An Immersive Visualization System for Virtual 3D City Models

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***Abstract*—Virtual 3D city models are essential visualization tools for effective communication of complex urban spatial information. Immersive visualization of virtual 3D city models offers an intuitive access to and an effective way of realization of urban spatial information, enabling new collaborative applications and decision-support systems. This paper discusses techniques for and usage of fully immersive environments for visualizing virtual 3D city models by advanced 3D rendering techniques. Fully immersive environments imply a number of specific requirements for both hardware and software, which are discussed in detail. Further, we identify and outline conceptual and technical challenges as well as possible solution approaches by visualization system prototypes for large-scale, fully immersive environments. We evaluate the presented concepts using two application examples and discuss the results.**

Keywords: visualization system, immersive environments, virtual 3D city models, virtual reality

I. Introduction

An increasing number of applications and systems use virtual 3D city and landscape models to integrate, manage, and visualize complex 2D and 3D urban geodata as well as associated geo-referenced thematic data. A growing number of cities are creating and continuing virtual 3D city models as a fundamental 3D geodata resource. Meanwhile, the Open Geospatial Consortium has established the international encoding standard CityGML [1] for the representation, storage, and exchange of virtual 3D city and landscape models, implemented as an application schema of the Geography Markup Language (GML).

3D virtual environments (VEs) serve to interactively visualize virtual 3D city models; MacEachren [2] defines four factors that contribute to the virtuality of such an VE: (1) *immersion*: describes the sensation of being in a VE; (2) *interactivity*: the user is able to change the viewpoint or parts of the environment; (3) *information intensity*: refers to the level-of-detail the objects or geoinformation are represented, and (4) *intelligence of objects*: e.g., objects exhibit a context sensitive behavior. Modern geo-media technology, such as power walls, cylindrical projection walls, and *cave automatic virtual environments* (CAVEs) (Fig. 1), opens an intuitive access to complex 3D spatial models, broader audiences, and enables new fields of applications. As a characteristic feature, geomedia technology provides large *field-of-view* (FOV) and high image-resolution, which facilitate the user's immersion.

Lutz [3] distinguish between three types of immersive VEs based on the utilized media technology and the covered *field-of-view*: (1) *Immersive desktop VE* only cover a certain (small) areas of the FOV, (2) *semi-immersive VE* utilize large-scale displays, such as powerwalls, that cover almost the entire FOV and (3) *fully immersive VE*. Fully immersive VE utilize CAVEs, whose projection surface is capable of covering the user's FOV completely. These VEs are well-suited as tools for effective communication of complex virtual 3D city models and their thematic contents since immersion eases the creation of cognitive maps and mental frame-of-references, which in turn leads to an increased performance in spatial tasks [4].

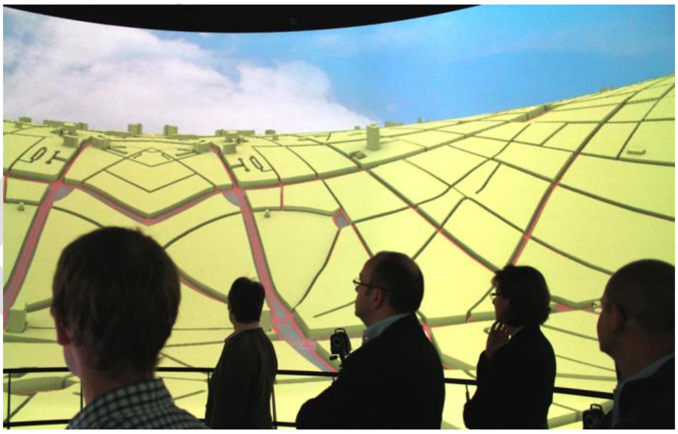

Figure 1. Advanced visualization technique as application example for an immersive 3D virtual environment that enables a collaborative analysis and exploration.

Isaacs et al. [5] pointed out that today's GIS are often dominated by the view of experts and technically based 2D concepts, while the underlying data has three or more dimensions. Further, they are usually not well suited to communicate information to a group of (non-expert) stake-holders. Instead, fully immersive VEs enable a simultaneous exploration of the underlying 3D models by multiple people in an intuitive and collaborative way. Especially projects that require public access to visualization (e.g., urban planning) can take advantage of these environments to show and discuss programs, plans, and variants in early planning phases.

