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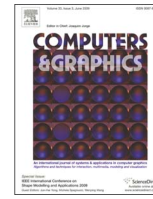

Technical Section

Line density control in screen-space via balanced line hierarchies ☆

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For the visualization of dense sets of 3D lines, view-dependent approaches have been proposed to avoid the occlusion of important structures. Popular concepts consider global line selection based on line importance and screen-space occupancy, and opacity optimization to resolve locally the occlusion problem. In this work, we present a novel approach to improve the spatial perception and enable the interactive visualization of large 3D line sets. Instead of making lines locally transparent, which affects a lines spatial perception and can obscure spatial relationships, we propose to adapt the line density based on line importance and screen-space occupancy. In contrast to global line selection, however, our adaptation is local and only thins out the lines where significant occlusions occur. To achieve this we present a novel approach based on minimum cost perfect matching to construct an optimal, fully balanced line hierarchy. For determining locally the desired line density, we propose a projection-based screen-space measure considering the variation in line direction, line coverage, importance, and depth. This measure can be computed in an order-independent way and evaluated efficiently on the GPU.

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1. Introduction

Integral lines such as streamlines or pathlines are among the most popular means for visualizing 3D flow fields, because they can convey to the user in an intuitive way the structure of these fields. For thorough overviews of flow visualization techniques in general, and integration-based techniques such as integral lines in particular, let us refer to the state-of-the-art reports by Weiskopf and Erlebacher [1] and McLoughlin et al. [2], respectively.

However, occlusions and visual clutter are quickly introduced when too many lines are shown simultaneously. Thus, especially in three dimensions a major challenge is to select a set of lines—containing as few as possible elements—that captures all relevant flow features. A number of effective selection strategies for integral lines have been proposed, for instance, approaches which determine the line set in a preprocess via importance- or similarity-based criteria [3–6].

In general, pre-selecting the lines cannot account for the problem that parts of relevant lines are occluded by less important parts of other lines being closer to the viewpoint in the rendered image. To avoid such occlusions, screen-space approaches either select the rendered lines dynamically on a frame-to-frame basis, for instance, by considering line importance and local screen-space occupancy [7,8], or they locally adapt the line opacity to fade out those parts of foreground lines that occlude more important lines [9]. Omitting entire lines has the advantage that the remaining lines are not fragmented, meaning that properties like the line length can still be conveyed. On the other hand, this strategy can result in unnecessarily sparse depictions, since in some areas a removed line might not have caused any disturbing occlusions. Opacity adaption, in contrast, resolves the occlusion problem locally by discarding line segments instead of entire lines. This enables to emphasize relevant focus information while preserving the "surrounding" context that does not obscure relevant structures. The focus+context principle underlying this approach has been studied extensively in the context of volume rendering by Viola et al. [10].

Opacity adaption, on the other hand, can affect negatively the perception of spatial relationships between lines in the context region. Increasing transparency causes a simultaneous desaturation of the object color, which is perceived as increasing distance from the viewer. Due to this effect, which is known as aerial perspective, transparent parts of a line can seem to flatten out or even bend away from the viewer.

We propose an alternative approach which avoids this effect. Instead of using transparency, we adapt locally the screen-space density of the lines to their importance. In this way, the spatial perception of the lines remains unaffected. The spatial adjustment of the line density is achieved via the use of a precomputed, fully balanced line hierarchy, and the selection of lines from this

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hierarchy at run-time according to image-based density control attributes. The particular hierarchy ensures that lines are removed uniformly in the domain, and the removal of individual line segments is contiguous and does not cause fragmentation.

Our particular contributions are:

- A novel combination of line clustering and minimum cost perfect matching to construct a fully balanced line hierarchy.
- A number of view-dependent, yet order-independent control parameters to locally steer the line density.
- A scalable embedding of local line density control into the line rendering process.

We demonstrate our method for flow visualization in a number of real-world examples, and we compare the results of our specific modifications and extensions to other view-dependent line selection and rendering approaches. Some data sets that have been visualized by using our approach are shown in Fig. 1. Our evaluations include perceptional as well as performance and scalability issues, and they demonstrate the suitability of the proposed approach for interactive applications. On the downside, since our method splits less important lines into segments, it can become difficult to determine the length of these lines from the visualization. Furthermore, compared to opacity optimization, which smoothly fades out the less important lines, our approach generates sharper, more abrupt line endings, which, in some cases, can give a less smooth overall impression.

2. Related work

Finding an as small as possible set of integral lines which represent a multi-dimensional flow field and its dominant structures in a comprehensive way is challenging. One way to approach this problem is to use line seeding strategies considering criteria like the line density [11–14], the line distribution [15–21], the information entropy in the seeded lines [22], or the coverage of specific flow features [3,4,6] or geometric line features [5,23].

