Line Drawings of 3D Shapes

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COS 426
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April 24, 2014
Line drawings

Convey most important features of a shape

Flaxman (1805)
Lines in 3D Scenes

- Aid comprehension
- Evoke hand-drawn style
- Allow abstraction
Range of Line Drawings

• “Line drawing” is not a single style
• Immense range of approaches
  – Loose to controlled
  – Sparse to developed
  – Abstract to veridical
  – Emotional to explanatory
Loose vs. Controlled
Abstract vs. Veridical

Picasso

Gustave Moreau
Emotional

Michelangelo
Explanatory
CG Line drawings

What styles can we understand & reproduce?
Pretty Easy

1922 Locomotive Cyclopedia
Hard

Tadao Ando
Harder

Flaxman
Really Hard

Picasso
Just right?
Research Challenges

• Technical / Algorithmic:
  – Efficient shading, temporal coherence, extraction
  – Level of detail, stroke visibility, texturing
  – etc.
Real-Time Hatching
Emil Praun, Hugues Hoppe, Matthew Webb, and Adam Finkelstein
*Proceedings of ACM SIGGRAPH 2001*

Coherent Stylized Silhouettes
Robert Kalnins, Philip L. Davidson, Lee Markosian, and Adam Finkelstein
*ACM Transactions on Graphics 22(3) (SIGGRAPH 2003)*

Line Drawings from Volume Data
Michael Burns, Janek Klawe, Szymon Rusinkiewicz, Adam Finkelstein, and Doug DeCarlo
*ACM Transactions on Graphics 24(3) (SIGGRAPH 2005)*
Fast High-Quality Line Visibility
Forrester Cole and Adam Finkelstein
*Proceedings of i3D 2009*

Directing Gaze in 3D Models with Stylized Focus
Forrester Cole, Doug DeCarlo, Adam Finkelstein, Kenrick Kin, Keith Morley, and Anthony Santella,
*Eurographics Symposium on Rendering 2006*

Self-Similar Texture for Coherent Line Stylization
Pierre Bénard, Forrester Cole, Aleksey Golovinskiy, and Adam Finkelstein
*Proceedings of NPAR 2010*
Research Challenges

• Technical / Algorithmic:
  – Efficient shading, temporal coherence, extraction
  – Level of detail, stroke visibility, texturing
  – etc.

• Theoretical:
  – What lines to draw?
  – How do artists make drawings?
  – How do people perceive drawings?
Overview

1. What lines to draw?
2. How do artists make drawings?
3. How do people perceive drawings?
Many collaborators, including...

Doug DeCarlo
Rutgers

Szymon Rusinkiewicz
Princeton

Tom Funkhouser
Princeton

Forrester Cole
Princeton
Part 1:
What lines to draw?

“Suggestive Contours for Conveying Shape”
Doug DeCarlo, Adam Finkelstein, Szymon Rusinkiewicz, Anthony Santella
What lines to draw

Silhouettes:
– boundary between object and background
What lines to draw

Contours:

– occlusion boundaries

– surface normal perpendicular to view direction

[Saito & Takahashi 90, Winkenbach & Salesin 94, Markosian et al 97, ...]
What lines to draw

Ridges and valleys (crest lines)
– local maxima of curvature
– creases: infinitely sharp folds

[Thirion & Gourdon 92, Interrante et al 95, Stylianou & Farin 00, Pauly et al 03, ...]
What lines to draw

There are other lines...

Hypothesis: some are “almost contours”
Suggestive contours

What does “almost contours” mean?
• points that become contours in nearby views
Contours

Points where \( n \cdot v = 0 \)
Suggestive contours: *definition 1*

Contours in nearby viewpoints

(not corresponding to contours in closer views)
Suggestive contours: definition 2

\[ n \cdot v \] not quite zero, but a local minimum
(in the direction of \( w \))
Minima vs. zero crossings

Definition 2: Minima of $n \cdot v$

Finding minima is equivalent to:
• finding zeros of the derivative
• checking that $2^{nd}$ derivative is positive

This leads to definition 3.

Derivative of $n \cdot v$ is a form of curvature...
Radial curvature: $K_r$

Curvature in projected view direction, $w$:

– Extension of [Koenderink 84]
Suggestive contours: definition 3

Points where $\kappa_r = 0$ and $D_w \kappa_r > 0$

$\kappa_r = 0$ (inflection points)

$\kappa_r > 0$

$\kappa_r < 0$

$\kappa_r$ increasing

$\kappa_r$ increasing
Qualitative structure

Suggestive contours fall into two categories

anticipation

contours only

contours + suggestive contours

extension
Continuity of extensions

The suggestive contour lines up with the contour in the image
Results...

contours

contours + suggestive contours
Results...

contours

contours + suggestive contours
Results...
Summary

Suggestive contours:

- new family of lines for NPR
- improve perception of geometry
- naturally complement contours
Algorithmic Line Drawing

• Occluding contours
• Ridges and valleys
• Suggestive contours
• Apparent ridges
• Abstracted shading
• Suggestive highlights
• Principal highlights
• Demarcating curves
• Laplacian lines
Part 2:
Where Do People Draw Lines?

