

Published Research on Line Drawings from 3D Data

The following list contains papers describing algorithms for producing line drawings from 3D data, as well as research on the perception of line drawings. Papers marked with an asterisk (*) are the most closely related to this course, and are recommended reading. Detailed bibliographical information follows this annotated list.

Before 1990

- [Appel 1967] Introduces an efficient algorithm for discovering hidden lines in drawings of 3D shapes by propagation of *quantitative invisibility*.
- [Waltz 1975] Applies the technique of constraint satisfaction to search for consistent labelings of lines in line drawings of polyhedral scenes. It works from exhaustive catalogs of all possible configurations of line junctions.
- [Barrow 1981] Describes algorithms for the reconstruction of surfaces from line drawings by making a range of assumptions (i.e. about surface smoothness).
- [Stevens 1981] A description of how repeated arrangements of lines in line drawings can give rise to shape percepts. Parallel lines (cutting lines), geodesics and lines of curvature are investigated.
- [Koenderink 1982] A discussion of what lines artists might be drawing. It includes a proof that ending contours must terminate in a concave way, yet points out that artists often draw convex endings.
- * [Koenderink 1984] Seminal paper establishing the relationship between the curvature of the contour in the image (the apparent curvature) and the Gaussian curvature of the corresponding point on the surface.
- [Pearson 1985] Examined the use of image valleys for producing line drawings from photographs.
- [Canny 1986] Classic method for edge-detection in images.
- [Malik 1987] The generalization of line labeling [Waltz 1975] to curved surfaces. It also includes an algorithm for pruning away unlikely interpretations.

1990

- [Dooley 1990] Describes automatic generation of boundary, silhouette, discontinuity, and iso-parametric lines to depict 3D objects. Main focus is on stylization with an importance, line type, and hiddenness matrix.
- [Elber 1990] Defines boundary, silhouette, discontinuity, and iso-parametric curves mathematically. Describes curve extraction, intersection, and visibility methods for B-spline surfaces. Visibility propagates quantitative invisibility.
- [Koenderink 1990] Well-known and well-respected book on geometric and perceptual aspects of shape.

- * [Saito 1990] Uses 2D image processing algorithms to draw discontinuities, edges, and iso-parametric lines over 2D renderings of 3D models.

1992

- [Knill 1992] Describes perceptual experiments that suggest our perceptual systems assume that surface markings (i.e. reflectance boundaries) line along geodesics on the surface.
- [Rossignac 1992] Introduces a method of hidden-line removal for contours using the hardware z-buffer.

1994

- [Hsu 1994] Introduces a comprehensive framework for describing and rendering heavily stylized complex 2D strokes.
- [Saito 1994] Proposes interactive visualization of volumetric data by hierarchically sampling areas of interest from the data and rendering oriented lines.
- * [Salisbury 1994] Presents interactive user-driven methods for creating line drawings by painting texture and tone over a 2D reference image, with optional extracted edges.
- * [Winkenbach 1994] Describes general principles for creating computer generated line drawings from 3D models. Introduces stroke textures to apply resolution-dependent texture and tone to 3D polygonal surfaces. Describes *indication*, a technique for elision of detail in drawn textures to enhance comprehensibility of line drawings.

1995

- [Elber 1995a] Describes generation of line-art drawings using iso-parametric curves to cover freeform surfaces. A lighting model affects the density of curves and noise is added to avoid a synthetic look.
- [Elber 1995b] Presents several ideas for the improvement of line drawings from 3D surfaces. Suggests performing depth cuing by modulating line width and intensity, drawing thin light strokes for background lines. Trimming of background lines near intersections is also suggested.
- [Interrante 1995] Suggests using ridge and valley lines as an aide to transparent isosurface visualization. Lines are extracted from an isosurface and opacity is modulated by principal curvature.

1996

- [Interrante 1996] Describes rendering of transparent isosurfaces using short strokes directed along principal curvature with length modulated by principal curvature magnitude.
- [Koenderink 1996] A psychophysical study that measures and compares shape percepts from (external) silhouettes, line drawings and shaded images. It uses the same psychophysical tasks as [Koenderink 2001].

