Non-Photorealism in 3D Geovirtual Environments

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Abstract: We describe how non-photorealistic 3D rendering, a new class of rendering techniques in the scope of real-time 3D computer graphics, can be applied to 3D geovirtual environments. Non-photorealism promises a number of solutions for effective and comprising interactive information display in cartography and GIS. We discuss inherent limitations of real-time computer graphics due to its strong dedication to photorealism for a long time. We explain a non-photorealistic 3D rendering technique for 3D city and landscape models as important classes of 3D geovirtual environments. The technique is based on stylized edges, edge-enhancement, tone-shading, procedural texturing, and shadowing used to render common building blocks such as building models, vegetation models, and ground-space models in an illustrative, expressive graphics style in real-time. We also outline future directions in non-photorealism and its applications to geovisualization.

1 Motivation

3D geovirtual environments serve to present, explore, analyze, and manage geo-referenced data and information. These environments become part of an increasing number of applications, for example in form of interactive 3D maps, 3D city models, or 3D landscape models. The quality of information display, however, is still defined by the inherent quality of real-time 3D computer graphics dedicated for the last 30 years to rendering technology that aims at the production of realistic images.

For a significant number of applications in cartography and GIS, classical 3D computer graphics and photorealism are not adequate:

- To visualize complex information, photorealism does not provide optimal means for visualization because it does not facilitate the integration of additional non-realistic information. For example, a photorealistic depiction of a virtual 3D city can hardly be "augmented" by thematic information because façade, roof, and street textures are massive image elements.
- To visualize abstract information, the means provided by classical computer graphics appear to be non-optimal. For example, we can hardly display sketches of uncertain information or vivid, cartoon-like depictions of a campus map.
- To visualize complex information by a minimum of display resources, such as on mobile devices, photorealism frequently fails due the visual complexity inherent to photorealistic images. For example, a scaled-down version of a digital photography has a drastically lower information level compared to a scaled-down version of a hand-drawn sketch of the same scenery.

In the following we briefly discuss limitations of photorealism (Section 2). Then, we give an overview of non-photorealistic rendering technology (Section 3). We also introduce the characteristics of expressive and illustrative city and landscape depictions (Section 4). Next, we

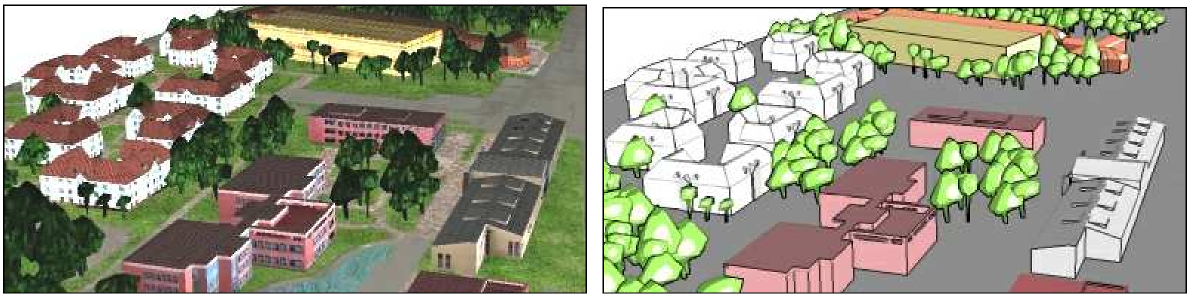

Figure 1: Photorealistic and non-photorealistic depictions of the same 3D model. In both cases, real-time rendering allows user to interact with the 3D geovirtual environment. (Images: LandXplorer)

outline building blocks of 3D city and landscape models as an important category of 3D geovirtual environments (Section 5), and we present a technique for their non-photorealistic real-time rendering (Section 6). We finally discuss applications (Section 7) and sketch future directions (Section 8). This contribution is based on and extends previous findings given by Döllner and Walther (2003).

2 Photorealism and Its Limitations for Geovisualizations

The concepts of photorealism in 3D computer graphics still define principle techniques used for visualizing geoinformation in 3D geovirtual environments. In the scope of Virtual Reality, a large collection of algorithms and data structures provides efficient rendering of large, complex 3D terrain data and heterogeneous geo-spatial objects (e.g., digital terrain models by Duchaineau et al. 1997, large collections of heterogeneous objects by Davis et al. 1999). These methods are focusing on efficient rendering and require high quality of texture and geometry data. Numerous optimizations for virtual environments have been developed such as discrete and continuous multi-resolution representations of geometric objects, view-frustum and occlusion culling, imposter techniques (Schaufler 1998), scene-graph optimizations, and recently out-of-core visualization techniques, which directly render large amounts of data from external memory in real-time. Akenine and Haines (2002) provide a general introduction to these subjects.

While research in Virtual Reality provides efficient solutions for handling complex 3D scenes, it does not provide alternatives to the *physically oriented illumination models* and graphics designs. For example, the Phong illumination model, which approximates the physical interaction of light in 3D environments, is actually shaping current visualizations–it was not possible until recently to develop alternatives if real-time rendering was required because it forms part of the hardware-implemented rendering pipeline. This situation changed fundamentally with the advent of programmable computer graphics hardware.

Another limitation represents *single-pass rendering*. The rendering engine traverses the scene description in a single pass to generate the image and directly sends graphics data to the graphics hardware. However, a large number of graphics designs become possible only by more complex, multiple rendering passes, which collect data, prepare intermediate images, and can perform imaging operations. Edge enhancement, for example, requires one rendering pass that detect discontinuities in the z-buffer, and one rendering pass that detects discontinuities in an intermediate image encoding surface normals, and overlays both intermediate images with the final image (Nienhaus and Döllner, 2003).

