Visualizing Movement Dynamics in Virtual Urban Environments

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ABSTRACT

Dynamics in urban environments encompasses complex processes and phenomena such as related to movement (e.g., traffic, people) and development (e.g., construction, settlement).

This paper presents novel methods for creating human-centric illustrative maps for visualizing the movement dynamics in virtual 3D environments. The methods allow a viewer to gain rapid insight into traffic density and flow. The illustrative maps represent vehicle behavior as light threads. Light threads are a familiar visual metaphor caused by moving light sources producing streaks in a long-exposure photograph. A vehicle's front and rear lights produce light threads that convey its direction of motion as well as its velocity and acceleration. The accumulation of light threads allows a viewer to quickly perceive traffic flow and density. The light-thread technique is a key element to effective visualization systems for analytic reasoning, exploration, and monitoring of geospatial processes.

CR Categories and Subject Descriptors: I.3.6 [Computer Graphics]: Methodology and Techniques; I.3.7 [Computer Graphics]: Three Dimensional Graphics and Realism.

Additional Keywords: Visual Spatial Analytics, Illustrative Visualization, Cartography.

1 INTRODUCTION

Geospatial data about dynamics represent a major category of geo-information. In particular, dynamics taking place in urban environments more and more becomes an essential subject in real-time visualization applications that analyze, explore, present and document complex processes and phenomena. These are typically related to movement dynamics, e.g., flow of traffic and people, development dynamics, e.g., construction steps and settlement phases, and usage dynamics, e.g., varying load of radio networks and energy infrastructures.

Visual representations of traffic flow and density in virtual urban environments, e.g., 3D city models, provide substantial decision support in urban planning. While a large repertoire of efficient techniques exists for visualizing the static components of such environments (e.g., digital terrain models, building models, and vegetation), less is known about illustrating dynamics. Visual representations of movement dynamics such as glyphs [21] are often purely artificial and can hinder the understanding [19] of the depicted dynamics. This paper introduces a novel technique to visualize traffic flow and density in urban environments by means of light threads, which symbolize dynamics by glyphs integrated into a 3D city view. The derived experiential maps provide rapid insight into movement dynamics in urban environments.

"Depiction is essentially an optimization problem, producing the best picture given goals and constraints" [6]. The intention of a depiction is typically specified by *cognitive goals* (i.e., ease of understanding depicted information), *affective goals* (i.e., invoking emotions), or *motivational goals* (i.e., motivating to participate in depicted concepts) [18]. Constraints are set by the limitations inherent to the used 2D medium, e.g., an image can have low-resolution and is, in particular, static.

Figure 1: A long-exposure photograph can illustrate the motion of vehicles. The accumulation of light threads of every vehicle illustrates the flow and density of traffic.

We present illustrative maps of urban spaces that enable experiential cognition of movement dynamics in static images. We achieve this by follow the principles for developing effective depictions introduced by Norman [13]:

- Our visual representations are *appropriate*; they communicate contents and structure of urban space and related movement dynamics with nothing distracting, extraneous, or contradictory in the makeup.
- Our visual representations are *natural*; they match closely the information that they present. We illustrate vehicle behavior and movement dynamics using light threads. Light threads are a visual metaphor caused by moving light sources producing streaks in a long-exposure photograph (Fig. 1). Light threads can turn humans' cognition of vehicular behavior in an experiential rather than in a reflective mode [13].
- Our visual representations *match the task* that is to be performed, that is, assessing traffic flow and density in geospatial environments.

The light threads illustration technique considers Tufte's *design strategy of the smallest effective difference*, i.e., making visual distinctions as subtle as possible, but still clear and effective [20]. For that purpose we "map invisible properties onto visible attributes" [18]. Using a vehicle's front and rear lights for light threads produces vast streaks of varying width and highlights of varying brightness in a static image to convey a vehicle's direction of motion as well as its velocity and acceleration. At a microscopic scale, light threads communicate the dynamics of every vehicle. At a macroscopic scale the accumulation of light

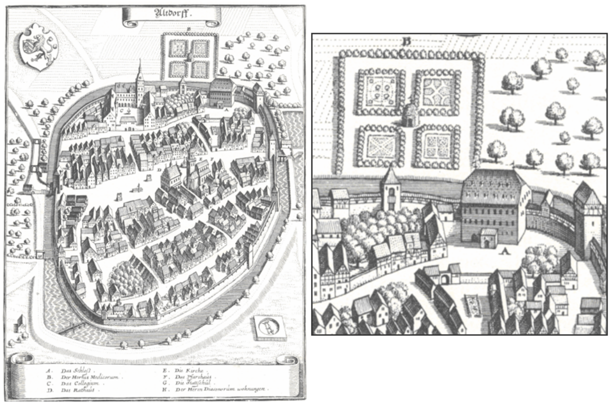

Figure 2: The village of Altdorf (Bavaria) from Merian (ca. 1640), taken from his „Topographia Germaniae“.

threads provide insight into the traffic flow and traffic density in urban space.

