Chapter Five: Uniformly Distributed Surface Texture

The previous chapter described how the qualitative shape of certain transparent objects might be more intuitively communicated when the locations of the valley, and possibly ridge, lines on its surface are selectively emphasized. Not all surfaces, however, can be easily characterized by prominent shape-based features. Of particular relevance to the driving application for this dissertation, it appears that the isointensity surfaces of radiation dose, whose shapes and locations need to be understood in the context of the overlying skin surface, the underlying target volume and the proximal anatomical structures, are often relatively smooth and featureless, and the depth information that can be communicated by their ridge and valley lines sparse to nonexistent. In this chapter I describe my investigations into various methods for effectively communicating local shape and depth information in a more uniform and continuous fashion across smoothly curving transparent surfaces concentrating, in particular, on the design of sparse opaque textures whose properties represent both qualitative and quantitative local surface shape measures in what will hopefully be a perceptually relevant and intuitively meaningful way.

In order to determine how to most effectively represent the shape and depth of a layered transparent surface with sparse opaque texture, much guidance and inspiration can be drawn from observations of the various techniques successfully employed by artists and illustrators to represent shape using patterns of line. First, however, I will briefly describe the state of the art in computer graphics for representing or enhancing the appearance of transparent surfaces with what can be defined as sparse, opaque texture.

5.1: Previous work in computer graphics using texture to represent or enhance transparent surfaces

The idea of using opacity-masking texture to enhance the visibility of transparent surfaces is not new. Dooley and Cohen [1990] demonstrated the use of textured transparency in image space, illustrated in figure 5.1-left, in which a texture opacity mask consisting of a pattern of pixel coordinates in screen space is used to define the opacity of the surface region that is represented in each pixel. Levoy et al. [1990] introduced the use of solid-grid textured transparency, illustrated in figure 5.1-center, in which an opacity mask consisting of a pattern of voxel coordinates in object space is used during volume rendering to control the opacity of the material represented in each voxel. Palmer [1992] described a method for surface-based textured transparency, illustrated in figure 5.1-right, in which a procedurally-defined two-dimensional texture image is used to modulate the opacity (and color) of the surface regions to which it is mapped.

The technique of representing a continuous surface by a set of discrete elements such as points, lines or other graphical primitives, has a long history in many applications that use computer graphics for interactive data display. Originally designed more for the purpose of
Figure 5.1: Examples of the use of various different types of texture to enhance the visibility of a layered transparent surface. (From left to right: image-space texture [Dooley and Cohen 1990], solid grid texture [Levoy et al. 1990], two-dimensional procedurally-generated texture, mapped onto a three-dimensional surface [Palmer 1992].)

rendering efficiency than as a method for improving the comprehensibility of a surface, it can be argued that this approach actually serves both purposes quite well. Connolly [1983] pioneered a technique widely used in molecular graphics for representing the solvent-accessible surface of a molecule by a collection of color-coded dots (figure 5.2-left) or lines (figure 5.2-right).

Figure 5.2: Connolly dot and line surfaces [Connolly 1983].

In radiation therapy treatment planning, transparent skin and dose surfaces are commonly represented in three dimensions by a stack of “contour rims” representing the outlines of these structures on the two-dimensional CT slice planes (figure 5.3-upper left [Sailer et al. 1992]). Distinct line styles (such as dotted or dashed) can be used with this technique to help differentiate multiple superimposed surfaces (figure 5.3-upper right [Photon Treatment Planning Collaborative Working Group 1991]). In a similar technique, proposed by Bauer-Kirpes et al. [1987], the contour rims of isodose surfaces are represented not by lines but by a strip of rectangles, referred to as a “barrel hoop” (figure 5.3-lower left). In other methods, particles, such as tiny spheres, have been used to represent surfaces. Finally, there is the method of wire-frame drawing, illustrated in figure 5.3-lower right [Kijewski 1994], in which a polygonally-defined surface [Fuchs et al. 1977] is represented by the collection of lines that represent the edges of the surface tiles.
5.2: How artists represent form with line

Line patterns have been used for centuries to represent three dimensional figures in flat drawings. It therefore seems appropriate to begin this investigation into promising techniques for using line to represent shape by briefly reviewing what artists and illustrators have written on this subject over the years in textbooks describing their pen-and-ink methods.

Thickness, spacing and orientation appear to be the three most important and often discussed line characteristics. Sullivan [1922] demonstrates how the relative weight of the line used to surround an object determines whether the outline is perceptually grouped with the object or with the background, or, alternatively, whether the line stands apart from both and demands recognition as an entity in its own right. He goes on to describe how the amount of “depth” conveyed in an image will vary considerably depending on the effectiveness with which the outline is drawn; in the cases where the line assumes its own identity, he says, an extra measure of flatness will be imparted to the image which is, in most cases, undesirable. It should be noted that Sullivan is referring here to outlines which are drawn for the sole purpose of separating figure from ground, lines which have no intrinsic, viewpoint-invariant meaning on the surface itself.
Figure 5.4: An illustration demonstrating the potential significance of stroke characteristics, from [Pitz 1957]. A dramatically different effect is achieved in these two images although little more is changed than the lengths and directions of the lines used to represent the tonal values. Of particular note here is the dynamism or sense of radiant flow in the image on the left in contrast with the relative serenity or stillness in the same scene in the depiction on the right.

