Real-time Principal Direction Line Drawings of Arbitrary 3D Surfaces

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Introduction and Related Work

Computer-generated line drawings [4,7] are becoming an increasingly popular method of non-photorealistic rendering (NPR). While many factors contribute to an effective line drawing-- quality of line, line placement and density-- line direction is among the most critical for conveying surface shape. The principal directions hold particular promise in this respect [2]. In a human perceptual study, subjects displayed consistent biases toward perceiving surface contours (lines drawn on the surface) as being aligned with the principal directions [5]. Despite the potential for principal directions and their suggestion by previous authors [1,2,7], there are currently no available techniques for using them to render viewpoint-independent line drawings of arbitrary 3D surfaces. The line drawing algorithm of Markosian et al. [4] handled arbitrary 3D surfaces, but line direction was chosen in a viewpoint-dependent manner and lines tended to cluster on silhouette edges with little interior curvature information.

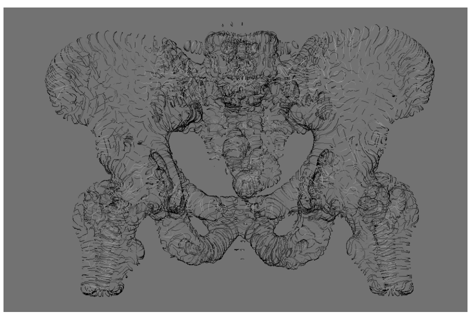

Figure 1: Principal direction line drawing (without hidden surface removal) of a bone/soft tissue boundary surface in a CT volume data set.

Interrante [2] used a 3D principal direction texture to show the shapes of transparent isosurfaces in volume data. Stalling [8] suggested line drawing based on 3D streamlines following the principal directions. Figure 1, derived by these methods, was a motivating factor for this research. However, because of the desire to handle not only volume data but also surface data, this work focuses on the application to polygonal meshes. The major contribution of this work is to motivate the use of principal directions in line drawings and show how to apply them to arbitrary polygonally defined 3D surfaces. The result is a viewpoint-independent set of shaded strokes which can be rendered in real time.

Estimating Principal Directions on a Polygonal Mesh

Much of the difficulty of this problem lies in accurately computing smoothly continuous estimates of the principal directions at arbitrary points on a potentially coarse polygonal mesh. The method we use was proposed by Taubin [6]. First, adjacency information and vertex normals are computed. Then for each vertex v_i, we construct a symmetric matrix M_{v_i} based on the weighted sum of the projected directional curvatures of the edges in the neighborhood of v_i. The eigenvectors of M_{v_i} are the normal and two principal directions which together form an orthonormal basis at v_i. To determine the principal directions we must restrict M_{v_i} to the tangent plane and then diagonalize the 2x2 submatrix of the transformed M_{v_i}. The principal curvatures can be calculated with a simple linear transformation on the corresponding eigenvalues. The algorithm is linear in time and space as a function of the number of vertices and faces of the polygonal surface.

Tracing Lines Over the Surface

The collection of estimated principal directions results in a vector field over the surface. We trace long curved strokes whose directions are determined by the flow of the vector field. To maintain an approximately even line density and avoid line crossings, the choice of each line's starting point and length is crucial. We extend the placement strategy of Jobard et al. [3] from 2D images to the 3D surface. Line starting points are chosen randomly on the surface with the constraint that they lie at a minimum distance from existing lines.

In umbilic regions where the surface shape is locally planar or spherical, the principal directions are undefined because there is either zero or equal curvature in all directions respectively. If a vertex with an undefined principal direction is surrounded by vertices with well-defined principal directions, the line direction is linearly interpolated from points in the neighborhood. If there are no neighboring well-defined principal directions or if there is a sudden change in surface curvature, the line is terminated. After the coordinates of all the lines are determined, there are several visual enhancements we used to improve the overall image. Line shading and hidden line removal were added using the normals of the underlying mesh. To give the image a hand-drawn appearance, the principal directions were jittered in a random fashion to cause waviness in the lines. We found that a slight waviness of less than 1% is enough to provide the desired effect while allowing the lines to still flow in the principal directions.

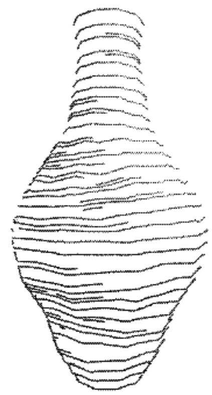

Figure 2: Principal direction line drawing of a vase. Mesh consists of 400 triangles.

Implementation and Results

We implemented this work in OpenGL. Our implementation used triangular meshes but is generalizable to other polygonal meshes. There are several rendering parameters which may be varied for different visual effects, such as the number of lines, line density, length, or waviness. Figure 2 shows the technique applied to a coarse triangular model of a vase.

Conclusions and Future Work

We are engaged in ongoing efforts to refine and improve the techniques used to estimate the principal directions, and want to immediately begin to apply this technique to more complex models. Future work will incorporate additional methods for maintaining continuity through umbilic regions and aesthetically merging opposing lines of force. The perceptual efficiency of principal direction lines for the understanding of surface shape will hopefully be a continuing area of research.

Acknowledgments

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