NPR Techniques for Scientific Visualization

Victoria Interrante
University of Minnesota

1 Introduction

Visualization research is concerned with the design, implementation and evaluation of novel methods for effectively communicating information through images. For example: How do we determine how to portray a complicated set of data so that its essential information can be easily and accurately perceived and understood? How can we measure the success of our efforts? Where should we look for insight into the science behind the art of effective visual representation?

For many years, photorealism was the gold standard, and the goal in visualization was to achieve renderings of scientific data that were as nearly indistinguishable as possible from a photograph. However in recent years, there has been an upsurge of interest in using non-photorealistic rendering (NPR) techniques in scientific visualization. What does NPR offer to visualization applications? What are some of the important research issues in developing NPR techniques for data visualization? What are the recent advances in this area? My presentation in this half-day course will attempt to survey these topics, beginning with a discussion of the motivation for using NPR in scientific visualization and continuing through an overview of recent research in the development and assessment of NPR techniques for visualization applications.

2 Motivation and Background

Historical examples of the use of 'non-photorealistic rendering' techniques in scientific visualization can be found in the hand-drawn illustrations from scores of textbooks across multiple fields in the sciences [Loe64][Law71][Zwe61][Rid38]. The universal goal in such illustrations was to clarify the subject by emphasizing its most important or significant features, while de-emphasizing extraneous details [Hod89]. Although a photographic depiction has the potential to capture the exact appearance of an object as we actually see it, with subtle and complex details of coloration and texture fully represented with perfect accuracy (at least for one exemplar), a drawing offers the possibility to clarify structural or conceptual information that may be difficult to perceive even in a very good photograph [Add86][RS56][HM86][FH78][Por81]. Drawings are also useful for portraying information that does not have a physical correlate, or which cannot be captured or represented photographically [Con83]. Finally, by virtue of their inexact and suggestive (as opposed to explicit) character, some kinds of drawings have the potential to embody a certain amount of ambiguity, allowing flexibility in the interpretation of the object or information portrayed [SPRSF94][SSRL96][Las00]. Recently developed computational methods for applying non-photorealistic rendering techniques to the visualization of scientific data [ER00][GGSC98][GSGSR99][Hea01][IFP95][IG98][KML99][TC00] seek to satisfy similar objectives.

3 Case Studies from my Research

In the attached papers (see appendix) I describe recent results from my own research in the design, implementation and evaluation of non photorealistic rendering techniques for the visualization of 3D surface shape and multivariate data.

4 References

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[16] George R. P. Lawrence. Cartographic Methods, Methuen, 1971.

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Non-Photorealistic Rendering in Scientific Visualization

Victoria Interrante
University of Minnesota

Outline

- Motivation and Objectives
  - What does non-photorealistic representation offer?
- Overview of Recent Work in the Field
- Examples/Applications from My Own Work
  - Artistic enhancements for conveying 3D shape
  - Texture synthesis for multivariate visualization

Why Non-Photorealistic Rendering?

- Let's look at some applications …
- Drawing vs. photo

Visualizing Anatomy

- A photographic depiction captures the exact appearance of the object as we actually see it
- Subtle, complex details of coloration and texture are fully represented, with great accuracy
- A drawing offers the possibility to clarify structural or conceptual information that may be difficult to perceive in even a very good photo.

Photo vs. Drawing

- Hand-drawn illustrations are routinely used to emphasize important features that are difficult to capture in a photograph, while minimizing secondary detail
- Drawings are also useful to portray information that cannot be captured or represented photographically, such as hidden surfaces
- But are drawings always preferable to photos?

Controlled Experiments in Picture Perception

- Are drawings better than photographs for communicating information effectively?

Speed of imitation of finger position, in seconds (mean):
- 0.039 photo
- 0.044 shaded drawing
- 0.070 line drawing
- 0.046 cartoon

Speed of naming open switch, in seconds (mean)
- 0.690 photo
- 0.719 shaded drawing
- 1.169 line drawing
- 0.288 cartoon

T. A. Ryan and Carol B. Schwartz, "Speed of Perception as a Function of Mode of Representation", American Journal of Psychology, 69, pp. 60-69, 1956.

Their Conclusion:

- Superiority of performance (photograph vs. drawing) varies with the application
- Response times were consistently longest for the basic line drawing images

Pictorial Communication

Results of a study with 400+ adult subjects testing identification rate under different display conditions:

- 59% - black+white photo
- 67% - photo with background removed
- 72% - line drawing w/ detail + shading
- 62% - line drawing wo/ shading, little detail
- 61% - silhouette
- 49% - stylized depiction

”The so-called 'simple' stylized drawings are evidently not simple in anything but appearance, making greater demands on the person trying to interpret them".

D. Fussel and A. Haaland. "Communicating with Pictures in Nepal: results of practical study used in visual education", Educational Broadcasting International, 11(1): 25-31, 1978.

Study of Picture Preferences

- Surgeons rated the ‘schematic’ representation *least* preferable; the ‘semi-schematic’ and ‘realistic’ representations were preferred in equivalent numbers.

K. Hirsch and D. A. McConathy, "Picture Preferences of Thoracic Surgeons", Journal of BioCommunications, Winter 1986, pp. 26-30.

Why use Artistic Enhancement?

- To clarify the pictorial representation:
  - Emphasize important information
  - Minimize visual salience of secondary detail
  - Hierarchically guide the attentional focus
  - Convey the ambiguity of uncertain information

From Photograph to Drawing

- There are some easily definable rules
- There is a lot of room for artistic license
- Obtaining an ideal translation is exceptionally more complicated than would appear at first glance

Why use Non-Photorealistic Representation?

