
- Difficult to detect shadows
- Final reconstruction still coarse (noisy)

Voxel Coloring

Good things:
- Shape from photo-consistency
- Multi-view approach
- Model intrinsic scene colors and texture
- Voxel based
- No correspondences

SPECIAL CASE 1: space carving

Space carving is a binary voxel coloring
SPECIAL CASE 2: shadow carving

Camera

Light source

Voxel Coloring

- Scene definition
- Consistent scene
- Voxel coloring

NOTE: need a Lambertian model

Uniqueness

Multiple consistent scenes

A spatial ambiguity

A color ambiguity
Uniqueness

Possible solution: use invariants

- Hard points (Laurentini '95)
- A voxel is color invariant if:

  \[
  \forall \text{pair of scene } S', S'' \text{ consistent with the images, } V \in S' \cap S'' \Rightarrow \text{color}(V, S') = \text{color}(V, S'')
  \]

GOAL: build a color invariant scene

Tractability

- There are \( M^N \) possible assignments!
- An explicit search is not feasible
- Further constraint

Visibility Order Constraint

- Camera perspective projection model
- Visibility order constraint:

\[
\text{Layered scene decomposition}
\]

\[
\begin{align*}
V_1 & \in \text{Layer 2} \\
V_2 & \in \text{Layer 5}
\end{align*}
\]

- \( V_1 \) closer to \( C \) than \( V_2 \)

Compatible camera Configurations

- Allow voxels to be topologically sorted
Given a pixel $p$, find the voxel $V_p$ such that:
- $V_p$ is photo-consistent
- $V_p$ is the closest to $C$

$V_p$ is color invariant!

The scene $S_c = \{V_p, p=1, \ldots, l_n\}$ is:
- color invariant
- is the closest consistent scene to $C$

NOTE:
- not a minimal reconstruction
- aperture problem
Algorithm complexity

- voxel coloring visits each $N^3$ voxels once
- project each voxel into $L$ images

$\rightarrow O(LN^3)$

NOTE: not function of the number of colors

Experimental results

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

Experimental results

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

Experimental results

- Room + weird people
Voxel coloring: conclusions

**Good things:**
- model intrinsic scene colors and texture
- no correspondences
- no surface assumptions

**Limitations:**
- Lambertian assumption
- Constrained camera positions
- no surface assumptions