Looking at achieved *graphics quality* in the scope of 3D geovirtual environments, inherent limitations of VR techniques also become apparent: Photorealistic rendering techniques require and, therefore, depend on geometric and graphical detail to achieve impressive results (Figure 1a). For example, a 3D city model without high-resolution façade textures typically remains an inconsistent visual artifact. The lack of sufficient detail is often frustrating–not only because highly detailed data would actually be required at early stages of construction but also because without such detail the visual results are not convincing from a perception's and an observer's point of view.

In conclusion, computer graphics aligned to photorealism does not provide optimal solutions for vivid, expressive, and comprehensible visualizations of geoinformation. In particular, it does not provide optimal means for visual abstraction and, thus, for visualizing abstract and complex geoinformation. Therefore, photorealistic depictions frequently are neither cognitively adequate nor adequate with respect to the tasks to be supported by interactive applications and systems. Figure 1b compares both photorealistic and non-photorealistic depictions for the same 3D city model.

3 Elements of Non-Photorealistic Computer Graphics

With the advent of non-photorealistic computer graphics a repertoire of illustrative, expressive, and artistic graphics techniques becomes viable to developers and designers of 3D geovirtual environments. Most researchers agree that the term "non-photorealistic" is not satisfying because the notion of realism itself is not clearly defined nor its complement, the non-photorealism. Nevertheless, "non-photorealism" (NPR) has established itself as a key category and discipline in computer graphics starting around 1990.

Non-photorealistic computer graphics denotes the class of depictions that reflect true or imaginary scenes using stylistic elements such as shape, structure, color, light, shading, and shadowing that are different from those elements found in photographic images or those elements underlying the human perception of visual reality. As Durand (2002) points out, non-photorealistic computer graphics offers extensive control over expressivity, clarity, and aesthetic, thereby the resulting pictures "can be more effective at conveying information, more expressive or more beautiful". Strothotte and Schlechtweg (2002) as well as Gooch and Gooch (2001) give a broad introduction to concepts and algorithms of non-photorealistic computer graphics.

Generally characteristics of non-photorealistic rendering techniques include the ability to *sketch* geometric objects and scenes, to *reduce visual complexity* of images, as well as to imitate and extend classical depiction techniques known from *scientific and cartographic illustrations*. Furthermore, today's programmable computer graphics hardware supports the implementation of non-photorealistic 3D rendering techniques. Therefore, most techniques can be used in interactive or even real-time applications and systems. Fundamental techniques of real-time non-photorealistic 3D rendering address the following characteristics:

- **Lighting and Shadowing**. The programmable rendering pipeline allows developers to implement new illumination models such as the model introduced by Gooch et al. (1998). In addition, real-time shadow techniques can be seamlessly integrated and, thereby, provide a valuable depth cue;
- **Coloring and Shading**. Non-photorealism allows for vivid and domain-specific color schemes. Cartoon-like appearance is achieved by specialized color schemes such as tone shading;
- **Edges and Silhouettes**. Edges as visually important elements can be treated as "first-class" objects in depictions, i.e., they can be enhanced and stylized. Isenberg et al. (2003) give an overview of algorithms for outlines and silhouettes;
- **Texturing**. Texturing is used as a fundamental computer graphics operation (Haeberli 1990) to outline the principle curvature of surfaces, to simulate strokes using virtual brushes, to

procedurally generate textures, and to implement image-based operations such as image overlays, image blending, convolution filtering, etc.

Technically, non-photorealistic 3D rendering techniques are implemented by redefining the geometry stage and rasterization stage of the standard 3D rendering pipeline using application-defined procedures, known as *shaders*, which implement geometric transformations, illumination calculations, and pixel shading. For example, we can substitute the classical Phong illumination model by a cartoon-like illumination shader, which reduces the number of shades per color. Furthermore, non-photorealistic rendering takes advantage of multi-pass rendering, that is, they process a 3D scene description several times, generating and combining intermediate image into a final image. This way, for example, enhanced edges and shadows can be included in the overall rendering process.

4 Non-Photorealistic 3D City and Landscape Models

We have designed and implemented a system for non-photorealistic, real-time visualization of 3D city and landscape models as two important categories of 3D geovirtual environments. Conceptually, the motivation and strategies of non-photorealism is not entirely new to cartography.

4.1 Historic 3D City and Landscape Depictions

The roots of historic *3D city and landscape depictions* date back over more than a thousand years. In pre-medieval times, depictions primarily revealed symbolic-allegoric contents, partially composed of landmark buildings but without adhering to topological and geometrical properties and relationships. Instead, topology and geometry were deduced from philosophical, mythical, or religious concepts. In medieval times, topology and geometry of urban areas were increasingly transferred to depictions, starting with orthogonal-like projections and being advanced by perspective drawings starting in the 16th century.

Matthäus Merian (1593-1650) is among the most prominent “city modelers”: He established the first systematic production of city depictions as commercial products – manufacturing more than 2,150 European city views in his “Topographia”, a book series with more than 30 volumes (Figure 2a). In his tradition, many cartographers further developed these

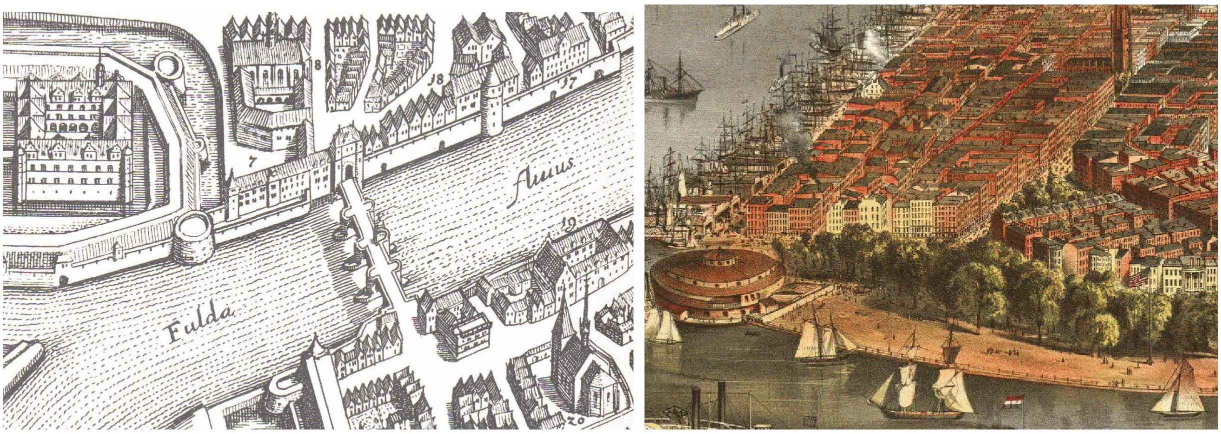

Figure 2: Left: Part of a Merian city depiction of the City of Fulda, Germany. Right: Part of a bird’s eye view map of the City of New York (1870).