- To allow greater differentiation in the salience of the visual representation
  - Emphasize critical features
  - Minimize the visual salience of secondary details
  - Hierarchically guide the attentional focus

Other Advantages in Non-Photorealistic Representation

- Allows greater differentiation in the specificity of the visual representation
  - To convey information at an early stage of definition
    - to facilitate designer's working with ideas
    - to allow clients to envision multiple possibilities in a design
  - To convey uncertain information
    - to explicitly represent the level of confidence in the data

Other Advantages in Non-Photorealistic Representation

- Allows the expression of multiple styles
  - potentially increasing the 'dynamic range' of information that can be communicated
  - establishing a 'mood' that can influence the subjective context within which the information is perceived and interpreted

Introducing Ambiguity

- specific → universal (one person .. everyone)
- complex -> simple (progressive reduction of detail)
- realistic -> iconic (requiring more translation)

Scott McCloud. Understanding Comics: the invisible art. Harper Perennial, 1994.

Visual Representation in Architectural Design

- Different requirements for different phases of the process, from abstract to concrete
  - Schematic Design
  - Preliminary design
  - Design development
  - Contract documents
  - Shop drawings

Paul Laseau, Architectural Representation Handbook, McGraw-Hill, 2000.

From Art to Scientific Visualization

- Illustrations interpret physical reality; distill the essential components of the scene
- We seek algorithms that can make explicit some of the intuition that artists rely upon to create an effective visual representation

My Fundamental Philosophy

There is a science behind the art of effective data representation

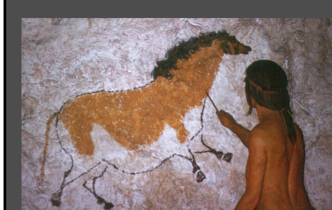
Creating images that facilitate the understanding of a set of data

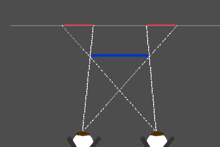
- Design/Conceptualization
  - Defining an appropriate representational approach
- Implementation
  - Developing new algorithms for image generation
- Evaluation
  - Objectively determining which techniques are more effective when and why

Creating images that facilitate the understanding of a set of data

- Design
  - inspiration from practices in art, illustration
  - insight from research in visual perception
- Implementation
  - computer graphics, computer vision, mathematics
- Evaluation
  - quantitative assessment of impact on task performance

Clarifying Depth Discontinuities: insights from psychology and art

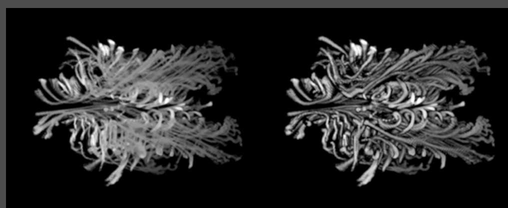




Ken Nakayama and Shinsuke Shimojo (1990) "Da Vinci Stereopsis: Depth and Subjective Contours from Unpaired Image Points", *Vision Research*.

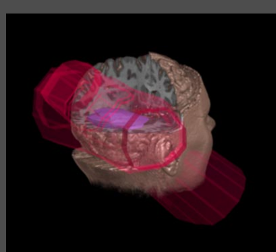
Gaps evoke the impression given by inter-ocularly unpaired regions

Clarifying Depth Discontinuities with Visibility-Impeding Halos



Victoria Interrante and Chester Grosch (1998). "Visualizing 3D Flow", *IEEE Computer Graphics and Applications*, **18**(4): 49-53.

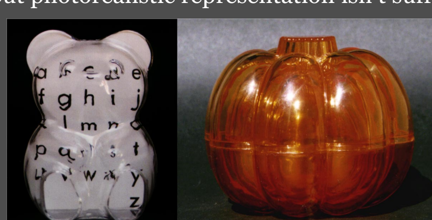
Conveying the 3D Shape and Depth of Transparent Surfaces



Radiation Therapy Treatment Planning

Portraying Overlapping Surfaces

- Transparency offers the best potential solution
- But photorealistic representation isn't sufficient

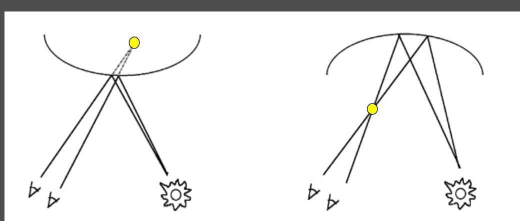


Why are transparent surfaces difficult to adequately perceive?

- Weak occlusion cues
- Minimal shape-from-diffuse shading
- Unreliable depth information from specular highlights
- Refraction emphasizes silhouettes, but distorts underlying objects

Highlights: Shape but not Depth

In a stereo view, specular highlights will not lie on a curved surface but will appear to float either above or below it

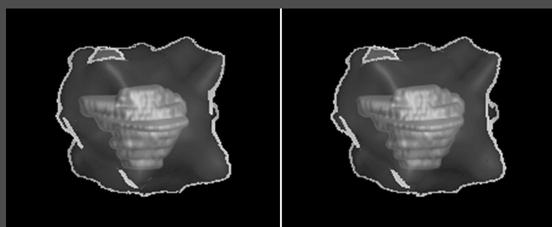


A. Blake and H. Bülthoff (1991) "Shape from Specularities", *Phil. Trans. Royal Soc. of London, B*, 331: 237-252.

Creating a Feature Line Drawing

- Silhouettes
  - separate figure from ground
- Contour lines
  - emphasize discontinuities
    - in depth (*viewpoint dependent*)
    - in curvature (*viewpoint independent*)
- Other Essential Lines
  - Express the underlying form
  - Delineate meaningful features
  - Can be difficult to capture algorithmically

