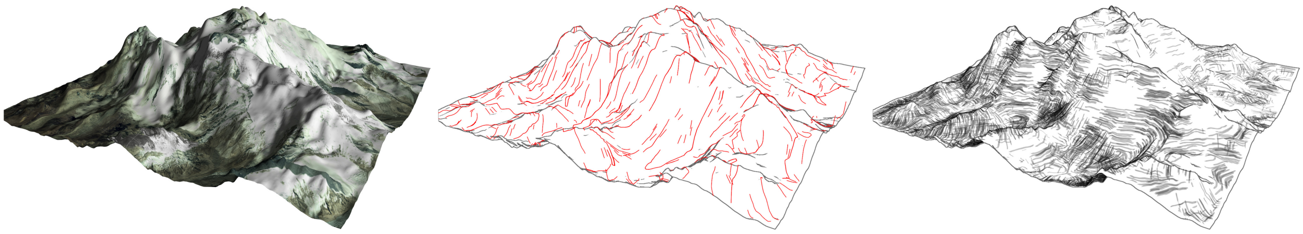
Vision, Modeling, and Visualization (2017)
M. Hullin, R. Klein, T. Schultz, A. Yao (Eds.)

Structure-aware Stylization of Mountainous Terrains

Julian Kratt[1] Ferdinand Eisenkeil[2] Marc Spicker[1] Yunhai Wang[3] Daniel Weiskopf[4] Oliver Deussen[1]

[1]University of Konstanz, Germany
[2]IABG mbH, Germany
[3] School of Computer Science and Technology, Shandong University, China
[4]University of Stuttgart, Germany



(a) (b) (c)

Figure 1: *Our method takes an input terrain geometry and texture (a); based on geometric features such as crest lines, smoothing is applied and streamlines are computed in a structure-aware distribution (b), hatching styles are computed to create the final illustration (c).*

Abstract

We present a method for the stylization of mountainous terrains that allows creating abstract representations in different rendering styles. Our method consists of two major components: structure-aware terrain filtering and streamline-based hatching. For a given input terrain we compute different Levels-of-Detail (LoD) according to a crest line oriented importance measure and then filter each LoD accordingly. We generate flow fields for each LoD and compute streamlines to direct the production of hatching lines. The combination of crest and silhouette lines with streamline-based hatching allows us to create a variety of styles in different Levels-of-Detail. We evaluate our method using several terrains and demonstrate the effectiveness of our method by composing a number of different illustration styles.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Line and curve generation I.3.3 [Computer Graphics]: Picture/Image Generation—Viewing algorithms I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Curve, surface, solid, and object representations

1. Introduction

Terrain illustrations are needed for a wide variety of applications ranging from map production to geo-visualization and geographic information systems, interactive computer games [Döl07], flight and driving simulators and planning systems for navigational tasks. Simplified methods might feed head-mounted displays when only the most important features of a terrain should be shown [FHT08].

Mountainous terrains are special types of terrain, they have a fractal structure and are subject of strong pluvial and fluvial erosion with corresponding flow patterns forming valleys and ridges. This is why artists used streamline-like illustrations to depict mountain areas from early on (Figure 2). In traditional Chinese paintings this form of rendering is widely used [Sir56]. We combine state-of-the-art streamline placement techniques with Levels-of-Detail (LoD) heightmap smoothing approaches as well as modern real-time rendering methods to generate images that have a similar appearance as real artistic terrain sketches. The goal of our work is to provide landscape and terrain renderings that a artist would draw as well as the possibility to navigate through an artistic looking 3D environment.

Our representation highlights characteristic features such as ridges and valleys and combines them with hatches produced from streamline-based placement methods. Unlike previous methods [BSD*04, WS06] we use the streamlines not just directly, but as guiding paths for different kinds of hatches. The line style of these hatches is determined by the underlying terrain type (snow, rocks, forest, etc.) and the overall style of the intended illustration. Figure 1 shows an input terrain with crest lines and the resulting terrain illustration.

Figure 2: *"Compartive Heights of Mountains". Streamline-like strokes are used to illustrate the relative heights of the world's mountains. Engraved by D. Duncan, Glasgow, and published by Blackie & Son, Glasgow, 1862.*

Given an input terrain, we compute a number of Levels-of-Detail depending on the terrain size and the application. To characterize the important structures in these levels, we compute a hierarchy of crest lines [YBS05] and filter the terrain for each LoD. We developed an adaptive filtering mechanism based on the distance to the closest crest line, which enables us to smooth the terrain while keeping important features. From the input terrain we generate a flow field by computing a structure tensor [HH07] on the height field. This field is smoothed for each level using our adaptive filtering in order to provide smooth transitions between levels. To capture prominent structures of each terrain level seed points are randomly sampled close to crest lines and streamlines are adaptively evolved starting at seed points.

The main contributions of this paper are as follows:

- a new structure-aware terrain filter that smooths the terrain while keeping important structures,
- a method for vector field smoothing on terrain levels,
- a stylization method based on streamlines that visualizes terrain classes and important features coherently on different Levels-of-Detail.

Our results show that the proposed technique is effective in creating a variety of spatially coherent styles such as charcoal or Pen-and-Ink renderings that can be achieved by adapting different stroke and hatching parameters such as spatial stroke density and stroke length. Moreover, our approach is simple and efficient and runs at interactive framerates for medium-sized terrain models.

2. Related Work

Related work encompasses non-photorealistic rendering methods, flow visualization as well as interactive terrain rendering methods.

Non-photorealistic rendering: A number of works introduced non-photorealistic rendering for enhancing 3D scenes and images [RC12]. The perception of 3D geometry in many cases is enhanced by depicting and exaggerating geometric features within non-photorealistic rendering [CGL*12]. Common features are silhouettes, ridges and valleys [NJLS05], contours and suggestive contours [DFRS03]. A stable ridge and valley detector is described by Yoshizawa et al. [YBS05].