- [Salisbury 1996] Suggests representing pen-and-ink drawings with a grayscale image, a set of discontinuity segments, and associated stroke textures for the purposes of producing consistent drawings at any scale and resolution. A novel edge-reconstruction algorithm allows low-resolution grayscale images to be up-sampled while maintaining sharp discontinuities. Line drawings are created by rendering the stroke textures on the grayscale image.
- [Thirion 1996] Introduces the marching lines algorithm for extraction of line loops along intersections of two closed surfaces in 3D space. Describes drawing crest lines as an aide to visualizing isosurfaces by intersecting a maximal curvature surface with the isosurface.
- [Winkenbach 1996] Describes rendering line-art drawings from parametric freeform surfaces. Details controlled-density hatching to modulate line width based on proximity to other lines. Also introduces a method to construct a planar map for a parametric surface and a method of rendering shadows with strokes.

1997

- [Ma 1997] Argues for the benefit of extracting feature lines (contours, ridges and valleys) from unstructured triangular meshes. Presents some results in the context of augmenting fluid flow visualization.
- * [Markosian 1997] Introduces a fast randomized algorithm for finding and tracing contours on polygonal surfaces. Exploits frame-to-frame temporal coherence and uses random probes to locate contour seed points and trace contours along the surface. Uses an accelerated quantitative invisibility propagation method to differentiate hidden lines.
- [Masuch 1997] Describes a system for creating animated line-drawings from 3D polygonal objects.
- [Rieger 1997] Presents comprehensive derivations and analysis of intensity ridges and valleys, edges, and other lines defined on images.

1998

- [Belyaev 1998] Details and derives formulas for ridges and valleys on implicit surfaces. Uses these to generate ridges and valleys on an implicit surface as the intersection curves of a ridge and valley surface with the implicit surface.
- [Bremer 1998] Describes a method of extracting silhouettes from implicit surfaces using a seed-and-traverse method. Seeding is performed by ray-surface intersection and walking along the surface to a silhouette. Traversal is done by Euler integration with a penalty to avoid iterative drift.
- [Elber 1998] Describes a method for creating line art renderings from freeform parametric surfaces based on a uniform point sampling of the surface that is independent of the surface parameterization.
- [Gooch 1998] Proposes an NPR color shading model to augment line drawings in technical illustrations.
- [Hamel 1998] Introduces transparency in line drawings by modifying line width, density, or style for occluded surfaces. Uses several static 2D renderings of a scene with transparency enabled and disabled as input to a line drawing algorithm.

- [Koenderink 1998] A comprehensive overview of the structure of relief (i.e. images, height fields, etc...) that covers everything from the historical development of the concepts of ridges and valleys, to differential structure, to linear features such as the occluding contour and cliff curves (closely related to suggestive contours). Note: this was written for physicists, so expect math.
- [Masuch 1998a] Extends the daLi! system for creating animated line-drawings from 3D objects with frame-to-frame coherence.
- [Masuch 1998b] Describes an application of the daLi! line-drawing system in visualizing ancient architecture.

1999

- [Barequet 1999] Introduces a method for efficiently detecting silhouette edges in 3D meshes by solving a dual problem of intersecting a plane with line segments.
- [Belhumeur 1999] A theoretical development of the ambiguity present in shaded imagery. The generalized bas-relief transformation also preserves contours and shadow boundaries.
- [Benichou 1999] Details a method that allows for real-time selection and rendering of a complete set of silhouette edges from a 3D mesh after a preprocessing of the mesh.
- [Elber 1999] Introduces an interactive method for rendering of silhouette strokes from freeform models. Generates silhouette-oriented strokes in a preprocessing step and uses an accelerated data structure to selectively render them in real-time.
- [Gooch 1999] Outlines aspects of an interactive technical illustration system for 3D polygonal models. Describes hardware and software methods of drawing silhouettes as well as NPR shading models and shadows.
- [Raskar 1999] Describes a hardware-accelerated method for rendering silhouette edges. It renders back-facing polygons offset towards the camera, such that they show through front-facing polygons.