Highlighting Silhouette Edges in Stereo is Problematic



Viewpoint- Independent Feature Lines: ridges and valleys

- Specular highlights tend to cling to ridges
- Valleys tend to remain in shadow
- We perceive objects as subdividing into parts along their valley lines

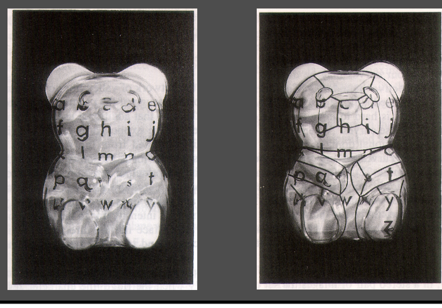
Donald D. Hoffman and Whitman A. Richards. "Parts of Recognition", *Cognition*, vol. 18, pp. 65-96, 1984.

Salient Features of the Contour

- Our eye fills in missing segments along curves of minimum energy
- This process is more robust for contour deletions *between* vertices than for deletions across them

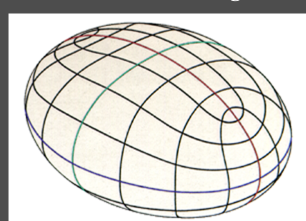
Irving Biederman (1985) "Human Image Understanding: Recent Research and a Theory", Human and Machine Vision, Azriel Rosenfeld, ed., Academic Press, pp. 13-57.

Can Marking the Ridges and Valleys Help?: a "kitchen experiment"



Ridge and Valley Lines: definition

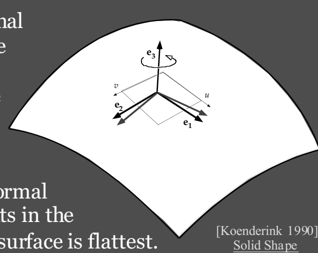
- The locus of points where the principal curvature assumes an extreme value along a line of curvature



Hilbert and Cohn-Vossen (1952) Geometry and the Imagination

Computing the Principal Directions

- Begin with an orthogonal frame $(\vec{e}_1, \vec{e}_2, \vec{e}_3)$, where $\vec{e}_3 = \vec{n}$, and $\vec{e}_1$ and $\vec{e}_2$ span the tangent plane
- Rotate the frame so that $\vec{e}_1'$ points in the direction of greatest normal curvature, and $\vec{e}_2'$ points in the direction in which the surface is flattest.



[Koenderink 1990] Solid Shape

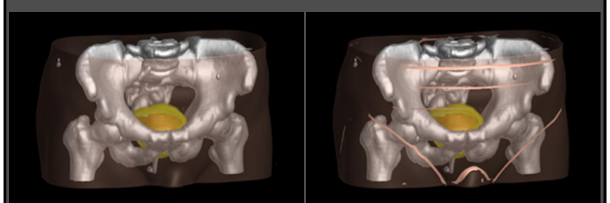
Computing the Principal Directions

- The frame rotation can be obtained by diagonalizing the second fundamental form matrix: $A = \begin{bmatrix} \tilde{\omega}_1^{13} & \tilde{\omega}_1^{23} \\ \tilde{\omega}_2^{13} & \tilde{\omega}_2^{23} \end{bmatrix}$

  which describes how the surface normal changes as you move very slightly away from the origin of the frame across the surface in the $\vec{e}_1$ and $\vec{e}_2$ directions;
- When $\vec{e}_1$ and $\vec{e}_2$ coincide with the principal directions, there is no sideways "twist" in the surface normal direction as you move in these directions; terms $\tilde{\omega}_2^{13}$ and $\tilde{\omega}_1^{23}$ are zero.

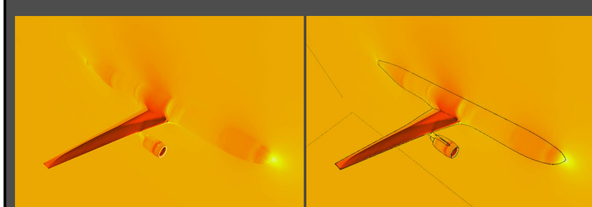
[Koenderink 1990]

Using Ridge and Valley Lines to Emphasize Intrinsic Shape Features



Victoria Interrante, Henry Fuchs and Stephen Pizer (1995)
"Enhancing Transparent Skin Surfaces with Ridge and Valley Lines", *IEEE Visualization '95.*

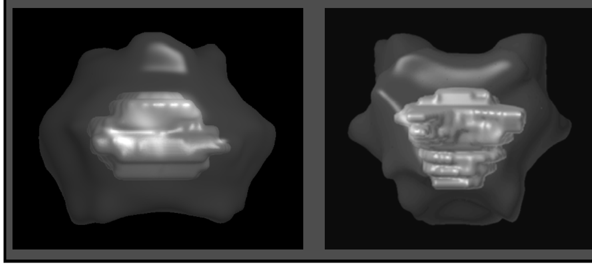
Using Locally Important Edges to Capture the Structure of Faceted Objects



Kwan-Liu Ma and Victoria Interrante (1997)
"Extracting Feature Lines from 3D Unstructured Grids", *IEEE Visualization '97.*

Conveying the 3D Shape of Arbitrary Smoothly Curving Surfaces

Adding texture could help, but what texture will show shape best?