1.1 Judging the Efficacy of Motion Representations

Cutting [4] analyses techniques for depicting motion in static images from a perceptual point of view. He presents the following criteria to judge the efficacy of representations of motion in the contexts of science, art, and culture:

- **Evocativeness.** Indicates whether a motion's representation succeeds in convincing an observer of a sense of motion, that is, "*is motion perceivable in the image at all?*"
- **Clarity of object.** Indicates whether an observer can clearly identify the object whose motion is represented. Clarity of object is almost required in science whereas a suggestive image is often sufficient and even wished in art.
- **Direction of motion.** Indicates whether a motion's representation conveys its direction clearly. Here, the observer's
- **Precision of motion.** Indicates whether a motion's representation depicts the amount of motion properly, so that an observer is able to predict it. Precision of motion is crucial in the context of science, e.g., to communicate time-variant data.

Cutting also emphasizes that the experience of an observer can assist the assessment of motion and should be considered for evaluation. We review light threads according to these principles to evaluate their efficacy in representing the movement dynamics in urban space.

1.2 Experiential Maps in Cartography

Experiential cartographic illustrations are meaningful visual interfaces for building effective systems for analytic reasoning about geospatial processes.

Traditional historic city maps convey spatial as well as thematic information. Matthaeus Merian (1593-1650) is among the most prominent "city modelers": He invented and established the first systematic production of city maps as commercial products – manufacturing more than 2,150 European city views in his "Topographia". The city views mostly abstracted and idealized the urban situation. In particular, distortions and integrated multi-perspective views in a single image characterize the depictions. Merian also included meta-components such as legends and compass to guide the viewer. At their time, the 3D city maps served to clearly communicate economy and defense situation of cities. Figure 2 shows an experiential cartographic map produced by Merian.

Route maps are common visual interfaces that depict paths and directions efficiently. Agrawala and Stolte introduce a smart depiction system [1] that designs and generates cartographic route maps in a hand drawn style automatically [2] based on the generalization techniques and the principles of mapmaking and the abstraction techniques found in hand drawn route maps. In particular, they remove unnecessary distracting information in the route maps but emphasis meaningful cues such as the turning points of the route. The resulting experiential maps reveal the most essential information in a simple way that let users feel aware of a route.

Our illustrative, experiential maps of movement dynamics in virtual urban environments are an approach to situational aware [7] cartography. The goal of this work is to provide effective visual interfaces for systems that enable analytic reasoning, exploration, and monitoring of geospatial processes. Primary application areas include decision-support systems for city planning that aim at a public participation and traffic guidance systems for congested traffic avoidance.

Classic orthographic maps do not offer an exact embedding of information into the virtual 3D environment, i.e., they provide less information dimension. We choose an illustrative 3-dimensional representation that reduces the visual complexity in an image of urban space while conveying the geospatial as well as the related time-variant information at a high cognitive quality. The implementation uses techniques borrowed from non-photorealistic computer graphics [9][17] and illustrative visualization [8], which are based on the principles found in graphics design, perceptual psychology, and cognitive science.

2 ILLUSTRATIVE REPRESENTATION OF URBAN SPACE

Illustrative 3D city maps [5] are visual representations of 3D city models complementary to Virtual Reality visualizations. They aim at accomplishing the following:

- Concentrate on visual representations that emphasize high perceptual and cognitive quality that effectively communicates the contents, structure, and relationships of urban objects as well as related thematic information while reducing unneeded distracting details.
- Enable meaningful visual representation even in the case of scarce urban spatial information since high-quality and complete data is rarely available for large-scale urban areas.
- Enable the fully automated generation of representation.
- Enable a meaningful visual representation for exploration and for visual analysis even on small display devices.

Applications of illustrative 3D city models are primarily all of the various visual interfaces to urban spatial information required, for instance, in city development planning, city information systems, and mobile maps.