Although GIS and 3D visualization systems (e.g., CAD, BIM, VR tools) already support desktop and semi-immersive VEs, they cannot be directly used for fully immersive VEs due to both technical and conceptual reasons. In particular, they frequently lack advanced visualization and rendering techniques, e.g., non-photorealistic rendering [6], image-based abstraction [7], sound rendering, or multi-perspective view techniques [8] (Fig. 1).

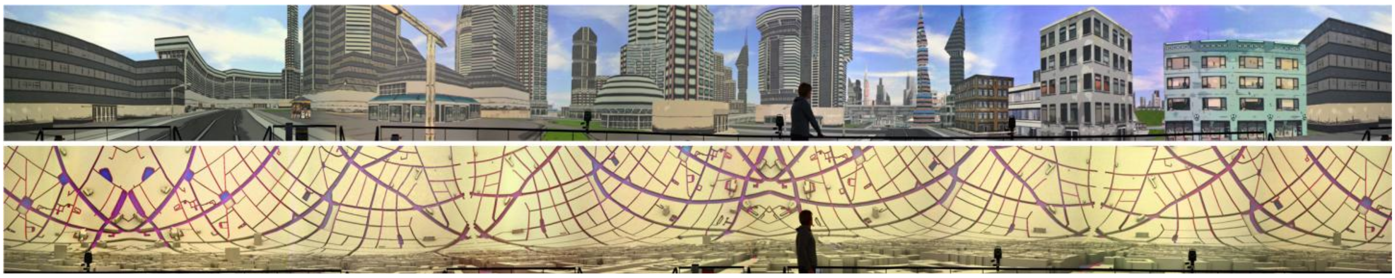

Figure 2. Visualization of 3D virtual citys in the Elbe Dom. The viewer is completely enveloped by the 360° visualization and the size of the prjection surface enables a 1:1 scale visualization. Upper image: The façade textures of the virual city model are abstracted to emphasize characteristic colors and structures. Lower image: 3D multi-perspective views bend the distant parts of a 3D virtual city model upwards. Compared to the upper image, more spatial information are presented.

The remainder of the paper is structured as follows: We present a prototype system for fully immersive VEs based on virtual 3D city models, motivated by the fully immersive VE facility "Elbe Dom" at the Fraunhofer institute, a 360° cylindrical projection system (Section II). Developing an application for fully immersive VEs implies a number of requirements that are discussed in Section III. We give an overview of challenges and solution approaches regarding 3D rendering that we have been faced with during our implementations in Section IV. Next, results of our case studies are outlined in Section V. Finally, conclusions are given and future work is sketched in Section VI.

II. The Elbe Dom Facility

The "Elbe Dom" facility (www.vdtc.de) at the Fraunhofer IFF (Germany) is a multi-user 360° cylindrical projection system suitable for large-scale interactive visualization (Fig. 2). The cylindrical projection surface is 6.5m tall and has a diameter of 16m; the cylinder is bent inward at the lower part to simulate a floor projection. Due to its dimensions the Elbe Dom is particularly appropriate for visualizing large spatial 3D models, in particular virtual 3D city and building models, on a scale of 1:1. Its fields of application include, for instance, factory design, spatial simulation and training, urban planning, and marketing [9]. Due to its size and capacity, it especially facilitates the common visualization and exploration of virtual 3D city models among a group of people.

The projection is performed using six laser projectors, each with a FOV of 68° and a resolution of 1600 × 1200 pixels. A laser projector creates a sharp image that is independent of the distance to the projection surface. The projectors cover 43% of the maximum resolution of the human eye [10]. The laser projectors are not capable of active or passive stereo.

The image synthesis is performed using a rendering cluster with one computer per projector (Section IV-A). An additional appliance synchronizes the software running on the cluster and handles input devices. A tracking system with 12 infrared (IR) cameras enables determination of position and orientation of objects, e.g., controllers or users, in real-time and with a precision of 2mm. Tracking of hands and fingers enables wireless interaction using gestures. A touch table in the center of the user platform enables additional interaction.

The sound system, comprising of 11 loudspeakers, can be configured to create acoustic 3D scenery within an area of 4m in diameter. This enables spatialization of each sound source in the VE for multiple users.

III. Immersive Environments

Several aspects create and strengthen a viewer's feeling of immersion regarding a VE. In the following, these requirements are discussed.

Field-of-View (FOV): A large FOV increases the size that an image of 3D VEs occupies on the retina. Any restriction of the image size on the retina makes the visualization less immersive because any periphery around the presentation area has an impact on the user's perception. Large displays, e.g., projection walls, potentially increase retinal image size and, therefore, improve immersion. Fully immersive VEs envelop the viewer and allow for head movement while still covering the user's FOV.