Transparency Representation in an Opaque Medium

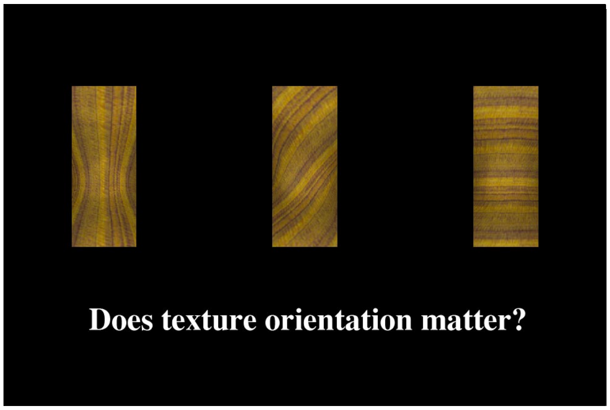
Giuseppe Croff, *Veiled Nun*, 1869.

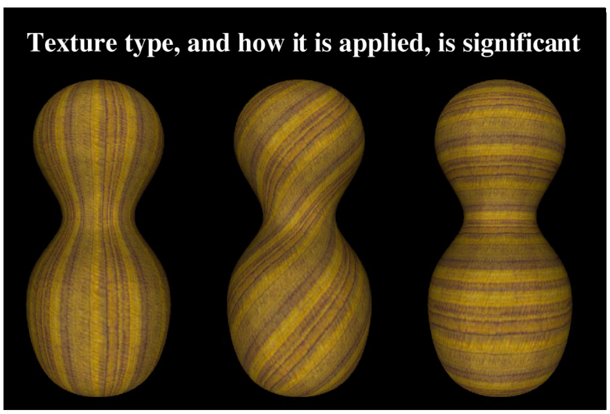
Artistic Inspiration

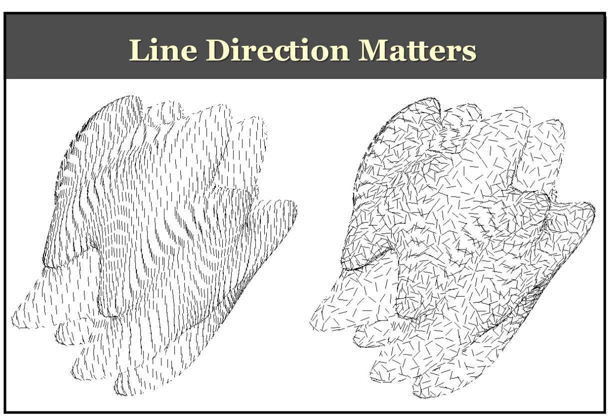
- Russell Drake's "single line system of shading"
  - the flow of the shape is conveyed through the directions of the carefully drawn strokes
  - multiple overlapping surfaces are displayed with clarity
- But not all artists use line in this way.

Lumbosacral and Sacro-iliac fusion . Russell Drake, medical illustrator, Mayo Foundation, 1932.

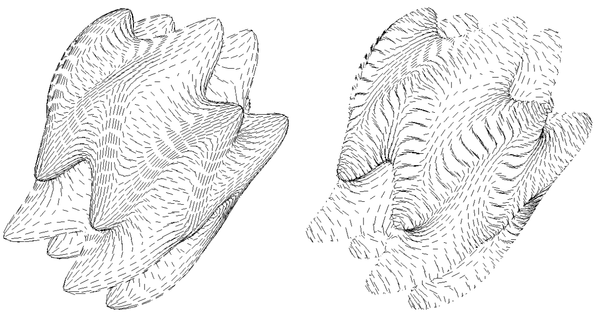
Paul Richer, Artistic Anatomy. Translated and edited by Robert Beverly Hale, Watson-Guptill Publications, 1971.

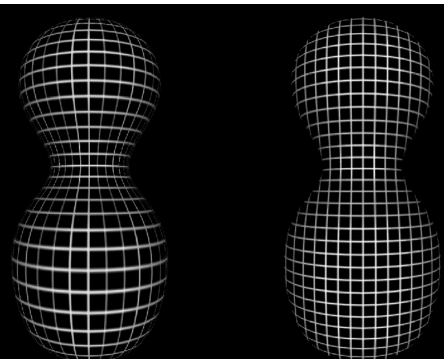

Does texture orientation matter?


Texture type, and how it is applied, is significant


Line Direction Matters

Line Direction Matters





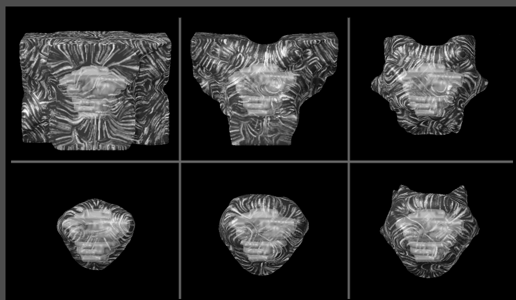
Surface grid texture
(aligned with the principal directions)

Solid grid texture
(aligned with the coordinate axes)

A Principal Direction Texture

- Long, curved strokes following the *flow* of the principal directions over a surface

- A single, solid texture, defined once for all isosurfaces in a smooth 3D distribution



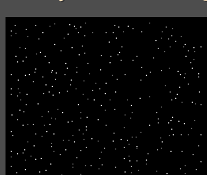
A series of transparent level surfaces in a 3D dose distribution from a 5-beam treatment plan for prostate cancer, each shown in relation to the physician-defined target region.