In contrast to 3D techniques, 2D abstraction methods aim at clarifying and exposing essential structures in images [DS02]. Segmentation-based rendering [KWH06], enhanced representations of photographs [OBBT07] and videos [WXSC04, WOG06], or line representations [BTS05, JNLM05, LMLH07] are important examples.

Early work for real-time hatching was provided by Praun et al. [PHWF01] by mapping additive textures on regions of the input surface according to their curvature. Zander et al. [ZISS04] provide a hatching technique that is based on the curvature information and uniform streamline seeding. However, in comparison to our approach they do not use a shape dependent seeding strategy and their results have a very synthetic appearance while we focus on generation of artistic looking results. In order to create time coherent line-art illustrations Kim et al. [KYYL08] present an image based hatching technique by combining real-time principal direction estimation, stroke propagation and stroke mapping. Even if they have convincing results, their approach suffers from artifacts such as the shower-door effect. It has also no improvements according to different Levels-of-Detail. Lawonn et al. [LMP13] use streamline rendering in one particular style to create hatching-like structures on the surfaces of objects. In their work lighting conditions are not considered while we select rendered streamlines based on illumination. In addition our method uses sophisticated streamline placement in order to avoid crossings.

Today it is well-understood that no form of view-independent feature lines is sufficient for adequately representing 3D shapes [LBSP14]. Consequently a combination of view-dependent 2D and 3D features is needed to produce satisfying shape representations. Methods for an appropriate generation of (view-dependent) silhouettes are given by Isenberg et al. [IFH*03] who describe methods for polygonal models. Interrante [Int97] describes how principal directions and principal curvatures of a surface can be used to guide the placement of lines for an intuitive 3D representation. Kalogerakis et al. [KNBH12] create different hatching styles by learning from artist drawings combined with analyzing the input geometry and the view dependent rendering.

Streamline placement and rendering: Streamlines are most common in flow visualization for depicting the directions within a flow field [WE05]. Illustrative rendering of streamlines can be useful in scientific visualization [BCP*12]. Liya et al. [LHS08] present a seeding strategy for a minimum set of streamlines that ensure visual clarity, based on distance fields of streamlines. They also provide a rendering strategy for streamlines in 3D that avoids cluttering by minimizing overlapping and intersections [LwS07]. Xu et al. [XLS10] present a seeding algorithm in areas with high entropy and additional seeding in areas where the conditional entropy is high. Inspired by this work, we place more streamlines around crest lines to capture the local structure near salient regions.

Our method requires smoothing of flow fields, since we want to visually abstract distant parts of our terrains. We were inspired by noise reduction of diffusion tensor images [DGA05]. Since in our case the flow field is generated by the gradient of a height map, smoothing can be done by interpolating the gradient at the vertex positions of the map [MMMY97]. However, this results in artifacts, so more sophisticated methods have been provided [HAM11]. To avoid inconsistencies by interpolation or approximation of the input, we directly smooth the given vector field.

Mesh smoothing with shape preservation: Feature driven smoothing within subdivision methods was done by Amresh and Farin [AFR02] as well as by Li and Ma [LM09]. Isenberg et al. [IHK03] provide a GPU implementation for achieving interactive frame rates by using the view-direction as a hint where subdivision has to be applied. These methods have in common that they produce additional geometry. In contrast, we want to simplify the geometry in our Levels-of-Detail and thus need different methods that allow this. Also image processing techniques can be applied to the corresponding height field image in the context of terrain smoothing and simplification. Previous work on edge-preserving smoothing (e.g. bilateral [TM98] or Laplacian filter [PHK11]) can be used to remove small details in the height field image while maintaining important features of the terrain. These methods, however, are designed to preserve edges in an image and thus may produce unwanted sharp creases in the terrain. Tasdizen and Whitaker [TW03] developed a feature preserving smoothing approach based on a variational generalization of anisotropic diffusion. Their methods is computational expensive. Moreover, in contrast to our approach, a hierarchical production of different Levels-of-Detail representations can not be achieved. Desbrun et al. [DMSB00] also use anisotropic diffusion to denoise gray-scale images such as terrain height fields.

Terrain rendering: Terrain rendering covers a variety of methods ranging from the generation of artistic panorama maps towards realistic rendering [BST09]. Kennelly and Kimerling describe NPR techniques for terrain rendering in a cartographic context [KK06]. Mower [Mow09] extracts silhouettes, creases and slope lines from digital elevation models to create Pen-and-Ink landscape illustrations. The work most relevant for our approach is proposed by Buchin et al. [BSD*04] and by Way and Shih [WS06]. Buchin et al. create terrain illustrations by using light intensities on the terrain surface for creating stroke-based renderings. Strokes start at uniformly sampled points within the terrain and flow downhill, the selection of strokes to be rendered is based on light variation. In contrast to them, our work combines state-of-the-art streamline placement with rendering of crest lines and furthermore uses the streamlines as guiding paths for our hatching lines to create different kinds of strokes.

Way and Shih [WS06] provide an approach that uses streamlines to represent terrains inspired by Chinese landscape paintings. Their approach, however, is limited to streamlines that are generated for each triangle in the terrain mesh. Moreover, the resulting streamlines are textured with a fixed type of Chinese drawing style. In our work we extend their approach by modifying our streamline-based hatches according to the terrain type. We also use lighting information for streamline rendering and a more sophisticated streamline placement as well as an adaptive stroke parametrization that allows us to render different drawing styles. In addition, we apply the method proposed by Whelan et al. [WV03] to enhance our terrain renderings with silhouettes from depth images. Mat and Visvalingam [MV02] provide an evaluation that shows that silhouettes are important for terrain rendering. A fast approach for such renderings with a GPU implementation is given by Mower [Mow14].