techniques, for instance, cartographic relief depiction and panorama maps, and 3D city maps. For landscape models, Humphry Repton (1752-1818) became famous with his vivid and comprehensible depictions of landscapes published in his “red books”. These works show that design and production of 3D city and landscape depictions does not only involve technical challenges but also requires an artist’s experience.

The most prominent depictions of 3D scenes include panoramic maps of cities and landscapes as well as bird’s-eye views of cities, which are available today for most major cities; Bollmann (1986) gives an overview of techniques regarding 3D city maps; Mehlhorn (1984) introduces techniques focusing on architectural drawings of urban areas. The historic maps in Figure 2b illustrate a few principles of their design: choosing colors carefully; simplifying geometric structures; and sketching dimensions of and relationships between objects. Their rich contents and visually pleasing design triggers the curiosity of the observer. They also show a high degree of visual clarity and geometric abstraction–preferring abstraction to realism.

4.2 Characteristics

In our approach, we aim at illustrative, interactive visualizations of 3D city and landscape models in a way that is complementary to Virtual Reality visualizations. The approach can be characterized as follows:

- Concentrate on illustrative, expressive visualizations emphasizing on high perceptual and cognitive quality to effectively communicate contents, structure, and relationships of urban objects and landscape objects as well as related thematic information.
- Enable meaningful visualizations even for the case of scarce spatial information since high-quality and complete sets of geodata tend to be rarely available for large-scale urban areas or landscape.
- Enable fully automated generation of visualizations while offering great flexibility in the degree of control of graphical parameters.
- Achieve real-time rendering and, thereby, allow for interactive manipulation, exploration, analysis, and editing of all aspect of 3D city and landscape models.

5 City and Landscape Modeling

Depictions of 3D cities and landscapes can be considered to be map-related representations of 2D and 3D spatial data. In addition to 2D information such as topographic maps, thematic maps, and 2D ground plans, we include 3D geodata, for example, 3D terrain models, 3D building geometry, and 3D vegetation objects.

5.1 Data Sources

The underlying data of 3D city and landscape models can be delivered from various different acquisition techniques, which cluster into methods based on photogrammetry, active sensors, and hybrid sensor systems (Hu et al., 2003). Ribarsky et al. (2002) describe a typical process for acquiring data used to construct 3D city models. Identifying, categorizing, reconstructing building geometry by automated methods represents a major research challenge (Förstner, 1999) and aims at acquiring 3D building data at low costs and high quality. An important additional data source represents administrative records such as the cadastre due to its legal status but mostly they do not explicitly contain 3D information. As minimal input to 3D city and landscape models we assume that at least 3D digital terrain models, 2D ground plans, and building height data can be provided. A complementary, challenging source of city data describes Parish and Müller (2001): They develop a procedural modeling technique for generating city and landscape data.

5.2 Building Models

Buildings are major visual objects of 3D city models. In general, digital data of buildings can be acquired based on administrative data (e.g., cadastre records), laser scanning, and aerial photography.

Building Geometry. To construct block models one can extrude 2D ground polygons to heights derived from laser scans. In practice, high-quality, precise models of large areas are hardly available due to involved time and costs efforts. For this reason, the non-photorealistic 3D rendering technique should allow for generating compelling depictions of most buildings' geometry in an automated way. In addition, the technique should support 3D CAD models of landmark buildings. Although only a small percentage of buildings in typical 3D city model are specified this way, they possess a high visual importance and need to be seamlessly integrated into the depiction.

Building Roofs. Roof modeling represents a specialized stage of the construction process, which generates generalized roof geometry based on a coarse classification whereby the best fitting roof model is assigned to an individual building. In practice, roofs as essential visual elements provide visual structure for large numbers of aggregated buildings. Illustrative visualization precisely shows this non-exact roof information using generalized roof geometry without suggesting details that do not exist in the data. Felkel and Obdrmalek (1998) introduce a roof generation technique based on the automated calculation of straight skeletons within a ground polygon.

As the sides of buildings provide more characteristic information about them than the roofs, the roofs can be scaled down in height while the main bodies of the buildings are scaled up. This is done in traditional panoramic views of cities to meet the spectator's expectation, who is used to seeing the city as a pedestrian.

Building Appearance. For most urban areas no detailed data about building appearance can be assumed. Although laser scanning and photogrammetry allow for capturing facade textures, time and cost efforts are still high. Procedural approaches for grammar-based building designs offer an interesting alternative; Wonka et al. (2003) introduced the term "instant architecture" for a procedural approach to generating building appearance. In our approach, we want to be able to cope with few and less precise appearance data. As elementary graphics attributes, color, material, and facade classification should be available, which generally can be derived from most data sources and administrative data records.

Building Quality Levels. Building geometry as most important category of data can be generally classified into five quality levels (Altmeier and Kolbe, 2003):

- *Level 0:* 2D ground plans with included landmark buildings;
- *Level 1:* Cubature objects, typically derived by extruding 2D ground plans to an average or known height;
- *Level 2:* 3D objects, with an approximated outer geometry including roofs, terraces, chimneys, etc.;

- *Level 3:* Architectural 3D models including detailed façade designs and exact geometry;
- *Level 4:* Architectural 3D models as in level 3 with additional interior design.

