

SUPPORTING AUTOMATED PEN AND INK STYLE SURFACE ILLUSTRATION WITH B-SPLINE MODELS

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KEYWORDS: non-photorealistic rendering, terrain rendering, computer graphics

ABSTRACT:

This paper introduces a methodology for constructing pen and ink style landscape illustrations using B-spline surface models. After a brief discussion of the history of 19th and 20th century manual techniques and recent developments in automated non-photorealistic rendering (NPR) techniques, the paper discusses polynomial models for surface rendering and their implementation in the OpenGL graphics interface. The paper then discusses the generation of silhouettes and form lines for topographic surfaces from a set of triangulated vertices obtained from polygonal tessellations. An implementation of the methodology outlined in the paper is described and tested. The results are analyzed and suggestions for further research are presented.

1. INTRODUCTION

In the 19th century, William Henry Holmes, Grove Karl Gilbert, and William Morris Davis perfected the construction of pen and ink style representations of physiographic forms and processes (Fernlund 2000). Their drawings are characterized by a restrained application of strokes, each contributing a critical aspect of landform structure or process. Rendered features may be view-dependent, such as the silhouette of a hill against the sky, or represent some view-independent aspect of surface morphology, such as hydrologic ridges or valleys. Almost all such representations are rendered within perspective models. Later artists such as Armin Lobeck (1939, 1958), Erwin Raisz (1948) and Eduard Imhof (2007), produced a number of excellent works detailing the construction of pen and ink style landscape representations for students of physical geography.

To date, most attempts at automating pen and ink style surface rendering have been generated from digital elevation models supported by regular grid cell or triangulated irregular network structures. Although such models promote efficient surface processing, an 'artistic' rendering of the extracted features often requires an application of arbitrary smoothing techniques to remove angularity from linework on surfaces other than open rock faces. This paper presents a methodology, its implementation, and results for feature extraction and pen and ink style rendering from B-spline surface models. Polynomial surface representations are not, of course, new to automated cartography. Maxwell and Turpin (1968) propose the use of polynomial models for topographic surface representation for civil engineering projects. Although attractive with respect to the minimal storage capabilities of the time, such models require untenable execution times when applied to the modeling and rendering of fine-resolution surface processes. Fortunately, fine surface detail is often unwanted in pen and ink style representations of eroded landscapes. Furthermore, 3rd degree polynomial surface patches can be 'stitched' together while maintaining continuity at joins.

Both characteristics make polynomial surface patches artistic and reasonably efficient tools for pen and ink style rendering without resort to additional smoothing operations.

2. A BRIEF ANALYSIS OF MANUAL PEN AND INK STYLE SURFACE RENDERING

Davis's *Practical Exercises in Physical Geography* (1908) and its accompanying atlas provide students with a set of illustrations depicting archetypal land forms and exercises for interpreting them. The illustrations provide very clear examples of Davis's use of line density to depict variation in slope and directionality in illumination. His work is characterized by the application of innumerable, short strokes depicting drainage and surface forms. On first glance, many of his strokes look as though they are formed from long, drafted strokes. On closer inspection, many turn out to be composed of very short hatch marks. Even silhouettes and hydrologic ridge lines are sometimes drafted as a collection of short hatches pointing in the direction of steepest slope.

Lobeck (1958) provides explicit instructions for interpreting geomorphic features with linework but shading technique, varied by line density based on slope and lighting characteristics, is largely left as an interpretive exercise for the student. Imhof (2007), on the other hand, provides detailed instructions for rendering shading through hachures.