Levels-of-Detail approaches for terrain rendering: Since terrains typically contain huge amount of data, Levels-of-Detail approaches have to be introduced. Hoppe [Hop96] provides a method to represent terrains using progressive meshes that enables viewers to smoothly change Levels-of-Detail based on the camera position. Cignoni et al. [CGG*03] introduce the *BDAM* technique, that simplifies terrain meshes by optimizing their triangulation. Another approach is to recursively subdivide triangle meshes using longest-edge bisection for a view-dependent refinement, following smooth blending of geometry using geomorphing [LP02]. Losasso and Hoppe [LH04] use geometry clipmaps to provide visual continuity by caching terrain data in a set of nested regular grids. The grids are incrementally refilled as the viewpoint changes. An in-depth overview and comparison of general Level-of-Detail techniques for geometric surfaces is provided by Luebke et al. [LWC*02].

3. Overview

Input for our system are synthetic fractal terrains as well as real-world terrains obtained from earth observation techniques such as airborne LiDAR [Axe99]. We use the corresponding height and texture information since we modify our rendering style according to the underlying type of ground. Figure 3 gives a brief overview over the whole processing pipeline from offline preprocessing steps up to real-time rendering.

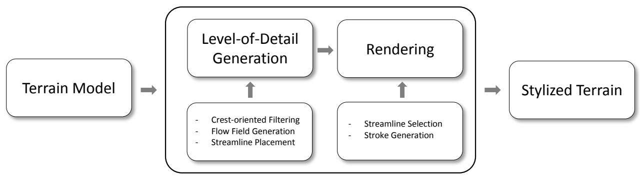
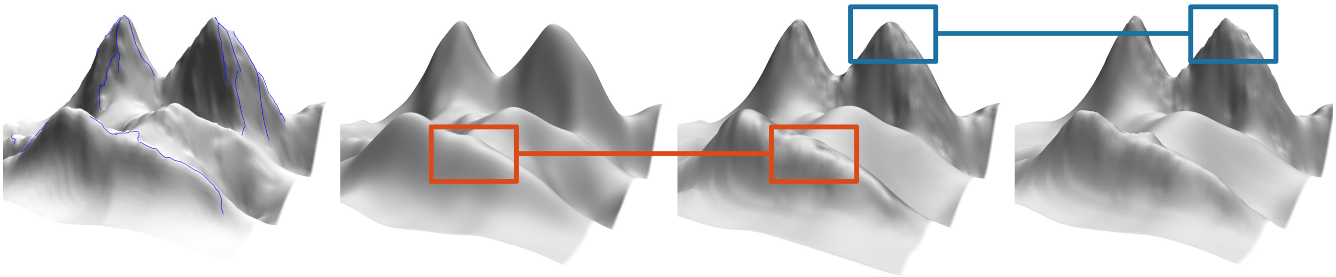


Figure 3: *System Overview. In a preprocessing step we produce different Levels-of-Detail for a given input terrain. Here, we use crest-oriented filtering to smooth the terrain levels. A flow field is generated for each level and streamlines are placed. In the rendering step, streamlines are selected based on the LoD and strokes are generated depending on the underlying terrain type to produce a stylized model.*

Crest-oriented Filtering: In preparation for view-dependent rendering we create four Levels-of-Detail. This number is heuristically determined and can be changed by the user. To obtain the different levels we detect crest lines on the input terrain by using the method

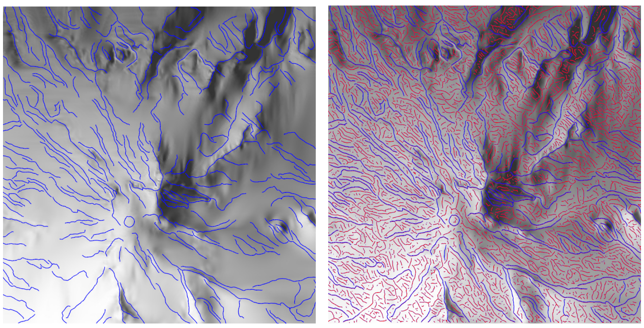


(a) (b) (c) (d)

Figure 4: *Structure-aware filtering: (a) terrain model with crest lines (indicated in blue); (b) filtering of the terrain using a uniform Gaussian filter kernel results in inappropriate flattening, here we use a size which is the maximal size of our structure-aware filter; (c) structure aware filtering with the Savitzky-Golay filter; (d) with our modified Gaussian filter, parts with a small distance to a crest line remain well in their elevation, while other details are smoothed (cf. boxes).*

by Yoshizawa et al. [YBS05]. Their approach delivers ridge and valley lines with a number of quality measures such as *ridgeness*, *sphericalness* and *cyclideness* assigned to them. By thresholding these quality measures unessential crest lines can be filtered out.

In our work we consider the *ridgeness* and continuously increase a threshold to create a hierarchy of crest lines. In particular, the used thresholds for all our examples are $(3, 5, 12, 16)$. These values can be interactively adapted by the user. For each threshold we obtain a set of crest lines which are assigned to the different terrain levels. A set of lines in a coarse level is part of a set for a fine level. Only very important crest lines are shown for the coarsest level. Figure 5 depicts two different levels of crest lines. This division of crest lines allows us to filter terrain levels differently based on the assigned sets of crest lines. For doing so, each set is mapped to a texture and a distance transform is applied [KKB94]. The resulting distance field serves as a weighting factor for a Gaussian smoothing filter for the terrain geometry. Our goal is to smooth the terrain only in areas far from crest lines, thus maintaining the overall terrain shape while smoothing out unimportant details. The resulting height fields are then used for the illustration.