Our technique is focusing on processing and generating buildings of level 1 and 2. In addition, it integrates buildings of level 3.

5.3 Vegetation Models

Vegetation objects are dominant objects in 3D city and landscape models. We distinguish between vegetation objects without and with individual characteristics. In the former case, objects are generally placed automatically based on a distribution function, for example, lawns and bushes. In the latter case the objects are placed and modeled as individual 3D objects, for example, large trees.

To model a specific kind of vegetation object, a 3D geometry prototype is designed using the xfrog modeling software for organic objects. The prototype can be instantiated multiple times, and it can be varied with respect to parameters such as height, density of foliage, and geometric distortion to derive copies with sufficient individual visual characteristics. Deussen et al. (2005) provide a survey of modeling and rendering virtual 3D landscapes with vegetation objects as major building blocks. Paar and Rekittke (2005) give an overview of the interactive authoring system Lenné3D for virtual 3D landscape models.

5.4 Terrain and Environment Models

Digital terrain models are used as reference surfaces for all 2D and 3D objects contained in a 3D city and landscape model. These objects need to adapt to the terrain surface such as buildings and vegetation objects. The environmental space summarizes all spatial objects except buildings and terrain model:

- Transportation networks (road and street networks, public-transport networks, …)
- City furniture (street lights, advertising boards, …)
- Population and traffic objects (people, animals, cars, …)

In our approach for non-photorealistic 3D rendering, we handle transportation networks as part of the ground space model, and represents city furniture, population objects, and traffic objects as additional scene geometry. So far, we did not investigate specialized non-photorealistic techniques for these object categories.

5.5 Thematic Information

Thematic information associated with 3D city and landscape models are defined and required by most applications. Typical thematic information includes:

- Building information such as occupancy, industrial/residential usage, year of construction, state of restoration etc.
- Environmental information such as air pollution, noise exposure etc.
- Demographic information such as family, age, and ethnical structures

Non-photorealistic depictions should allow us to visualize thematic information by explicit representations such as 2D labels as well as by mapping thematic information to the various graphics parameters. For 3D city models, for example, we can support mapping thematic

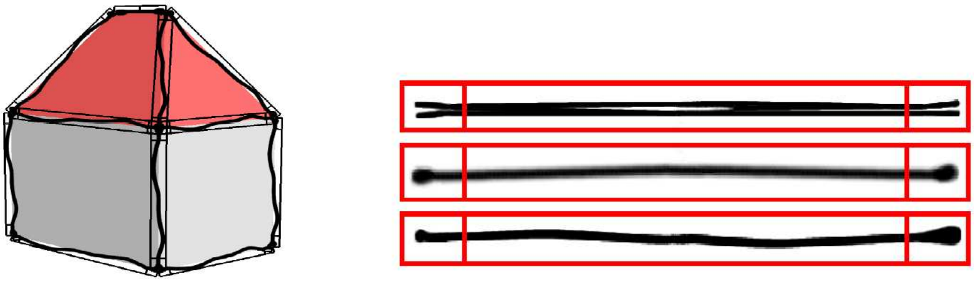

Figure 3: Stylized edges modeled as rectangular billboards attached to principle edges of 3D geometric objects (left). Different stroke textures (right).

information on appearance parameters such as edge styles, roof colors, façade structure and composition.

6 Non-Photorealistic Rendering of 3D Geovirtual Environments

The non-photorealistic rendering of 3D city and landscape models needs to guarantee a number of key qualities with respect to the perception of the model contents:

- **Orientation Cues.** In a complex and dense area landmarks serve as means of orientation for the user. Landmarks consist mainly of those buildings that are known a priori to the user – typically monuments and buildings of public interest. Therefore, they require an exact geometric and graphical 3D model. The visualization should guarantee that landmarks, even if they are nearly out of the view volume, do not disappear.
- **Shape Cues.** In many visualizations, shape is derived from shading. In non-photorealistic depictions, shades are rarely used to communicate that information. Instead, contours and edges are drawn. In particular, *stylized edges and edge enhancement* is used for separating the faces of an object. To further clarify the appearance of shapes, *tone shading* is applied.
- **Depth Cues.** In classical 3D city and landscape maps, using orthogonal projections the monocular depth cues linear perspective, relative size and, texture gradient are not available. However, occlusion and known sizes provide depth cues. Frequently map designers place objects of known size (e.g., people, trees, animals) in the scenery. Furthermore *shadows* and fog can be used to aid depth perception. Interactive visualization additionally provides motion-based depth cues. Goldstein (1999) and Ware (2000) give a comprehensive overview of depth cues.

6.1 Stylized Edges

Edge enhancement, as one of the aspects of our rendering technique, operates in object-space. For each edge to be drawn, on the fly we create an edge-aligned quad facing the viewer, and use textures to simulate strokes.

We draw the edges using thin rectangular billboards fastened to or near to the start and end points of the edges as in Figure 3a. The billboards are drawn using a stroke texture that can be partially transparent. We decompose each edge into three segments: start segment, middle segment, and end segment. For each, different stroke textures (Figure 3b) can be configured. The texture for the middle segment is repeated according to the length of the stroke. The stroke texture defines the style of strokes. A transparency parameter controls the weight that is given to edges in an image. This way, edges can be faded in and out.