2.1. Previous Work in Automated Pen and Ink Style Rendering

Techniques for automating pen and ink style landscape rendering fall into the paradigm of non-photorealistic rendering (NPR). This project employs an NPR rendering approach, referred to by Markosian and others (1997) as "an economy of line," that comes closest to the intent of Davis, Lobeck, and other masters of pen

A special joint symposium of ISPRS Technical Commission IV & AutoCarto
in conjunction with
ASPRS/CaGIS 2010 Fall Specialty Conference
November 15-19, 2010 Orlando, Florida

and ink landscape representation. This approach attempts to depict the essential form of an object using a minimal number of strokes. We can classify the types of strokes as:

- Silhouettes—lines representing borders between visible and invisible regions from the point of view of the observer;
- Creases—lines representing important features that must be rendered without regard to the viewer’s position; and
- Form lines—lines depicting overall surface curvature.

Most of the previous work in NPR techniques for landscape rendering share this aesthetic but approach it with different techniques. Lesage and Visvalingam (2002) implement p-stroke sketching, a technique that shares similarities with the work of Tanaka (1932) on illuminated contours. Later work by Buchin and others (2004) describe a system for producing pen and ink representations through the application of scanned, hand-drawn slope and loose lines from a look-up table. Linework is assembled as a seamless patchwork of raster scans with density dependent on surface slope and lighting conditions. Their surface analysis is based upon the calculation of gradients and surface curvature. Large patches are filled in first; smaller patches fill the remaining spaces. Conflict resolution procedures prevent linework collision. Mower (2008, 2009) investigates the use of triangulated irregular network (TIN) surface models for fast pen and ink style rendering. Using an adaptive resampling technique that renders relatively constant-area triangular facets in screen space independent of depth from the viewpoint, it extracts silhouettes, creases, and form lines from the DEM relative to the observer’s point of view, and renders them as line segments on the surface. A comparison of their output to Lobeck’s line drawings show that the implementations rendered features similar to those of a comparable drawing but tended to undergeneralize surfaces due to noise in the underlying TIN model.

2.2. Using Polynomial Surface Modeling as a Framework for NPR

Lobeck (1958) suggests that the student visualize landscapes as surfaces of ideal geometric solids (cones, cylinders, hemispheres, etc.). This project takes the spirit of Lobeck’s advice and generalizes surfaces as polynomials derived from grid cell digital elevation models (DEMs). This has several important implications:

- Given that an appropriate tessellation of the surface polynomial produces triangular facets with relatively constant and sufficiently small screen space, linework density will vary minimally with respect to perspective depth;
- Local surface variations will be smoothed with respect to the polynomial surface,
- Calculation of surface properties can be performed easily through the calculation of normals for the tessellated facets; and
- The approach is relatively simple to implement and allows for experimentation with a limited number of variables.

2.3. Polynomial Surface Models

Much of the early work in DEM data structures and interpolation involving the use of polynomial equations for surface modeling is summarized by Mark and Smith (2003). Momentarily limiting our discussion to 2-dimensional curves for simplicity, polynomial representations are sensitive to the number of control points that influence the shape of the curve in their vicinity. A Bezier curve described by n control points (a polynomial curve of order n or degree $n - 1$) is shown in Equation 1 (Piegl and Tiller 1997).

$$C(u) = \sum_{i=0}^n B_{i,n}(u) P_i \quad (1)$$

where $0 \leq u \leq 1$, $B_{i,n}(u) = \frac{n!}{i!(n-i)!} u^i (1-u)^{n-i}$, and P_i is a control point.

In Equation 1, $B_{i,n}(u)$ is referred to as a blending or basis function, u is a normalized parameter with a value of 0 at the start of the curve and 1 at its end, i is the index of the current control point, and n is the degree of the curve (the number of control points minus 1). Unfortunately, Bezier basis functions become numerically unstable as n increases and the dependant values of the factorial computations exceed those that can be represented in standard integer or floating point storage types. Fortunately, low order Bezier curves can be appended or ‘stitched together’ to form larger piecewise polynomial curves under specified constraints of continuity at the joins. For rendering purposes, the most popular of these forms is the B-spline (or basis spline) curve. Like Bezier curves, B-splines extend easily to 2-dimensional surface representations through the addition of a second parameter v . The influence that a particular basis function exerts over a portion of the surface is controlled by 2 arrays of ‘knots,’ values that specify the range in u and v over which the value of a basis function is non-zero. A piecewise surface is infinitely differentiable in its interior but not so at its joins; this project utilizes piecewise surfaces of degree 3 with continuity up to the 2nd derivative at joins, sufficient for rendering purposes without producing noticeable edge artifacts.