2.1 Compositional Representation of 3D City Models

Buildings are the basic components of 3D city models. In general, the digital data of buildings can be acquired based on administrative data (e.g., cadastre records), laser scanning, and aerial photography. In practice, for large areas of 3D city models no explicitly modeled buildings are available. For this reason, a building's geometry has to be generated automatically. Buildings can be constructed as simplified block models by extruding 2D ground polygons to certain heights.

Environmental components include all kinds of spatial objects that set up the environmental space of a 3D city model. Examples include transportation networks (roads, rail, etc.), vegetation objects (trees, lawns, etc.), and population and traffic objects (people, cars, etc.). Most environmental components can be modeled and handled as additional 3D scene geometry. For geometric modeling 2D polygons define the basement on top of a terrain model that represents roads, sidewalks, lawns, streets, etc. Extruding these 2D polygons generates the relevant 3D geometry.

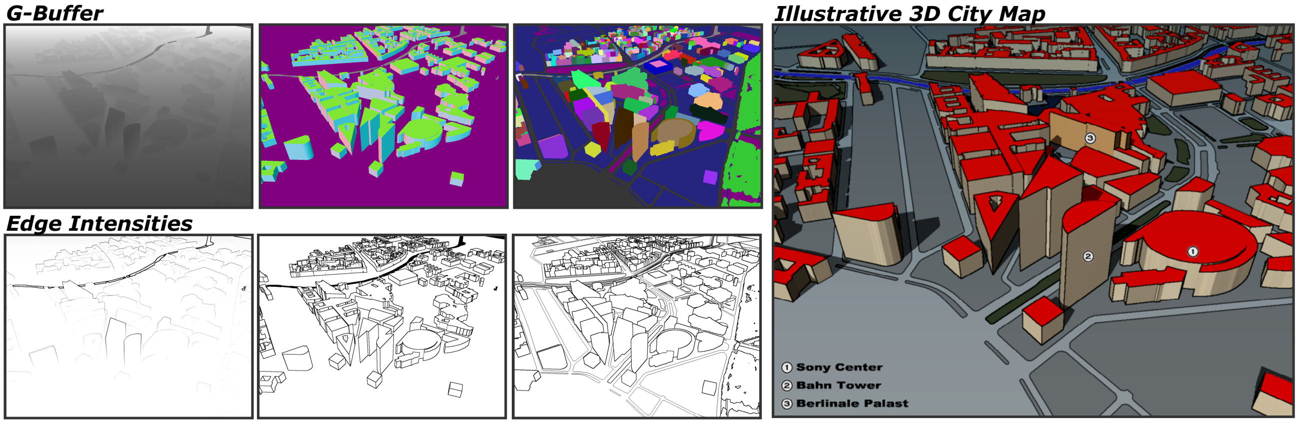

Figure 3: Image space edge enhancement assist in a homogenous and a generalized display of the 3D city models for illustrative maps.

Thematic information, e.g., demographic or building information, associated with components is defined and required by applications of 3D city models. Building information include, for instance, occupancy and industrial or residential usage.

2.2 Visual Representation of 3D City Models

Illustrative 3D city models apply the following strategies to give a meaningful visual representation:

2.2.1 Vivid Coloring

Vivid coloring chooses effectively applied colors in such a way that the overall appearance of the illustrative map is characterized by maximal visual clarity as well as unambiguousness with respect to individual objects. In contrast to photorealistic images, vivid coloring emphasizes objects, their classes and roles in contrast to their physically-based light interaction. Cartographic city maps use a reduced color scheme for shading. In colored drawings the illustrator usually simplifies the realistic colors of the urban objects and greatly reduces the number of colors used.

2.2.2 Depth and Spatial Cueing

Depth and spatial cues are important to facilitate the perception of depth and spatial coherence in projected images of 3D scenes. In illustrative maps, terrain and building related cues dominate. For this reason, illustrative maps use shadows as essential depth cues. We use shadow volumes [3] to mask lit and shadowed areas in 3D cities for later shadow application.

In addition, color-based depth-cueing can be applied, resting upon the fundamental principle of tri-chromatic generalization of human color perception [22]. The intensity and saturation of a color is changed according to the viewer distance: more distant objects are rendered in more de-saturated colors whereas the intensities of colors remain constant.

Classical 3D city maps apply orthogonal projections, which do not provide monocular depth cues such as linear perspective, relative size, and texture gradient. However, occlusion and known sizes can provide depth cues in this case. Frequently, map designers place objects of known size, e.g., people or trees, in the scenery, which are not contents of 3D city model in a strong sense.