Given the start and end points of an edge, we want to draw a sketchy line along the edge. In hand drawings, lines along edges usually do not start and end exactly at the ends, but near the

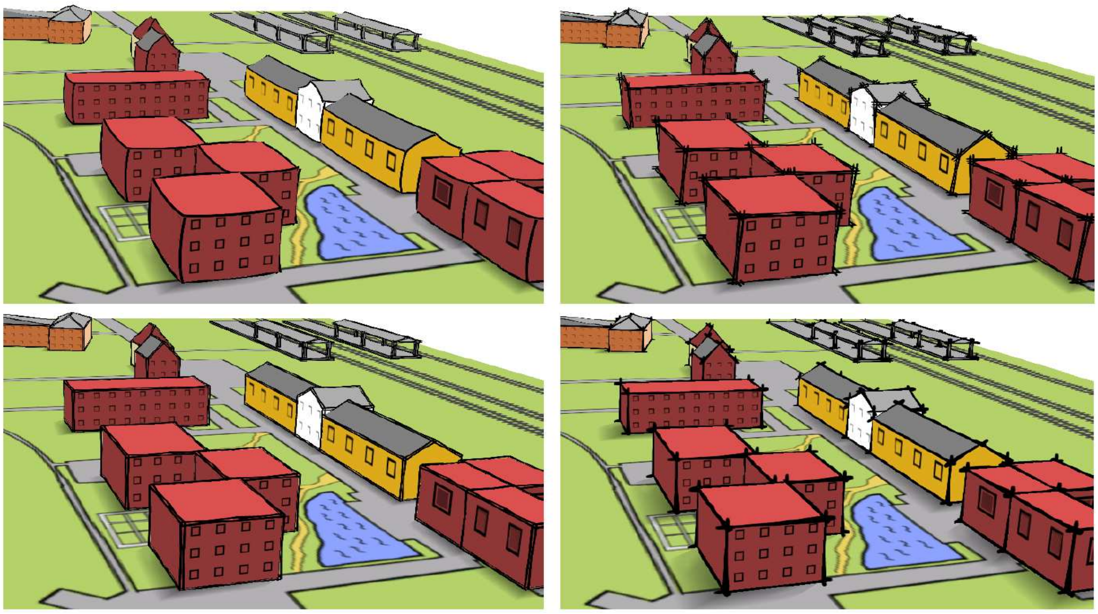

Figure 4: Variants of stylized edges. Top left: curved edges; bottom left: multiple strokes; top right: distorted multiple strokes; bottom left: distorted strokes with different brush pattern.

ends. This results in a higher visual quality and expressiveness. Inspired by this, we introduced two rendering parameters, one determining the tilting angle and one the length of the line. To express uncertainty, tilting and length can be varied as illustrated in Figure 4. After moving the starting and end points according to the tilt and length parameter, we apply cylindrical billboarding, using the vector from the starting point to the end point as an axis. For implementation, we can employ per-vertex programming on the graphics hardware for calculating the billboards.

Edge drawing in object-space allows us to control appearance attributes such as stroke form, stroke width, brightness, color, length, and exactness. For example, the actual drawn edge can be stretched, shrunk, or disturbed to express fuzzy, sketchy, or slightly overlapping outlines. The object-space approach offers a high degree of expressiveness, in particular, if the underlying model explicitly defines edges as in city models. When rendering a complex scene we do not always want to draw all edges and not necessarily all edges with the same level of detail. For instance in our implementation we draw only the edges that are best visible to the viewer using three textures as explained above. Edges with low visible importance are either drawn using only the texture for the middle or not at all. As criteria the actual length of an edge in image space and the distance to the camera can be used.

6.2 Edge Enhancement

Image-space edge enhancement detects visually important edges such as silhouettes, borders, and crease edges. The enhanced edges result in a homogenous and generalized visual depiction of 3D building geometry while emphasizing their principle composition.

We obtain these edges by extracting discontinuities in the normal buffer and the *z*-buffer. First, encoded normal and *z*-values of 3D scene geometry are rendered into a float buffer. Next, we extract discontinuities by rendering a screen-aligned quad, textured with the float-buffer texture and sampling neighboring texels to identify abrupt changes. The resulting image contains intensity values that represent edges of 3D scene geometry (Figure 5). The image is stored as

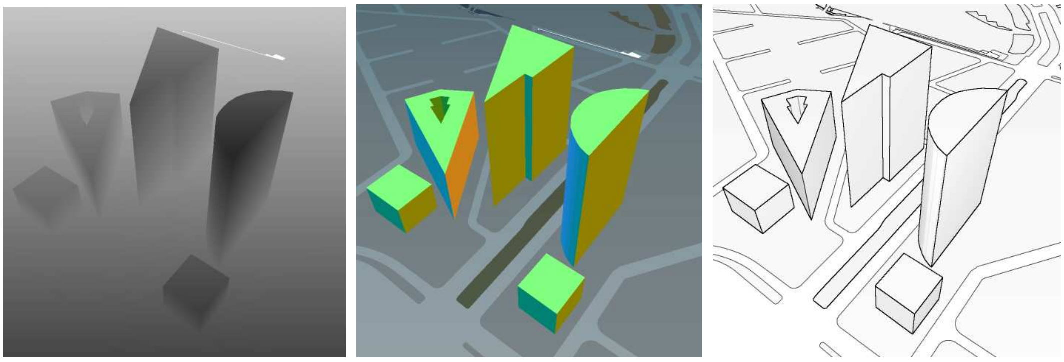

Figure 5: Image-based edge detection. Depth images (left), surface-normal image encoded by artifical colors (center), and image of the edge-enhanced building geometry (right).

texture, the *edge map* (Nienhaus and Döllner, 2003). Edge maps allow for enhancing edges with varying visual weight since they can be blended into 3D scene geometry. In our examples, we reduce the “edge-ness” in the image with increasing camera distance.

The edge-map technique is able to handle 3D scene geometry of any complexity; it is well suited for large-scale 3D data and virtually independent from the number of polygons. So, it is especially well suited for the ground geometry, which generally contains a high number of curved shapes leading to a large number of short edges. Furthermore, it does not require any pre-calculated information about topology and geometry of 3D objects.

6.3 Tone Shading

Maps of city models attempt to maximize visual clarity. Most importantly, edges are enhanced to stress the contours of buildings. Colors are chosen according to semantics and aesthetics – they do not necessarily correspond to the natural colors. The overall number of colors is kept small. Strothotte et al. (1994) propose graphical techniques of a sketch rendering system based on insights from perceptional psychology.