Display Resolution: Given the display size, the distance of the viewer to the display, and the maximum resolution of the human eye, the resolution of the display must be adequately chosen to create a perspicuously image. If the resolution of the displays is insufficient, single pixels of the display can be distinguished. This appears incorrect, distracts the viewer, and decreases immersion.

Interaction: Interaction is essential to immersive VEs. On one hand, the user should be given full control of the six degrees-of-freedom (DOF), i.e., the user can move and rotate around the three main axes. On the other hand, interaction should be constrained to avoid "getting-lost" situations or object collisions. Movement controls based on metaphors (e.g., walking, helicopter, airplane etc.) in combination with constrained 3D navigation strategies assist the user and help to increase user acceptance [11]. Further, the input device should not imply restrictions on the user's physical location to allow free physical movement within the physical VE facility.

Depth cues: Depth perception is the visual ability to estimate the distance to and between objects, and thus to perceive the world in three dimensions. A strong perception of depth may lead to an increased sense of immersion [12]. The depth sensation is generated by a variety of *depth cues* [13, 14], which can be classified into *monocular*, perceived with a single eye, and *binocular* cues, perceived by both eyes. For example, binocular cues are convergence and stereopsis. The most known and used monocular cue is linear perspective, which is the convergence of parallel lines at infinity. This effect causes also depth cues such as relative size, texture gradient, and height-in-visual field. Other important cues are occlusion, motion parallax, light, shading, shadows, accommodation, and defocus blur, as well as aerial perspective.

3D Soundscape: A plausible 3D soundscape creates acoustic immersion and thus increases overall immersion. Paterson et al. [15] show that a semantic-based and location-aware soundscape increases immersion and emotional engagement, which is preferable for a fully immersive VE, i.e., the soundscape should be representative and typical to the local urban sounds [16].

Presentation Scale: Another aspect that contributes to an immersive environment is the scale of the presented objects. Ideally, a scale of 1:1 can be used to visualize virtual 3D city models to achieve a high degree of immersion.

The Elbe Dom projection wall envelops the viewers completely, covers their FOV, and is well suited for 1:1 scale visualization. The centered visitor platform exhibit space for approx. 40 viewers to collaborative work within the fully immersive VE. The 3D sound system is capable to stream a soundscape to further increase the degree of immersion. Beside different wireless input devices, e.g., space mouse and gamepad, the IR cameras can be utilized for user tracking and gesture-based user interaction. Since the Elbe Dom does not support active nor passive stereo, the VE applies special rendering techniques to synthesize effective depth cues.

IV. Challenges for Rendering Systems

The implementation of an interactive system for fully immersive VEs introduces several challenges for visualization, rendering and interaction. The following section describes conceptual as well as technical challenges and outlines solutions.

A. System Architecture

For high-resolution, multi-display systems, rendering should be distributed using *rendering clusters* because a single computer is usually not capable to simultaneous generate images for all projectors in real-time. Rendering clusters are compounds of multiple render computers (*render nodes*). Ni et al. [17] and Soares et al. [18] provide an overview of algorithms, architectures, and technologies for high-resolution displays and parallel rendering.

Parallel rendering algorithms can be classified into sort first, last, and middle [19]. The *sort first* algorithm segments the viewport or projection surface and distributes these among render nodes. *Sort last* segments and distributes the geometry among nodes and composes the generated images afterwards. Compositing requires image transfer between nodes and often requires modifications of rendering techniques, e.g., anti-aliasing [20]. *Sort middle* is a combination of both: the geometry is distributed for vertex operations followed by classification and distribution by their screen position for rasterization. Image transfer as well as distribution of geometry increase network traffic and synchronization overhead.

Ni et al. [17] classifies rendering cluster systems by means of data distribution. In a *client-server* system, the user interacts with a single instance of the application running on a client that decompose the rendering task into subtasks and delegate them to rendering servers. In a *master-slave* system, an instance of the application runs on every client and stores all necessary data locally. The master synchronizes all clients and handles

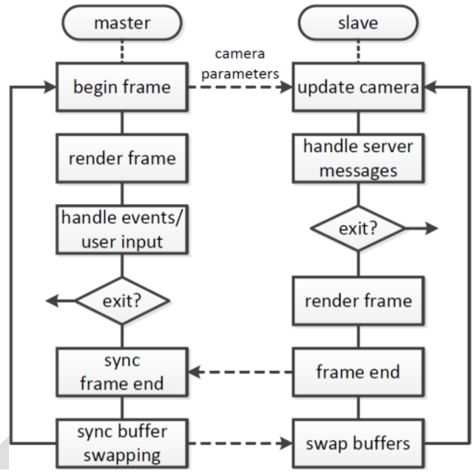

Figure 3. Overview of the render cluster synchronization. At the beginning and at the end of a frame, the master PC is responsible for a synchronization of the view and configuration parameter as well as a synchronous buffer swap of all slave computers.

user input. In contrast to client-server systems, the rendering-task is performed by every client.

