Interactive Rendering and Stylization of Transportation Networks Using Distance Fields

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(a) Perspective projection at a high zoom level. (b) High contrast orthographic projection.

Figure 1: Rendering of an OpenStreetMap data set using different map stylizations.

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Abstract: Transportation networks, such as streets, railroads or metro systems, constitute primary elements in cartography for reckoning and navigation. In recent years, they have become an increasingly important part of 3D virtual environments for the interactive analysis and communication of complex hierarchical information, for example in routing, logistics optimization, and disaster management. A variety of rendering techniques have been proposed that deal with integrating transportation networks within these environments, but have so far neglected the many challenges of an interactive design process to adapt their spatial and thematic granularity (i.e., level-of-detail and level-of-abstraction) according to a user's context. This paper presents an efficient real-time rendering technique for the view-dependent rendering of geometrically complex transportation networks within 3D virtual environments. Our technique is based on distance fields using deferred texturing that shifts the design process to the shading stage for real-time stylization. We demonstrate and discuss our approach by means of street networks using cartographic design principles for context-aware stylization, including view-dependent scaling for clutter reduction, contour-lining to provide figure-ground, handling of street crossings via shading-based blending, and task-dependent colorization. Finally, we present potential usage scenarios and applications together with a performance evaluation of our implementation.

1 INTRODUCTION

The efficient rendering and visualization of transportation networks within interactive virtual 3D environments is an important feature for a number of today's applications, such as Google Maps and Earth or Bing Maps. The presented work enables an efficient way of rendering complex transportation networks with a flexible parametrization and stylization.

Motivation. Transportation networks represent important features in 3D geovirtual environments, such as virtual city and landscape models. This class of infrastructure networks comprise, e.g., street networks, rail road networks, and cycling tracks. Their high-quality visualization is crucial for a number of applications within these environments, such as navigation systems and digital maps to support orientation and wayfinding in the real world. In addition to high visual contrasts (Vaaraniemi et al., 2011), the visualization quality comprises a number of further aspects such as anti-aliasing, and coherence in the continuation of line segments. To achieve this for the stated applications, dynamic scaling (Kersting and Döllner, 2002) or zoom-dependent rendering of massive transportation networks using abstract or cartographic styles is required. One can basically distinguish between three major approaches how current systems and applications perform their rendering:

Geometry-based: This approach relies on explicitly pre-computed textured geometry for network segments and junctions, based on the network topology. Depending on the level-of-details required, this exhibits memory consumptions of the resulting geometries and textures.

Texture-based: This approach rasterizes the mapping results of geometry-based approaches into a single or multiple textures required for texturing the underlying terrain model (Kersting and Döllner, 2002). Using this approach, however, the rendering quality can suffer due to sampling and aliasing artifacts caused by insufficient texture resolution.

Stencil-based: This approach uses the concept of shadow volumes for rendering transportation networks on top of digital terrain models (Vaaraniemi et al., 2011). It extrudes the network geometry and applies a stencil shadow volume algorithm. The shadow volume must be recomputed if the network configuration changes, e.g., due to interactive filtering.

These classes of existing approaches for rendering and visualization of transportation networks often assume a *static* input geometry, mapped to textured geometry for rendering, or additionally require the computation of intermediate geometry (shadow volumes). However, there are visualization approaches that require the handling of dynamic networks as the result of filtering or modification during the visualization process (Haunert and Sering, 2011). Further, an increasing geometric complexity of transportation networks due to more detailed representations also increases the memory footprint of each of these techniques accordingly. Furthermore, the change in network colorization or similar tasks requires an update of the intermediate rendering representations, which can become a time consuming process, depending on the complexity of a transportation network.

Problem Statement. The above characteristics of existing techniques limits their application with respect to view-dependent rendering of massive, possibly dynamic transportation networks that supports interactive filtering and colorization by simultaneously retaining a low memory footprint. Based on these functionalities, the design of an interactive rendering technique is faced with the following challenges and requirements:

R1: Pre-processing of discrete level-of-details consume additional memory and often yield incoherent rendering when switching between these levels during zooming or within perspective projection. Therefore, levels of detail should be computed on-the-fly during the rendering and based on current viewing settings.

R2: Increasingly detailed transportation networks require high amounts of main and/or video memory. Therefore, the network representation should exhibit a minimal memory footprint and facilitate fast updates.

R3: View-dependent cartographic stylization of transportation networks are key features for a number of applications. Therefore, the rendering technique should provide a sufficient parametrization, i.e., covering level-of-detail rendering, as well as interactive filtering and highlighting.

Contributions. With respect to the challenges stated above, this paper presents a new real-time rendering technique for the cartographic rendering and visualization of complex transportation networks. It is based on a single-pass computation of distance fields for an effective geometric representation (Frisken et al., 2000) combined with parameterized stylizations performed in screen space. The presented approach relies on a compact memory representation of transportation networks to provide a minimal memory footprint compared to existing techniques. Based on this representation, route geometry is efficiently generated on-the-fly during rendering, enabling interactive modifications of the depicted contents. Further, the technique does not rely on adjacency information.