Major inspirations for our work were cartographic picture maps and other hand drawings of cities. In colored drawings the illustrator usually abstracts from the realistic colors of the urban objects and greatly reduces the number of colors used in the representation. In general only two or three colors and for each color only two or three tints are used.

The choice of the colors is based on aesthetic and other reasons as well as the actual colors of the city. Inspired by this we decided to use a two-tone or three-tone shading for the faces, which assigns the color according to the angle of the face to the light as illustrated in Figure 6.

Technically this can be done in the same way as cartoon shading but instead of the intensity we use the dot product of the normal of the face and the light direction to determine the color. We observed that three tone shading supplies better results for interactive applications than two tone

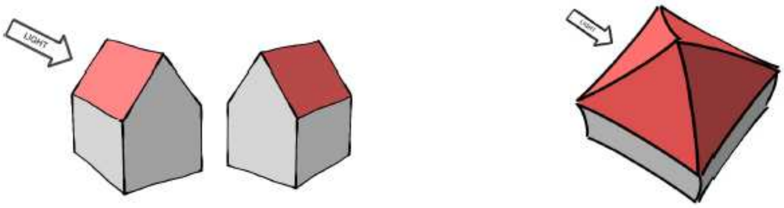

Figure 6. Examples of depictions using two-tone shading and three-tone shading.

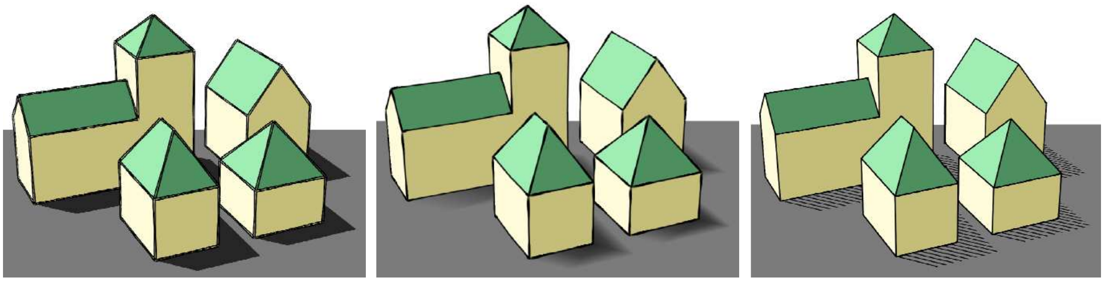

Figure 7: Three types of shadow casting: Hard shadows, soft shadows, and hatched shadows.

shading because neighboring faces of one building will have different colors assuming the building does not have more than four sides. Using two-tone shading this is not the case. Thus there is much less contrast when moving through a scene and the light direction is much harder to determine. This, of course, is not a problem in traditional cartography where the scenes are static and the light direction can be chosen suitably. Often the light shines from the upper left. This can also be done with our shading when producing static scenes.

6.4 Shadows

In architectural drawings shadows are used for conveying three-dimensionality and spatial relationships, which aids the comprehensibility and naturalism, and, for adding vividness. Shadows in 3D city and landscape models are important depth cues and facilitate the perception of spatial coherence through the image. In city planning, shadows also represent a critical property of designs that needs to be visualized. For example, the length of shadows represents a measure for the heights of the buildings. Shadows should not obscure any parts of the geometry. Also they should harmonize with the rest of the drawing and be clearly recognizable.

There are different types of shadows in computer graphics: Hard shadows are derived by building a geometric shadow volume. Within that volume, all scene parts are drawn darker. Soft shadows are conceptually similar except that the darkness varies, a blurred impression results. Ware (2000) argues that soft shadows do not need to be physically correct in order to be convincing and recommends using soft shadows instead of hard shadows. In our approach, we simulate shadows by adding textured-quads to the ground plan of each building in the direction of the projected light direction to draw the shadowed region on the reference surface. Selfshadowing and shadowing between faces are ignored: shadows are only calculated with respect to the reference surface. We support three types of shadow, hard shadows, soft shadows, and hatched shadows as shown in Figure 7. The hatched shadows are a typical element of architectural drawings (Mehlhorn, 1994).

To calculate shadows, we use a real-time implementation (Everitt and Kilgard, 2003) of the shadow volume technique (Crow, 1977). In a pre-processing step, the illustrative visualization technique computes shadow volume geometry for a given 3D building geometry. In Phase 1 of our rendering algorithm, this geometry is used together with the 3D scene geometry to generate the stencil value zero for lit areas and non-zero for shadowed areas. For later use in shaders, the shadow information in the stencil buffer is copied into an alpha texture. To apply the texture in subsequent rendering phases, we create a screen-aligned quad that fits completely into the viewport of the canvas so that the texture coordinates (*s*,*t*) of each fragment produced for the quad correspond to windows coordinates.

6.5 Non-Photorealistic Façade Generation

To automate the depiction process for large-scale 3D city and landscape models, we combine texture elements to facades using multi-texturing for facades and walls for which we do not have an individual texture. In a preprocessing step we create multiple sets of texture coordinates for each façade and wall, which are used by a fragment shader to compose the facade texture for each building. To compose a façade procedurally, the algorithm has the following principle steps:

1. The material texture is wrapped around the facade;
2. The window texture is copied to all estimated windows of the facade;
3. The door texture is placed at explicitly given door position of the facade;
4. Inspired by hand-made drawings we blend between the facade color and the material texture so that the material is visible at some irregular formed areas.

To reduce the visual complexity of the resulting image, the shader uses different levels of detail of window texture and door texture dependent on the viewer distance. In contrast to mip-mapping, the use of explicit LOD textures allows us to consciously leave out details instead of compressing too much details into an unrecognizable size by filtering.