When lines are used to represent surfaces areas rather than boundaries of form, the thickness and spacing of the individual strokes is often varied over the image depending on the “tone” desired in each region. Gradations in tone can be represented in many different ways: by changing the spacing between strokes of equal thickness, by changing the thicknesses of strokes whose central axes are more or less equally spaced, or by varying the width of each stroke along its length. Sullivan [1922] emphasizes the importance of proper spacing, a theme that is reiterated in almost every book describing the art of drawing:

... lines may be placed so far apart relative to ... the space occupied that they hardly appear as a tone, but as individual lines, independent of each other except insofar as their parallelism is marked. They then take up a position which may challenge the supremacy of the main constructive lines of the drawing, so that the adjective is more forcible than the noun, as in a common and senseless form of swearing, or they may appear, not as belonging to and suggesting surface or an intangible shade or shadow, but as something positive, either as construction or pattern.

Pitz [1957] cautions that when the lines comprising a tone are spaced 1/16” apart or more, the eye is more likely to be conscious of them as individual elements. Guptill [1976] suggests an even closer spacing, writing that, as a general rule, the strokes used to represent a tone should be placed 1/32” (0.8mm) apart if the drawing is to be viewed from a distance of about 2ft. In the samples of work by medical illustrators shown at the end of this section, we can see that relatively larger line spacings are common.

Although it is clear that styles vary, it is important nevertheless to take somewhat to heart the admonishment against representing strokes, or any texture elements, in such a way that they take on a character of their own. Our primary intention in adding opaque markings to transparent surfaces is to allow the form of the depicted objects to be more easily and intuitively understood. To the extent that the individual texture markings are unduly prominent, they may do more harm than good, distracting the attention of the observer, confusing the appearance of
the picture and adding visual “noise” that detracts from rather than enhances the overall effectiveness of the presentation. This may be one reason that the circular texture elements are so rarely employed by scientific and medical illustrators for the purpose of more explicitly depicting surface shape.

While variations in tone are important for representing the patterns of light and shade that are defined by illumination, this is not the only way in which they are commonly used. An important concern in any illustration is emphasis, and Guptill [1976] demonstrates how to define the focus of attention in a drawing by varying the contrast with which different parts of the scene are depicted (and, concomitantly, varying the amount of detail that is represented in each part). The lengths of the individual strokes and the precision with which they are drawn and placed on the page (including the regularity of the patterning and the amount by which the individual strokes fluctuate in direction) also influence the impression conveyed by a drawing.

In terms of the effectiveness with which shape and depth are portrayed, however, the most important line characteristic by far appears to be orientation. (This should not be interpreted as meaning that shading somehow plays a lesser role, but only as an acknowledgment of the fact that tonal variations can be equivalently conveyed by a multitude of different particular line styles. The essential shape of an object, both within and apart from the shading, is conveyed most clearly by the orientations of the lines that fill and bound its form.) Sullivan [1922] is particularly adamant about the importance of stroke direction in line drawings, saying

...all a fastidious spectator’s pleasure in a drawing may be destroyed by a wrong use of direction in a space of modelling, no matter how fine the lines composing it may be, or how pretty the general effect.

There are a number of different commonly-accepted techniques for defining line orientation. Possibly the simplest approach, and incidentally the one that communicates the least amount of information about shape and depth, is to not vary the line orientation at all but merely to consistently apply the strokes in a uniform vertical or horizontal direction. This is the effect achieved in computer graphics when an image-space texture is applied. Although the orientation of the lines is independent of the three-dimensional space occupied by the depicted objects, our perception of form is nevertheless affected by the choice of line direction. Pitz [1957] illustrates and explains the effects of a variety of different directed stroke techniques; figure 5.5 shows excerpts from this work, demonstrating how the use of vertical lines can emphasize height, horizontal lines can emphasize width, and lines that follow the edges of the forms can emphasize their volume.

Figure 5.5: An illustration of the biasing effects of various stroke textures, from [Pitz 1957]. Vertical lines emphasize height, horizontal lines emphasize width, and lines that follow the outer edges of the forms emphasize volume.
Guptill [1976] describes how, even for a very simple scene, there seem to be an almost infinite variety of different ways in which lines can “follow the form” of a surface. The upper group of illustrations in figure 5.6 depicts, for example, his demonstration of eight different combinations of edge-following uni-directional line textures that can be applied to the visible faces of a shaded cube.

Just as there may be a great many equivalently appropriate techniques for representing the surface of an object with line texture, there are also many ways in which, if inappropriately used, texture lines can misrepresent surface shape, orientation or depth. Guptill [1976] points out, in addition to the above-mentioned effects of vertical and horizontal strokes, that diagonally oriented textures can convey a sense of expansion, making things look relatively larger than they otherwise might. Diagonal lines are also problematic in that, in some instances, they can make parallel lines appear to converge or diverge, as demonstrated by the well-known Zöllner illusion. (Gillam [1980] discusses the implications that many of the classical geometrical illusions have for shape and depth perception.) Guptill advises, however, that “as a general rule, a subject offers some hint as to a natural arrangement of lines, and when this is followed there is little danger of distortion”.