The presented stylization model effectively decouples geometry from appearance parameters such as width, color, or texture. It facilitates interactive level-of-detail (LoD) as well as level-of-abstraction (LoA) rendering (Semmo et al., 2012). It further supports localization of route networks (e.g., color schemes, line styles), and interactive view-dependent filtering based on virtual lens metaphors (Tominski et al., 2014). To summarize, this paper makes the following contributions to the challenges stated above:

1. It presents a concept for high-quality cartographic rendering, which is exemplified for complex street networks.

2. It provides an interactive hardware-accelerated rendering technique that facilitates a minimal memory footprint for network representation.
3. It introduces interactive stylization and colorization mechanisms using deferred texturing and distance transforms.

The presented approach has a number of applications beyond the rendering and visualization of street networks. For instance, it can be applied to the rendering and stylization of planar graphs as well as visualization of aircraft trajectories.

The remainder of this paper is structured as follows. Section 2 reviews related work concerning the visualization and rendering of transportation networks, in particular considering street networks. Section 3 discusses design principles of transportation network depictions from the viewpoint of cartography. Section 4 introduces the concept for rendering image-based rendering of transportation networks using distance fields and deferred texturing. Section 5 gives details regarding a fully hardware-accelerated implementation of this concept. Further, Section 6 demonstrates the rendering technique using different application examples and discusses limitations and ideas for future work. Finally, Section 7 concludes this paper.

2 RELATED WORK

Transportation networks are well-researched in 2D map design (MacEachren, 1995; Kraak and Ormeling, 2003; Tyner, 2010), but only few works deal with their representation in interactive 3D virtual environments. In the following, we give an overview on related works that deal with the modeling and rendering of transportation networks including positioning in 3D space and visualization techniques that deal with the challenges of visual clutter and occlusion.

2.1 Modeling and Rendering of Transportation Networks

Generalization is a key concept for modeling and transforming transportation networks into human-readable maps (MacEachren, 1995; Jiang and Claramunt, 2004), comprising operators such as simplification, displacement, and deformation (Foerster et al., 2007), while preserving spatial relationships and topology (Tversky and Lee, 1999; Agrawala and Stolte, 2001). Generalization techniques have been effectively used for the design of destination maps (Kopf et al., 2010) and sketch maps to draw contour lines excessively wavy or fuzzy and express uncertainty (Tversky and Lee, 1999; Skubic et al., 2004). Most generalized models base on connectivity graphs where vertices represent segments of named street and links represent street intersections (Jiang and Claramunt, 2004). These models are typically provided via commercial products (e.g., Navteq), generated procedurally (Galin et al., 2010; Beneš et al., 2014), or authored in hierarchies (Galin et al., 2011). In our work, we use OpenStreetMap as a collaborative platform with free access to geospatial data (Haklay and Weber, 2008).

A common challenge in rendering transportation networks in 3D virtual environments is the projection onto digital terrain models. First approaches use geometry-based methods to directly combine vector data with a 3D terrain mesh (Polis et al., 1995; Weber and Benner, 2001), but only provide precomputations without the capability for dynamic stylization. A first approach for level-of-detail rendering uses texture-based mapping to project vector features on 3D terrain models (Kersting and Döllner, 2002). Similar approaches use principles of shadow mapping for perspective parameterizations by taking the current point of view into account (Schneider et al., 2005), continuous level-of-detail methods (Wartell et al., 2003), and shading for dynamic feature editing (Bruneton and Neyret, 2008). However, the approaches are less suited for 3D presentations of transportation networks in close view distances because of the limitation in detail and sharpness. Further, they require explicit level-of-detail mechanisms which results in additional computational costs. Other methods utilize the hardware-accelerated stencil buffer with a type of shadow volume (Schneider and Klein, 2007; Vaaraniemi et al., 2011), or completely rely on screen-space rendering (Ohlarik and Cozzi, 2011) to reduce computational costs. However, the later approach is limited with respect to the generation of view-dependent level-of-abstraction visualization (Semmo et al., 2012).

Our work presents a compromise between texture-based and geometric approaches using distance fields to effectively reconstruct geometric properties of complex shapes during shading (Frisken et al., 2000). We employ distance maps to stylize transportation networks in real-time utilizing bilinear sampling for a piecewise-linear approximation of feature contours. In particular, this approach has been proven effective for the magnification of glyph contours, even with low-resolution distance maps (Green, 2007). Previous algorithms use vector propagation to compute these maps by an approximate Euclidean distance transform (Danielsson, 1980), e.g., jump-flooding (Rong and Tan, 2006), or provide work-load efficient methods to compute an exact distance transform on the GPU (Cao et al., 2010).

Previous work demonstrates the effective use of distance fields for real-time rendering of water surfaces, where respective distance and orientation information is computed to guide the stylization and annotation (Semmo et al., 2013). Our approach works similar, but exhibits a more straight forward approach for generating the distance maps because of lines being a more simpler geometric representation than polygons. In particular, we demonstrate the effective usage of distance maps for stylization, such as rendering of contour lines, the view-dependent scaling, and handling of street crossings (Vaaraniemi et al., 2011).

2.2 Visualization Techniques For Transportation Networks

According to a user's background, task, and perspective view, often too much irrelevant (cluttered) or too few information is visualized (Shneiderman, 1996), and thus not a meaningful map design is provided when rendering transportation networks (MacEachren, 1995). To address this concern, major related work is found in focus+context and zooming-based visualization techniques.