2.2.3 Edge Enhancement

In illustrations, shades are rarely used to communicate shape information; instead, outlines are drawn because outlines (e.g., edges where the visibility of the surface changes) of 3D shape are one of the strongest visual cues [12] and "important for figure-to-background distinctions" [10]. Edge enhancement detects and outlines perceptually important edges to provide a homogenous and perceptually optimal visual depiction and, therefore, facilitate object recognition.

Saito and Takahashi introduce G-Buffers [16] as 2-dimensional data structures that store properties of projected 3D scenes such as surface normals, depth values, and object identifiers. G-Buffers are stored as 2D image so that image post-processing can derive image enhancements, e.g., we can extract discontinuity edges.

Perceptually important edges of 3D scene geometry are classified as follows:

- A *silhouette edge* represents a junction where two polygons adjoin, whereas one polygon is visible and the other one is occluded along the junction (i.e., the visibility of the surface changes).
- A *border edge* is a boundary of a polygon, i.e., an edge where no other polygon adjoins.
- A *crease edge* is a junction where two polygons adjoin, whereas both polygons are visible along the junction (i.e., the visibility of the surface remains unchanged) and form a certain angle above some threshold.

In terms of G-Buffers, abrupt changes in the depth buffer occur at silhouette edges and border edges, whereas abrupt changes in the normal buffer typically occur at crease edges.

In case of urban environments a lot of faces are parallel to one another, e.g., buildings, roofs, and basement geometry and the scene measured from the front-most buildings to the buildings close to the horizon is typically large with respect to depth, especially if viewed from a birds-eye-view. As a result, both the normal and the depth buffers are not sufficient to produce adequate outlines. Encoding each building as well as the basement geometries by individual color values, i.e., object IDs, constitute an ID buffer whose discontinuities then complements the assembly of perceptually important edges. As a result, outlines display both building-to-building and building-to-ground distinctions and accentuate the outlines of roads, sidewalks, lawns, etc. Figure 3 depicts the G-Buffers, the derived edge intensities for edge enhancement, and an illustrative 3D city model.

Because image-space algorithms are virtually independent of a scene's geometric complexity [10] they are particularly well suitable for huge 3D city models and also apply well to high tessellated basement geometry.

2.2.4 Abstracting Building Facades

Abstracted facades are important visual cues in illustrative 3D city maps for recognizing individual buildings. In general, facades enable observers, for example, to estimate the building height (counting the number of floors). In dense urban areas, humans appear to identify and relate buildings based on their characteristic

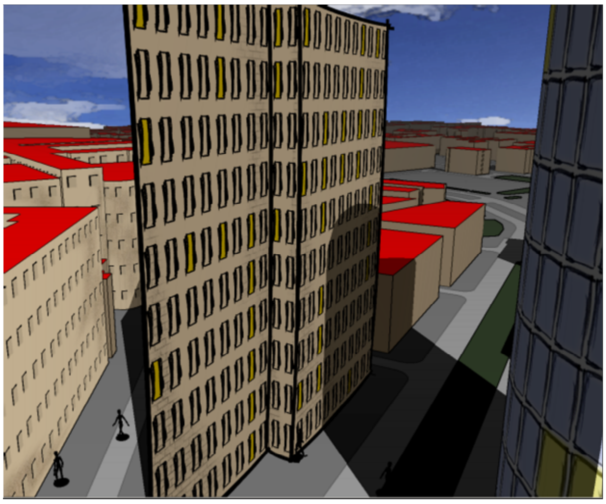

Figure 4: Procedural facades encode a building's characteristics and meta-information. Additionally integrated geometry, e.g., people, can provide cues in urban space.

coloring schema (e.g., material colors), architectural style (e.g., timber-framed, baroque, post modern), and arrangement of window, door, and floors, and the building usage aspects (e.g., business or residential usage). In most applications, the detail information of photorealistic facades is not desirable because they increase the visual complexity and, therefore, complicate recognizing the principle appearance of buildings, for instance, when looking at buildings from a bird's-eye perspective. In contrast, procedural facade texturing encodes just a building's characteristics and meta-information. A building's procedural facade includes number of floors, position and size of windows and doors, structure, material, and colors (Fig. 4). Compared to photography-based textures, they do not accurately reflect the real appearance but indicate their principle structure, composition, and usage at a lower visual complexity.