3. CREATING AND RENDERING GEOMETRY

The author wrote the pen and ink rendering system described in this paper in C++ with links to the OpenGL v. 2.1 software interface for graphics rendering hardware. OpenGL provides a high-level interface for non-uniform, rational, B-spline (NURBS) curves and surfaces (Shreiner and others 2008) that can also be used to construct the uniform, non-rational, B-spline surface renderings of the type implemented in this project. In either case, the surface is specified by a regular (but not necessarily square) grid of 3-dimensional control points. The NURBS rendering engine creates a polygonal tessellation over the region described

by the control points such that the screen space occupied by a polygonal facet is independent of its distance from the viewpoint in world space. Figure 1 illustrates an enlarged wireframe view of a portion of a tessellation.

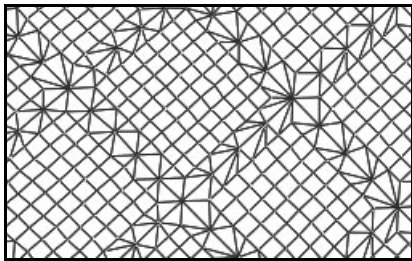


Figure 1. A large-scale view of a tessellated B-spline surface.

OpenGL provides callback functions that allow the programmer to retrieve the vertices of a tessellated surface. The vertices can then be incorporated into a TIN data structure through functions provided by the open source CGAL geometry library (CGAL Editorial Board 2007). CGAL provides an interface for building a 2D Delaunay triangulation from a set of 3D vertices using easting and northing for spatial coordinates and elevation as a triangulated vertex attribute. Although CGAL provides an n-dimensional triangulation interface, 2D triangulation is generally most appropriate for non-wrapping sections of topographic surfaces.

3.1 Building a B-spline Surface from Elevation Data in OpenGL

Figure 2 illustrates the project data stream. Elevation samples are extracted from 10m horizontal resolution grid cell DEM source files in USGS 1:24000 native format and stored in an internal rectangular grid (referred to here as an arbitrary grid). The samples in the arbitrary grid are passed to the NURBS renderer which interprets them as control points for a degree 3 B-spline surface. The rendering engine produces 2 products: 1) an image held in the graphics hardware z-buffer (the surface mask), and 2) a set of 3D points representing the vertices of the tessellated B-spline surface. Figure 3 shows a sample rendering of a B-spline surface using a non-emissive color. The vertices are passed to the CGAL Delaunay triangulation interface where they are assembled into topologically-related lists of triangle facets, edges, and vertices. Form lines and silhouettes are rendered from edges as appropriate. The image, rendered in the emissive background color (without terrain shading) serves as a surface mask to hide linework that may be rendered behind the surface closest to the observer's point of view. See Mower (2009) for a complete description of this process.

