A HYBRID DECISION SUPPORT SYSTEM FOR 3D CITY PLANNING

Frank Steinicke, Klaus Hinrichs, Timo Ropinski

Institut für Informatik, Westfälische Wilhelms-Universität, Einsteinstraße 62, 48149 Münster, Germany
{fsteini,khh,ropinski}@uni-muenster.de

KEY WORDS: Decision Support System, Spatial Planning, Hybrid System, Virtual Reality

ABSTRACT:

In recent years virtual reality based geographic information systems (VRGIS) have been employed successfully to accomplish city planning tasks. Tracking technologies and stereoscopic visualization of three-dimensional structures support the user to gain a better insight into complex datasets. Moreover, large projection-based displays have considerable potential to enable collaboration in co-located VRGIS setups, i.e., several city planners can design virtual 3D city models simultaneously. However, these systems often lack intuitive interaction concepts and therefore are mainly used as advanced visualization tools. In this paper, we present a hybrid city planning system that uses desktop-based environments as well as semi-immersive virtual reality (VR) systems to support the planning process. The objective of this approach is to enhance the design process of development plans based on similar work processes that are performed in real-world planning tasks. Our system provides an advanced desktop-based interface to edit digital geoobjects, and it supports intuitive interaction concepts for semi-immersive VR systems to arrange the resulting entities in development plans. To assure the usability and relevance of our system, city planners were closely involved in the development. In this paper both the hard- and software architecture of the entire system as well as VR related interaction metaphors and their evaluation are discussed.

1. INTRODUCTION

Civil works affect both the environment and the inhabitants of a city, the cityscape as well as the quality of life of the residents are influenced by the appearance of buildings, road networks, planting, and green spaces etc. Therefore, city planning plays an important role. To facilitate a visual impression of how a proposed construction would integrate into the environment, city planners design development proposals based on cadastral data, which is available for every town in Germany.

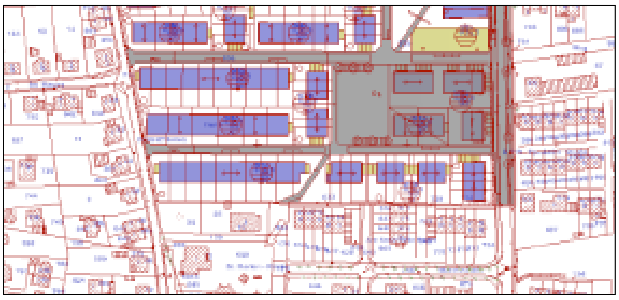

Figure 1. Example section of a development plan within cadastral information

As depicted in Figure 1 cadastral data usually contains building footprints, number of floors and floor's height for each building, parcel boundaries, and other information. Within such a development plan, city planners define entities, for example buildings and recreation areas, associated with a set of constraints, which specify what types of geoobjects are allowed and what requirements have to be incorporated. After city planners have agreed to a certain development plan, two different procedures are commonly used.

One approach is to deliver the development plan to an architectural office. On the basis of these plans digital virtual 3D models are generated, and exemplary three-dimensional visualizations of these planned areas are returned to the city planner. This procedure has the following two major shortcomings. First, the returned visualizations are static insofar as city planners cannot explore the 3D models interactively. Second, city planners cannot perform modifications to the 3D models, which, for instance, have been proposed after reviewing the 3D visualization. Instead, the architectural offices have to be asked again to incorporate these modifications into the 3D model. During a planning task, this usually takes several iterations resulting in inefficiency as well as unnecessary expense. A common alternative is to build physical block models usually made of wood, plastic or paper. Figure 2 illustrates such a physical block model for the development plan partly shown in Figure 1. In such a shared setup urban planners interact with each other, e.g., by modifying positions of bricks representing buildings. Changing the appearance or geometry of most objects in the model is often awkward, since most elements are inflexible and fixated to the model. Furthermore, the creation of these models is a very time consuming task, which requires high efforts in terms of money and manpower. Thus, simpler solutions to visualize planned development areas are desired.