3 ILLUSTRATING TRAFFIC FLOW AND DENSITY

Traffic or vehicular traffic represents omnipresent time-variant flows in urban environments. Traffic flow visualizations can reveal phenomena of cluster formation and backward propagating dense traffic. In general, a traffic flow indicates the principle motion direction of the vehicles, whereas a traffic density indicates the amount of vehicles at a point in time.

At a macroscopic level of abstraction, traffic can be represented by a vector field and visualized by fluid dynamics [21]. This view neglects that vehicles do not interact by simply following the physical laws, but also due to the reactions of human drivers, which can lead to unpredictable paths. At a microscopic level of abstraction, traffic can be represented by the dynamics of every vehicle. Since we aim at a natural visual representation rather than a scientific visualization, we choose the microscopic level of abstraction for illustrating traffic flow and density in static images.

3.1 Light Threads – A Visual Metaphor

As a visual metaphor for representing traffic flow and density we introduce light threads. Conceptually, light threads are dynamics glyphs [13] that reproduce the vast streaks and the highlights that appear in long-exposure photographs when capturing moving light sources. The faster a light source moves the thinner become the streaks and the weaker appear the highlights. The slower a light source moves the vaster become the streaks and the brighter become the highlights, which then can leads to overexposed selective highlights in case of no moving light sources.

We implement light threads to illustrate the time-variant paths of every vehicle in urban space in a certain time interval.

3.1.1 Rendering Light Threads of a single Vehicle

We model each vehicle by its center and length. This lets us derive its four light sources: the positions of the two front lights and the two rear lights as well as their light direction vectors, which correspond to the vehicle's major axis in both directions. Then, we trace the time-variant paths of the vehicle's light sources for a given time interval, whereas the duration of the time-interval corresponds to the exposure time of the virtual photographic camera.

We spatially integrate the time-variant path of each light source by rendering point sprites [3] at discrete points in time. Scaling the point sprites according the light's distance from the camera ensures a perspective correct size.

The point sprites are textured with an image of a disc: a bright yellowish disc maps to the point sprites that represent the front lights and a reddish and slightly smaller disc maps to the point sprites that represent the rear lights. The alpha values of both textures fade from 1 to 0 according to a Gaussian-like curve depending on a texel's distance from the center of the texture.

We texture a light's point sprite with a perfect shape of the disc if the light faces the viewing direction (i.e., its direction vector and the vector from the camera position to the light source are collinear). Otherwise, we scale the disc non-uniformly depending on the angle (i.e., the dot product) between the light direction and the viewing direction to yield an ellipsoidal shape. We then align the major axis of the ellipsoid along the image-space motion direction; hence, we avoid a sparse coverage of the motion path and, thus, assure continuous path integration in image-space. If the light's direction faces away from the viewing direction, we discard the point sprite from rendering. In this way, the front and rear lights are only visible if they are oriented towards the viewer.

Because light is almost additive, we additively blend the fragments' color values produced for the point sprites into a floating-point framebuffer [11] using alpha blending. Rendering all point sprites of a light source's motion path successively then produces highlighted colors close to the path's center that fade out at the border according to the distribution of the alpha values of the disc or ellipsoidal shape.

As a result, the accumulation of point sprites produces a streak of constant brightness and width in the framebuffer in case of a non-accelerated motion of a vehicle. Brighter highlights and vaster streaks appear for slow motions and weaker highlights and thinner streaks appear for fast motions. If the speed of the motion changes the tinctorial strength and the width of the streak vary accordingly. Figure 5 shows light threads that communicate the vehicles' direction of motion, varying velocity, and varying acceleration.

3.1.2 Accumulation of Light Threads

The light threads of a single vehicle convey its time-variant data: its position, velocity, acceleration, and direction of motion. At a microscopic level of abstraction, we combine the light threads of every vehicle's dynamics. That is, we integrate their light threads in one image by accumulating them in the same framebuffer. This produces bright highlights where light threads overlap or produces even thicker light threads where vehicles follow approximately the same motion path though temporally deferred. For instance, a crowd of vehicles heading in the one direction following a road produces overexposed highlights and intermixed light threads with only small in-between gaps, which