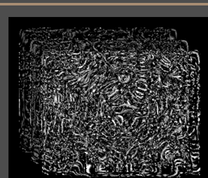
Line Integral Convolution (a review)

- Introduced by Cabral and Leedom [93]
  - A new method for conveying directional information through patterns of correlation in a texture
- Extended by Stalling and Hege [95]
  - define long, accurate streamlines using an adaptive 4^{th} order Runge-Kutta integration method
  - resample the streamlines via a C^1 continuous cubic spline interpolation, to obtain equally spaced points
  - compute weighted sums of the input texture values over a fixed number of points along the streamlines

Defining the LIC Stroke Texture

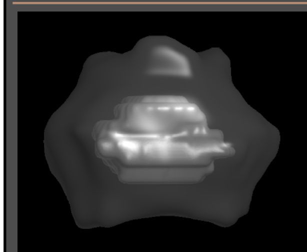
Begin with a sparse set of evenly-distributed points





Advect the empty space along with the full to help finesse the problem of aesthetic streamline placement

Conveying the 3D Shape of Arbitrary Smoothly Curving Iso-Surfaces



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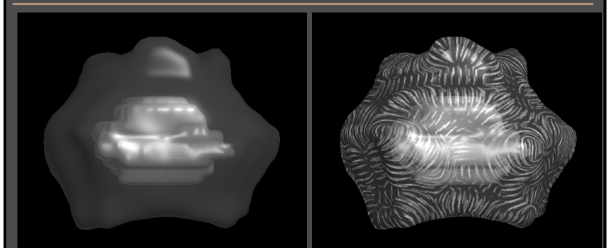


Victoria Interrante (1997) "Illustrating Surface Shape in Volume Data via Principal Direction-Driven 3D Line Integral Convolution", *SIGGRAPH 97*.

Shape from Texture

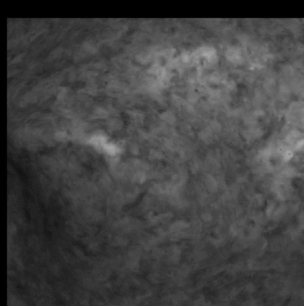
- Showing shape with a line-like texture seems to contradict the shape-from-texture research which asserts that shape perception is impeded by texture pattern anisotropy

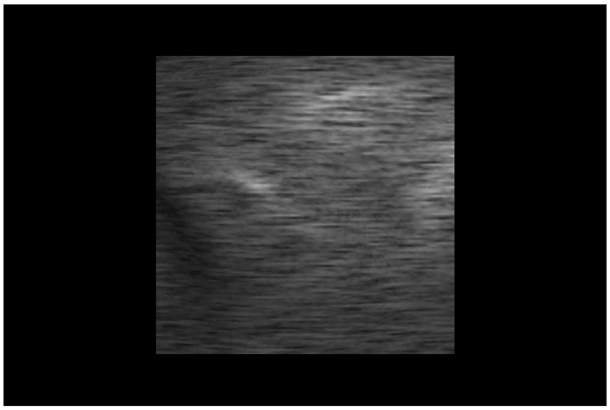
How Does Texture Orientation Affect Surface Shape Perception?

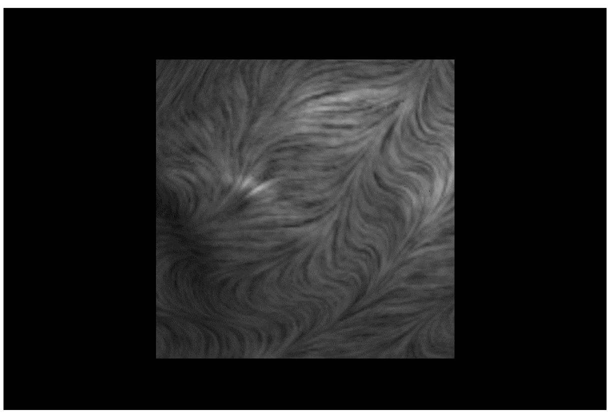
- Can anisotropy in the principal directions help?
- Does anisotropy in non-principal directions hurt?
- Do these effects hold for shaded displacement texture?
- To what extent are these effects mitigated by stereo viewing?

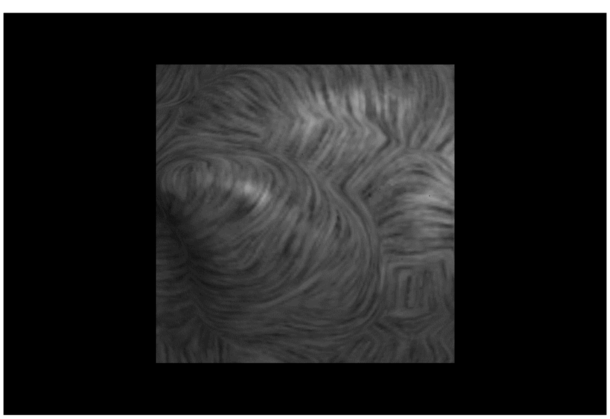
Compared Four Direction Types

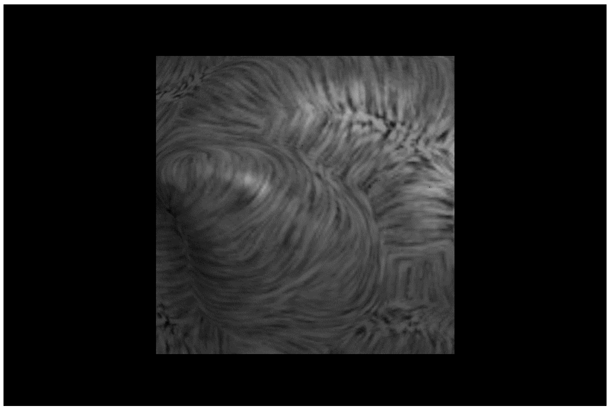
- Principal direction (pdir)
- Uniform direction (udir) = (-ny, nx, 0)
  - zero geodesic curvature
- Random direction (rdir) : rotate udir about $\vec{n}$ by a random angle $\theta \in [-\pi/2 .. \pi/2]$
  - effectively isotropic
- Sinusoidally varying direction (sdir): rotate udir in the tangent plane by a coherently varying angle $\theta = 10\pi(x+y+z/n)$