Even though these techniques can be very effective in determining a good representative set of lines, they do not consider how much occlusion is produced when the seeded lines are rendered from different viewpoints. As a consequence, even though a good coverage of the domain or the relevant flow features in object-space can be achieved, lines representing relevant features may be occluded in the rendered images.

To overcome this limitation, view-dependent rendering strategies for 3D line sets have been introduced. The method by Tong et al. [24] deforms occluding lines that should not be in focus, so that the focus is revealed. Even though this approach can effectively avoid occlusions, the deformation of lines can give a wrong impression of the underlying flow field. Most alternative techniques generate an initial set of “important” lines, and determine for each new view the subset to be rendered—possibly enhanced with additional lines that are generated for this view—so that occlusions are reduced and more important lines are favored over less important ones [7,8,25]. Indicators for the amount of occlusion in the rendered images can be based on the “overdraw”, i.e., the number of projected line points per pixel [7,8], or the maximum projected entropy per pixel [25].

When selecting and rendering entire lines, less important lines might be removed entirely, even though only a small part of it actually occludes some part of a more important line. In the worst case this can result in a subset in which only the most important lines are kept, yet contextual information represented by less important lines is lost (see the upper right image of Fig. 2). This interferes especially with the focus+context paradigm, which suggests to show an importance-filtered fraction of the data set, i.e., the focus, embedded into context-conveying positional cues. Viola and Gröller [10] and Krüger et al. [26] discuss this paradigm in the context of volume rendering, and they propose guidelines which we also consider in our work. For integral lines, Marchesin et al. [7] and Ma et al. [8] address this problem by adding short fragments of less important lines in regions not yet occupied.

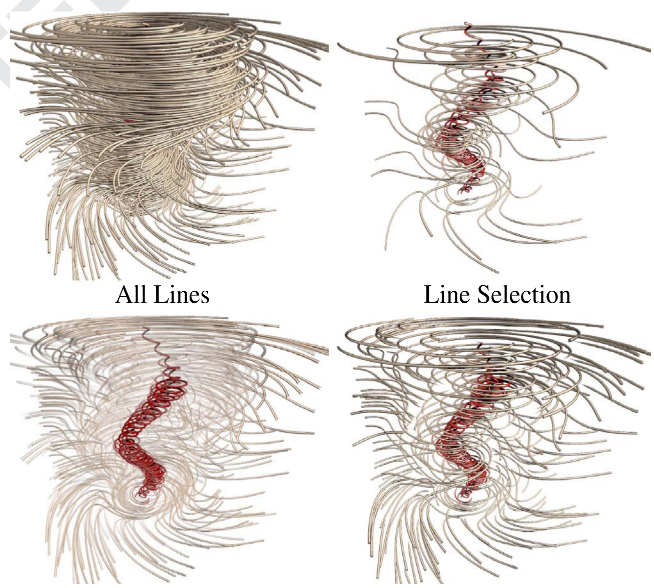

Fig. 2. Different approaches to reveal the focus region in the Tornado dataset.

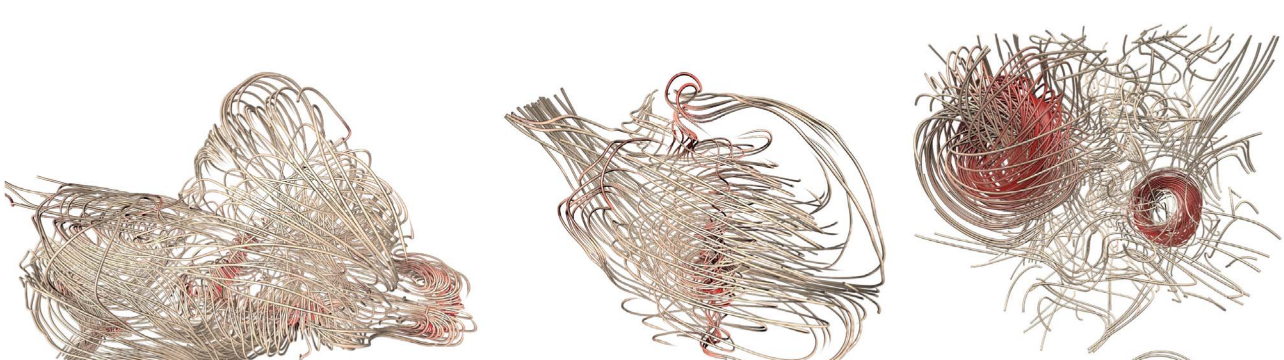

Fig. 1. Visualization of flow fields (Aneurysm I/II, Rings) using line density control. Line color ranges from red (high importance) to light brown (low importance). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

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