Several software frameworks and APIs exist, e.g., VR Juggler [21], FlowVR [22], and Equalizer [23], that implement one or several of the algorithms described above. These frameworks are optimized toward one single application running on the cluster. Nam et al. [24] presents a synchronization algorithm for multiple parallel applications on high resolution displays.

For our prototypes, we have implemented a sort-first, master-slave system to minimize synchronization overhead, network traffic, geometric clustering, and image compositing. Every rendering node synthesizes images for the connected projector. The synchronization is limited to camera and visualization parameters as well as frame lock (Section IV-B).

B. Synchronizing Render Nodes

A main challenge for multi-projector systems is to ensure that the images of the different projectors appear as a single and coherent high-resolution image. This can be achieved by *gen-lock*, *data-lock*, and *frame-lock* [18]. Gen-lock is the synchronization of the video signals, e.g., for active stereo rendering. The implementation is mostly in hardware and requires only a configuration on software side.

Data-lock is the synchronization of the rendering data. An important aspect of data-lock is camera synchronization since every change of the position and/or orientation of the virtual camera requires an update on all render nodes. Data-lock is application specific and has to be implemented in software. Fig. 3 shows the synchronization concept of our implementation. At the beginning of every frame the master node broadcasts events and parameters of the virtual camera to all slave nodes, which update their local camera parameterization.

Frame-lock ensures that all projectors display the next frame simultaneously. Missing frame-locks results in tearing-artifacts due to time discrepancy of the displayed images. Although, hardware frame-lock is possible, it can be implemented in software with minor or no intrusion into existing applications. This way, the implementation is independent of graphics hardware used. Frame lock is achieved by synchronization at the end of every frame (Fig. 3). The slave nodes inform the master that the image can be rendered and wait (`frame end`). The master sends a release message as soon as all slaves are ready (`sync buffer swapping`). Rendering parameters for advanced rendering techniques are synchronized at the beginning of every frame.

C. Challenges for Rendering

Depth cues are important for depth perception, and thus for the feeling of immersion, in particular, if users perceive an environment in a scale of nearly 1:1. We have implemented several depth cues within the real-time rendering pipeline [25]. Perspective projection is used, e.g., linear perspective, texture gradient, height-in-visual-field, occlusion, and motion parallax. Shadows and shading are strong cues for communicating shapes of and distances between objects. We rely on real-time lighting techniques, in particular, on ambient occlusion [26] for simulating global illumination effects. Further, techniques such as deferred lighting [25] can be used to render a large number of dynamic light sources.

Mather points out that “the realism of computer-generated images should also be enhanced by the addition of selective blur to background regions” [27] because defocus blur, also known as depth-of-field, is an important depth cue. It can be assumed that during interaction and exploration the users focus near or mid-range objects. Thus, blur is only applied for background objects that are not in the user's focus (Fig. 2). Aerial perspective is the effect of decreased contrast and saturation of distant object due to light scattering in the atmosphere. In computer graphics this effect is often approximated by distance fog.

Depth perception by stereopsis is important in near- and mid-fields but has only a diminished role for objects further then 10m [14, 28] and thus for visualization of virtual 3D city models in 1:1 scale.

Besides the implementation of the described depth cues to improve the feeling of immersion, the visualized scene should be arranged in such a way that depth cues are facilitated. For instance, in our use prototype system, we add background objects, a horizon, and sky to create depth-related and scale-assigning reference objects.

Despite depth cues, photorealistic visualization has additional requirements. Visual errors and low resolution textures distract the user and thus reduce the immersion. Especially phenomena and objects that the human is familiar with, such as vegetation, sky and clouds, require specialized rendering techniques that depict these phenomena as realistic as possible.