In cooperation with the city development, city planning and transport planning office as well as the land surveying and land registry office of the city of Münster in Germany, we have developed solutions for these problems. An objective of this cooperation is to develop computer-aided concepts, which serve the needs of professional city planners and provide a convenient alternative to current planning tasks. City planners demand that the developed strategies should be based on their current work processes resulting in physical block models as well as computer generated 3D visualizations. However, the city planners desire to have more independent and sophisticated control over both approaches; they want to be able to generate digital virtual 3D city models and to create three-dimensional visualizations autonomously. Furthermore, the intuitive comprehension when viewing a physical block model should be obtained.

In consideration of these two major demands, we decided to develop an interactive 3D residential city planning software system, which runs in *virtual reality* (VR) systems as well as in desktop-based environments. To ensure the adaptation of the planning system into already existing setups and databases, a simple *geographic information system* (GIS) interface has been integrated to import the required data. Virtual reality based geographic information systems (VRGIS) are increasingly used for planning tasks, since VR technologies provide better perception and com-

Figure 2. Example section of a city development plan within cadastral information (left) and a corresponding physical block model made of wood downscaled to 1:1000 (right)

prehension of complex 3D structures (Beck 2003). However, most VR systems support only a subset of the full desktop-based functionality since menu-handling or specification of numeric values or strings is even more difficult in VR than in desktop-based environments users are familiar with. Hence, VRGIS are often only used for exploration (Dodge *et al.* 1998, Beck 2003). In order to enhance the interaction in VRGIS we have developed intuitive interaction metaphors, which facilitate the efficient design of development plans.

In this paper, we present the system architecture of our *3D residential city planner* and describe a hybrid system setup supporting both desktop-based and VR-based design of development plans. In particular, we propose advanced concepts for generic interaction tasks, whose benefits have been proven in usability studies. The paper is structured as follows. In Section 2. the architecture of the 3D residential city planning software is explained in detail. Section 3. discusses the hybrid system components in which the residential planning software is used, involving standard desktop-based environments as well as a table-top-based VR system. In Section 4. concepts which enable intuitive desktop- and VR-based interactions are proposed and their evaluation is discussed in Section 5. Section 6. concludes the paper and gives an overview of future research directions.

2. 3D RESIDENTIAL CITY PLANNER

The *3D residential city planner* is an ongoing project involving a student group at our department, the city development, city planning and transport planning office as well as the land surveying and land registry office of the city of Münster (Steinicke *et al.* 2006).

During the development phase of the software, city planners expressed their desire for flexible approaches to visualizing 3D city models. Although photorealistic rendering is important, it is not the only requirement; especially non-photorealistic rendering (NPR) supports comprehension of structures and relations similar to physical block models. Furthermore, during exploration interactive frame rates are more important than photorealistic appearance. However, realistic visualizations like the renderings provided by architectural offices are also desired.

Due to these demands, we have chosen VRS, the Virtual Rendering System (Döllner and Hinrichs 2002), as core graphics library for building virtual 3D city models. VRS is an object-oriented and scenegraph-based C++ graphics library, which has proven its benefits for GIS applications. It introduces the usage of two different graphs. *Geometry graphs*, which store the visual appearance of virtual objects collected in scene nodes, are combined with *behavior graphs* to represent the behavior of virtual objects in terms of interaction and animation. VRS supports photorealistic renderers, such as POVRay or Radiance, but also real-time renderers, e.g., OpenGL, and allows switching between these renderers at run time. Furthermore, VRS is extensible to a VR software system by using the *Virtual Reality VRS* (VR^2S) component (Steinicke, Ropinski and Hinrichs 2005a), which handles all VR related issues.

The 3D residential city planner consists of four conceptual components:

1. The **converter tool** parses the cadastral data and converts it into a scenegraph structure, which is used to represent the corresponding geodata.