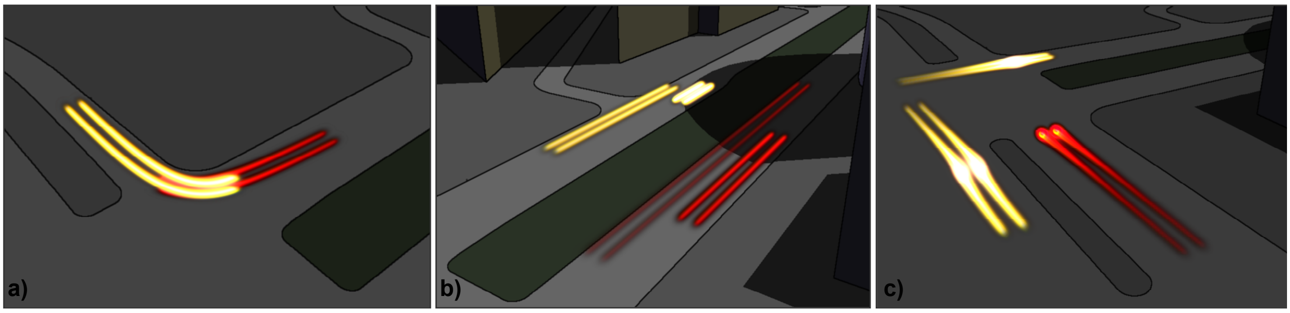

Figure 5: Light threads visualize the direction of motion of every vehicle (a), their velocity (b), and their acceleration (c).

gives accumulated threads a streamlines-like appearance and thus represents the traffic flow effectively [21].

Consequently, light threads encode not just the dynamics of individual vehicles; their accumulation encodes the traffic flow and the traffic density in urban space (Fig. 6).

3.2 Cartographic Integration

Light threads are insignificant as long as they are not embedded into maps of urban environments. We integrate the encoded dynamics information into the illustrative 3D city maps. Because illustrative maps of urban space achieve a high cognitive quality, they, thus, allow an observer to register light threads as the vehicles' dynamics. The reduced visual complexity of these maps avoids graphical interference and perceptual disturbances with the projected time-variant data so that the data can be interpreted easily.

In order to avoid overexposed highlights for all light threads we scale the color intensity of the light threads in the floating-point framebuffer before integrating them into illustrative maps. Furthermore, we increase the perceptibility of light threads by reducing the brightness of the illustrative map. The adjusted contrast in brightness then increases the perceived intensity of light threads [15].

Embedding the light threads into the illustrative maps leads to a novel thematic experiential map. The reduced visual complexity in this map allows us to target lower resolution images. Thus, the thematic map can be distributed as mobile maps to small display devices.

3.3 Efficacy of Dynamics Representation

In the following, we review the efficacy of light threads as a methodology for representing motion in static images based on the criteria introduced by Cutting (s. 1.1).

3.3.1 Evocativeness

The most obvious way to represent motion in a still image is through the use of blur in a long-exposure photograph [5]. Light threads represent overexposed moving light sources, which are integrated into the context of urban environments. While the environment remains still and clearly recognizable the moving light sources appear blurry and, hence, invoke in an observer a feeling of motion in the static image.

3.3.2 Clarity of Object

In a visual representation of traffic, the accumulation of light threads causes a dominant color and leads to brightened and thickened threads. Thus, the threads produced by a single vehicle can only be identified if the vehicle's path deviates from a main flow. Otherwise, its threads are indistinguishable from the ones of the other vehicles. Even if the motion of just one vehicle is displayed, the vehicle's shape cannot be identified because a camera with a long exposure time captures almost only the background at the vehicle's positions through motion (Fig. 1).

Nevertheless, the contexts the light threads are used in lets the humans' experience reveal clarity. Although, an object cannot be identified, humans can instantaneously interpret light threads as visual representation of moving vehicles and consequently can interpret their accumulation as traffic flow.

3.3.3 Direction of Motion

Light threads convey the direction of motion clearly. The color of a vehicle's light threads correspond to either the vehicle's front lights (yellow-white) in case the moving direction of the vehicle faces towards the camera, or its rear lights (red) in case the moving direction faces away from the camera. Because vehicles move in 2-dimensinal space and because they are positioned onto a given basement, e.g., the present road infrastructure, the direction of motion is clearly predictable (Fig 5a). In conclusion, the direction of the overall traffic flow, which is also aligned to the road infrastructure, is also clear.

3.3.4 Precision of Motion

Although non-moving lights produce overexposed areas in an image while fast moving lights produce thinned threads of less brightness, the precise amount of a vehicle's velocity cannot be predicted by an observer properly. But the observer can estimate the amount of velocity by giving a fuzzy approximation, such as *fast*, *slow*, *very fast*, or even *stopping* (Fig 5b). The same applies to the acceleration. Although, an observer cannot estimate the acceleration precisely, the varying brightness of the light threads due to a change in velocity is a subtle cue that lets sense the acceleration (Fig 5c).