(a) (b)

Figure 5: *Two sets of crest lines with varying degrees of details. Lines of (a) are entirely contained in (b).*

Streamline Placement: In order to guide our stroke based rendering, we compute streamlines in each Level-of-Detail. Here, the orientation of streamlines is derived from a flow field we compute from the terrain level with most details using a structure tensor. This orientation field is then successively smoothed for all coarser LoD. If we would compute a flow field on all LoD separately, the differences between orientations in these fields would be too large. This would lead to inconsistencies in the rendering between the transition of two successive levels.

Streamline Selection and Rendering: Based on the camera position the LoD is chosen for all parts of the terrain. In order to enable blending between different terrain levels and to achieve spatial coherence, a lookup table is computed that stores the nearest neighbors for all streamlines and is accessible in form of a texture. The lines are placed using similarity-guided streamline placement [CCK07]. In addition to their approach we adapt line placement in order to react to changes of the local lighting. The terrain is now shown by combining streamline based hatches with crest and silhouette lines, which we compute from depth differences as introduced in [DS00].

4. Terrain Processing and Rendering

After computing terrain levels, crest lines and creating the segmented texture for the ground we process the crest lines in order to achieve a smoothed version of the terrain that still contains important details. This is needed since in our illustration we want to show important terrain features but at the same time we want to indicate terrain details mostly by the texture of our strokes and not by high-frequency geometry variations.

4.1. Crest-oriented Filtering

Our structure-aware filter uses the distance to the nearest crest line for controlling the amount of smoothing. Each set of crest lines is thus mapped to a texture on which we perform a distance transform to generate distance maps D_i for each terrain level i. Our crest-oriented filtering is a variant of anisotropic filtering inspired by the Savitzky-Golay filter [SG64]. We modulate a Gaussian filter kernel depending on its distance $D_i(x,y)$ to the closest crest line stored in D_i. This enables us to keep the terrain geometry around crest lines, (especially its elevation) while smoothing unimportant details far away from these lines. This is done for each level.

$$G_i(x,y) = \frac{1}{2\pi^2} e^{-\frac{x^2+y^2}{2\cdot\sigma^2}}, \qquad (1)$$

with the standard deviation σ computed by:

$$\sigma = \min\left(r_{max}, \omega e^{D_i(x,y)} - 1\right). \qquad (2)$$

The strength of the filter is controlled by ω which we heuristically set to $\omega = 5$, $r_{max} = 20$ for a typical terrain resolution of 256×256 height values. Figure 4 shows the effect of different filters applied to the terrain mesh. As the uniform Gaussian kernel smooths even important features, the Savitzky-Golay filter (Figure 4(c)) preserves prominent structures better but also flattens the terrain in important feature positions. In contrast our modulated filter applied in Figure 4(d) keeps the elevation and local area around crest lines.

4.2. Streamline Placement

For sampling and tracing streamlines on the terrain we produce a flow field. We use the initial height field without smoothing to generate a flow field with a structure tensor T [HH07] at each position p of the height field H:

$$T(p) = \begin{bmatrix} (H_x(p))^2 & H_x(p)H_y(p) \\ H_x(p)H_y(p) & (H_y(p))^2 \end{bmatrix}, \qquad (3)$$

where $H_x()$ and $H_y()$ denote the spatial derivatives in $x-$ and $y-$direction. The tensor is smoothed with Gaussian blur in order to generate a smooth initial flow field before the eigenvectors and eigenvalues are calculated. Figure 6 shows an example field. Compared to direction fields computed from principal curvatures [KWKV07], the structure tensor field leads to a smoother representation of local structures, especially line structures.

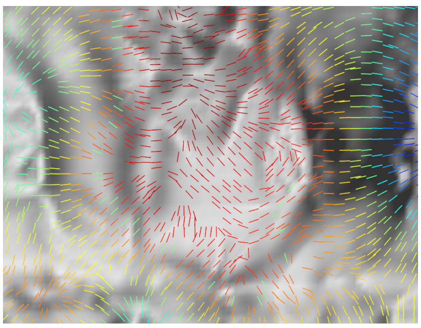
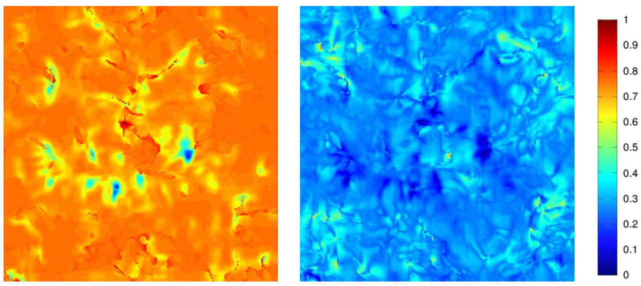


Figure 6: *Resulting flow field by applying the structure tensor to the height field. The color of the vectors indicates the terrain height.*

Structure-aware Smoothing: Although we are able to directly derive the vector field of level l with the structure tensor based on the smoothed height field, this introduces inconsistencies as reported from diffuse tensor imaging [MMMY97]. To provide coherent changes between the vector fields of two successive levels, the vector field of level l is directly obtained by smoothing the vector field of level $l-1$.

In order to apply our structure-aware filter to a smoothed vector field, we first convert the initial vector field of the highest level into a scalar angle field by calculating each angle between the eigenvectors derived from the structure tensors and the x-axis. Then, we employ the same structure-aware smoothing operator that we use for the height fields and calculate the flow field from the smoothed angle for the next level. This decreases the distance between the angle fields of two consecutive levels.

Figure 7 compares the accumulated distances over all LoD between flow fields that were generated separately for each level (a) and flow fields that were each derived from the previous level using our method (b). Here, the distances between two angle positions is computed with the l^2-norm. It can be shown that our approach leads to low accumulated distances in almost all areas (indicated in blue color).