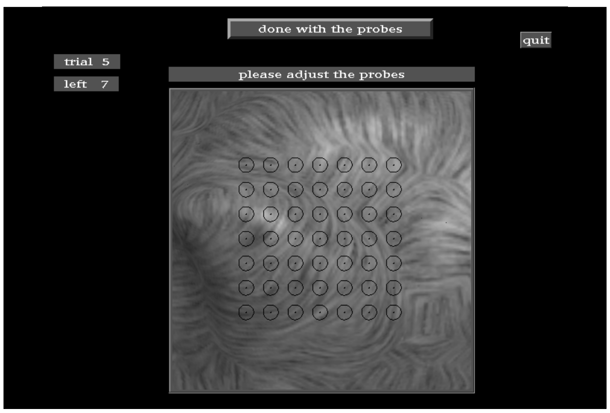






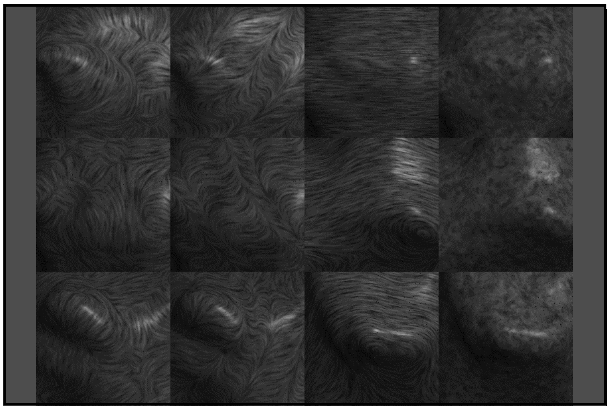


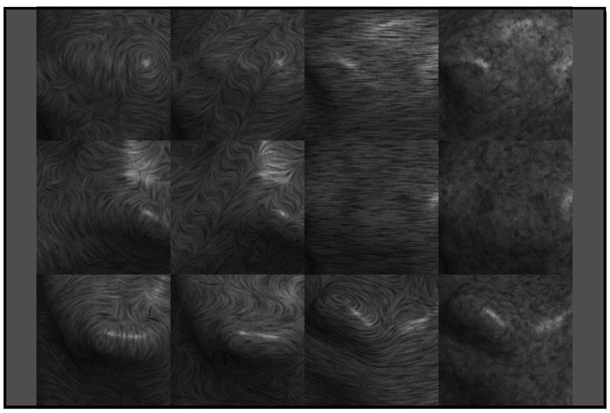




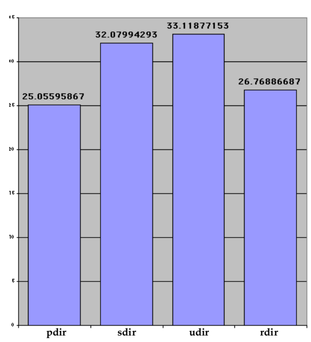
Experiment Details

- 4 different texture patterns: pdir, sdir, udir, rdir
- 6 different surface stimuli
- 49 probes per image, same points for each texture
  - users were asked to reconstruct the surface
- 2 different viewing conditions: flat, stereo
- 5 subjects (naïve to purpose of experiment)
  - Split into two groups; each saw half of the data
  - Four sessions, 6 surfaces each, randomized presentation order, 2 sessions of flat images followed by 2 sessions with stereo images

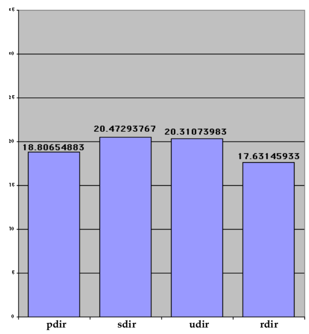




Mean alignment error (3D angle), flat viewing condition



Mean alignment error (3D angle), stereo viewing condition



Experiment's Conclusions

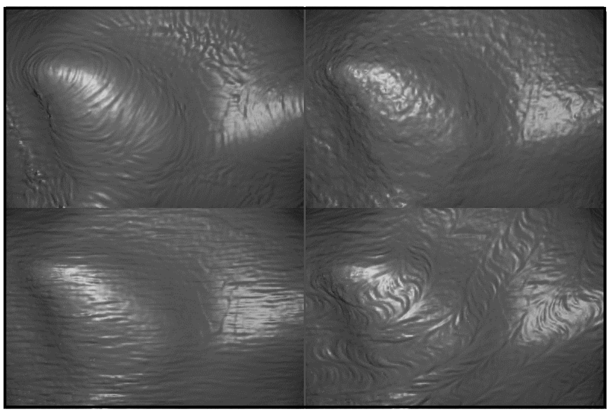
- Texture pattern orientation has a statistically significant effect on surface shape perception
- Shape perception is poorer in the presence of anisotropic textures that have nonzero geodesic curvature
- Shape perception seems equivalently good from the anisotropic texture that is aligned with the first principal direction as it is from the isotropic texture