Focus+context describes the concept to visually distinguish between important or relevant information from closely related information (Furnas, 1986). Many interface schemes exist to allow users to attain both focused and contextual views of their information spaces, i.e., detail+overview, zooming, and cue techniques (Cockburn et al., 2009). Focus+context route zooming uses principles of scaling to magnify regions of interest and for disocclusion management (Qu et al., 2009). Other techniques employ global deformations and degressive projections in panoramic maps for disocclusion of routes (Takahashi et al., 2006; Falk et al., 2007; Degener and Klein, 2009), or scale surrounding 3D objects (e.g., buildings) using view-dependent optimization techniques (Hirono et al., 2013). Further techniques employ interactive lenses as established means to facilitate the exploration of transportation networks, e.g., for magnification (Karnick et al., 2010; Haunert and Sering, 2011), which are quite versatile in their parametrization for clutter reduction (Tominski et al., 2014).

Another typical approach to deal with the problem of overcluttered displays is *contextual zooming*, where hierarchical route maps of varying resolution may be used for effective navigation (Wang et al., 2014). A first approach for dealing with the problem of visual clutter in 3D perspective views has been presented in (Vaaraniemi et al., 2011) via view-dependent scaling of stylization features. The concept presented in our work supports the required parametrization for these visualization techniques.

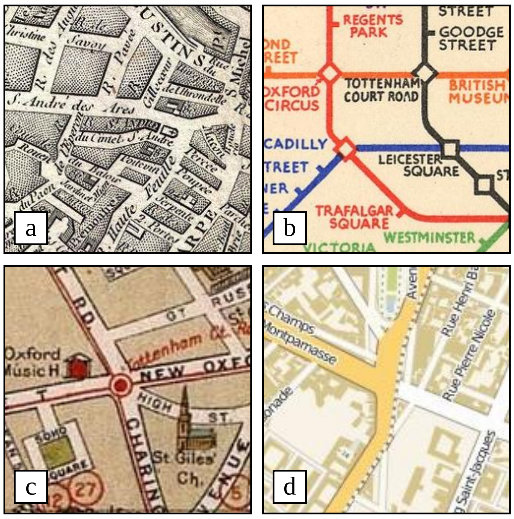


Figure 2: Exemplary maps depicting transportation networks: a) Paris in 1787 designed by Louis Brion de la Tour, b) the famous *Pocket Underground* map from 1933 by Harry Beck, c) London in 1913, d) contemporary map of Paris.

3 DESIGN PRINCIPLES FROM CARTOGRAPHY

Well-designed illustrations of transportation networks accentuate the figure-ground relationship, and communicate hierarchical and meta-information (e.g., street names). To this end, we studied textbooks on map design and thematic cartography (Imhof, 1975; MacEachren, 1995; Kraak and Ormeling, 2003; Tyner, 2010), and examined the works by famous cartographers and map designers (e.g., Harry Beck, Figure 2b). From our empirical analysis, we extracted three groups of design aspects according to the 2D semiotic model (Bertin, 1981): graphical elements (e.g., lines, points) and their position, and graphical variables (e.g., color, line thickness, decoration elements such as labels).

Graphical Elements. In general, two approaches for the depiction of transportation networks exist: (1) non-explicit elements by the principle of surroundedness (MacEachren, 1995) for effective figure-ground destinction on maps, for instance where streets are formed as a unit via enclosing features (Figure 2a), and (2) the explicit graphical depiction via connected lines and points (nodes) (Figure 2b-d) on which we focus in this work. In modern maps, *(P1) contour lines often surround fine-textured fills or solid colors to add visual contrast and improve the figure-ground perception* (MacEachren, 1995). Hierarchical representations of street networks often have *(P2) primary streets overlap secondary or tertiary streets*. In sketch maps, these lines or con-

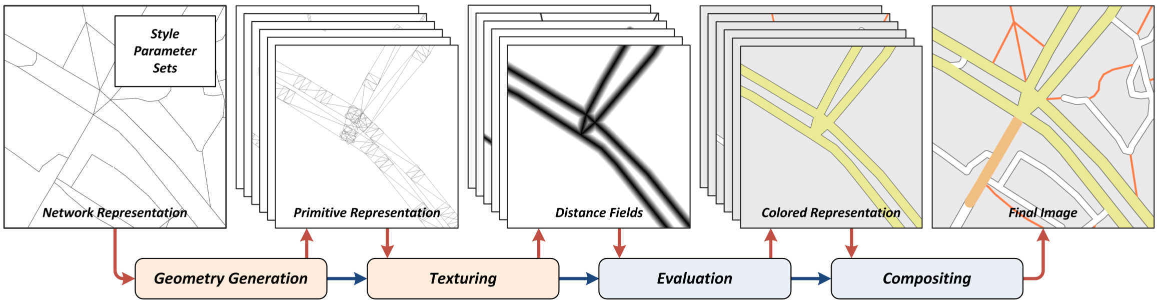


Figure 3: Schematic overview of the rendering pipeline for transportation networks. Given a compact network representation and stylization parameters, textured geometry and distance fields are synthesized per network category within a single rendering pass. The results are then used for stylization and image composition in a post-processing pass.

tours are often drawn excessively wavy or fuzzy to express uncertainty. Following a level-of-abstraction concept, *(P3) dynamic filtering and scaling of these geometric features improves the perception of roads at high view distances and avoids overcluttering*. The choice of shape often varies in thematic cartography, ranging from solid lines to dotted representations (e.g., to discern between car driving and biking directions). Finally, labels are primary design elements to enrich networks with meta-information. By convention, *(P4) names follow principal line directions and are placed within streets, or outside line segments and oriented with links*, e.g., the latter in schematized maps (Figure 2b), to ensure legibility (Imhof, 1975).

