Conveying 3D Shape and Depth with Textured and Transparent Surfaces

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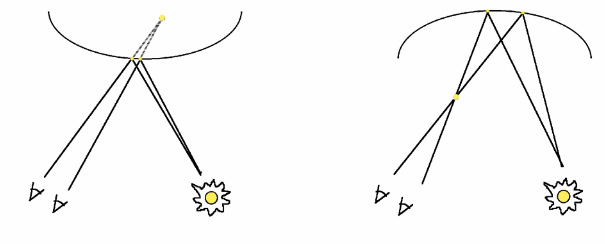
In scientific visualization, there are many applications in which researchers need to achieve an integrated understanding of the three-dimensional shapes and relative depth distances of multiple overlapping objects. Transparent surface rendering has the potential to be a useful device, in many of these cases, for simultaneously portraying multiple superimposed structures in a single image, so that their complex spatial relationships can be more accurately and comprehensively inferred. The challenge is to determine how to portray the outermost objects in such a way that they can be both effectively seen, and also seen through, at the same time. In this article we briefly review a variety of issues in transparent surface rendering, and describe some novel graphical techniques that aim to enhance the representation of external transparent surfaces, while maintaining the visibility of internal structures, through the careful design and application of sparsely distributed opaque surface markings. Integral to this discussion is an analysis of the effects that various texture pattern characteristics, such as orientation, have on surface shape perception.

The Trouble with Plain Transparency

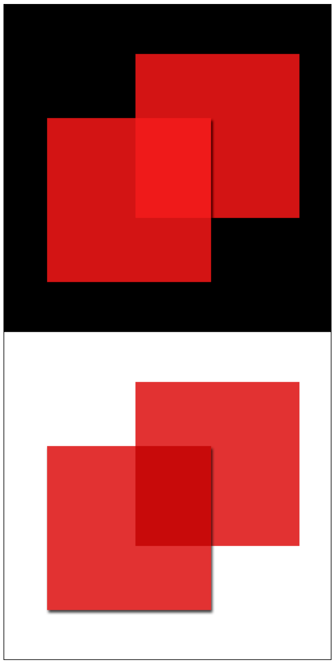
In computer graphics images, as in everyday experience, smoothly finished external transparent surfaces can be surprisingly difficult to adequately perceive. Not only is the depth distance between an outer transparent surface and inner opaque entities typically difficult to assess, but even the depth order relationships can at times appear ambiguous, and the subtle shading cues that might otherwise reveal the 3D shape of a gently curving external transparent surface are often masked by the gradients of transmitted intensity of the underlying opaque inner structures.

Essentially, there is a lack of sufficient information in the visual stimulus to allow an observer to accurately interpret the either the geometry or the layout of the multiple objects in the scene. Complicating matters is that, in normal stereo vision, specular highlights, are not perceived to lie *on* a reflective surface but rather appear to float in space either above the surface, if it is concave, or below the surface if it is convex[1].



Incident light is specularly reflected by smooth, shiny materials in a preferred direction determined by the angle of incidence with respect to the surface normal. Thus, on a curved surface, the highlight due to a given light source will appear to lie in a different position on the surface when viewed from one eye than when viewed from the other. Instead of perceiving the highlight to be in two locations at once, our visual system forms a single unified percept of the highlight floating in space. Psychologists have shown that people can use the direction of the displacement of the highlight to disambiguate bumps from depressions[1].