![Figure 5.6: Different pen-and-ink techniques for representing the surfaces of a simple object, from [Guptill 1976]. Upper group: Eight different combinations of edge-following textures that can be used to shade the faces of a cube. Lower group: four alternative texturing approaches: outline (no texture), stipple, crosshatch, diagonal lines.](image)

Lines, of course, are not the only texture elements that can suggest a distortion of surface shape. Op artists, and in particular Victor Vasarely, demonstrated how surface markings could be successfully manipulated to create stunningly vivid and often incongruous portrayals of depth. Figure 5.7, after Vasarely’s Tupoo-3 [1972], shows how the impression of curvature conveyed by a distorted pattern of surface texture can dominate the impression of flatness conveyed by contradictory shape-from-shading and non-generically ambiguous shape-from-contour cues.
Figure 5.7: An illustration, after Tupa-3 [Vasarely 1974], showing how texture can be misused to distort the appearance of surface shape. One of the keys to the success of this picture lies in the non-generic positioning of the surface; from this very specific viewpoint, the straight lines are technically consistent with either a flat or distorted cube (from any other angle, the projections of the lines would be different for the two alternative configurations). The effect of the texture gradients is impressive, especially when one notes that the surface illumination can only be consistent with a planar, faceted object.

Sullivan [1922] offers three alternative techniques for defining the orientations of the strokes in a line texture so that they “follow the form” and communicate the surface shape in an intuitively meaningful way, as illustrated in figure 5.8. (The distribution of the strokes is defined, in all three cases, by the patterns of illumination, which he says convey relief best when generated by a proximal light source of relatively low intensity.) The first, and by his admission simplest, of these approaches is to define the direction of the strokes according to the “fall of light upon the object”. He suggests two ways of doing this, schematically portrayed in the upper portion of figure 5.8: either along the radiating rays of light or at right angles to them. It inevitably occurs with this approach, however, that at some points the direction of the texture lines closely parallels the direction of bounding contour, and Sullivan says that when this happens the “turn” of the form is not well-represented and the impression of depth is diminished. The second general approach, which he describes as probably the most difficult and demanding the greatest knowledge of the form itself, is to orient the strokes “at right angles to the length of the form”.

Medical illustrators, in particular, seem to favor this “form-following” convention for using line to depict surface shape, as can be observed in the samples of artwork reproduced in figure 5.9 [Sweet (in Bunnell 1944), Loechel 1964, Hagen 1990, Drake 1932]. The basic form of the hand, in the upper-left illustration, is represented primarily by outline and valley lines. Of particular note is how the parallel strokes (which appear to lie in the direction of maximum curvature) are used around the wrist to bring the drawing “out of the plane” and convey a sense of depth distance between the outer skin surface and the underlying structures. In the illustration on the upper right, the artist presents anatomical information educed from an x-ray, along with surgical annotations, in a clearly understandable figural context. Interior strokes are used to represent shape (where they appear to be oriented in the direction of greatest normal curvature), direction (arrows) and texture (in the area below the stomach), as well as outline and
Figure 5.8: An illustration of some alternative conventions for determining stroke direction — following the light or following the form, from [Sullivan 1922]. Left: concentric circles emanating from the light source. Center: radial lines emanating from the light source. Right: strokes “taken through the form at right angles to its length”.

tone (note that a neutral line orientation is chosen when the purpose is to represent color rather than shape in the case of the distinguishing breast features). In the illustration on the lower left, lines are used to indicate shape and to differentiate the component elements of the figure. The artist here seems to be following the line drawing style advocated by Drake, in which the strokes are applied in a manner that suggest deformations of a ruled surface. An advantage of this approach is that it permits a consistent line direction to be used for the representation of an undulating structure and also allows separate structures to be easily differentiated (note the difference in the direction of the lines used to represent the main body of the colon and the lines representing the muscle running along the center of it). The illustration in the lower right shows Drake's technique implemented in a drawing by the master himself. Line orientation conveys shape; width and spacing convey shading; the strong outline separates figure from ground. Describing the pen-and-ink techniques illustrated in figure 5.10, Drake [1987] says

...think of [a surface] as a metal sheet with a series of parallel lines and then think of bending this sheet ... it is only natural that the lines on the receding surfaces become closer and closer together as they recede. ... Similarly, if lines are made to converge on the sides as well as receding on the top and bottom, a spherical shape will result. This can be demonstrated by thinking of [the surface] as a rubber sheet. ...If we press a finger into the rubber, the lines at the high spot will become separated, converging on the sides, and become closer together at the top and bottom. This is the foundation of line drawing...
Figure 5.9: A representative sample of medical line illustrations. Upper left: [Ralph Sweet, in Bunnell 1944]; upper right: [Loechel 1964]; lower left: [Hagen 1990], lower right: [Drake 1932].

Figure 5.10: An illustration of Drake’s system for representing shape with line, from Drake [1987]. Left: a flat surface, aligned with the image plane. Center: this same surface, rotated slightly about the vertical axis in the plane and bent backwards in depth along the top and bottom edges. Right: line techniques for modeling a protrusion in the planar surface.
Drake and other artists also emphasized the different treatment required for representing transparent vs. opaque surfaces with patterns of line. In figure 5.11 [Hodge 1980] we can see that the tone of the lines on the opaque surface vary in basic accordance with the surface reflectance. On the transparent surface, which is not characterized by Lambertian shading, the tones are used instead to emphasize the brilliance of the specular highlight by sharpening its contrast with the surrounding surface.