Graphical Variables. In many maps, *(P5) a hierarchy of emphasis is drawn among reference elements, such as different line weights and colors* to portray different grades of roads (Figure 2b/d). In modern maps, *(P6) streets are tinted using qualitative color schemes to represent street classes* and distinguish them from the underlying terrain. This association may enable cognitive grouping of each network type (Kraak and Ormeling, 2003). To date, standardized color schemes for transportation networks have not been established but vary from country to country. But it can be observed that *(P7) yellow established as a conventional color tone for main streets, with a discrete gradation towards grey and white shading for tertiary roads* (Figure 2d). Lately, principles for color blindness have also been examined by the example of OpenStreetMap (Kröger et al., 2013). All these graphical variables may additionally change according to the zoom level to avoid overcluttered displays. In the following, we consider these principles for an interactive design process in 3D virtual environments.

4 CONCEPTUAL OVERVIEW

This section presents an overview of the concepts for our rendering and stylization approaches. Figure 3 shows a schematic overview of our proposed rendering pipeline comprising control and data flow. It basically consists of the following three stages:

Preprocessing: This stage loads and transforms a given transportation network with its associated meta data into a compact representation (attributed point cloud) for efficient rendering and a low memory footprint. This operation is required to be performed only once per data set (Sec. 4.1).

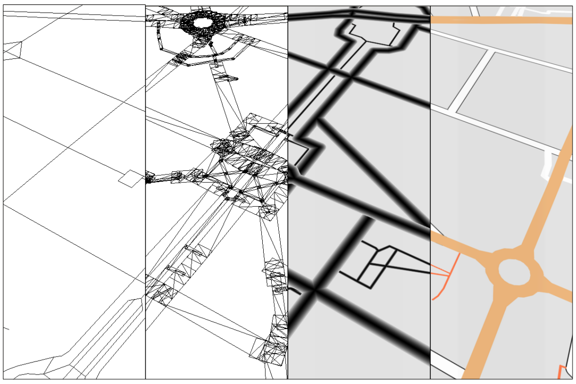
Distance Transform: Starting from the preprocessed input, this stage synthesizes textured polygons of respective widths that are subsequently rasterized into distinct distance-field buffers for each network category (Sec. 4.2).

Stylization and Compositing: In this stage, deferred texturing based on the generated distance fields is performed in screen space using a single post processing pass (Sec. 4.3). It enables application-wise procedural and raster-based texturing for colorization with level-of-detail support. The resulting colors of each network category are subsequently composited in a bottom-up approach with respect to their ranking.

The remainder of this section describes the data representation and assumptions, followed by a more detailed description of these stages. The data representation is exemplified for street networks.

4.1 Representation of Networks

One advantage of our approach is that the geometry of transportation networks can be generated on-the-fly (R1). This way, the video memory footprint of the transportation network can be minimized (R2) while only geometry within the current view-frustum is generated. We use OpenStreetMap (OSM) data as input (Haklay and Weber, 2008). OSM provides free access to a variety of data types for route map synthesis. This includes not only road data and 2D terrain information, but also 2D building footprints, water surfaces, and specific landmark information.



(a) Lines. (b) Polygons. (c) Distances. (d) Styled.

Figure 4: Overview of the processing stages, starting with input data (a) over generated polygons (b) to distance fields (c) and stylized network segments (d).

According to the design principles of Section 3, cartographic route depictions can be synthesized by a hardware-accelerated rasterization of line segments (represented by rectangular geometry). Using modern GPU capabilities (geometry shaders), the geometry synthesis and tessellation can be completely performed on graphics hardware, which however requires the geometry of input lines and additional route data to be represented as per-vertex attributes. To this end, the attributed topological representation of a street network is prepared for GPU-based representation (Sec. 5.1) during a pre-processing stage. The attributed graph is encoded by a node buffer and a segment buffer, both suitable for hardware-accelerated rendering. Therefore, the nodes basically comprises their position and grade, i.e., the number of segments adjacent to the respective node, while the segments comprise indices to the nodes and the rank of a route segment. In addition to the ranks supported by OSM, we introduce a specific rank for highlighted routes that overrides all OSM ranks. Further, the segments' lengths in world space units are encoded for optional length-parametrizations.

4.2 Distance Field Computation

Figure 4 shows the process of computing distance fields for a given network configuration. It basically comprises two stages that can be efficiently performed on graphics hardware. Thereby, two basic aspects can be distinguished: (1) the *primitive conversion* between point and polygons and (2) the *texturing* of the synthesized polygons.

Geometry Synthesis. The step for geometry synthesis converts point primitives – issued for rendering – to triangle strips, similar to (Trapp et al., 2013). This can be efficiently implemented using geometry shaders to minimize the memory footprint for representing a street network. It also enables batching (Wloka, 2005) to reduce the number of draw calls.

Based on this compact network representation, polygons are created for each line segment's (Fig. 4(a)) respective *cap* and *segment* (Fig. 4(b)). Figure 5 illustrates this process in more detail. Further, vertex texture coordinates are computed for each polygon and yields distance drop-offs during rasterization (Fig. 4(c)). The resulting polygons can be efficiently encoded using triangle strips.