(a) (b)

Figure 7: *Flow field distances (accumulated l^2-norm): (a) distance for flow fields generated separately for each level; (b) distance for flow fields derived from previous levels.*

Structure-aware Placement: To produce spatially coherent terrain illustrations in different terrain levels, we create a hierarchy of streamlines that we use in a next step to create strokes or hatchings. Since crest lines are the most dominant features in our terrain, we use them for guiding streamline seeding. Similar to Li et al. [LHS08], we use the distance fields from the crest lines as density distribution to sample seed points for the generation of streamlines within the terrain. For different Levels-of-Detail these seed points are sampled independently. Since we produce a hierarchy of streamlines starting from the coarsest LoD, we only add streamlines at seed positions where no streamline has been produced so far. The seeding strategy is illustrated in Figure 8.

Starting from the points sampled in the neighborhood of crest lines, we place long streamlines next to such lines since they have a large visual impact on the terrain structure. Production of a streamline is done by sampling along the directions of the flow field created in the previous step. We use the method of Chen et al. [CCK07] to determine the elongation of the streamlines, where we specify a minimum and maximum length l_{min}, l_{max} for the streamlines. These parameters depend on the Level-of-Detail, in coarser levels long streamlines are used in order to represent the terrain with a small number of lines (typical values: $[3,12]$ for level 0 to $[54,64]$ for

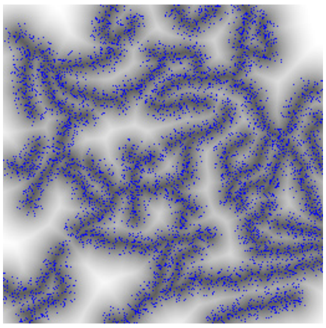
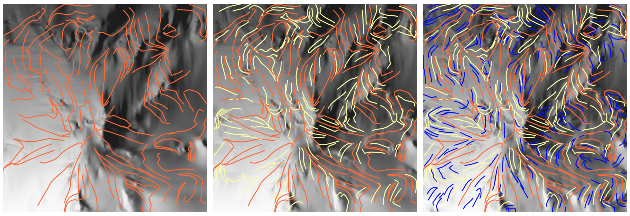


Figure 8: *Distance field used as density distribution. The sampled seed points are given in blue.*

level 4). In detailed levels, short streamlines are allowed since more dense details are needed for the visual representation.

Streamline data and neighboring information are stored in textures for each terrain level (see Section 4.3). This allows graphics hardware to efficiently access neighboring lines and to change the hierarchy and Level-of-Detail at rendering time.

Figure 9 shows the hierarchical placement of streamlines. In Figure 9(a), streamlines of highest order are shown. All of them emerge from the crest lines. In Figure 9(b) and (c), new streamlines are successively added, however only at places where the distance to the existing streamlines is large enough.



(a) (b) (c)

Figure 9: *Streamline placement: (a) lines of highest order in orange; (b) and (c) additional streamlines of lower order in yellow and then in blue. Based on the seeding, streamlines are not generated in areas without slopes.*

4.3. Streamline Selection and Rendering

At rendering time, all generated streamlines at all terrain levels are rendered using different transparencies and blending. The visibility of a line segment depends on its assigned terrain level, which is selected based on the distance to the viewer. A streamline becomes visible if the line is part of the displayed terrain level at the corresponding position, otherwise the line is not visible. Since we provide several hatching styles for different types of terrain (snow, stone, forest, etc.), we change the representation of the streamlines by subsampling each segment and creating new lines for cross-hatching, orthogonal-hatching and wiggly lines. These representations are invariant to lighting and are pre-computed. For rendering, the stroke lines are converted to quads within the geometry shader and a stroke texture is mapped onto it.

Implementation: To process streamlines efficiently using graphics hardware we store associated information in a texture as depicted in Figure 10. Vertex positions of lines p and $q \in V$ (V is the set of all streamlines of a terrain level) are stored successively in a position texture in non-spatial order. The beginning of each line is coded in form of meta information $\#_p$ and $\#_q$, that holds the number of vertices of a line. The following texture entries store the 3D information of each line vertex. This allows us to access all necessary information about the entire streamline on the GPU. For maintaining temporal coherence during camera movement, we apply alpha blending of the generated strokes at transitions of terrain levels. In order to compute a correct blending every stroke has to have information about its nearest neighbor in the next Level-of-Detail.

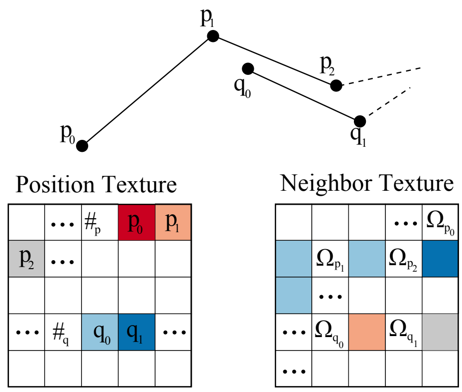
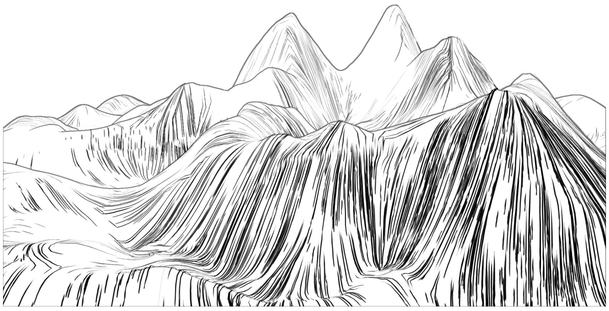


Figure 10: *Streamline data texture for GPU-based neighbor selection. The vertex positions are mapped to a position texture and a neighbor texture. This allows us to retrieve neighboring information between strokes directly on the GPU.*

To provide this information on the GPU we build up a neighbor texture as illustrated in Figure 10. For every streamline vertex this texture stores its nearest neighbors in a certain radius. Ω_{v_n} stores the number of neighbors for each vertex v_n. The following entries are the texture coordinates of the neighbors in the position texture. Each vertex on the GPU has associated information about its location in both textures.