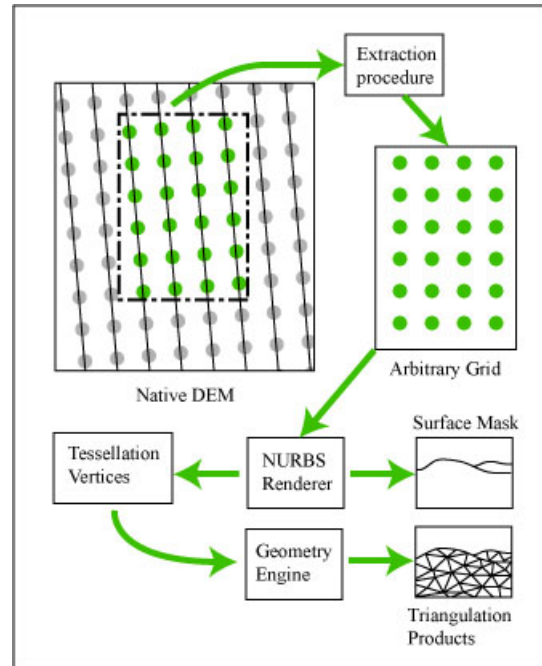


Figure 2. The data stream. The NURBS rendering engine uses a rectangular grid of extracted samples (the arbitrary grid) to create a rendered image (the surface mask) and a set of polygon vertices from the dense surface tessellation. The geometry engine assembles the tessellation vertices into a Delaunay triangulation with topological relationships among the triangle facets, edges, and vertices (triangulation products).

To reduce unnecessary processing, tessellated vertices are projected to viewport (screen) coordinates and rejected for triangulation if they are located outside the bounds of the window.

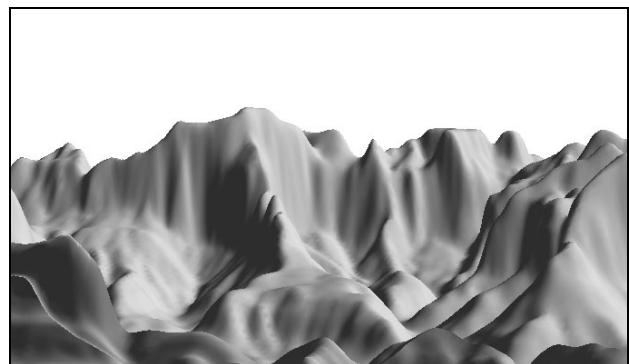


Figure 3. An arbitrary grid rendered as a B-spline surface with non-emissive gray shading. The viewpoint and viewing angles for this image are shared with those of Figures 8 through 13.

Although a surface mask requires emissive shading in the background color, this figure uses non-emissive shading for purposes of illustration.

3.2 Finding and Rendering Silhouettes

For the observer, a silhouette is the line marking the boundary between surface and sky. We can look for silhouettes in the triangulation by checking the visibility of pairs of adjacent triangular facets. If one of the facets faces the viewer and the other faces away, the boundary between them is a silhouette. Visibility is determined by the angle made between the facet normal and the vector from the observer to the facet. If the angle is between 0 and 90 degrees, the facet is visible; otherwise it is invisible. If one of the adjacent facets is visible and the other is not, the edge is rendered as a silhouette. Since the surface tessellation produces a very dense triangulation, edges are sufficiently short to suggest curvature when rendered with other connected segments. Figure 4 shows the silhouettes that were generated for the scene in Figure 3.

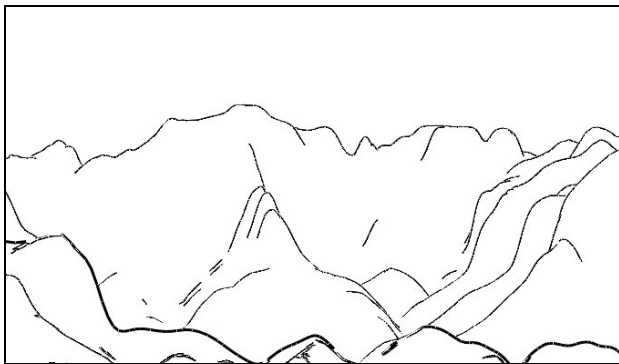


Figure 4. Silhouettes generated for the scene in Figure 3. The surface is rendered in emissive white and now serves as a depth or surface mask, hiding silhouettes drawn behind the surfaces nearest to the viewpoint.

3.3 Drawing Form Lines with a Dense Drainage Direction Model

Form lines are considerably more difficult to define than are silhouettes. An inspection of many of the illustrations produced by Davis suggests that most of the drafted form lines can be interpreted as drainage direction vectors (Figure 5).