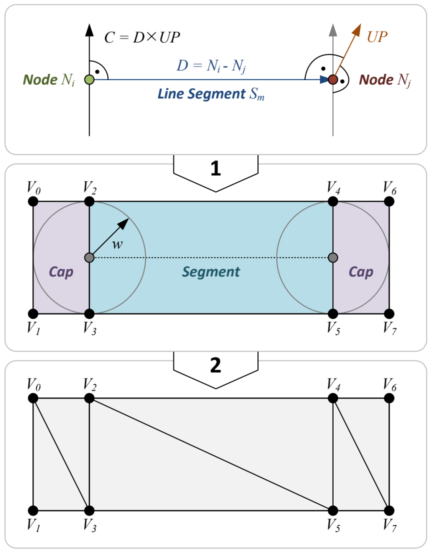


Figure 5: Schematic overview of the geometry synthesis.

During geometry synthesis, only segments within the current view-frustum are considered for processing, i.e., to reduce the amount of geometry information submitted to the clipping and rasterization stages of the hardware-accelerated rendering pipeline. The major advantage of this concept is the respective computation of distance fields per street category. This enables a flexible stylization and image compositing at the rendering stage.

Distance Texturing. Once the geometry synthesis has been performed, the respective texture coordinates are interpolated during rasterization. The required distances are computed using regular bilinear sampling using fragment shaders. The required distance textures are effectively represented using a single 2D texture array, whose layers can be indexed according to the type of geometry (cap or segment) and the grade of the node. The individual 2D texture layer encode the distance drop-off. Different distance textures can be used for caps of different grades, i.e., at junctions or endings. Using textures for the distance representation enables flexibility in design and allows a simplified implementation.

Blending. One major challenge in street rendering is to provide seamless transitions between adjacent and consecutive segments. In (Vaaraniemi et al., 2011) three different techniques are described for geometry-based approaches to avoid gaps. Our approach bypasses this geometric computation problem by combining segments using minimum blending (Bavoil and Myers, 2008): given two distance values d_{src} and d_{dst} of fragments belonging to different segments, the resulting value that is written to the render buffer is computed by $d_{res} = \min(d_{src}, d_{dst})$.

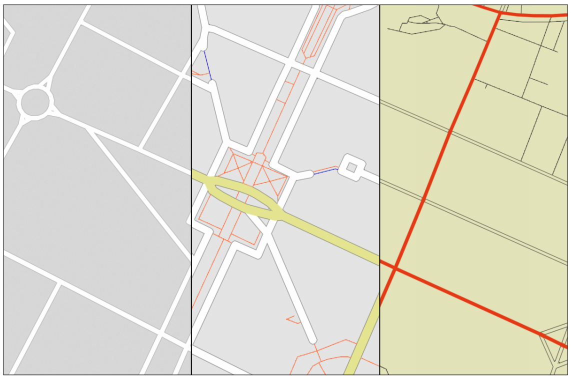
4.3 Stylization of Street Networks

Given the generated distance fields, the stylization is performed in a single post-processing stage via deferred texturing using individual style parameters defined per network category.

Style Parametrization. Our approach enables the stylization of segments based on their category. A *style parameter set* $S = (w, d_M, d_B, C_M, C_B) \in \mathcal{S}$ basically comprises the following parameters: the width $w \in \mathbb{R}_+$ of a geometric segment in world space coordinates; the respective distances $d_M, d_B \in [0,1]$, with $d_M + d_B = 1$ for differentiation between main and border segment color (P1); as well as the color of main and border segments (C_B, $C_M \in [0,1]^4$). In addition, a style parameter set may comprise raster-based or procedural 2D texture maps for example-based rendering (e.g., sketch maps (Kopf et al., 2010)).

Level-of-Detail Concept. The presented style parametrization can be further extended to define level-of-detail (LoD) variants for each style (R3). This is especially useful for a number of applications (Sec. 6.1), such as (1) counterbalancing perspective foreshortening of segments at high distances from the virtual camera, (2) enable interactive filtering using lens-based interaction metaphors (Tominski et al., 2014), as well as (3) the reduction of visual clutter (Jobst and Döllner, 2008). Therefore, the definition of a style parameter set is extended with an additional LoD parameter $lod \in [0,1] \subset \mathbb{R}$ to yield a list of *LoD tupels* $S_{lod} = (lod_0, S_0), \ldots, (lod_n, S_m))$ with $lod_i < lod_{i+1}$ and $S_i \in \mathcal{S}$. During runtime, a LoD value is computed per vertex and per fragment (Sec. 5.3). Given a value lod, the neighboring LoD tuple with $lod_i < lod \leq lod_{i+1}$ are fetched and the resulting (interpolated) style is used $S_{lod} = interpolate(S_i, S_{i+1}, \alpha)$, with $\alpha = \frac{lod - lod_i}{lod_i - lod_{i+1}}$.

Style Evaluation. The process of converting the generated distance fields into respective colors using the previously described style definitions is denoted as *style evaluation*. It is performed on a per-fragment basis using an additional post-processing step.



(a) (b) (c)

Figure 6: Examples of different street stylizations computed via a single set of distance fields.

To outline potential use cases, Figure 6 shows different street stylizations computed from a single set of distance fields: Figure 6(a) uses a constant line width for a single stylization parameter set and all street categories, while Figure 6(b) applies different stylizations for each street category. Figure 6(b) depicts the highlighting of a single street category that contrasts the remaining scene.