4.4. Hatching

For more artistic representations such as Pen-and-Ink or pencil drawings, we do not render the streamlines directly, but generate new geometry along the streamline segments that is rendered in form of strokes. To realize hatching-like structures we sample positions on the streamline segments and create small textured quads that represent strokes. We create a set of different styles that are assembled by dividing the streamline into multiple sub-segments that do not necessarily have the same slope and arrangement as the streamline. Each style has a different kind of sub-segmentation that is shown in Figure 12. After these additional line segments have been generated, they are transformed to quads with a stroke texture.


(a)

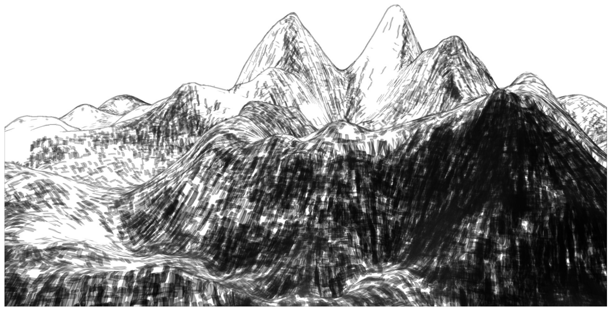

(b)

Figure 11: *Different rendering techniques for synthetic terrain: (a) Pen-and-Ink style; (b) Charchoal cross-hatching style; In both images the full range of Levels-of-Detail is shown.*

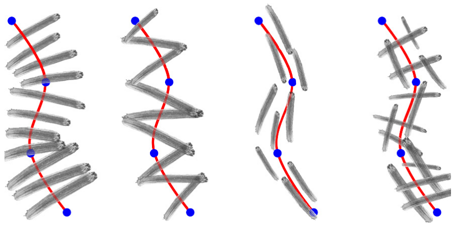

(a) (b) (c) (d)

Figure 12: *Different hatching styles: (a) strokes orthogonal to the streamline; (b) zigzag strokes along the streamline; (c) parallel strokes along the streamline; (d) cross-hatching.*

In comparison to the method by Hertzmann and Zorin [HZ00] we are able to produce hatchings interactively and adapt them locally. The parameters *density*, *separation*, *minimal*, *maximal length*, *width* and *type* of the strokes directly depend on the features of the underlying terrain mesh, texture and lighting and the user is able to influence these parameters.

- The *density* initially is provided by the user and varies based on the lighting conditions. To reproduce dark shadowed areas, a larger number of strokes is rendered. If the terrain shading becomes lighter, strokes are discarded from rendering to reduce their *density*.
- The *separation* parameter is also initially provided by the user and varies based on local variances in the texture. The separation influences where the strokes can be placed in the local neighborhood of a streamline. The separation is increased if the local variance in the texture is high. This results in strokes that are placed in such a way that the distance to the streamline is increased.
- If the local curvature of the terrain is high, the *length* of the strokes is decreased. It is increased if the curvature is small. This results in short strokes for small peaks and long strokes for features in the terrain that have a large dimension. Since both, long and short strokes, are reasonable for producing hatchings [KYYL08], we use both of them for our rendering.
- The *width* of a stroke is given by its distance to the camera, since broad strokes are drawn for low LoD and narrow strokes for high LoD. Since we place the strokes in 3D and not on a canvas, we get the different sizes of the strokes directly through the perspective projection.
- We use segmentation of the terrain texture to identify different classes of ground (*snow*, *stone* and *forest*) [CJSW01]. These classes regulate the *type* of the rendered line style. For areas that show high variance in the terrain texture, such as forests, cross-hatching is applied while areas with low variance are represented using long and smooth lines.

5. Results

We implemented our method on a PC with Intel Core i7 CPU and an NVIDA Geforce GTX 980 graphics board. Our experiments show that our terrain rendering system is able to achieve real-time performance: while the placement of strokes takes between 15 and 30 seconds, the rendering performance of the strokes is between 30 and 300 fps.

Using crest-oriented filtering, we can generate a number of different Levels-of-Detail for a given terrain while preserving its characteristic features. The number of levels is initially set to four and can be adapted by the user. Figure 11 illustrates the results with different Levels-of-Detail applied to a synthetic terrain. This result is produced by using parallel line-hatching as well as cross-hatching style for all LoD. Most of the features have been filtered in lower Levels-of-Detail, while fine details are shown for regions close to the viewpoint.

By using different hatching styles, our method can resemble a variety of drawing techniques. Figure 15 depicts the results of different rendering styles: Pen-and-Ink hatching, charcoal and pencil. All these stylized renderings keep the coherent streamline pattern that characterizes the terrain structure. Figure 13 shows a visual comparison between our method and the approach presented by Praun et al. [PHWF01]. Their technique is similar to ours in terms of real-time applicability and visual coherency of strokes. The terrain, however, is only represented with parallel and cross hatches which limits the perceived information about important structures of the terrain.

We tested our pipeline using several data sets, where all consist of 256×256 vertices. The visual result of our method mainly depends on the placement of the streamlines in each level. The placement can be directly influenced by the parameters given in Chen et al. [CCK07]. Figure 14 shows the results of different lighting conditions on a terrain. The method allows us to represent the shading information of the input terrain faithfully.