Choosing an Appropriate Shading Model for Rendering a Transparent Surface

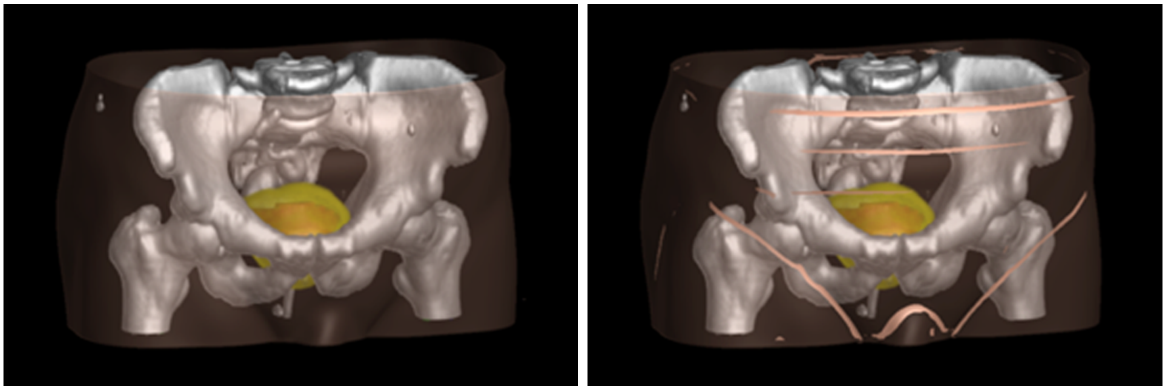


There are several common shading models that can be used to represent transparent surfaces. The choice of shading model is important because it affects the type of transparent surface that is simulated. One of the most commonly used models is *additive transparency*, in which the final intensity I at a point is defined as a linear combination, weighted by the surface opacity $\alpha \in (0,1)$, of the intensity I_f of the transparent surface and the intensity I_b of the background: $I = I_f\alpha + I_b(1-\alpha)$. This model results in surfaces that appear to be made of gauze; when the surface is folded upon itself multiple times, the result converges to the color of the transparent material. An alternative is *subtractive* or *multiplicative transparency*, in which the transparent surfaces are modeled as filters that impede the transmission of light, so that as multiple surfaces are overlapped the result gets progressively darker, tending towards black.

Top: additive transparency; Bottom: subtractive transparency

Emphasizing Essential Lines

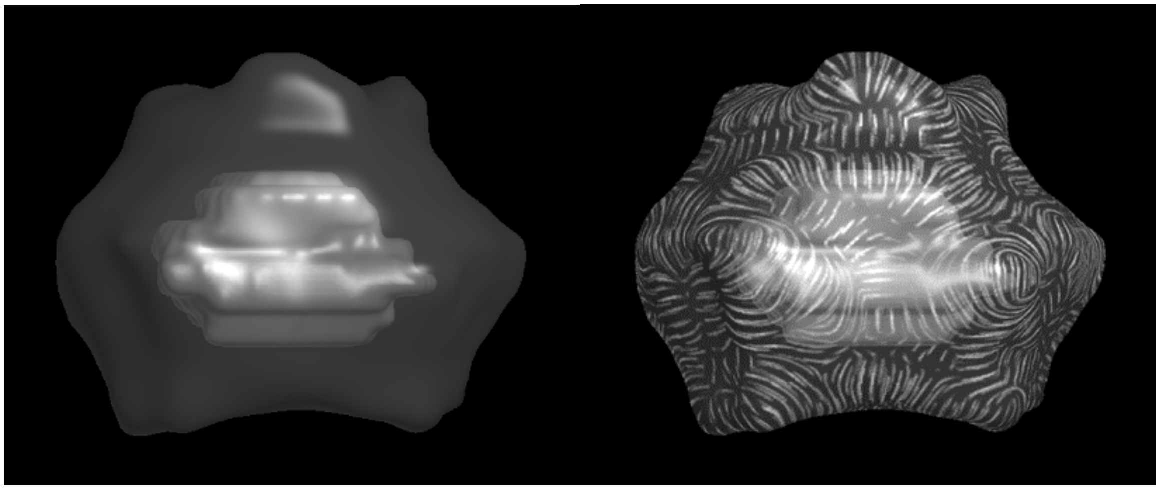
By adding detail, in the form of sparse opaque markings, to an external transparent surface, we have the potential to more effectively convey both its intrinsic shape features and its depth distance from underlying structures. The challenge is to decide what sort of markings will be most appropriate, and to define an algorithm for determining how to place them over the surface. Silhouette lines are appropriate to enhance on faceted objects, but on smoothly curving surfaces they can be problematic because they will not lie in the same place over the surface in the views from each eye. On complicated surfaces that exhibit multiple inflections of Gaussian curvature, *valley lines* can be useful for conveying important additional shape information. These lines are defined as the locus of points that lie at minima of negative curvature in the direction of greatest normal curvature over the surface, and their perceptual relevance is affirmed by research that suggests that people tend to subdivide objects into parts along their valley lines[3]. The figure below illustrates the use of valley lines on a transparent surface in a scientific visualization application[8].



Above left: a typical rendering of some of the multiple surfaces of interest in a radiation therapy treatment plan for prostate cancer. Above right: an enhanced rendering[8], in which opaque feature lines have been added along the major creases in the skin surface, with the intent to clarify the structure of the form and draw attention to the location of sensitive soft tissue structures that have to be kept outside of any beam path.