![Figure 5.11: A demonstration of the different techniques required to represent transparent and opaque spheres with line texture, by Gerald P. Hodge ©1980 (from Hodges 1989).](image)

The use of line in scientific illustration in fields such as biology or entomology, where faithful reproduction of the specimen is the primary task, appears, to me, to be slightly more delicate and subdued than in medical line illustration, where the object is often as much to convey a concept as it is to accurately portray a specific anatomical structure, although in many cases the same conventions are used for defining line orientation. In scientific illustration, great emphasis is put on the detailed representation of patterns of light and dark, and there is a standard convention of portraying the light as coming from above and from the left [Hodges 1989].

Despite its simplicity as a device for representing tone, cross-hatching has been singled out by several authors as a generally inelegant use of line. Sullivan [1922] is particularly adamant, counseling that

*Except as the rhythmic solution of forces of line or for the establishment of a neutral tone, [cross-hatching] is better avoided, it then having no value, unless as a correction of an error in tone, when of course, it stands as a confession of underlying weakness. This is probably the reason why cross-hatching, unless as the resolution of opposing forces of line, becomes increasingly unpleasant the more elongated the included white “diamond” becomes, as the weakness of intention in the original lines is made more manifest.*

Zweifel [1961] reiterates the benefits of using meaningfully directed lines, which can indicate shape as well as shading (the term “hachure lines” is used in this case to refer to directed short strokes):
...hachure lines which follow the contours of the subject may show the form more effectively than stipple in many instances ... A few well-placed hachure lines will show the contours of the subject satisfactorily, whereas it would require several thousand stipple dots to give the same effect.

A fundamental theme running through this entire section is that line direction is important for showing shape and that there seem to be specific, intrinsic surface shape features that can guide the determination of “appropriate” line directions. Inspired by this insight, I set about to see whether, perhaps, I could define a texture consisting of short, opaque “strokes” locally oriented in the direction of maximum normal curvature, that might when applied to a transparent surface help convey an intuitively meaningful impression of the surface shape as well as provide direct evidence of the surface location in depth.

5.3: Past work with principal direction texture, automatic pen-and-ink illustration techniques

The idea that by portraying the principal directions and principal curvatures on a surface we can somehow “more effectively” communicate its shape of course has its precedents. Frobin and Hierholzer [1982] computed the principal curvatures and principal directions on height surfaces defined in discretely sampled, acquired data of the human back and displayed them as a pattern of cross-hairs on a two-dimensional grid, as shown in figure 5.12. Their goal was to portray the shape of the back using a meaningful and orientation-independent representation, and they describe the results they were able to achieve with differential geometry-based descriptors as an improvement over the alternative approach that relied on Moire topography, in which “shape information is heavily overlaid and obscured by position-dependent and virtually irrelevant structures”.

Figure 5.12: An illustration by Frobin and Hierholzer [1982] in which information about back shape is communicated by short strokes on a grid, oriented in each of the principal directions, with lengths proportional to the magnitudes of the principal curvatures. Although the lengths and directions were computed from the three-dimensional data, the lines themselves appear to be drawn in the image plane. Frobin and Hierholzer [1982] were among the first to explicitly compute the principal directions on a surface defined by acquired data, and to use these quantities to define a “stroke texture” that intends to communicate the essential features of the shape.
Researchers in computer vision also pursued the idea that an intrinsic surface description could be assembled from local differential geometry measurements computed on surfaces in acquired data. Brady et al. [1985] proposed an approach wherein local estimates of the directions of principal curvature were “linked” across a surface and planar “lines of curvature” extracted (although it appeared in my reading that their proposed procedure for linking the principal directions would be practically applicable only in situations where the lines of curvature were collinear with the axes along which the local measurements were taken; in all other cases it seemed that jumping between neighboring lines of curvature would be nearly unavoidable). Sander and Zucker [1987] also computed principal direction vectors on surfaces in three-dimensional data. Their goal was to derive an analytic surface representation from acquired data and to define and categorize the various patches of this surface according to the properties of their Gaussian curvature.

There has been a recent spate of effort by researchers in the computer graphics community to develop techniques for “automatically” generating line-drawing surface representations in the style of pen-and-ink illustrators. Saito and Takahashi [1990] defined a “hachuring” pattern based on the surface parameterization of a torus (in terms of a solid grid this effect could be achieved by the union of a set of planes rotated at discrete angles about an axis through the center of the torus and a set of planes offset at discrete intervals along this same axis), and applied it in proportion to the surface shading indicated by an illumination map, to achieve the strikingly authentic-looking line art representation shown in Figure 5.13. Although for this specific surface the lines happen to run in accordance with the principal directions, it must be noted that this relationship will not hold in the general case.

Figure 5.13: A computer-generated line drawing illustration by Saito and Takahashi [1990]. The strokes are defined by an orientationally-invariant surface parameterization and applied in proportion with the surface shading.