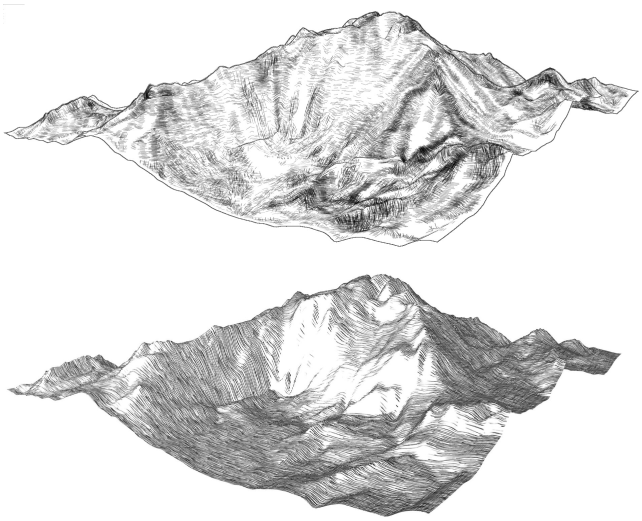


Figure 13: *Visual comparison between our method (top) and the real-time hatching approach presented by Praun et al. [PHWF01] (bottom).*

User Feedback: To get feedback about a proper selection of the hatching styles as well as the right parametrization of the stroke placement, we performed a small study with eight users who had some drawing experience. The users were presented multiple stylized terrains with automatically derived hatching styles and stroke parametrization. Each session took 15 minutes. We asked them to determine the underlying texture information (snow, stone, forest, etc.) of the different hatching styles. From their answers we found that snow areas were detected right in almost 90% of the cases, forests and stones could not really be distinguished by the subjects. Then we asked them to interactively adapt the stroke placement parameters. We recorded these changes and compared them with the initial values. It turns out that in most cases our pre-sets were only slightly modified by the users. The most important problem pointed out by the users was the discrepancy between stroke results and terrain textures, mostly due to the shadows that are incorporated into the terrain texture but that were not segmented out as a special class. We plan to adopt state-of-the-art segmentation algorithms to alleviate this issue.

6. Limitations

There are some limitations in our method. Since our hatching is guided by streamlines, we might not generate proper strokes for flat terrains, where we cannot extract enough crest lines to construct distance fields for streamline seeding. As suggested by Way and Shih [WS06], we would like to explore axe-cut strokes for smooth cliffs and surfaces of more flat rocks. Furthermore, our current texture segmentation method cannot efficiently handle photos with spatially complicated illumination effect such as small shadows. For the segmentation process semantic knowledge has to be introduced to automatically find a meaningful classification such as forest. Lastly, we solely used terrain meshes with a resolution of 256×256, with this amount of data interactive frame rates are possible. For larger-scale terrains a more efficient rendering strategy with more sophisticated data structures must be found.

7. Conclusion

In this paper we proposed a new approach for automatically generating a variety of stylized terrain illustrations. By combining our structure-aware crest-oriented filter and a hierarchical representation of streamline-based hatches, the terrain structure can be illustrated in different Levels-of-Detail. The resulting strokes are enhanced by contour lines generated by detecting depth discontinuities. Using a GPU implementation we provide an interactive framework that allows users to interactively explore and change a terrain illustration. In the future, we will perform a user study to evaluate our results in cooperation with artists. Also the method will be extended by using additional information about vegetation and urban structures.

8. Acknowledgements

The authors want to thank the German Research Foundation (DFG) for financial support within project A04 and B01 of SFB/Transregio 161. Furthermore, this work was also financially supported in part by DFG within the project 509/14.

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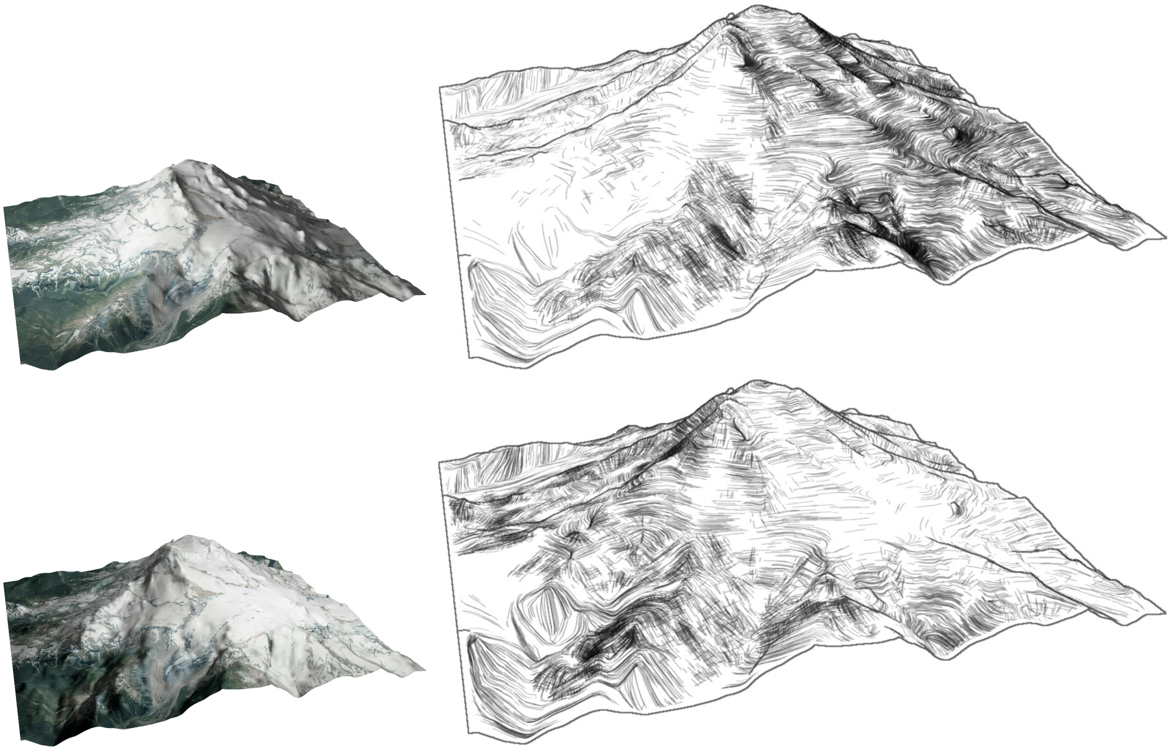


