Quantification of gaseous structures with volumetric reconstruction from visual hulls

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2011-11-18
Introduction

- Methane gas (CH$_4$) one of the most harmful greenhouse gases
- Increasing emissions of CH$_4$ from landfills/municipal waste (3%-19% of amounts of anthropogenic sources world wide)
- Fixed point measurements
- Limited accuracy
Background

- Quantitative volumetric quantification is difficult with existing fixed point measuring techniques.
- Special-purpose IR imaging can make gas plums visible in 2D images (Åhlén et al., 2010).
- Goal: Estimation of 3D volumes from 2D camera images.
Related work

Multi-View Geometry (Hartley & Zisserman, 2003)
- Visible surface triangulation from point clouds
- Point correspondences are used to determine camera relations needed for 3D triangulation

Shape-from-Silhouette based 3D reconstruction (space carving)
- The Visual Hull concept (Laurentini, 1997)
- 2D silhouette and camera parameters define a general cone in 3D
- Intersection volume of several cones forms the visual hull
Visual Hulls - Properties

Quality of Visual Hull reconstructions

40 randomly chosen camera positions

16 binary silhouettes

3D reconstruction result using a 512^3 voxel grid
Quality of Visual Hull reconstructions (Fredriksson 2011)

Salient visual artifacts exist for 40 and more silhouettes
Volume converges rather quickly — but unknown ground truth

Reconstruction results for different number $N$ of silhouette images

Percentage of occupied voxels using a $512^3$
Visual Hulls for Volume Estimation

**Estimation Volume of Gaseous Structures**
- Visual quality is not important
- Visual details contribute little to volume

**Research objective:**
Identifying the sources of variation in measurement
Visual Hulls for Volume Estimation

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Identifying the sources of variation in measurement
a) Number of camera views (practically limited)
b) Variation of silhouette extraction (segmentation accuracy)
**Visual Hulls for Volume Estimation**

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**Research objective:**
Identifying the sources of variation in measurement
a) Number of camera views (practically limited)
b) Variation of silhouette extraction (segmentation accuracy)
c) Base-line bias/offset (depending on object structure)
Evaluation Method

General Approach

- Simulation (Gas/Smoke)
- Raw Volume
  - Volume Segmentation
  - Silhouette Ray-Casting
    - Reference Volume
    - Silhouette Images
      - Visual Hull
        - Reconstruction
        - Reconstructed Volume
- Comparison
**Evaluation Method**

**Ground Truth Data Generation:**

Wavelet Turbulence Simulation (Kim et al., 2008)
We used source-code at [http://www.cs.cornell.edu/~tedkim/wturb/source.html](http://www.cs.cornell.edu/~tedkim/wturb/source.html)

Naïve implementation and randomly sampling volumes from a time series

Volume size: $512^3$ size, scalar data

Segmentation using thresholds $t$ ranging between 1% - 40%

![Simulation](image1)

- Simulation (Gas/Smoke)
- Volume Segmentation
- Silhouette Ray-Casting
- Silhouette Images
- Visual Hull Reconstruction
- Comparison
- Reconstructed Volume

![Raw Volume](image2)

- Reference Volume
- Silhouette
- Comparison

![Silhouette](image3)
Evaluation Method

Controlled Silhouette Generation:

- Synthetic data + Synthetic camera → Control of image formation process
- GPU-Based Volume Ray-Caster
- Renders volume binary silhouettes based on same classification criteria
Evaluation Method

Visual Hull Reconstruction:

- GPU-based, multi-pass render algorithm
- Slice-by-slice reconstruction of volume
- Use 2D projective texture mapping to render silhouettes
- Stencil-buffer used to count region overlap
- Transfer render buffer to 3D volume data
  - Rendering passes for a volume of size $x \times y \times z$ voxels
  - $n$ screen filling polygons per pass for $n$ different silhouettes
1. Silhouette acquisition
(here 2 views only)
Implementation of VH algorithm

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2. The Visual Hull (Analytical Result)
3. Volumetric Reconstruction

- Render Screen Filling Quads
- Project silhouette 1 on quad
3. Volumetric Reconstruction

- Render Screen Filling Quad
- Project silhouette 1 on quad
- Project silhouette 2 on quad
3. Volumetric Reconstruction

- Render Screen Filling Quad
- Project silhouette 1 on quad
- Project silhouette 2 on quad
- Keep only pixels, where all silhouettes have been drawn

Identify Overlapping Regions using Stencil Buffer

Silhouette 1
Silhouette 2
3. Volumetric Reconstruction

- Render Screen Filling Quad
- Project silhouette 1 on quad
- Project silhouette 2 on quad
- Keep only pixels, where all silhouettes have been drawn
- Save render buffer
3. Volumetric Reconstruction

...render next slice/polygon...

Start over with next slice

Silhouette 1

Silhouette 2
3. Volumetric Reconstruction

identify overlap...

Identify Overlapping Regions using Stencil Buffer

Silhouette 1

Silhouette 2
3. Volumetric Reconstruction

read/copy render buffer
and render next slice
Implementation of VH algorithm

3. Volumetric Reconstruction

...repeat for remaining slices...
Results of the Reconstruction

- Reconstruction results for varying numbers of silhouette images
- Segmentation threshold $t = 1\%$
Evaluation

Volumetric comparison:

Same threshold for ground truth data and silhouette generation

Compare original volume with reconstructed volume

Volumetric enumeration of original $O$ and reconstruction $R$

Ratio $R/O$ for varying $n$ and $t$
Results & conclusions

- Rapidly converging volume size
- Systematic overestimation (~150%)
- Segmentation accuracy as important
- 8 camera views seem sufficient for volumetric estimation
Acknowledgements

Peter Jenke, lecturer of computer graphics, for implementation of volumetric smoke simulation and volumetric reconstruction

Julia Åhlén, associate professor, for images and fruitful discussions of the real case

Linus Fredriksson, student of the International Bachelor Program in Computer Science at HiG, for conducting pre-studies and provision of images
Thank you for your attention!