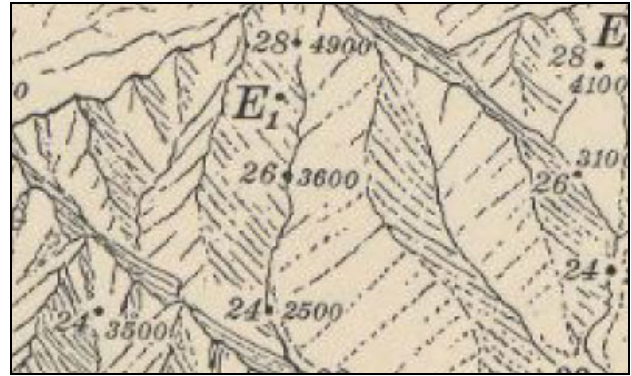


Figure 5. A section of an illustration by W.M. Davis. Form lines perpendicular to ridges mimic drainage direction vectors. Differential density of form lines suggests an illumination source from the left. From Davis (1908), *Atlas for Practical Exercises in Physical Geography*.

The program developed for this project (PenAndInk) implements this approach through a 2-step procedure incorporating an illumination model (Figure 6). First, a drainage direction map is created. For every vertex in the triangulation, the connected vertex with the steepest downhill slope is identified and marked as its sink. The edge containing the starting vertex (the source) and sink vertices represents the drainage direction vector for the source. Second, the normal of the source's parent facet is evaluated to determine the slope of the facet and its illumination value with respect to the user-specified light source vector. Edges that belong to facets with steep slopes and aspects facing away from the incoming light source are rendered with lines of maximum thickness. Those belonging to facets on gentle slopes facing the light source are rendered with the thinnest form lines or none at all. The width of a given stroke is calculated using Equations 2 through 4:

$$SlopeC = SR \times MW \times SW \quad (2)$$

$$ShadeC = (1 - w) \times MW \times (1 - SW) \quad (3)$$

$$WF = SlopeC + ShadeC \quad (4)$$

where SR is the slope of the facet, stated as a ratio from 0 to 1 (where an SR of 1 is equivalent to a vertical slope), MW is the maximum line width in points, SW is a ratio from 0 to 1 expressing the weighting of slope over lighting (where a slope weight of .4 implies a lighting weight of .6), and W is the weight of the line in points. Slope weighting is controlled by a user interface parameter.

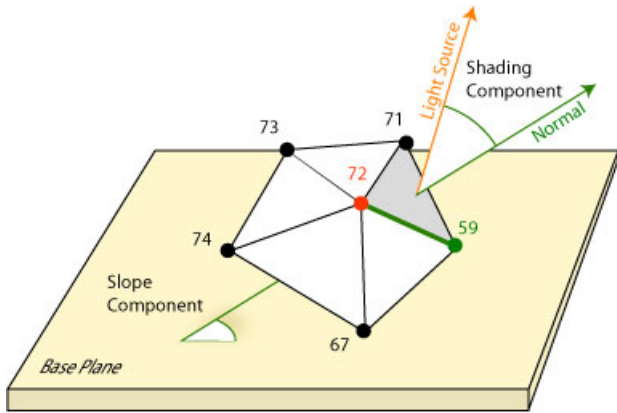


Figure 6. The form line attenuation model. For the source vertex at 72 m elevation, the vertex at 59 m is found to be the sink. The green edge represents the drainage direction. The angle between the parent facet normal and the light source vector provides the shading component. The angle between the normal and the base plane provides the slope component.

The dense triangulation produced from the tessellated vertices, combined with an appropriate initial form line width, provides a smooth shading gradient from steep and shadowed regions to those that are flat and directly illuminated. Since edges in a Delaunay triangulation are guaranteed not to cross one another, conflict resolution is not required and no additional geometry need be created. Figure 7 describes a portion of a scene rendered by PenAndInk.