Clarifying the Flow of the Form

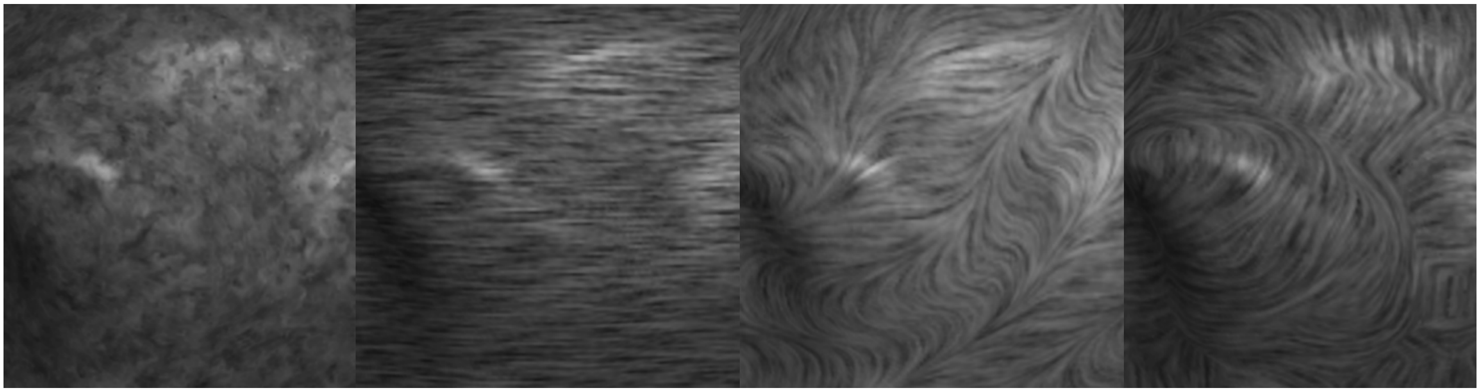
Not all smoothly curving surfaces have shapes that can be well-captured by a small set of feature lines. An alternative approach[7] is to apply a texture of uniformly distributed[10] sparse opaque markings over the transparent surface. However the choice of texture pattern, and how it is applied over the surface, has to be made with care. Lest the texture do more harm than good, it must be aesthetic, unobtrusive, of a style appropriate to the application, and applied in a way that emphasizes rather than masks the curvature of the form. Inspired by the example of line drawings in medical illustration, we have developed an algorithm[6], illustrated in the figure below, in which 3D line integral convolution[11] is used to synthesize a solid texture of sparse opaque strokes following the vector field of principal directions over the transparent surface.



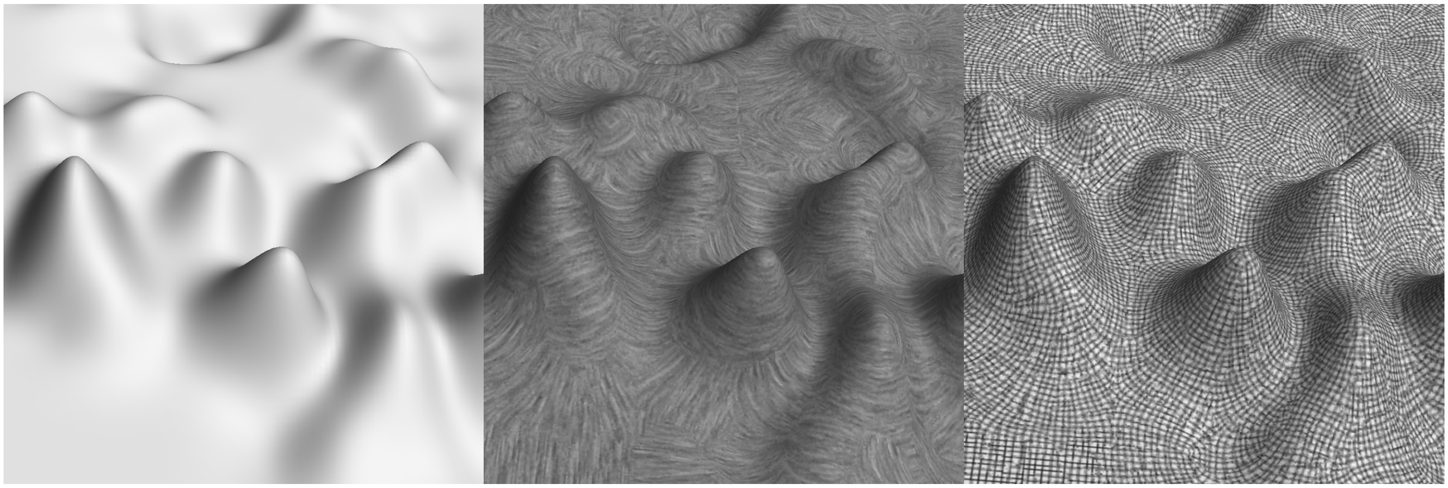
Above left: a prototypical scientific dataset involving layered transparent surfaces – a level surface of radiation dose enclosing an opaque treatment region; Above right: an enhanced rendering[6] of this data, in which the outer transparent surface has been augmented with a see-through texture designed to emphasize its shape.