5 INTERACTIVE RENDERING

This section presents a prototypical implementation of our concept using OpenGL and the OpenGL Shading Language (GLSL). The real-time image synthesis is separated into two rendering passes: the first pass creates the distance fields using off-screen rendering and the second pass applies stylization using deferred texturing based on these distance fields. We first cover the required data structures for hardware-accelerated rendering, before presenting details for these two passes.

5.1 GPU-based Data Representation

This section discusses the used GPU data structures that enable efficient data access and updates, and thus facilitates efficient rendering, while simultaneously exhibiting a small memory footprint for the network representation.

Network Representation. For a compact representation and efficient access to a network topology, nodes and segments are stored using individual buffer objects (Figure 7). A *node buffer* stores the positions of a network graph's vertices. An additional *segment buffer* encodes two indices to this buffer and the street category of the respective segment. This representation can be considered as attributed point cloud, similar to the concept described in (Trapp et al., 2013).

During runtime, the node buffer is bound as vertex-attribute source, while the segment buffer is drawn using point primitives. Thus, only one draw call is required to issue the rendering of a transportation network. Using the indices encoded in each point, a geometry shader fetches the node positions from the node buffer as well as the stylization parameters for the segment category, and performs the computation as described in Section 4.2.

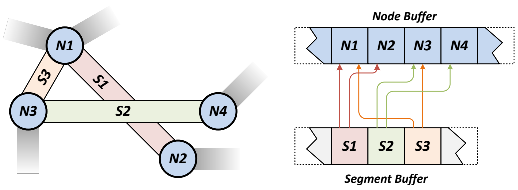


Figure 7: Schematic overview for the combination of node and segment buffer objects (left) for a compact representation of street network geometry (right).

Stylization Parameters. The concepts presented in Section 4.3 enables to reuse stylization parameter sets. This is considered in our implementation by encoding distinct sets using uniform buffers, e.g., indexed by a street category and LoD.

Textures and Framebuffer Objects. The distance textures are represented using single color channels with 8-bit value precision and a resolution of 512^2 pixels. Further, 2D texture arrays are used for the storage and access of the generated distance fields. These texture arrays can be directly used for render-to-texture. Figure 8 shows an exemplary configuration of a framebuffer object. The individual layers are aligned in descending order with respect to a segment's rank. During the geometry pass, each layer can be directly addressed for rasterization, and later used for bilinear sampling. However, this requires the texture arrays to have the same image resolution, i.e., of the viewport, and the same texture precision.

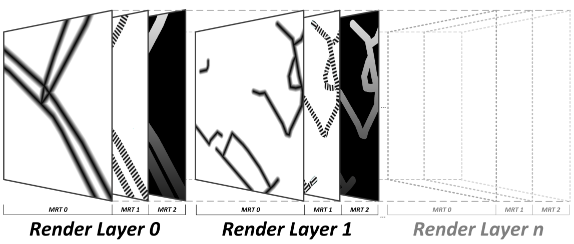


Figure 8: Exemplary render-to-texture configuration for multiple segment categories. Each render layer comprises three render targets (width distance field, respective length distance-field, and linear fragment depth).

5.2 Distance Field Computation

To enable an efficient rendering performance, the computation of the required distance-field geometry is performed within a single rendering pass. This is achieved by using the combination of render-to-texture (RTT), layered rendering, and multiple render targets (MRT) with separable blending functions. The polygonal representation of each segment is computed using a geometry shader with a constant primitive output of six triangles. It also applies view-frustum and back-face culling prior to rasterization. Further, the shader maps network categories to their respective layers stored in the framebuffer objects.

5.3 Stylization and Compositing

The final stylization of a transportation network, based on the generated distance fields, is performed using fragment shaders in a subsequent compositing pass. By rendering a screen-aligned quad, i.e., a quad that covers the complete viewport, a fragment shader computes for each render layer at each screen pixel: (1) the respective LoD level and interpolates the style parameters, and (2) subsequently performs deferred texturing to compute the resulting color. Finally, bottom-up compositing yields the final pixel color (Porter and Duff, 1984).

Level-of-Detail Computation. Multiple approaches are possible to define how respective level-of-details are computed within our prototypical implementation. We basically distinguish between three different LoD computation variants (see Sec. 6.1 for applications):

Global LoD: The LoD level is set at a global network scale, i.e., it is equal for all segments in a 3D scene and can be set using uniform variables. For example, this enables explicit coupling of zoom levels to levels of detail.

Distance-based LoD: The respective LoD level is computed based on the distance of a fragment or vertex to the virtual camera. The distance is computed in linear eye-space, therefore it yields linear interpolation of LoD levels. This approach enables view-dependent LoD rendering and seamless transitions between different LoD.

Texture-based LoD: This approach is similar to the distance-based computation, but the LoD level is encoded using a texture, i.e., the LoD level is determined using texture sampling. This enables explicit LoD control by applying lens-based metaphors in world, camera, and screen-space as well as explicit definitions of region-of-interest functions (Semmo et al., 2012).

It is also possible to combine different LoD computations using a hierarchical approach, i.e., using a global LoD value as a basis that can be refined using distance-based or texture-based LoD computations, but which remains subject to future work.