Winkenbach and Salesin [1994] describe methods for automatically generating pen-and-ink style drawings of architectural models, in which the texture and tone of planar surfaces are defined by various combinations of “strokes”. Figure 5.14 illustrates an example of their very lovely work. Winkenbach and Salesin touch on many different important considerations such as how to automatically modify a texture pattern so that detail will fall out gracefully as the projected area of the patch decreases with depth distance or slant from the viewing direction; how to make each stroke look “natural” by introducing random variations in width, straightness and length; how to vary the amount of detail with which various regions of the figure are portrayed, both to selectively emphasize particular regions or features of the model and to “lighten” the overall appearance of the finished image.
Salisbury et al. [1994] describe methods for interactively applying detailed stroke textures to a two-dimensional image using higher-level drawing commands. They define a hierarchy of procedural and stored stroke textures that can fluidly represent changes in tone, and when the drawing is done on top of a “reference image”, they allow the orientation of the strokes to be defined to follow the direction of the two-dimensional illumination gradient, as shown in figure 5.15.

Figure 5.15: A semi-automatically generated line drawing illustration by Salisbury et al. [1994] in which stroke direction is defined by the intensity gradients in a two-dimensional image.

5.4: Applying principal direction texture to transparent surfaces

Realizing that the shapes and locations in depth of unadorned transparent surfaces are difficult to perceive, driven by the hypothesis that by adding opacity to specific small regions of the surface I might be able to better portray its shape and depth, and motivated by observations that some texturing styles had been deemed “more suitable”, by artists, for conveying surface shape information, I set about to implement an algorithm whereby I could apply a texture comprised of opaque short strokes, each oriented in the direction of maximum normal curvature, to the transparent isointensity surfaces of radiation dose defined in the pelvis and nasopharynx datasets introduced in chapter four.

The first step in my algorithm for applying a texture of opaque short strokes to a transparent isointensity surface is to locate the points on the surface at which each texture element should be applied. (It should be noted that standard solid texturing algorithms [Peachey 1985, Levoy 1990] do not require such a step; the textures in these cases are defined independently of the surface to which they are applied. We will see that there are both advantages and disadvantages to a surface-independent texturing approach. The principal advantage is the ease, speed of execution, and flexibility that come from being able to define one
texture pattern than can be applied to any level surface in the volume. The principal disadvantage is that it is not possible to explicitly portray any intrinsic shape features of the surface using texture patterns defined in this way.)

I begin the task of specifying surface texture element locations by using a “marching cubes” iso-intensity surface extraction algorithm [Lorensen and Cline 1987] to obtain a list of the centerpoints of each of the subvoxel-sized triangles that comprise the level surface that I want to texture. The datasets from which the images in this chapter (and the next) were computed were both of dimension 241x199x181 (containing approximately 8.6M voxels), and there were between 79,571 and 124,283 individual triangles in each of the six iso-intensity surfaces I examined.

In my first attempt at defining texture element locations I simply chose, at random, a percentage of the locations on the triangle centerpoint list, based on the value of an input texture “density” parameter. The problem with this approach, as I quickly discovered, is that it tends to result in patchy texture element distributions, in which some parts of the surface are sparsely represented while others are crowded with overlapping elements. To ensure a more even distribution of the texture elements over the surface, I developed a second approach, which involved prompting for a minimum inter-element distance parameter and then iterating through the triangle list, checking each point for candidacy as a texture element location by testing whether it was beyond the specified distance limit from each of the element locations that had already been selected so far. The spacings used to define the centerpoints of the elements in the surface textures shown in this chapter ranged from 3 to 18 voxel units, and the number of texture element locations selected ranged from 200 (in the case of the large dots) to 6277 (in the case of the small, tightly packed dots). There were 999 individual elements in each of the line segment textures. The program that I wrote to choose the element locations was very simple and, for these datasets and parameters, executed in about four minutes on an IBM RS/6000.

Once I had defined the real-valued point coordinates within the dose volume around which each of the surface texture elements was to be defined, the task of defining the axis along which each stroke would be oriented was passed to a second program, which took as inputs the list of point coordinates and the volume of dose intensities and calculated the principal directions and principal curvatures of the iso-intensity level surface passing through each of the specified points. The algorithm by which these values were computed has already been described in chapter four. The mathematics are fairly simple and straightforward, and the total execution time required for this step was on the order of about 30 seconds, again on the IBM RS/6000. The output of this second program is a set of “slabs”, each comprised of six rectangular, polygonal facets and each occupying a volume of about 20 voxels (for a stroke 4 units long, 1 unit wide and 5 units “tall”), defining the space within which all detected surface points will be rendered opaquely. During the ray-casting step of the basic volume-rendering program used to define the surfaces (which is also described in greater detail in chapter four), I then simply kept track, as the ray progressed through the volume, of all of the ray/slab intersections encountered so that I could determine whether or not a particular ray/surface intersection lay within one of the opacity-defining slabs. Because of the possibility that multiple slabs might overlap in some regions, I had to be careful to tag each of the six polygons comprising a slab with the same “slab number” so that I could distinguish cases in which a ray had entered and exited one slab from cases in which a ray had entered one slab and then entered another without exiting either.