Displacement Texture

- What is the impact of texture orientation if the texture is defined as a pattern of relief rather than as a pattern of intensity variations?
- Shape-from-texture perception could work differently with relief patterns than with patterns of coloration

Displacement Texture

- What is the impact of texture orientation if the texture is defined as a pattern of relief rather than as a pattern of intensity variations?
- Does shape-from-texture work differently with relief patterns than for patterns of coloration?
- Preliminary results suggest that performance follows a similar pattern



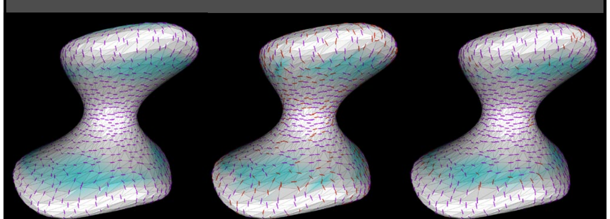
Conclusions

- Texture pattern orientation affects surface shape perception
- Shape perception is poorer in the presence of anisotropic textures that are unaligned with the principal directions
- Shape perception is as good with an anisotropic texture that is aligned with the first principal direction as it is with an isotropic texture

More Challenges

- How to compute accurate estimates of principal directions at the vertices in a polygonally-defined model?
- How to obtain a smooth vector field of principal directions that permits tracing long, smooth strokes that flow gracefully across umbilics and between regions of opposing directional dominance?
- How to apply oriented, image-based textures so that they follow the principal directions?

Estimating Principal Directions on Arbitrary Meshes



Exact Solution | Normal Curvature Method | Adjacent-Normal Cubic Method

J. Goldfeather, V. Interrante (2001) "Understanding Errors in Approximating Principal Direction Vectors".

Error Analysis

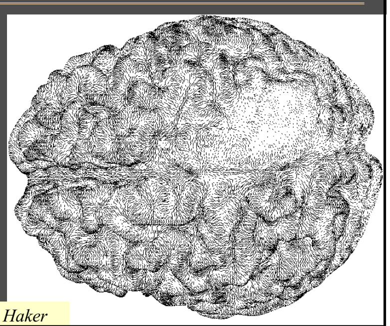
- All solutions follow these steps:
  - Find a least squares fit to $Ux = b'$ at p
    - For example: $\kappa'_{yi} = 2[(p-q_i)\bullet N'_p]/[(p-q_i)\bullet(p-q_i)]$ produces a system of equations $y_i^T W y_i = \kappa'_{yi}$ where y_i is the unit projection of pq_i on the tangent plane
  - Use the least squares solution x' to define the 2x2 Weingarten matrix W' at p
  - The eigenvectors of W' indicate the principal directions

Sources of Error

- Small errors in estimates of normal curvatures can produce huge errors in the estimates of the principal directions
- The problem is a combination of both the magnitude of the errors in *b*' and the direction in which they are made, which is influenced by the local geometry of the mesh
- The adjacent-normal cubic method does a better job of controlling the magnitude of the errors because it uses third-order approximations rather than second-order

Possible NPR Applications

- Use principal direction strokes to create interactively manipulable computer generated pen-and-ink style representations of arbitrary, polygonally-defined objects



Brain image by Steve Haker

Principal Direction Texture Mapping

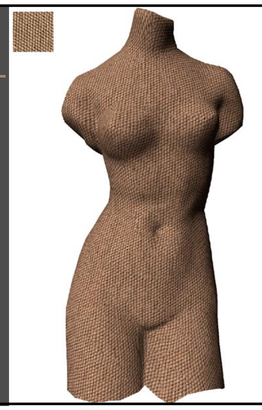
- Synthesize an arbitrary, image-based texture pattern over an arbitrary polygonal surface so that the dominant orientation of the texture follows the first or second principal direction over the surface

Fitted Textures

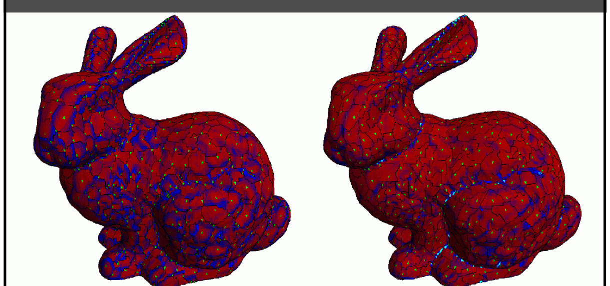
- Define a mapping
  - Partition the surface into nearly equally-sized, nearly planar patches
- Synthesize the texture
  - Generate the required texture from a given sample, maintaining continuity across boundaries

  [Efros and Leung 99]

Gabriele Gorla, Victoria Interrante and Guillermo Sapiro (2001), "Growing Fitted Textures over Surfaces".