2000

- [Deussen 2000] Details an algorithm for the creation of pen-and-ink drawings of trees. Uses silhouettes and hatching to render trunks and branches. Combines individual leaves into larger groups represented by abstract shapes to render foliage.
- [Ebert 2000] Introduces NPR rendering techniques for volume illustration. Topics covered include boundary and silhouette enhancement, feature halos, and tone shading.
- [Girshick 2000] Argues for the merit of using lines along principal directions for conveying 3D shape. Presents psychological evidence to support the importance of principal direction in perception. Describes the creation of principal direction vector fields on surfaces and the tracing of strokes through the vector field to create line drawings.
- * [Hertzmann 2000] Describes line drawing rendering techniques for smooth mesh surfaces. Includes algorithms for fast deterministic detection of silhouettes using a dual surface intersection, cusp detection, visibility, and computation of smooth direction fields suitable for hatching strokes.

- [Lake 2000] Describes drawing silhouette edges with special strokes based on underlying curvature, and screen-space stroke texturing for hatching and shading.
- [Northrup 2000] Details a set of rendering methods for lines extracted from 3D geometry. Describes how to smooth self-intersecting silhouette edges in image space and create longer, cleaner silhouette paths using an ID reference image. Suggests rendering line paths as texture-mapped triangle strips to achieve various artistic brush stroke effects.
- [Rossi 2000] Creates a specific style of line-art drawings from 3D models using hatching along principal directions. The object is rendered with surface information (normal, curvature) to image space where user-guided segmentation is performed. Hatching is applied to segmented components along their principal directions.
- [Sander 2000] Contains a section on efficient silhouette detection using a hierarchical cone structure.
- [Treavett 2000] Introduces 3D and multi-pass 2D methods for pen-and-ink rendering of volumes using procedural textures in a standard volume rendering pipeline. Discusses integration of the NPR steps with traditional rendering steps to generate images that are mixed photorealistic and NPR.

2001

- [Csébfalvi 2001] Presents a fast, automatic algorithm for visualization of contours in volumes by rendering areas of high gradient magnitude modulated by a view-dependent term. Details optimizations required to achieve interactive rendering.
- [Gooch 2001] Book describing a variety of non-photorealistic rendering techniques and effects.
- [Knill 2001] Connects the information provided by geodesics on surfaces with homogenous texture “flow”.
- [Koenderink 2001] A fantastic development that connects the bas-relief ambiguity [Belhumeur 1999] in shaded imagery with a series of psychophysical experiments that demonstrated that percepts arising from photographs of simply shaded objects respect this ambiguity. The psychophysical tasks described here could be used to measure percepts of NPR imagery.
- [Page 2001] Extracts ridge and valley lines from 3D objects using curvature estimated with a normal voting approach.
- [Praun 2001] Describes a hardware-accelerated method of rendering 3D polygonal models with light-dependent hatched shading in real-time. Textures are oriented along principal directions such that hatching marks convey surface shape.
- [Raskar 2001] Adapts previous two-pass hardware-assisted rendering techniques to single-pass rendering of silhouettes and creases using modern graphics hardware.
- [Watanabe 2001] Detects ridge and valley triangles on meshes by looking for curvature extrema on the “focal surface.” The extreme regions are thresholded and thinned.

2002

- [Isenberg 2002] Describes an algorithm that simplifies self-intersecting silhouette edges from 3D meshes to create longer, cleaner paths suitable for stylized rendering. Differs from previous approaches by using z-buffer techniques and avoiding the use of an ID reference image.

- [Kalnins 2002] Details an interactive NPR rendering system for 3D meshes which allows for artist annotated strokes and brush styles to be consistently rendered across multiple frames and viewpoints. Artist input from one viewpoint is synthesized and propagated for other viewpoints and several models of scale-varying hatching are introduced.
- [Lu 2002] Presents an interactive NPR volume rendering technique using stippling. Includes provisions for enhancement of silhouette and boundary regions and a method of sketching silhouette curves.
- [Lum 2002] Describes a hardware-accelerated parallelized NPR volume rendering method for large volumes. Renders with tone shading, silhouettes and depth cuing at interactive frame-rates on computer clusters.
- [Martin 2002] Introduces a method for creating flat silhouettes from 3D meshes suitable for stylized rendering. Results in an ordered stack of 2D filled polygons which together compose a line drawing of the 3D model.
- [Strothotte 2002] Provides an introduction and overview of NPR rendering methods and areas of application. Explains 2D and 3D algorithms for pen-and-ink, pencil-sketch, painterly-effects, and other NPR effects.
- [Webb 2002] Builds on [Praun 2001] by introducing refined control over hatching strokes, allowing for light areas to be textured with a few strong strokes.