Relating the effective exposure time used for generating the image to the visual cues included into the illustrative 3D city map (e.g., people, facades) lets an observer derive a precise approximation of the amount of motion. That is, the prediction of motion changes from an experiential task to a reflective task [13] if it has to be done precisely.

The visual representation of the traffic density results from the accumulation of light threads or in case of congestions from overexposed short or even dot-like light threads. Again, the exact amount of the traffic density can be hardly estimated but a fuzzy estimation can be given as well. Figure 6 illustrates the traffic density at different scales.

4 APPLICATION SCENARIOS

The following scenarios outline application fields of the light-thread based visualization of movement dynamics. In general, the experiential map serves as a generic tool, which can be applied to a whole range of geo-referenced time-dependent positional data.

4.1 Urban Transportation Planning and Monitoring

In urban transportation planning, concepts for traffic regulation require traffic monitoring and cautious reflections of the traffic flow and its density, for instance, with respect to one-way streets, street lane reductions, and traffic jams at junctions. City planners reconsider and compare alternative models, simulate and visualize sample traffic data, and, in the end, need to convince the general public, i.e., non-experts, of their decisions. Classical map-based visualization of traffic frequency data does not offer an exact embedding in the virtual 3D environment (e.g., per-lane data, crossings) and less information dimensions (e.g., speed, acceleration, stops). Illustrations of movement dynamics can be used as direct visual interface to complex traffic data. The depictions generate traffic maps, which enable humans to get an effective impression of traffic situations of varying scenarios rapidly. In particular, potential bottlenecks in traffic flow and congestions at peek-hours can be easily identified (Fig. 7).

In a similar way, the light-thread technique allows us to visualize movement dynamics in the fields of radio network operation. The movement data records the spatial position of a cellular phone, the field strength, the responsible antenna station, and events such as call drops. Light threads can visualize various information dimensions in a single image and allows experts to correlate the specific dynamics with the surrounding environment and its radio network relevant objects such as occluding buildings and antennae stations.

4.2 Real-Time Systems for Congestion-Awareness

Traffic guidance and control systems monitor traffic volumes and route traffic especially during peak hours, e.g., by manipulating traffic lights or lane use. In particular, electronic traffic signs display recommendations to advice road users to drive round. The recommendations provide only a binary rating for just a specific region or, perhaps, an additional more fuzzy rating, such as "*caution, viscous traffic ahead*". This leaves road users with no sense for the actual traffic. Furthermore, they generally cannot determine the overall expansion of a traffic jam, e.g., whether approach roads are jammed too. Consequently, the decision to either avoid the traffic or to proceed is based on a system's validation and not on one's own assessment.

Preferable from a user's point of view is to make a decision based on non-discrete data and clear insight into the present situation and, hence, to be aware of the traffic density. For instance, a user can plan an optimal route to by-pass the congestion taking into account being partially jammed only or he can proceed with a planed arrangement in case the congestion is less dense than assumed. That is, people should be able to base their (often spontaneous) decisions on fuzzy data.

A real-time system that monitors the current traffic flow and density (e.g., by tracing cell phones) could generate mobile maps of the dynamics in urban environments. Broadcasting these maps to mobile devices such as cell phones, PDAs, or navigation systems provide on-board information that assists in avoiding congested traffic and in decision-making while driving.

Taking this a step further, a presentation system that considers the current traffic flow and density at a larger scale and estimates the upcoming traffic by simulation helps viewers to understand the origin of traffic congestions and can lead to effective reasoning. Experienced users can probably assess traffic more efficiently and avoid congestion in advance by, for instance, behaving contra-cyclical.

5 CONCLUSIONS

This paper has introduced light threads as powerful, extensible tools to visualize geo-referenced, dynamic movement data as