Surface Partitioning



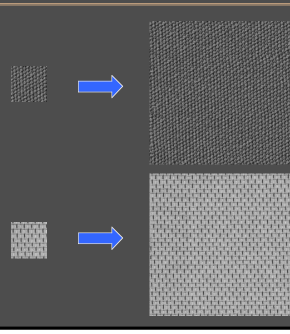
Before and after optimization; blue indicates amount of nonplanarity

Surface Partitioning

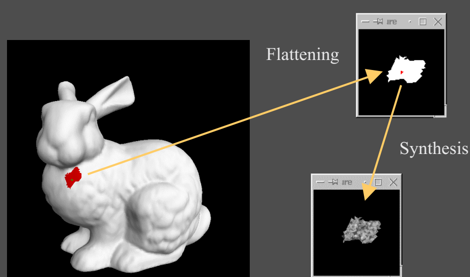
- Pick a random triangle T and assign it to a new patch P
- Add all triangles C connected to T that satisfy:
  - normal(C)•normal(T) > N_threshold
  - distance(C,T) < D_threshold
- Repeat until surface is completely covered
- Optimize with "triangle stealing"

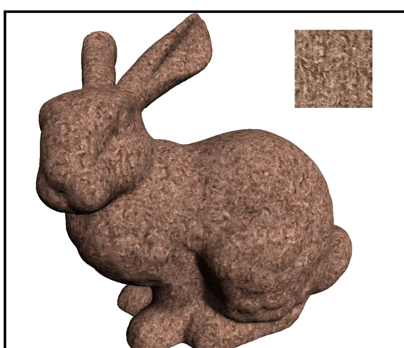
Texture Synthesis

- Two-pass version of Efros and Leung's Markov Random Field texture synthesis method
  - Exhaustive small neighbourhood matching
    - Saves the best matches for further processing
  - Selective processing at the most promising locations using the entire neighbourhood



Putting it all together

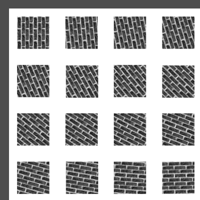




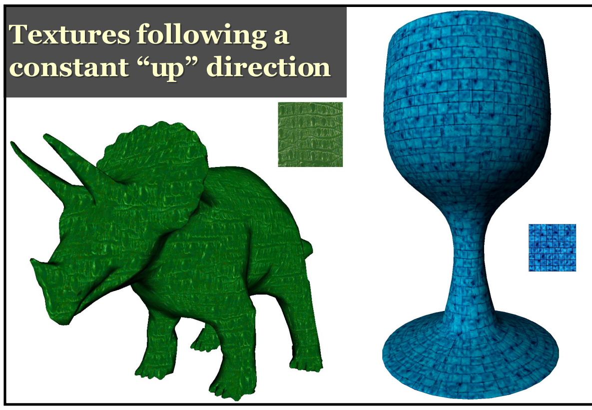
… Unoriented Texture Doesn't Work Well

Orienting the Texture

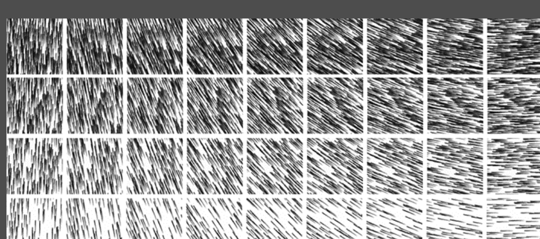
- User should not have to select the directions manually
- The texture direction should follow the surface curvature in a natural way
- The final result should be pleasant
- Change the target of the search a per-pixel basis to follow the specified direction
- Textures are pre-rotated improve performance

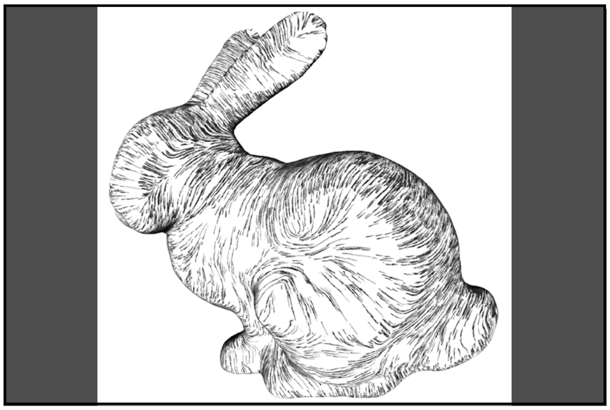


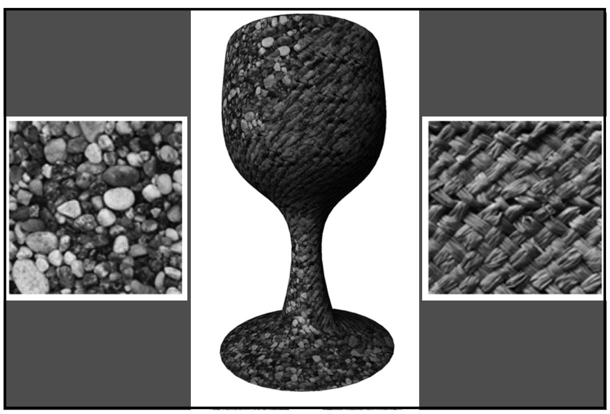
Textures following a constant "up" direction

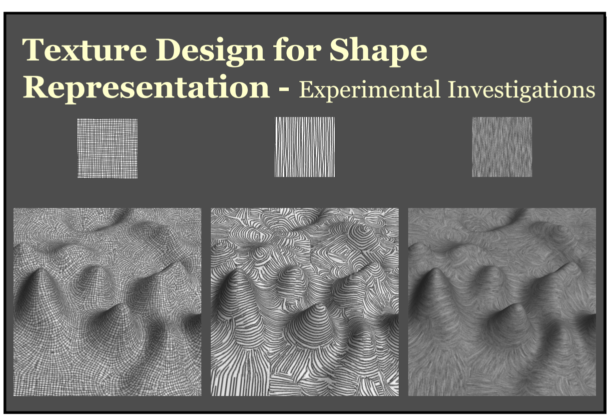


Indexing into an Array of Textures








Texture Design for Shape Representation - Experimental Investigations

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