The ray-casting steps were by far the most time-consuming part of the whole image generation process. While it was possible to define in under about 10 minutes exactly how a texture was to be applied to a surface, it often required up to several hours to generate a full-quality anti-aliased volume-rendered image of the transparent surface covered with these opaque texture markings. Most of this was due to the inordinate amount of time that had to be spent testing for intersections between the viewing rays and each of the tiny slab polygons. Although techniques for improving the speed of ray-tracing tasks such as this are well-known [Glassner
1989], because the purpose of my exercise was to explore different texturing approaches rather than to devise methods for efficiently implementing them, I did not make any effort to incorporate time-saving devices into the rendering code. One method to which I did sometimes resort, when I wanted to generate multiple views of a single surface, was to scan-convert the volumes enclosed by each of the polygonally-bounded slabs into a larger volume of the same dimensions as the volume containing the dose. Although it took a considerable amount of time to do the scan conversion with enough precision to adequately represent the tiny texture elements without visible aliasing (and I was never able, of course, to achieve the same crispness with the scan-converted textures), rendering was fairly quick once the scan conversion was complete because the isosurface opacity values could then simply be looked up (or trilinearly interpolated) from this second volume for every ray/surface intersection point as it was encountered. The principal direction texture images used in the observer study that I will describe in the next chapter were all generated using polygonally-defined rather than scan-converted texture, however, because of the greater precision with which the strokes can be defined using this former approach.

Having defined a method for generating images in which transparent surfaces could be “textured” with collections of opaque directed dashes, I was eager to assess the visual impact of this approach: did such textures appear the way I expected them to? did they really “show off the surface shape better”? how could I tweak the parameters to improve the “look” of the result? Despite my high hopes, it turned out to be relatively difficult to get even a rough, intuitive feel for the potential effectiveness of such a texturing method.

One of the reasons that it was so difficult for me to informally assess the “quality” of the principal direction texturing idea was that the character of the final images could be affected in so many different ways by so many different variables. Just to start, there were the parameters of element length, element width and inter-element spacing (element height was more constrained, having to be set large enough so that the surface/slab intersection would run the full length defined for the stroke, but not so large that uninvolved areas of the surface would be likely to fall within it). Figure 5.16, for example, illustrates two different instances of principal direction texture applied to an isointensity surface of radiation dose, demonstrating the kinds of effects that can result from changing various texture parameters. I experimented with the principal direction texture parameters for an unadvisably long time, adjusting various implementation details and experimenting with the effects of using different parameter values, but then began to suspect that there might be little to be gained through this exercise. As seen previously in the line-drawing example of the textured cube, within any given method there are probably a fairly

![Figure 5.16: Principal direction textures with constant element length. Left: spacing= 6 voxel units, width= .75 voxel units, length= 3 voxel units. Right: spacing= 8 voxel units, width= 1.5 voxel units, length= 4.5 voxel units.](image)
large number of different-looking but nearly equivalently effective possible variations in implementation style.

The general effect of the lines in the texture stroke images of figure 5.16 falls short in many ways from the effect of the lines in the medical illustrations of figure 5.9. One of the most obvious differences lies in the fact that the artists vary individual stroke placement, length and width across the images to reflect both shading and emphasis, aspects that are essentially ignored in the principal direction texture computation process described above. Because the pattern of illumination over a surface changes with changing object orientation or viewing angle, some difficult questions would have to be answered before shading information could be effectively incorporated. I have already discussed, in chapter four, several factors motivating the choice of a texture definition that is based on intrinsic surface properties. Element prominence or positioning can be effectively defined by factors other than shading, however.

One possible factor is surface curvature and, for several reasons, I assert that it makes particularly good sense to vary the length of a depicted stroke according to the magnitude of the curvature in the stroke direction. In the texture implementation I have described, the basic direction indicated by a stroke will correspond only to the direction of maximum normal curvature computed at the central point of the stroke, although texture elements will sometimes appear to be curved because of the changing curvature of the surface across the area where it passes through a texture slab. This means that the fidelity with which the displayed stroke direction matches the direction of a line of curvature degrades the farther away the line extends from the central point. For this reason, with this type of texture line implementation, it really doesn’t make sense to use long strokes. Within the restriction to relatively short strokes it seems advantageous, furthermore, to allow the strength of the direction indicated by each stroke be somewhat in keeping with the “significance” of the depicted orientation. One can imagine several ways in which the importance of a direction could be determined. The technique I implemented, which is illustrated in figure 5.17, bases this determination on the magnitude of the surface curvature in the indicated direction. (I felt that the loss of meaning in line direction was particularly evident in the flat spots on the surface where, because a little bit of noise could cause a large fluctuation in the results of the geometrical computations, the depicted orientation appeared to be essentially arbitrary.) Another possibility, which I did not implement, would have been to base the determination of “strength of direction” on an estimate of the local variation in normal curvature over different directions across the surface at the centerpoint of the stroke, possibly indicated by the difference in the signed magnitudes of the two principal curvatures computed there.

Figure 5.17: Left: texture element length is proportional to the magnitude of the normal curvature in the stroke direction. Right: element length is constant
5.5: Alternative texturing techniques

5.5.1: Aligning texture elements with the direction of steepest gradient descent

Lawrence [1971] describes the implementation of a once quite popular and very effective technique for illustrating cartographic relief called “hachuring”, in which the lengths, widths and directions of short strokes are defined, by a consistent set of rules, in such a way that they convey an strikingly three-dimensional impression of the depicted landscape. Lawrence puts forward the following six basic rules of “hachured relief”