6.6 Non-Photorealistic Terrain and Vegetation Rendering

To render digital terrain models, we apply edge enhancement to ground geometry such as streets, green-space areas, or rivers. Imhof (1982) studied extensively methods of terrain shading for classical cartographic depictions. Buchin et al. (2004) introduce a real-time rendering technique for non-photorealistic terrain depiction applying slope lines and tonal variations and using stroke textures to shade terrain surfaces.

3D vegetation rendering is confronted with the high geometric complexity of vegetation objects. For example, a regular tree typically consists of 50.000 to 100.000 triangles. Coconu and Hege (2002) describe a first hardware-accelerated rendering technique that copes with large scale vegetation objects such as trees in virtual 3D landscapes. The geometry models allows for both photorealistic depiction as well as non-photorealistic depiction. Terrain rendering and vegetation rendering are not explicitly addressed in this paper.

7 Applications of Non-Photorealistic 3D Geovirtual Environments

Applications of non-photorealistic 3D city and landscape models generally include visual interfaces to spatial information required by decision-support systems for city and landscape planning. Furthermore, 3D city and landscape models serve as architectural development models used to illustrate concepts and principles underlying suggested plans. City and landscape models also may facilitate people’s participation in decision-making through comprehensible representations. In geo-information systems, transport information systems, and radio-network planning systems city models play a fundamental role in visualizing data and monitoring processes related to urban and rural areas. In addition, 3D city and landscape models represent core elements of systems for cultural heritage such as described in Willmott et al. (2001).

Further applications can be found in education and entertainment, for example interactive gaming environments and comic worlds, and atmospheric and edutainment environments for narratives–imagine a cartoon-like story, taking place in a 3D non-realistically drawn “real city” or an Internet platform for neighborhood communication.

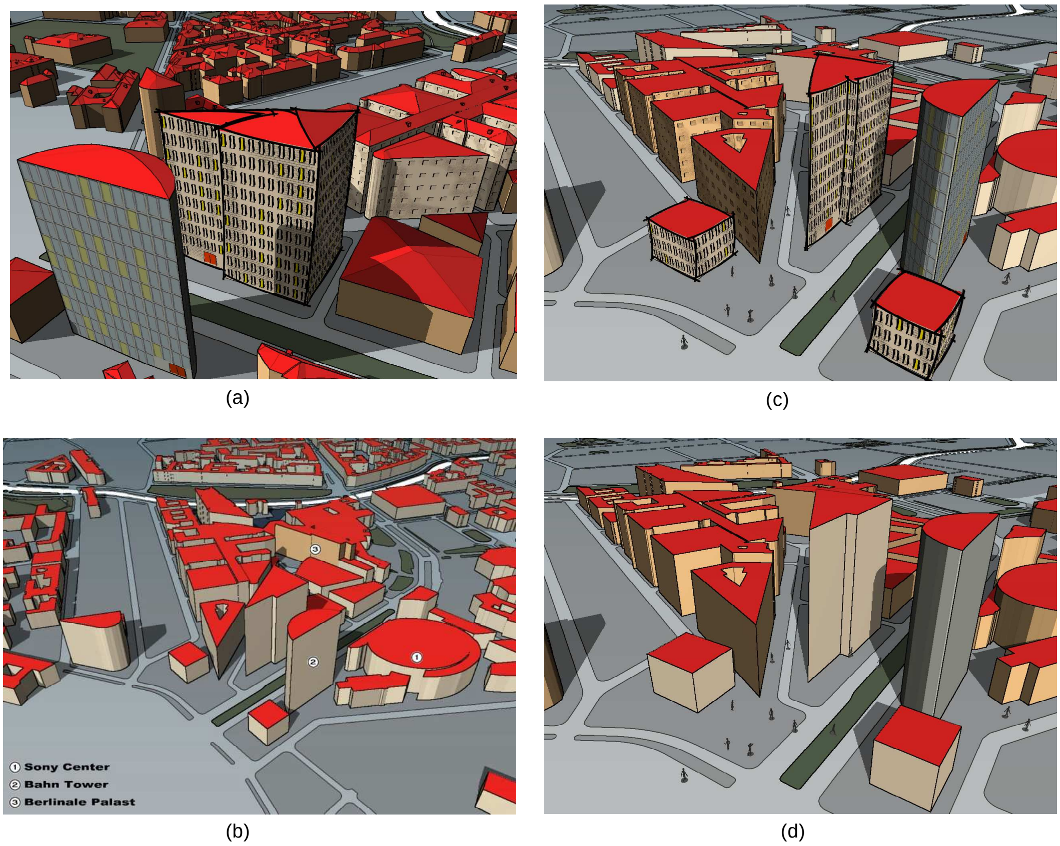

Figure 8: Examples of nonphotorealistic visualizations of the 3D city model of Berlin, a joint project with the Senate of City Development. (a) Detailed view of procedurally generated facade textures. (b) Bird's-eye view with reference numbers. (c) Stylized edges. (d) Same as in (c) without façade textures and stylized edges.

8 Conclusions

Non-photorealistic 3D rendering promises manifold new application areas for cartography and GIS such as illustrative maps, artistic maps, and informal maps. Most importantly, non-photorealism provides excellent means for visual abstraction as a primary technique to effectively communicate complex spatial information.

Nevertheless, non-photorealistic 3D rendering still raises several questions with respect to its impact to map-like and cartographic presentations. What are specific non-photorealistic 3D rendering techniques for interactive map-like depictions? How do non-photorealistic geovisualizations cooperate with photorealistic ones? How to generalize 3D geo-objects for non-photorealistic depiction?

Non-photorealistic 3D rendering turns out to an effective way to communicate spatial information of and thematic information associated with 3D geovirtual environments as exemplified for the case of 3D city and landscape models. In an ongoing case study on urban planning we already observed that non-photorealistic 3D city and landscape models achieve high user acceptance due to their visual clarity and conciseness. They also circumvent classical weaknesses of photorealistic 3D city and landscape models such as low-quality facade textures, inappropriate illumination, or high visual complexity induced by aerial photography. In addition, most observers evaluate the depictions as clear, aesthetically concise and pleasant. As part of this study, we are investigating the usage of the graphics parameters for urban data mining.