2. The **geobject model** is the collection of geoobjects and their properties. This model is generated during parsing of the cadastral data by the converter tool. Components of this model are buildings, building and traffic areas, trees etc.

3. The **visualization component** constructs the scenegraph representing the topological structure of the city model. Each scene node in the geometry graph representing a collection of geoobjects is associated with a visual appearance, e.g., by assigning colors or textures.

4. The **interaction component** manages required interactions with virtual 3D city models. A graphical user interface (GUI) supports certain interactions. Furthermore, VR-based interaction concepts such as arrangement of virtual buildings are incorporated.

Since the cadastral data is geo-referenced, virtual 3D city models consisting of building geometry and corresponding roof types can be generated automatically when using our software. Because there is no overall accepted standard for storing cadastral information, we have developed an interface that provides the required generality and flexibility to enable import of cadastral data from different sources. Based on this information the system generates a geo-referenced virtual 3D city model of the surrounding area, which is superimposed with aerial photographs to provide more realism and better cognition.

Within the geoobject model all geoobjects are aggregated in the class `CityModel`, which administrates all required information for a geo-referenced city model. Instances of type `GeoObject` provide the base from which all geoobjects, e.g., instances of type `Building` or `ParcelArea`, inherit. An instance of the class `Building` consists of one or more `BuildingParts` for handling different types of storeys and roofs. The other geoobjects are organized analogously, a similar approach has been proposed in (Döllner *et al.* 2005).

The visualization component is separated from the geoobject model of the virtual city. All required information to visualize the objects of an instance of the class `GeoObject` is handled via the class `AppearanceManager`. The visual appearance of each geoobject can be assigned randomly, or the city planner can define the appearance, for example by assigning specific textures to each geoobject. Since generated virtual 3D city models may consist of tens of thousands complex, textured geoobjects, it is not feasible to store each of these geoobjects in corresponding scene nodes of the scenegraph, because this would inflate memory requirements for storing the scenegraph and decrease performance when evaluating it. Due to the wrapping mechanism of VRS it is possible to store this enormous amount of data by using renderer-specific optimization strategies. To further increase performance, optional view-dependent level-of-detail algorithms are incorporated to enable switching between different levels of realism.

The interaction component provides standard techniques required for development tasks, e.g., editing or arrangement of virtual buildings. Moreover, different navigation and traveling metaphors are supported, for example *flying*, *gliding*, *walking* and *ufo-viewing* metaphors, i.e., an exploration with orthogonal view onto the virtual city model. When exploring a digital city model, arbitrary locations can be stored as *visual bookmarks* to be accessed later on, for example to generate smooth camera motions along a resulting path.

3. HYBRID SYSTEM SETUP

Since city planners are accustomed to physical block models and desire to use block models further or even in a VR-system get an impression, we use a semi-immersive table-top-based display system in combination with an optical tracking system to visualize virtual 3D city models in virtual reality. In comparison to physical block models, the usage of such a VR system setup enables sophisticated interaction with potential building plans, because interactive modification, e.g., changing the building geometry or other building parameters, are incorporated. However, for many interaction tasks, standard desktop devices provide sufficient input options; especially menu-based interaction tasks, e.g., project handling or input of numerical or string values, are certainly easier to accomplish in desktop-based environments than in VR-based environments.

Designing development plans may benefit from both 2D and 3D interactions. For instance, virtual buildings can be generated more easily in 2D, whereas these buildings can be arranged in a virtual 3D city model via the proposed table-top VR systems. In the following subsections we propose a hybrid system setup that support this strategy.