- stroke lines are oriented in the direction of the steepest slope;
- the length of each individual stroke is kept short, so that the lines appear to be arranged in rows rather than to flow individually down the entire length of the slope;
- the width and the length of each stroke reflects the steepness and the extent of the drop in height; short, thick lines represent short, steep slopes while long, thin lines represent long, gradual slopes;
- line spacing is consistent for all strokes representing a particular slope class;
- line thickness is consistent for all strokes representing a particular slope class;
- if illumination is depicted, the lines will be relatively thinner in the more highly illuminated areas. (Ridgway [1938] unequivocally states that “in a hachured relief, the light should appear to come from the west”)

Figure 5.18, from [Ridgway 1938], contrasts the effects of using contour vs. hachured relief. Ridgway states, and I concur, that contour representations do not pictorially describe relief, although it can obviously be determined quite precisely through conscious effort. Inspired by the vividness of the intuitive sense of depth conveyed by the hachuring method and by the way in which it appeared to clearly represent local surface orientation or “depth flow”, I determined to see whether defining texture element orientation according to the direction of steepest gradient descent might not in some ways show shape as well or better than defining it according to the directions of maximum normal curvature. I did not set out to fully implement the hachuring technique, however.

Figure 5.18: Methods for the display of cartographic relief, from [Ridgway 1938]. Left: contour lines of elevation. Right: “hachure” lines following the direction of steepest downward descent.
Hachuring was intrinsically designed to be applied to surfaces defined as height fields relative to a ground plane, and to represent these surfaces from a specific vantage point in which the viewing direction is perpendicular to the ground plane. To successfully apply hachuring to a surface in three dimensions, we need first of all to determine an appropriate definition of the “down” direction, and there are two general sorts of possibilities. The approach that I took was to choose one particular direction, based on the inherent up and down orientation of the human body, and then define the texture element orientation over the entire surface according to the component of the surface slope in this direction, at each texture centerpoint. Figure 5.19-center gives an example of the kind of results I achieved with this implementation. (The alternative possibility, that I did not pursue, would have been to allow the “down” direction to vary, defining it, for example, in terms of a “central point” within a vaguely spherical object or a “central axis” within a vaguely elongated one.) A more faithful implementation of the hachuring algorithm would have defined the element placement over the surface to be at more or less equal intervals along the level curves of depth in the selected depth direction, defined the length of each element to reflect the distance between these level curves, and defined the width of each element according to the local steepness of depth descent. My intent, however, was not to faithfully reproduce the hachuring method but rather to look specifically at the effect of defining element orientation in this manner, for the purposes of comparison with the principal direction method. To obtain a representation equivalent to the one shown in figure 5.17-left in the case of the principal direction texture, I also implemented an option within the slope texture algorithm to vary the element length according to the magnitude of the gradient descent, the results of which are shown in figure 5.19-left.

While slope-directed texture may have much more promise than is suggested by these images, the requirements of a fixed viewpoint and an explicit down direction greatly limit the general applicability of the slope-directed texturing method as it is presently defined. We clearly don’t want to have to remap the texture as the object orientation changes with respect to the point of view (it would be distracting to have the texture shift around over the surface), but it is unclear how effective such a representation can be if the lines are viewed from an angle very different from a top view. Figure 5.19-right gives one example of the kind of results that are achieved if we keep the depth direction fixed and allow the viewpoint to vary.

Figure 5.19: Examples of a sparse, opaque surface texture in which element orientation is defined according to the direction of gradient descent. Left: “depth” direction = view direction, element length is proportional to the magnitude of the gradient descent. Center: “depth” direction = view direction, constant element length. Right: “depth” direction is the same as in the other two images but is no longer aligned with the view direction.
5.5.2: Inspiration from flow visualization techniques

If we could figure out how to describe surface shape in terms of a flow, there are a number of good flow visualization techniques [van Wijk 1993, Cabral and Leedom 1993], that might be applied to the problem with some success. One possible definition of surface flow might be the “depth flow” (around protrusions, along ridges and valleys) suggested by Koenderink and van Doorn [1995], but while this concept is fairly well-defined in the case of a height function, considerable thought would have to be given to its meaning on a three-dimensional surface. We have seen that the line drawing style of some medical illustrators bears close resemblance to a texturing scheme in which the form is described by a medial axis and illustrated by strokes representing planar cuts through the surface along this axis. One possible definition of depth, then, might be phrased in terms of the radius of the medialness function. I did not investigate either of these approaches.

5.5.3: Empirical investigations

In chapter six I describe my controlled experiments to obtain meaningful information about the practical impact that the use of three different types of surface texture can have on people’s ability to make accurately judge the shape of a transparent surface and its depth distance from an underlying opaque object. This type of study is really the only valid way to obtain such information. My intention in this section is merely to introduce and show examples of a tiny selection of the varied types of different texturing methods that could potentially be applied to a transparent surface, to allow an opportunity for empirical comparisons and to provide a small glimpse at some of the issues I examined in my efforts to develop a technique for conveying surface shape in an intuitively meaningful way.

Figure 5.20 shows, on the left, a plain, untextured transparent isointensity surface of radiation dose surrounding an opaque treatment region, and on the right the same isointensity surface rendered opaquely. I maintain that the shape of the dose surface is more clearly visible in the opaque rendering, while information about the relative locations of the two surfaces is, obviously, communicated more effectively in the transparent rendering. My general aim, in defining some parts of the outer surface to be opaque and while other parts remain transparent, is to explore the extent to which it might be possible to improve the portrayal of both shape and depth together.