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References

Akenine-Möller, T., Haines, E. 2002. *Real-Time Rendering*. AK Peters Ltd, 2nd ed.

Altmaier A., Kolbe, T.H. 2003. Applications and Solutions for Interoperable 3D Geo-Visualization. *Proceedings of the Photogrammetric Week 2003*, Wichmann Verlag.

Bollmann, F. 1986. Entstehung von Bildstadtplänen. *Karlsruher Geowissenschaftliche Schriften*, Reihe A, Band 4, 93-98.

Buchin, K., Sousa, M.C., Döllner, J., Samavati, F., Walther, M. 2004. Illustrating Terrains using Direction of Slope and Lighting. 4th ICA Mountain Cartography Workshop, Vall de Nuria, Spain.

Coconu, L., Hege, H.-Chr. 2002. Hardware-Accelerated Point-Based Rendering of Complex Scenes. *Proceedings of the 13th Eurographics Workshop on Rendering Techniques*. Pisa, Italy, 43-52.

Crow, F.C. 1977. Shadow Algorithms for Computer Graphics. *Computer Graphics (SIGGRAPH '77 Proceedings)*, 11(2):242-248.

Davis, D., Ribarsky, W., Jiang, T.Y., Faust, N., Ho, S. 1999. Real-Time Visualization of Scalably Large Collections of Heterogeneous Objects. *IEEE Visualization 1999*, 437-440.

Deussen, O., Colditz, c., Coconu, L., H.-Chr. Hege. 2005. Efficient Modeling and Rendering of Landscapes. In: Bishop, I. and Lange, E. *Visualization in Landscape and Environmental Planning*. Spon Press, London, 56-61.

Döllner, J., Walther, M. 2003. Real-Time Expressive Rendering of City Models. *Seventh International Conference on Information Visualization, Proceedings IEEE 2003 Information Visualization*. 245-250, London.

Duchaineau, M., Wolinsky, M., Sigeti, D., Miller, M.C., Aldrich, C., Mineev-Weinstein, M. 1997. "ROAMing terrain: Real-time optimally adapting meshes", *Proceedings IEEE Visualization '97*, 81-88.

Durand, F. 2002. An Invitation to Discuss Computer Depiction. *Symposium on Non-Photorealistic Animation and Rendering (NPAR)*.

Everitt, C., Kilgard, M.J. 2002. "Practical and robust stenciled shadow volumes for hardware-accelerated rendering", NVidia Online Published Paper (http://www.nvidia.com).

Felkel, P., Obdrmalek, S. 1998. "Straight Skeleton Implementation", *14th Spring Conference on Computer Graphics*, 210-218.

Förstner, W. 1999. "3D City Models: Automatic and Semiautomatic Acquisition Methods.", *Proceedings Photogrammetric Week*, University of Stuttgart, 291-303.

Goldstein, E. B. 1999. *Sensation and Perception*. Brooks/Cole, US.

Gooch, A., Gooch, B., Shirley, P., Cohen, E. 1998. "A Non-Photorealistic Lighting Model for Automatic Technical Illustration", *Computer Graphics (Proceedings of SIGGRAPH 1998)*, 447-452.

Gooch, A., Gooch, B. 2001. *Non-Photorealistic Rendering*. AK Peters Ltd.

Haeberli, P. 1990. Paint by Numbers: Abstract Image Representations. *Computer Graphics (Proceedings of SIGGRAPH)*.

Hu, J., You, S., Neumann, U. 2003. "Approaches to Large-Scale Urban Modeling", *IEEE Computer Graphics and Applications*, 23(6):62-69.

Imhof, E. 1982 *Cartographic Relief Representation*. DeGruyter.

Isenberg, T., Freudenberg, B., Halper, N., Schlechtweg, S., Strothotte, T. 2003. "A Developer's Guide to Silhouette Algorithms for Polygonal Models", *IEEE Computer Graphics and Applications*, 23(4):28-37.

Mehlhorn, D.-J. 1994. *Zeichnen für Stadtplaner*. 2nd ed., Werner.

Nienhaus, M., Döllner, J. 2003. "Edge-Enhancement - An Algorithm for Real-time Non-Photorealistic Rendering", *Journal of WSCG*, 11(2):346-353.

Paar, P., Rekittke, J. 2005. Lenné3D – Walk-through Visualization of Planned Landscapes. In: Bishop, I. and Lange, E. *Visualization in Landscape and Environmental Planning*. Spon Press, London, 152-162.

Parish, Y., Müller, P. 2001. "Procedural Modeling of Cities", *Proceedings of ACM SIGGRAPH 2001*, 301-308.

Ribarsky, W., Wasilewski, T., Faust N. 2002. "From Urban Terrain Models to Visible Cities", *IEEE Computer Graphics and Applications*, 10-15.

Schaufler, G. 1998. *Rendering Complex Virtual Environments*. Dissertation, University of Linz.

Strothotte, T., Schlechtweg, S. 2002. *Non-Photorealistic Computer Graphics: Modeling, Rendering and Animation*. Morgan Kaufman.

Strothotte, T., Preim, S., Raab, Schumann, Forsey. 1994. "How to Render Frames and Influence People", *Computer Graphics Forum (Proceedings of EuroGraphics 1994)*, 13(3):455-466.

Ware, C. 2000. *Information Visualization*. Morgan Kaufman.

Willmott, J., Wright, L.I., Arnold, D.B., Day, A.M. 2001. "Rendering of Large and Complex Urban Environments for Real-Time Heritage Reconstructions", *Proceedings VAST 2001: The International Symposium on VR, Archaeology, and Cultural Heritage*.

Wonka, P., Wimmer, M., Sillion, F., Ribarsky, W. 2003. "Instant Architecture", *Proceedings of ACM SIGGRAPH 2003*, 669-677.