3.1 Desktop VR System

Nowadays, the most common human-computer interaction devices are the keyboard, the mouse or other pointing devices, in combination with a two-dimensional display. This combination has proven to be a very powerful concept for two-dimensional graphical user interfaces (GUIs). *Desktop VR systems*, sometimes referred to as *Window on World* (WoW) systems, are based on such setups and provide the simplest type of VR systems. Generally, only conventional monitors are used to display the VE either monoscopically or stereoscopically. Which graphic rendition is used depends on the content of the VE, i.e., 3D objects benefit from a stereoscopic projection, whereas 2D objects are usually displayed in monoscopic mode.

We provide the city planners with desktop VR systems to generate virtual 3D buildings as described later on in Section 4.1. For this purpose city planners are equipped with a standard desktop-based environment optionally extended by a stereoscopic monitor, either an autostereosopic display or a conventional CRT display in combination with stereo glasses. Since the full functionality of the 3D residential city planner is accessible via a mouse and a keyboard, the entire development process can be performed in desktop-based environments. However, when city planners confine the planning process to desktop-based environments, the mentioned benefits of VR systems cannot be exploited.

3.2 Responsive Workbench Environment

Since professional city planners desire to maintain the intuitive comprehension obtained when viewing a physical block model, we have chosen a semi-immersive responsive workbench (RWB) environment in combination with an optical tracking system to visualize interactive virtual 3D city models.

A Barco BARON RWB (Krüger *et al.* 1995) is used to present 3D city models stereoscopically in a way that enables city planners to work in an environment they are accustomed to (Figure 4). The images are projected onto the display's surface such that city planners perceive virtual 3D models as being attached to the surface (Figure 4). This is due to the fact that the images are rendered stereoscopically with negative parallax. The images are displayed in sequence and are synchronized with active shutter glasses the city planners have to wear.

The workbench is about $2\text{m} \times 2\text{m}$ large and 1.2m high. The display screen measures $1.36\text{m} \times 1.02\text{m}$ with a maximum pixel resolution of 1280×1024. The maximum refresh rate of 120Hz is ensured with a resolution of 1024×768 pixels, which supports comfortable working without flickering effects. As illustrated in Figure 4 the size and resolution of the workbench allows several planners to view virtual 3D models in a stereoscopic projection. The planners can walk around the RWB in order to view the virtual 3D city model from different perspectives. To enable such an exploration from several view positions, the system must be aware of the user's current position, which determines the virtual camera's position and orientation accordingly. For this purpose tracking systems are used.

3.2.1 Optical Tracking System High accuracy and wireless interaction is indispensable for precise and comfortable city planning, therefore an optical tracking system is used to determine the position of the planners as well as their input devices. The accuracy of the stereo-based optical tracking systems is in the range of submillimeters, and thus tracking errors are minor and precise interactions with virtual geoobjects displayed on the RWB are possible. Since lighting conditions around the RWB have to be darkened because the brightness of the projection itself is limited, *infrared* (IR) light in combination with IR-filters is used. The operation area of the tracking system is determined by the physical measures of the workbench, therefore a volume of about $3\text{m} \times 3\text{m} \times 1.5\text{m}$ has to be scanned. To enable an optimal tracking of this area two cameras are arranged above and beside the workbench.

Because of the many drawbacks of IR-LEDs, we have decided to use passive markers to be tracked by the system. These markers are made of small spheres covered with reflective material, so that light emitted by an IR-spot, which is positioned close to the camera lens, is reflected back the camera. Only the reflected IR light reflected by the markers passes through a filter, which is attached to the front of the lens. With corresponding tracking algorithms the position of each marker and thus the position and orientation of unique rigid body arrangements of such markers can be determined (Dorfmüller-Ulhaas 2002).