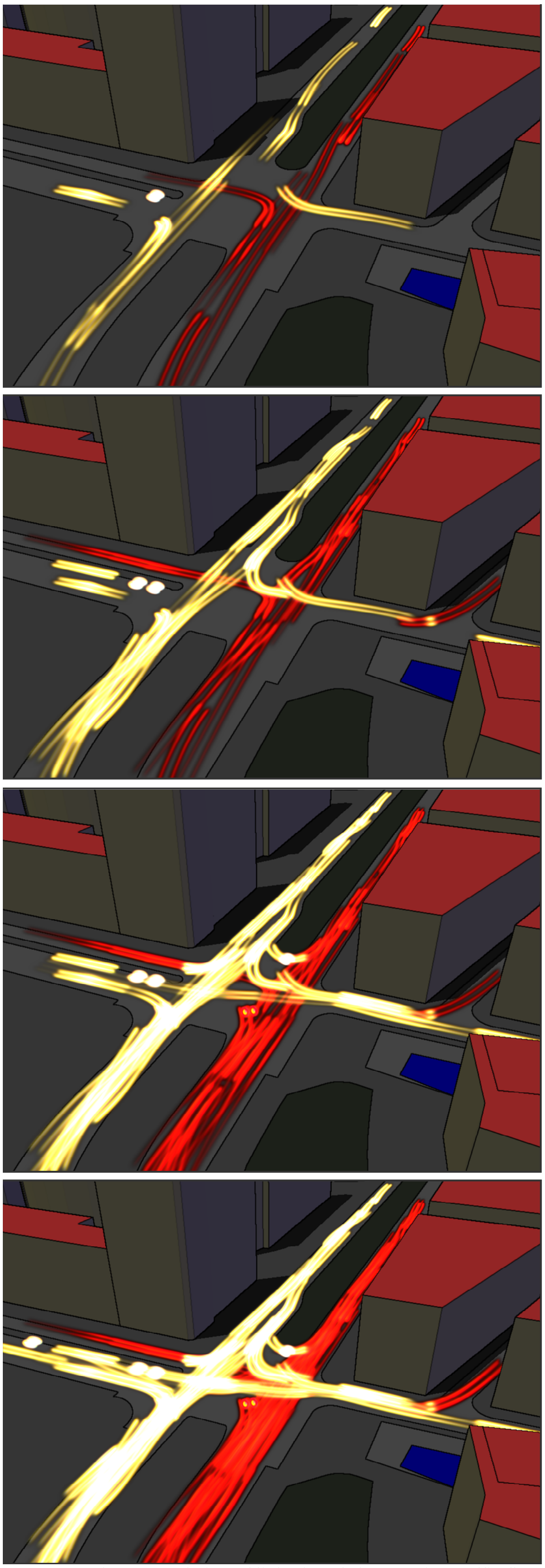

Figure 6: The accumulation of light threads let perceive traffic flow and traffic density. The images show the flow as well as density at different scales.

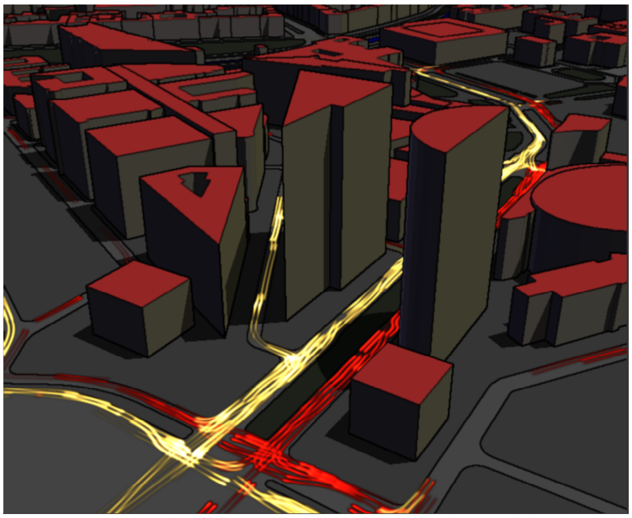

Figure 7: The experiential map illustrates the traffic flow and density at the Potsdamer Platz in Berlin at peek-hours.

required, for example, in visual geospatial analytics. It is based on a natural visual representing of dynamics by glyphs that are integrated in the virtual 3D environment. Illustrations of movement dynamics, for example, can directly express paths, speed, acceleration, and density of moving objects in virtual 3D city models. As essential characteristic, light-threads as well as their environment are visualized in an experiential way to provide a comprehensive, effective graphical encoding. The light-thread metaphor thereby matches the humans' cognitive model of movement dynamics. The technique supports efficient decision-making and analytic reasoning by both experts and non-experts. We further outlined potential application scenarios.

Future work will optimize the visual representation of events within time-dependent series of positional data (e.g., accidents, call drops) and adapt more precisely to non-vehicle traffic (e.g., paths of pedestrians). We also will investigate (1) how precisely the amount of dynamics can be predicted by an observer, (2) which cues of illustrative maps assist prediction, and (3) if specific views, e.g., an orthographic or a perspective aerial view, lead to different predictions.

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