Figure 5.20: An isointensity surface of radiation dose. Left: rendered as a transparent shell enclosing the target volume. Right: rendered as an opaque surface.
5.5.3.1: Element orientation

I have already described, in previous sections, both the motivation for and implementation of a texturing method in which short line elements are placed at fairly even intervals across a surface, oriented in the direction of greatest surface curvature and defined to be of a length proportional to the relative magnitude of the curvature in the depicted direction. Before presuming the preferability of such an approach, a few preliminary questions need to be at least raised if not answered: what kind of difference does line orientation make? what are the visual effects of applying texture elements to a surface in various alternative orientations? Figure 5.21 shows examples of several alternative methods for defining texture element orientation.

![Figure 5.21: Alternative methods for defining element orientation. Upper left: elements are oriented in the direction of greatest normal curvature. Upper right: element orientation is randomly determined prior to projection. Lower left: elements are oriented in the direction of gradient descent. Lower right: a constant predetermined element orientation is used. Texture element centerpoints, lengths and widths are identical in all four cases.](image)

5.5.3.2: Spot textures

In addition to the question of element orientation, there is also the question of element shape. There is some psychophysical evidence that people may be particularly good at perceiving subtle variations in the deformation of a circle into an ellipse and using this information to make fairly accurate local judgements of relative surface orientation [Stevens and Brookes 1987, Blake et al. 1993]. Although circular texture elements can sometimes describe slant and tilt very well, they are more ambiguous as descriptors of surface curvature. I have already
discussed some negative qualities of a relatively larger spot texture that makes it seem less than ideal for unobtrusively communicating surface shape information. As spot size and inter-element spacing decrease, however, the texture begins to more closely resemble a “stipple” pattern. Figure 5.22 shows the various effects of texture element size and spacing when orientation is unrepresented, and also demonstrates the importance of defining texture elements at specific locations on the surface rather than at regular intervals throughout the solid volume.

![Figure 5.22: Spot textures. Clockwise from the upper left: tiny dots, closely packed (similar in appearance to the “random dot” textures used in psychophysical experiments, but with the texture gradients appropriately represented); tiny dots, uniformly distributed in a slightly less dense manner over the surface; larger dots, uniformly distributed over the surface; larger dots, evenly spaced within the volume.](image)

5.5.3.3: Grid textures

One of the standard techniques for drawing lines on surfaces has been to simply mark the surface at regular intervals in object space. This is the effect achieved by the solid grid texture, which is shown in figure 5.23 in several variations. I have added nothing new here, and am showing these images only to illustrate one of the de-facto alternatives to the principal direction texture defined above.

One solid grid texturing method that I had wanted to explore but never got around to implementing defines a solid grid using spherical coordinates. With such a texture, the choice of centerpoint would be crucial, but it is not immediately clear what that choice should be; the lengths of the line segments between vertices would indicate the extent to which the surface differs in shape from a family of spheres centered about the same point.
Figure 5.23: “Solid grid” textures, marking the intersection of the surface with planes perpendicular to various axes of the volume. Upper left: a texture based on perpendicular planes at equal intervals along the “y” axis. Upper center: perpendicular planes at equal intervals along the “x” axis. Upper right: planes at equal intervals along both the “x” and “y” axes. Lower left: a texture based on perpendicular planes at equal intervals along the “z” axis. Lower center: the same texture as in the previous image, shifted in the volume by two voxel units in the axial direction. Lower right: a full solid grid texture, based on planes equally spaced along each of the three orthogonal axes of the volume.

5.5.3.4: Additional issues

Other texture issues that I didn’t touch on include variables of element connectivity or continuity and variables of a surface net, such as the number of edges per vertex, the angles at which edges meet at vertices, the lengths of the segments between various vertices, and so forth. Many different types of surface meshing schemes are possible, including Chebyshev nets [Koenderink 1990], ridge/geodesic line meshes [Cutting et al. 1993], “extremal” meshes [Thirion 1994], lines of curvature, etc.

In all cases, I defined the surface texture elements according to properties that were independent of the surface orientation or lighting. We have seen ample evidence that artists’ use of line to show shape appears to be closely bound with their use of line to show tone or shading. Ignoring (or ruling out) this shading aspect of line texturing may be a mistake. There are some difficult questions to be addressed, however, before shading information can be readily incorporated, not the least of which is how to ensure that the texture doesn’t change in any strident way with changes in object positioning, whether relative to the light source or relative to the viewpoint. Adopting a method for representing light in which the light is attached to the
surface and rotates with it is less than ideal; far less ideal is adopting an approach in which the texture markings move about in any noticeable fashion. In addition to varying the emphasis indicated by line element spacing, thickness or opacity in accordance with shape from shading information, there is also the possibility of varying the prominence of the texture as a function of either the distance from the silhouette or the angle that the surface normal makes with respect to the line of sight.

Rather than to exhaustively survey the possible texture pattern variables, my aim was to provide, through empirical observation and experimentation, slight insight into the different possibilities for using surface texture and the different kinds of results that can be achieved through varying different parameters. Before asking the importance of such differences, however, we must first investigate whether the addition of opaque texture elements to a transparent surface helps make its shape more accurately and intuitively understood and whether some kinds of texture show more promise in this respect than others (the real question of interest being what characteristics make one texture more effective than another). In the next chapter we begin to lay some groundwork for obtaining meaningful answers to these questions.
References for chapter five