Conveying Shape Through Texture on Opaque Surfaces

If one could design the perfect texture pattern to apply to any smooth surface in order to enable its shape to be more accurately and intuitively perceived, what would the characteristics of that texture pattern be? Recent research suggests that patterns with a strong directional component show shape best when the texture is everywhere oriented in the direction of maximum normal curvature (the first principal direction). Textures that contain significant geodesic curvature, or turn in the surface, tend to mask surface shape. Textures that follow both principal directions are beneficial for practical reasons, because it’s extremely difficult to define a consistent orientation for the first principal vector field, and in some cases no global solution exists, with the result that the texture pattern appears to rotate 90 degrees everywhere the first and second principal directions switch places. Recently developed surface texture synthesis algorithms[2] allow one to apply a wide class of 2D patterns over arbitrary polygonal models without seams or stretching, and in such a way that the pattern is constrained to follow a predefined vector field at a per-pixel level over the surface. This algorithm was used to create the images in the second figure below.



Studies have found that how a texture is oriented over a surface can significantly affect how accurately the surface shape can be perceived – anisotropic texture tends to mask surface shape when the direction of the anisotropy is not aligned with the principal directions of the form[4,5]. From left to right: An isotropic texture, a uniformly oriented anisotropic texture, an anisotropic texture that turns in the surface, an anisotropic texture that follows the first principal direction at every point.



Textures that follow both principal directions appear to show shape slightly more effectively than textures that follow only one[9]. Above left: A smoothly shaded, untextured surface; Above center: The same surface textured with a line integral convolution pattern that follows the first principal direction vector field at every point; Above right: The same surface, textured with an orthogonal grid pattern that is everywhere aligned with both the first and second principal directions.

Notes:

1. Andrew Blake and Heinrich Bülthoff (1991) Shape from Specularities: computation and psychophysics, *Philosophical Transactions of the Royal Society of London, B*, **331**, pp. 237-252.
2. Gabriele Gorla, Victoria Interrante and Guillermo Sapiro (2002) Texture Synthesis for 3D Shape Representation, *IEEE Transactions on Visualization and Computer Graphics*, to appear.
3. Donald D. Hoffman and Whitman A. Richards (1984) Parts of Recognition, *Cognition*, **18**, pp. 65-96.
4. Victoria Interrante, Sunghee Kim and Haleh Hagh-Shenas (2002) Conveying 3D Shape with Texture: recent advances and experimental findings, *Human Vision and Electronic Imaging VII*, SPIE **4662**.
5. Victoria Interrante and Sunghee Kim (2001) Investigating the Effect of Texture Orientation on the Perception of 3D Shape, *Human Vision and Electronic Imaging VI*, SPIE **4299**, pp. 330-339.
6. Victoria Interrante (1997) Illustrating Surface Shape in Volume Data via Principal Direction-Driven 3D Line Integral Convolution, *Computer Graphics, Annual Conference Series* (ACM SIGGRAPH 97), pp. 109–116.
7. Victoria Interrante, Henry Fuchs and Stephen Pizer (1997) Conveying the 3D Shape of Smoothly Curving Transparent Surfaces via Texture, IEEE Transactions on Visualization and Computer Graphics, 3(2): 98–117, April-June 1997.
8. Victoria Interrante, Henry Fuchs and Stephen Pizer (1995) Enhancing Transparent Skin Surfaces with Ridge and Valley Lines, *Proc. IEEE Visualization* ‘95, pp. 52–59.
9. Sunghee Kim, Haleh Hagh-Shenas and Victoria Interrante (2002) Showing Shape with Texture, *IEEE Visualization 2002,* poster presentation.
10. In our experience, employing unevenly distributed texture has been problematic; when some areas are left devoid of texture while others are uniformly covered, the empty areas tend to be perceived as holes.
11. Detlev Stalling and Hans-Christian Hege (1995) Fast and Resolution Independent Line Integral Convolution, *SIGGRAPH 95 Conference Proceedings, Annual Conference Series*, pp. 249-256.