D. Advanced Visualization Techniques

Photorealistic rendering techniques represent an obvious choice for visualizing virtual 3D city models. VEs, however, can also apply non-photorealistic rendering techniques. In particular, these techniques strengthen spatial relations, emphasize thematic information, decrease visual complexity, and, therefore, assist users in realizing 3D spatial models. Non-photorealistic rendering techniques usually require modifications to be applied in multi-projector systems, e.g.,

Figure 4. Example of a 3D building using a non-abstracted (A) and an abstracted (B) visualization technique. The abstraction reduces visual complexity and emphasizes characteristic facade details, such as edges.

they have to consider the physiology of the projection surface and different camera coordinate systems.

For example, the *multi-perspective views* (MPV) technique of Pasewaldt et al. [8] is based on global deformations that are computed in the virtual camera’s coordinate system. Since each projector in a multi-projector system utilize a specific virtual camera with a specific camera coordinate system, the global deformation is not coherent for all projectors, and discontinuities between projections are introduced. To utilize MPVs for fully immersive VEs (Fig. 1), two modifications were performed. First, the global deformations are computed in world coordinate system, which is identical for all virtual cameras. Thus, the generated MPVs are coherent and discontinuities are solved. Second, the configuration of the MPV has been modified in such a way that they are not aligned with the viewing direction of the virtual camera. Since the Elbe Dom has a cylindrical projection wall, a radial alignment around the viewers position is applied that equally deforms the geometry in all directions.

As already described in Section IV-B the software must assure that data, e.g., camera or visualization parameter, is synchronized (data lock). The synchronization of MPV configuration parameter is performed at the beginning of every frame (Fig. 3).

E. Input Devices and Interaction Concepts

Desktop input devices, such as mouse or keyboard, are not well suited for immersive VEs. They restrict user interaction: not all six DOF can be controlled simultaneously and wired devices imply restrictions on the user's physical position. Instead of desktop input devices, we utilized a wireless space mouse that enables simultaneous translation and rotation of the virtual camera.

Interaction in a fully immersive VE requires an "intuitive control" of all six DOF. To facilitate natural movement and to avoid collisions the user is assisted by smart interaction techniques [11].

Smart interaction techniques (e.g., semi-automatic pedestrian or helicopter interaction controls) indirectly map user inputs to camera control and further define constraints to avoid collisions or “getting-lost” situations. To prevent abrupt movement or direction changes, which may lead to simulator sickness [29], inertia is applied to the camera control. Thus, a user-indicated change in the direction leads to an acceleration or deceleration of the camera movement in the according direction.

As the discrepancy between the user's sense of balance and visual sense regarding body orientation and motion increase with speed and inclination of the camera, these should be capped at a certain value [29].

F. Semantic Soundscapes

Lacey et al. created a realistic soundscape for a virtual 3D city model by recording real-world sound samples and located them in a VE [16]. This process implies a high degree of manual work. A more generic approach is to utilize an urban sound catalog and locate the sound samples based on semantic information contained in, for example, a CityGML model [1]. The resulting representative soundscape appeared to be convincing and successfully create acoustic immersion [16] in our experiments.

V. Application Examples and Discussion

We presented our prototypical, fully immersive VE to a group of GIS experts, people of the public sector, as well as from universities. All participants had no or only few experience with fully immersive VEs. We prepared two different case studies: (1) an abstract visualization of a synthetic city and (2) a multi-perspective visualization of the virtual 3D city model of Berlin, Germany.

A. Abstract Visualization of a Virtual 3D City Model

One application example deals with the question "To what extend an abstract visualization of a virtual 3D city model can be immersive and, thus, is suitable for fully immersive VEs?" We prepared two different visualization of a synthetic city model: (1) a photorealistic and (2) a non-photorealistic rendering [6]. The non-photorealistic visualization utilizes a rendering technique that quantizes photorealistic façade textures and thus slightly reduces visual complexity while emphasizing characteristic structures and colors of the façade (Fig. 4). The abstraction technique is applied to the complete city model to achieve a consistent visualization. Further, we prepared a camera path used to rendering the virtual 3D city model and later gave the user the opportunity to manually explore the VE using a 3D space mouse. During the study, we observed the behavior of the participants and further conducted brief, unstructured interviews.

Due to large FOV and high display resolution, as well as a 1:1 scale, the users stated that they become completely immersed in the VE. During the camera path playback, we observed that users directly reacted to the camera movement, e.g., at fast sharp turns they leaned in the corner and they adapted to abrupt height changes. Afterwards, we asked participants to use the 3D space mouse to freely navigate through the VE. Although the users had only few experiences with such a device and VEs, they required almost no training to successfully navigate in the VE.