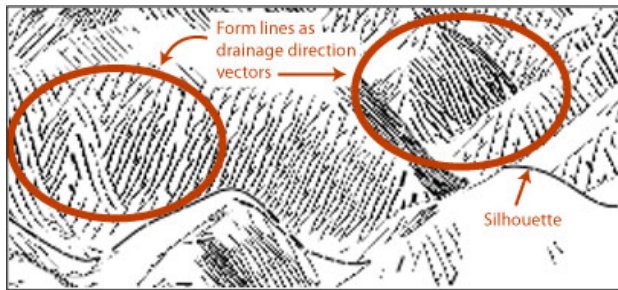


Figure 7. Linework rendered by PenAndInk shown at 1.5x enlargement over the original image.

4. RESULTS

A series of images in the vicinity of the West Temple feature in Zion National Park were generated from an arbitrary grid containing 120 rows and 140 columns of elevation samples with a horizontal resolution of 50 meters.



Figure 8. The West Temple feature of Zion National Park. The scene is shown at approximately 75% of its original size to satisfy the formatting constraints of the *Proceedings*.

Figure 8 shows the entire scene generated from a viewpoint at UTM coordinates 320249m E, 4116000m N, Zone 12, with an elevation of 2835m. The viewing azimuth and altitude are 295° and 0° respectively. A field of view of 18° and a vertical exaggeration factor of 1.5 were used to frame the scene. Figures 9 through 13 represent extracted portions of images that vary in maximum form line width, the weighting of slope over aspect for line density calculations, and the direction of the light source. The lighting, line width, and slope weighting parameters for these figures are listed in

Table 1.

Figure	Light Az. (degrees)	Light Alt. (degrees)	Max form line width (pts)	Slope weighting
8	250	45	3	40%
9	250	45	3	40%
10	250	45	2	40%
11	250	45	3	90%
12	250	45	3	10%
13	70	45	3	40%

Table 1. Lighting and line width parameters for Figures 8 through 13.



Figure 9. Maximum form line width of 3 points.



Figure 10. Same viewing parameters as the image in Figure 9 but with a maximum form line width of 2 points.

Figures 9 and 10 depict the same portion of the scene but differ in the maximum width permitted for form lines. Both images use a weighting of 40% for absolute slope (slope component) and 60% for lighting (shading component). Any line with an attenuated width less than 1 point is not rendered.

Figures 11 and 12 show the effect of changing the bias between the absolute slope and shading parameters. Both images use a maximum form line width of 3 points. With a weighting of absolute slope of 90%, gentle surfaces on Figure 11 demonstrate the domination of slope over shading in the attenuation of line widths. Figure 12 weights absolute slope by 10%, attenuating line width primarily by light source direction. Note the differences in rendering of the hilltop at the upper left of both images.



Figure 11. Maximum line width of 3 points. Line width attenuation is weighted by 90% for absolute slope, 10% for lighting. The flat hilltop at the upper left is bright.



Figure 12. Maximum line width of 3 points but line width attenuation is weighted by 10% for absolute slope and 90% for lighting. The hilltop at the upper left is now dark.

In Figure 13 the light source has been rotated 180° in azimuth from that of the other figures. Surfaces facing the lower right (the direction toward the light source) now receive high shading attenuation.



Figure 13. This figure uses the same line width parameters as Figure 9 but with a light source at an azimuth of 70 degrees.

5. CONCLUSION

This paper has demonstrated a non-photorealistic rendering methodology for topographic surfaces using pen and ink style strokes. It has provided a new technique for rendering form lines from a set of dense drainage direction vectors, attenuated by local slope and shading characteristics. Future work in this area will explore automated light source positioning to improve overall feature representation and the addition of hydrologic ridge rendering.

The author hopes that this work contributes to an understanding of the construction of pen and ink style landscape illustration while renewing interest in the artistry of the work of the 19th and 20th century masters of the discipline.

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