2003

- * [DeCarlo 2003] Describes a class of lines defined on a surface, *suggestive contours*, which complement the set of surface contours in depicting shape. Suggestive contours provide interior detail to line drawings and are defined at points with radial curvature of zero. Both object-space and image-space extraction algorithms are provided.
- [Dong 2003] Introduces new non-interactive silhouette and hatching algorithms for volumetric data sets. Hatching strokes for a surface are generated from the surface as well as from data throughout the volume enclosed by the surface.
- * [Isenberg 2003] Surveys a wide variety of silhouette extraction algorithms for polygonal models.
- * [Kalnins 2003] Describes a method for maintaining frame-to-frame temporal coherency for stylized silhouettes by propagating line stroke parameterizations between frames.
- [Kindlmann 2003] Transfer function-based rendering of contour and ridge and valley lines in volume data. Contour thickness is controlled using estimated curvatures, and ridges and valleys are emphasized by thresholding principal curvatures.
- * [Pauly 2003] Extracts ridge and valley lines from unstructured 3D point clouds. Performs a scale-space analysis to keep the most important lines at multiple scales.
- [Phillips 2003] Demonstrates that people can consistently mark ridges and valleys in shaded images. Also includes discussion on the presence of ridges and valleys in line drawings.
- [Sousa 2003a] Details a fast but non-interactive method for creating precise ink drawings from highly tessellated 3D models. A fraction of mesh edges are selected to become strokes and are drawn with width modulated by surface curvature.

- [Sousa 2003b] Describes a complete system for generating line drawings from 3D meshes. Extracts silhouettes, boundaries, ridges, and valleys; chains lines together; fits curves to paths; and renders paths sparsely with varying line width.
- [Whelan 2003] Introduces a method for augmenting silhouettes for rendering terrain, by including silhouettes computed from viewpoints different from the actual camera position.

2004

- [Ashikhmin 2004] Presents a simple image-based approach to rendering silhouettes from 3D meshes without any preprocessing of the mesh surface.
- [Brosz 2004] Introduces an improved method of silhouette selection by considering the stability of silhouettes over potential silhouette edges. Resulting silhouettes can be stylized and drawn with frame-to-frame coherence.
- * [DeCarlo 2004] Discusses the motion and stability of suggestive contours on surfaces and describes an algorithm for interactive suggestive contour extraction and rendering.
- [Gooch 2004] An evaluation of methods for facial illustrations and caricatures that compares photographs and drawings. It turns out that illustrations are learned faster than photographs in recognition tasks.
- [Grabli 2004a] Describes a Python-based programmable architecture for the creation of NPR line drawings. Includes capabilities for line-type selection, line chaining, and stylization as well as descriptions of the requisite data structures and support algorithms.
- [Grabli 2004b] Introduces a method for measuring density in line drawings and a simplification method based on such density information. Differentiates between density measured in a completed drawing versus density measured during the drawing process. Discusses indication as well as stroke prioritization.
- [Kalnins 2004] Discusses the previously introduced WYSIWYG NPR system in more depth, with sections about stroke representation, visibility, media simulation, temporally-coherent line stylization, and annotated hatching.
- [McGuire 2004] Describes GPU hardware methods for extracting and rendering stylized silhouettes from 3D meshes. Creates an edge mesh with edge information stored at its vertices, allowing for the vertex shader to operate on edge information.
- [Nagy 2004] Describes a GPU hardware method for rendering silhouettes on volumes. Uses texturing hardware and the fragment shader to generate thin image-space lines, which are then broadened and rendered.
- * [Ohtake 2004] Estimates curvature and curvature derivative of 3D objects using implicit function fits, then extracts ridge and valley lines using these estimates. Curvature-based filtering is used to keep the most significant lines.
- [Raskar 2004] Introduces a camera and multi-flash setup for acquisition of silhouettes of real-world objects.
- [Schein 2004] Presents a method for extracting silhouettes from volume data by modeling the data with trivariate tensor product B-spline functions and extracting silhouettes from the implicit function representation.