“Where Do People Draw Lines?”
Forrester Cole, Aleksey Golovinsky, Alex Limpaecher, Heather Stoddart Barros, Adam Finkelstein, Thomas Funkhouser, and Szymon Rusinkiewicz
ACM Transactions on Graphics 27(3), (Proc. SIGGRAPH 2008)
Prompt

Drawings

Average Drawing

Shape Features

Mathematical Descriptions
Algorithmic Line Drawing

• We investigate four definitions:
  – Occluding Contours [Hertzmann 2000]
  – Geometric Ridges and Valleys [Ohtake 2004]
  – Suggestive Contours [DeCarlo 2003]
  – Apparent Ridges [Judd 2007]
Style: Pure Line Drawing

Prompt Image

Solid, Smooth Feature Lines

Disallow:

Hatching and Shading

Sketchy Lines
Study Protocol

Steps:
1. Fold
2. Draw
3. Unfold
4. Trace
5. Scan

Prompt Page

Drawing Page
Collection Results

- 29 artists, art students and some professionals
- 208 drawings collected
- 170 “precise” drawings
  – Traced 90% of exterior silhouette within 1mm
Averaged Drawings
Matching CG Lines

- Occluding Contours
- Apparent Ridges
Categorization of Lines

- Contours explain 50-65% of all lines
- Other object-space lines explain 15-30%
- Image features alone explain approx. 5%
Result:

Known definitions explain 80-90% of lines
Other Definitions

- All CG line def. based on 1-2 local features
- Could we combine more?

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<th>Image-Space</th>
<th>Object-Space</th>
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<td>SurfMeanCurv</td>
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<td>SurfGaussianCurv</td>
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Features in Combination

Regression Tree Model:

```
ImgGradMag > 2433.08
  | ImgGradMag > 4706.19
  |   | 0.181
  |   | 0.0341
  | RadialCurvDeriv > 0.02
  |   | ViewDepCurvDeriv > 0.044
  |   |   | 0.0455
  |   |   | 0.0175
  |   | SurfGaussianCurv > -0.004
  |   |   | ViewDepCurv > 0.076
  |   |   |   | N dot V > 0.782
  |   |   |   |   | 0.0113
  |   |   |   |   | 0.0252
  |   |   | SurfMaxCurvDeriv > 0.014
  |   |   | SurfMinCurv > 0.022
  |   |   |   | 0.0044
  |   |   |   | 0.0125
  |   |   |   | 0.0023
...```

Predicted Probability

Artists’ Average
Synthesis Algorithm?

Find ridges in probability image

Probability Image  Synthesized Drawing  Artist’s Drawing
Unexplained Lines

10-20% unexplained for reasonable thresholds
Does it matter?

Ridges and Valleys

Artist’s Drawing
“How Well Do Line Drawings Depict Shape?”
Forrester Cole, Kevin Sanik, Doug DeCarlo, Adam Finkelstein, Thomas Funkhouser, Szymon Rusinkiewicz, Manish Singh
*ACM Transactions on Graphics 28(3) (Proc. SIGGRAPH 2009)*
Previous Work

• Koenderink [1996] studied single drawing
• Conclusion: perception from drawing almost as good as from photograph

[Koenderink 1996]
Study Goals

• Measure percepts for unfamiliar shapes
• Compare human and CG drawings
• Compare accuracy/precision with ground truth
Measuring Shape Perception

- *Gauge figure* due to Koenderink [1992]
- Commonly used to analyze shaded imagery

[O’Shea 2008]
Orienting a Gauge
Study Setup

All 12 models from previous study
### Study Setup

6 styles x 12 models - 2 duplicates = 70 prompts

<table>
<thead>
<tr>
<th>Artist’s</th>
<th>Contours</th>
<th>R. and V.</th>
<th>Sug. C.</th>
<th>App. R.</th>
<th>Shaded</th>
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</table>
Study Setup

70 prompts
x 90 gauges / prompt
x 8 opinions / gauge
x 2 settings / opinion

≈ 100,000 settings
Example Session
Study Setup

- 70 prompts
- x 90 gauges / prompt
- x 8 opinions / gauge
- x 2 settings / opinion

≈ 100,000 settings

x 4 seconds / setting

111 hours
So Much Data...

• Mechanical Turk to the rescue!
• Turker sets 60 gauges, gets paid $0.20
• Efficient even after throwing away garbage
  – “Garbage” is inconsistent data
  – About 80% of data is consistent
Data Collection

- 275,000 gauge settings
- 8 models x 90 gauges + 4 models x 180 gauges
- Each gauge 9 to 29 opinions, average 15
- 560 different people
- Most active 20% accounted for 75% of data
We made it this far.
Conclusions

• Most artists’ lines explained by CG definitions
• Lines can depict shape as well as shading
• People have similar interpretations of drawings
Thanks

Princeton University

– Forrester Cole
– Thomas Funkhouser
– Aleksey Golovinsky
– Kenrick Kin
– Alex Limpaecher
– Keith Morley
– Szymon Rusinkiewicz

Rutgers University

– Doug DeCarlo
– Kevin Sanik
– Anthony Santella
– Manish Singh

Independent Artist

– Heather Barros