Even though none of the participants experienced a virtual 3D city model in a fully immersive VE before, they gave positive feedback to both visualization variants. Compared to the photorealistic visualization, the façade texture abstraction was not perceived disturbing, some participants did not even noticed the quantization. Further, they stated that they realized a plausible, convincing depth perception without active or passive stereo. Thus, it is reasonable that utilizing ambient

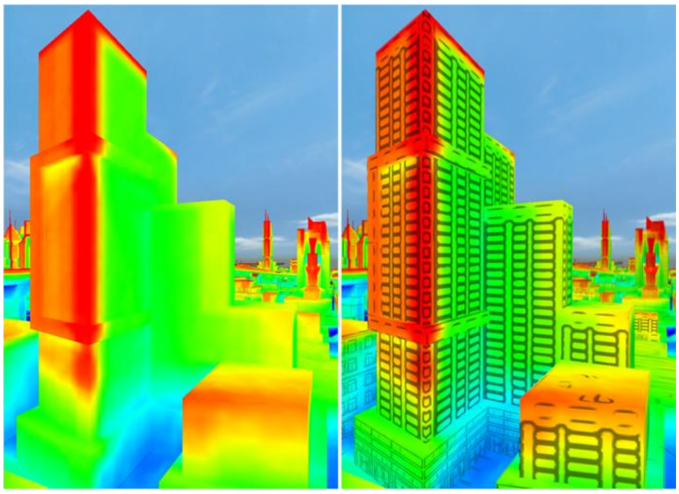

Figure 5. Visualization of thematic data: results of a solar potential analysis are mapped to facade textures in the 3D virtual city model (left image). Red indicates high solar potential and blue low solar potential. In the right image an image based abstraction of the original fac¸ade textures is added to emphasize the shape and spatial relations of the objects.

occlusion, fog, and selective background blur in addition to depth cues created by the real-time rendering pipeline, is sufficient for fully immersive VEs. Furthermore, the application of smart interaction techniques in combination with a space mouse eased the interaction with the VE. Finally, the participants stated that while they were immersed, they did not feel like a pedestrian, but a passenger of a kind of "space ship", mainly due to the helicopter interaction control used, and the absence of an urban soundscape.

B. 3D Multi-Perspective Views

In the second application example, we presented a multi-scale, multi-perspective visualization (MPV) of the virtual 3D city model of Berlin [8]. A block model of Berlin is bended upwards in the distant regions (Fig. 1). The MPV replaces the horizon by the virtual 3D city model, which increases screen-space utilization [8]. The combination of an upright projection in the foreground and orthographic projection in the background can be used to improve exploration of thematic information, e.g., results of solar potential analysis [31] (Fig. 5). To decrease visual clutter and emphasize the road network in the bended part of the visualization, single buildings are abstracted to building blocks [30].

In this application example, the participants stated that they did not feel as much immersed as in the abstract visualization experiment because the multi-perspective visualization appeared to be unknown and unusual, as well as initially distracting to the participants. Nevertheless, after brief training and explanation, the visualization approach was better understood and in later experiments accepted by the users. Thus, it seems generally feasible to use MPVs in fully immersive VEs, in particular to increase screen-space utilization, but it requires an introduction to the participants.

VI. Conclusions & Future Work

This paper discusses the application of fully immersive VEs for the presentation of virtual 3D city models. We have shown properties and requirements of immersive VEs by the example of the "Elbe Dom", a 360° projection system. During the development of visualization prototypes, we identified and handled different challenges that are discussed in detail. We evaluated our concepts and the application of two non-photorealistic rendering techniques in the fully immersive VE using two application examples.

We observed that an abstraction of façade textures has little or no implication on the feeling of immersion of the users. With non-regular perspective views, e.g., using multi-perspective views, we noticed a decrease of immersion. This requires further investigation and a user study to identify the reasons for the decrease. In both scenarios, we observed increased collaboration potential compared to visualization on a desktop PC. This underlines the assumption, that fully immersive VEs are well suited tools, to communicate, explore, analyze, and discuss virtual 3D city models to a group of participants, including non-experts.

The presented prototypes mainly focus on immersive visualization of virtual 3D city models and semi-automatic 3D interaction concepts. For future work, we plan to integrate automatic, dynamic 3D soundscapes to further increase immersion and to improve 3D interaction and navigation by adding movement constraints to the virtual camera to further reduce simulator sickness.

VII. ACKNOWLEDGEMENTS

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