Deferred Texturing. Given a respective style representation S at a computed level of detail, deferred texturing is performed. This limits the required computations to visible fragments only and therefore reduces the workload of the per-fragment computations of the rendering pipeline. Our system provides the application of procedural or raster-based textures, depending on the application. While simple coloring can be achieved using 1D procedural texturing according to distance fields, an additionally provided length parametrization (Fig. 8) can be used to apply 2D raster-based textures (P1). For instance, fuzzy or sketchy appearances can be achieved by using 2D noise or stroke textures (Kopf et al., 2010).

Bottom-Up Compositing. The evaluated per-category colors are finally composited using a bottom-up strategy (Porter and Duff, 1984). Therefore, the colors are blended starting from the lowest rank to the highest accordingly (P5/P6). This enables the correct overlapping between the different category ranks (P2) and alpha blending to visualize tunnels or similar constellations. Depending on the application, the blending procedure can take different aspects and data into account (P3), e.g., to consider only colors of the main segments and ignore respective outlines (Fig. 6(c)).

5.4 Performance Evaluation

This sections briefly discusses the runtime performance of our prototypical implementation. We tested our approach using OSM datasets of different geometric complexity (Tab. 1). The performance tests are conducted on the following test platform: Intel i3-3110M (2,4GHz, Dual Core, Hyperthreading) with Intel HD 4000 GPU running a Gentoo Linux (Kernelversion 3.12.6). The test application runs in windowed mode. The complete scene is visible in the view frustum, thus view-frustum culling is not performed but backface culling is enabled. For each measuring step, a total of 5000 consecutive frames are rendered. Finally, all records are averaged.

Table 1: Geometric complexity of the test data sets used in the runtime performance evaluation.

ID	Data Set	#Nodes	#Ways
A	Berlin 1	5571	1028
B	Istanbul	2004	263
C	Berlin 2	9502	1766

Table 2: Performance results rendering the test data sets at different output resolutions using different number of stylization definitions (in milliseconds).

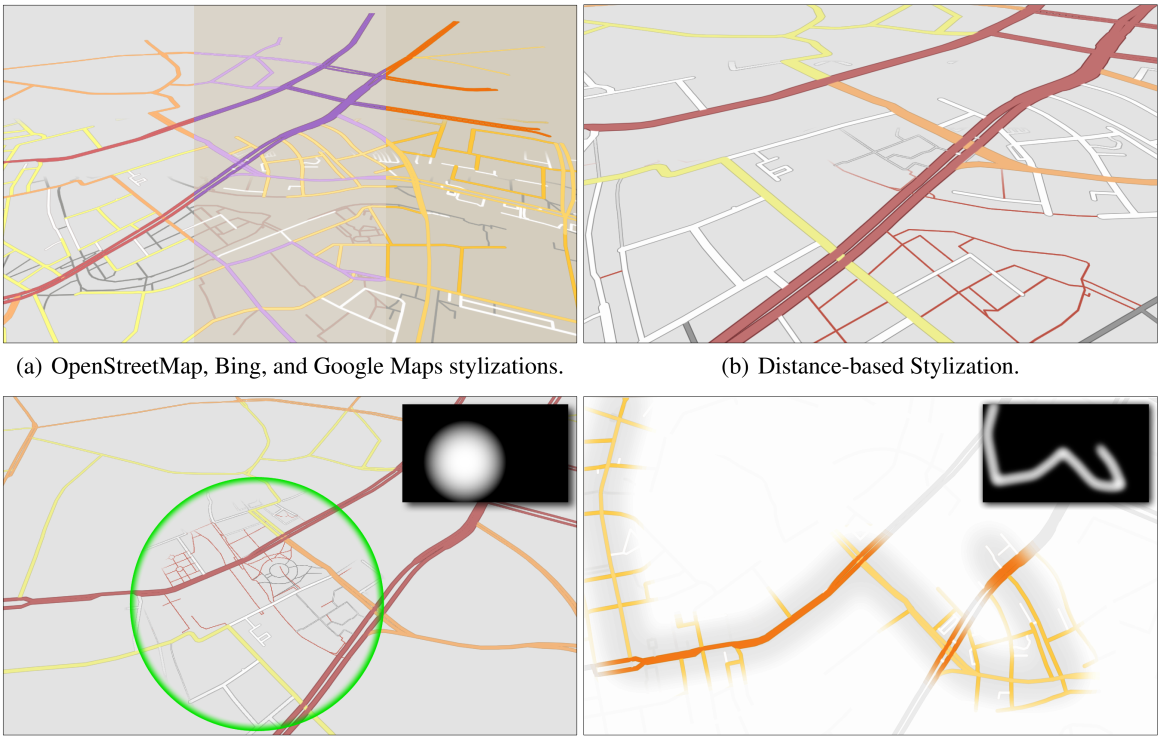
Resolution	ID	Parameter Sets			
		1	2	4	8
390 × 260	A	3.0	3.2	4.1	5.5
	B	2.9	3.3	4.1	5.4
	C	3.0	3.4	4.2	5.5
670 × 450	A	3.0	3.2	4.1	5.7
	B	2.9	3.3	4.2	5.6
	C	3.0	3.4	4.2	5.8
1280 × 800	A	25.5	29.0	36.1	50.1
	B	25.4	29.0	36.2	50.1
	C	25.3	29.2	36.2	50.2

Table 2 shows the results of our performance evaluation for different screen resolutions. The measured run-time latencies clearly indicate that our approach is fill-limited due to heavy per-fragment operations and limited by the number of applied parameter sets. Considering the low-end graphics hardware and non-optimized shader implementations, the achieved frame rate of more than 20 frames-per-seconds satisfies interactive time constraints.