Figure 14: *A terrain under varying lighting conditions.*

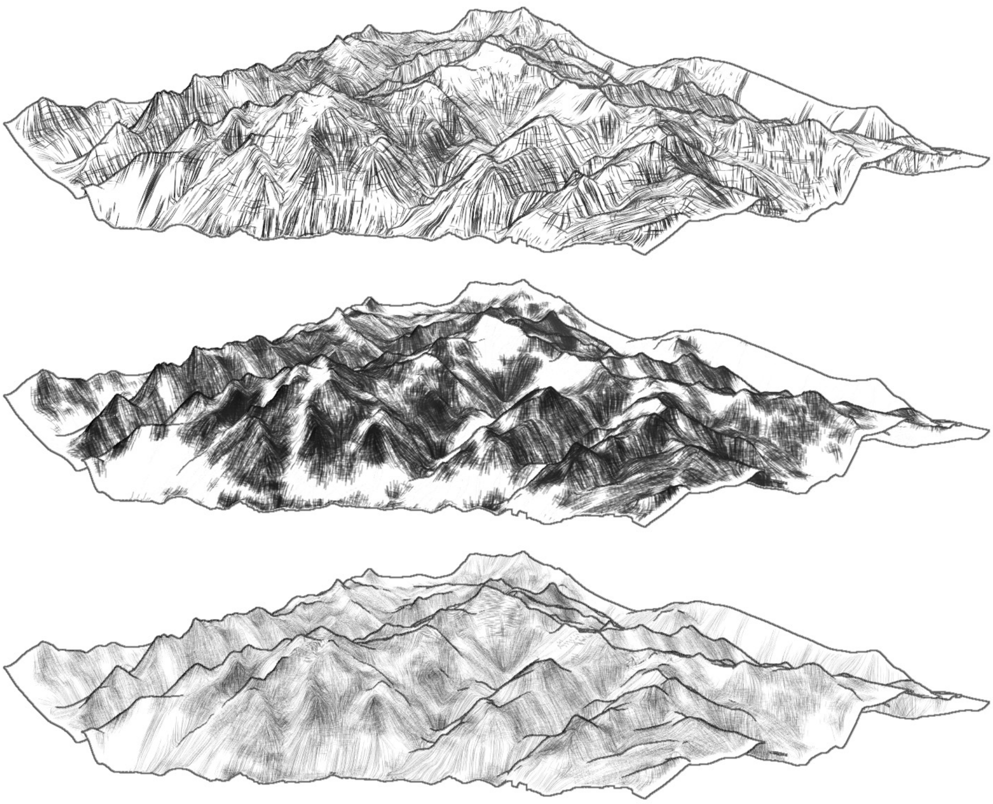


Figure 15: *Different rendering techniques: (top) Pen-and-Ink hatching style; (middle) Charcoal style; (bottom) Pencil style.*

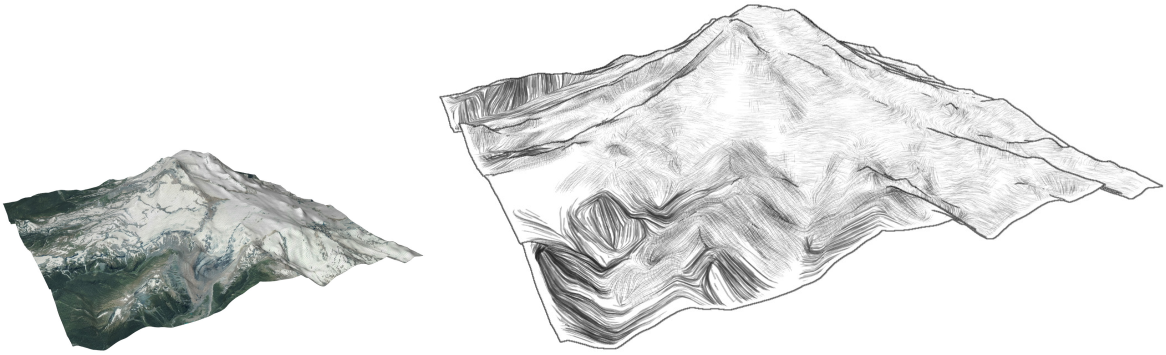
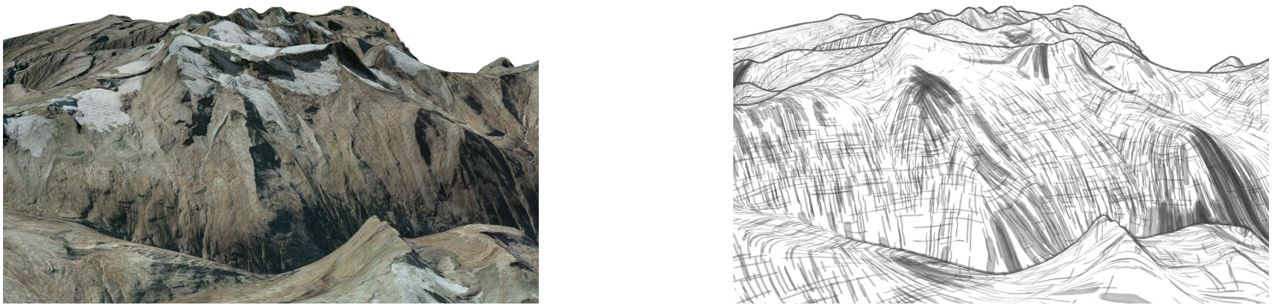


Figure 16: *A result of our method for the Mount Rainier terrain.*



(a) (b)

Figure 17: *Terrain rendering: (a) input terrain; (b) final terrain rendering with different stroke types.*

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