- [Wilson 2004] Introduces a method for rendering line drawings from complex 3D geometry in a comprehensible expressive manner. Areas of high complexity are rendered with abstraction by using a hybrid 2D/3D rendering approach.
- [Xu 2004] Presents an algorithm for real-time rendering of silhouettes from unstructured 3D point clouds.
- [Zakaria 2004] Introduces an algorithm for interactive extraction of stylized silhouettes from unstructured 3D point clouds.
- [Zander 2004] Describes an algorithm for high-quality rendering of hatching on 3D meshes by selectively rendering streamlines derived from surface curvature.

2005

- [Barla 2005] Introduces a clustering method to reduce screen-space line complexity. Similar lines are clustered together and replaced by a representative line.
- [Belyaev 2005] Extracts ridge and valley lines from noisy range data, including de-noising of normals via nonlinear diffusion and Canny-like nonmaximum suppression.
- [Burns 2005] Introduces an interactive method for probabilistic extraction and rendering of contours and suggestive contours from volume data.
- [Jeong 2005] Controls line density at different scales by computing a progressive-mesh representation of the model, then extracting lines on a mesh with an appropriate view-dependent level of detail.
- [Lum 2005] Uses an example based approach to allow the user to select which lines to render from a large candidate set. The user's examples are used to train a machine learning classifier.

2006

- [Coconu 2006] Presents a method for pen-and-ink illustration of scenes including large numbers of trees. Trees and other objects are represented by hierarchical set of spheres or other abstract shapes.
- * [Cole 2006] Presents an interactive system for placing visual emphasis in stylized renderings. Includes a method for temporally coherent line density control. Analyzes the effect of the emphasis using an eye-tracking experiment.
- [Isenberg 2006] Proposes a framework for storing multiple attributes, such as visibility, with a stroke throughout the rendering pipeline, and applying rendering effects based on these attributes just before the final drawing step.
- [Lee 2006] Describes a technique for rendering in a pencil drawing style. Contours are drawn with error and over-sketching, and hatching textures imitate pencil strokes.
- [Ni 2006] Controls line density at different scales by pre-computing multiple levels of smoothing for the target model. These different smoothed models are then interpolated at runtime, and lines extracted from the interpolated result.

2007

- [Breslav 2007] Defines a way to map screen-space patterns onto 3D models so that the patterns move closely with the model, but remain parameterized in screen-space. Related to [Kalnins 2003], but with 2D patterns instead of line textures.

- * [DeCarlo 2007] Introduces new object-space line definitions called *suggestive highlights* and *principal highlights*, which abstract the bright regions in a headlit image much as suggestive contours abstract the dark regions.
- [Goodwin 2007] Proposes adjusting stroke width based on density of nearby isophotes. As a result, strokes are wider in areas where a shaded image would be dark.
- * [Judd 2007] Describes a new object-space line definition called *apparent ridges*. Apparent ridges are geometric ridges when the surface normal points towards the camera, but become occluding contours when the surface normal becomes perpendicular to the camera.
- [Kaplan 2007] Presents an algorithm for determining the number of polygonal layers occluding a 3D line. This information can be used for, among other things, drawing occluded lines in varying styles.
- * [Lee 2007] Presents an image-space approach that creates line drawings by finding edges and ridges in a shaded image. The lines respond to lighting and viewing changes. Toon shading is used to augment the lines in areas of broad color.
- [Neumann 2007] Presents a variety of emphasis effects based on adjusting camera and style parameters inside an area of effect. Examples include locally changing line color and width, and spatially distorting the model.
- [Xie 2007] Introduces a method for extracting lines from a 3D model by examining lighting in object-space. Allows for the user to add and manipulate lights to control the resulting lines.
- [Yoshizawa 2007] Presents a method for finding ridge and valley lines on meshes using differential identities on surfaces and focal surfaces.

2008

- [Cole 2008a] Introduces partial visibility for stylized lines, along with improvements of the itembuffer technique [Northrup 2000] to reduce visibility aliasing.
- [Cole 2008b] Presents a study of artists' drawings designed to support analysis of the local surface features under the artists' lines and a comparison with current line drawing algorithms.
- [Shesh 2008] Presents a fast and temporally coherent stroke simplification scheme using an advanced datastructure called a deformable spanner.

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