Despite the GPU-based representation of a transportation network and the respective parameter sets, our image-based approach introduces additional costs in video memory. Given the horizontal w and vertical h framebuffer resolution, the required layers l (e.g., distance, length, and depth), the precision in Bytes b, as well as the number of street categories c, the additional memory consumption O can be estimated linearly with: $O = c \cdot w \cdot h \cdot l \cdot b$. For example, approx. 214 MB video memory is required for a full HD (1920×1080) rendering of a street network comprising nine categories with three render targets per layers at a floating-point precision of 32 Bit. Since distance fields are suitable for being interpolated linearly during sampling (Green, 2007), a precision of 8 Bit is sufficient for most applications, resulting in a memory consumption of approximately 50 MB.

6 RESULTS & DISCUSSION

This section presents a discussion of our results by means of application examples and by discussing limitations which lay the basis for future work.



(a) OpenStreetMap, Bing, and Google Maps stylizations.

(b) Distance-based Stylization.

(c) Lens-based Filtering.

(d) Region-of-Interest Rendering.

Figure 9: Overview of different application examples rendered with the presented approach.

6.1 Application Examples

We tested our approaches using different OSM data sets with different categorizations for route stylization. Figure 9 shows an overview of various application examples demonstrating the capabilities of our prototypical rendering techniques.

Localization. The support of different stylization parameters facilitates the generation of localized maps (e.g., in terms of color (P7)) without requiring to change the geometric representation. Figure 9(a) shows three different view-dependent stylizations that can be interchanged during rendering. Note how network segments with lower rank are faded in the rear part of the scene as well as the counterbalance of the foreshortening of the segments' widths.

Distance-based Stylization. In (Vaaraniemi et al., 2011) the view-dependent rendering of routes are introduced. This counterbalances the effects of 3D perspective projections such as perspective foreshortening, and thus visual clutter (Jobst and Döllner, 2008) in the rear parts of the 3D scene (Fig. 9(b)). This can be achieved using the presented LoD approach by enabling: (1) the fading of low-ranked route segments and (2) increasing the width of high-ranked route segments with increasing distance to the virtual camera (P3/P5). Thus, the depiction of low-ranked or unimportant routes can be omitted to avoid visual clutter while important routes are emphasized to counterbalance perspective foreshortening.

Interactive Lens-based Filtering. This focus+context functionality is common in visualization frameworks for interactive user-driven filtering (P3). To support this feature, the LoD approach is applied as follows (Fig. 9(c)): two distinct stylization parameter sets are defined for the focus and context region respectively. Here, the focus shows a detailed view on a route network comprising all route categories, while the context only depict the three major categories. A screen-space lens (see inset) is used to control the transition between the respective LoD levels.

Regions-of-Interest Visualization. Similar to lens-based filtering, the LoD approach can be used to explicitly highlight a certain navigation route, while omitting the rendering of the remaining network areas. Figure 9(d) shows an example of controlling the level-of-detail stylization using a region of interest (RoI) defined along a path of network segments. This can be used for highlighting segments relevant for navigation. The RoI is encoded using a texture (inset) that is referenced in network coordinates. The rendering of network parts that are not of interest is mostly omitted. A transition represented by a drop-off function conveys parts of the context required for navigation, e.g., junctions or routes with a high (important) rank.

6.2 Limitations

To this extent, the image-based approach presented in this paper is limited conceptually and technically. Despite being currently limited to render planar networks, the usage of distance fields causes two problems in the final depiction: *intrusion* and *protrusion*. Intrusion is caused if the distance field of two routes of the same category intrude each other because of a large line width parametrization. Thus, the rendering results can appear as being connected to the viewer. Further, protrusion appears where two street categories with different width parameter intersect, especially at T-junctions. Here, the distance field of a high ranked street protrudes the distance fields of a lower ranked street. Finally, the additional video memory required by our approach is a major technical limitation, especially for future implementations on mobile devices. With respect to these, future implementations for mobile platforms would require geometry shader functionality, e.g., in OpenGL ES.

6.3 Future Work

The presented approaches lay the basis for future research directions. Despite optimizing the implementation and enhancing the visualization by integrating internal labels (Vaaraniemi et al., 2014), the previously described limitations can be counterbalanced by adapting the cap geometry generation according to the node grade and the ranks of adjacent segments.

Further, our approach can be enhanced by applying adaptive or view-dependent tessellation or subdivision schemes of the input line segments to yield more smooth curves, e.g., for the rendering of roundabouts. Furthermore, the geometry creation stage can be extended by computing alternative geometric representations, e.g., to enable the application of street networks as visualization scenery. Also, the compact network representation also lays the basis for future research in view-adaptive generalization of transformation networks, solely performed on GPU.

7 CONCLUSIONS

This work presents an interactive, image-based approach for interactive rendering and cartographic stylization of transportation networks that is especially suitable for map visualization, which we exemplified for street networks. Our fully hardware-accelerated rendering technique enables the efficient storage of route network geometry and appearance variances while requiring only a single geometry and post-processing pass for image synthesis. It represents the basis for a number of applications in the context of 2D and 3D geovirtual environments, such as view-adaptive rendering of route networks, interactive filtering as well as highlighting.

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