3.2.2 Input Devices Passive marker tracking provides more flexibility in comparison to other technologies, e.g., electronic or magnetic approaches. Attaching certain devices with a unique rigid body arrangement of at least three markers results in arbitrary six degrees of freedom (DoF) input devices, i.e., devices whose position and orientation can be tracked. However, further input events such as button and gesture events are required to manipulate a development plan. For this purpose, we equip city planners with a haptic input device, which supports planning by

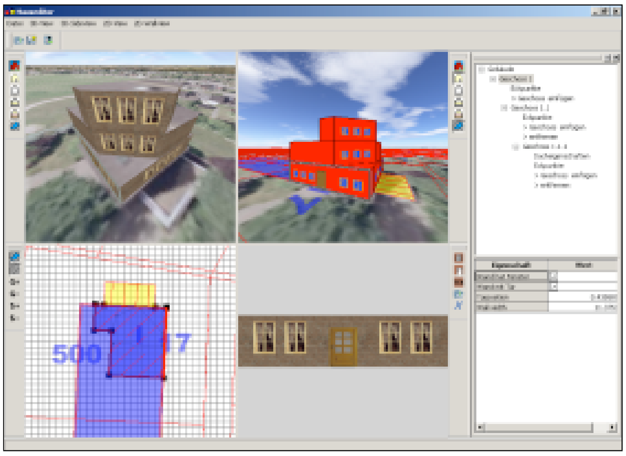

Figure 3. A screenshot of the two-dimensional building editor mode. The two-dimensional frames are displayed monosopically, whereas the previews of the three-dimensional building can be displayed stereoscopically

vibration feedback. In combination with sound signals this information can be used to give multimodal feedback about invalid interactions, e.g., collisions between virtual buildings during the planning process. This device is equipped with two input buttons, passive markers and the vibration unit, that enables transmission of haptic signals with different intervals. The buttons can be used similar to the buttons of a standard mouse, e.g., the left button for selection tasks, the right button to open 3D context menus.

4. HYBRID INTERACTION CONCEPTS

The 3D residential city planning system enables an easy generation of proposals for development plans, which can be modified and explored in both desktop-based as well as VR-based environments. As mentioned in Section 1., since VR technologies provide a better spatial cognition of complex structures, virtual 3D city models can be explored in VR systems more immersively than in standard desktop-based environments. However, when using VR technologies two-dimensional interaction tasks are more difficult to accomplish, because of the higher effort which is required when controlling six DoF devices (Bowman and Hodges 1997).

Hence, we suggest to perform 2D interactions in desktop-based environments, and to accomplish tasks, which require an immersive comprehension of the virtual environment in the described RWB system. Thus, with the described setup the following process is enabled. Generation and modification of geoobjects, in particular virtual buildings, are performed in desktop-based environments as described in Section 3.1. When a city planner finishes a virtual geoobject, he can deliver it to the second planner who works in the RWB environment. The second city planner can arrange these geoobjects in a virtual 3D development plan in a very intuitive and immersive way. In the next both subsections we will explain these concepts for both environments in more detail.

4.1 Generation of Virtual Geoobjects in Desktop-based Environments

One of the major tasks in city planning is the definition of building areas and specification of associated buildings. For this purpose the 3D residential city planner provides a geoobject modeler interface. Within this editor virtual geoobjects can be specified in terms of geometry, appearance, constraints etc. As illustrated in Figure 3 the editor's interface consists of six frames, i.e., a contextual 3D preview of the geoobject (upper-left), a 2D vector-based topview (lower-left), a lateral view showing the side of the geoobject (upper-middle), an orthogonal view focussing on one wall (lower-middle), a hierarchical structure view (upper-right) illustrating the tree structure of the geoobject, for example, in terms of stories and roofs, and a property view (lower-right) that comprises additional contextual information giving numerical and alphabetic information about the geoobject, e.g., associated streetname, position in Gaus-Krüger coordinates etc. While the two-dimensional frames are displayed monoscopically, the three-dimensional preview of the geoobject can be displayed stereoscopically.

In Figure 3 a screen shot of the geoobject modeler is shown for a virtual building. The urban planner can specify the building footprint of each story, and particular roof types can be assigned to the building. Moreover, windows, doors etc. can be arranged on the building surface and optional textures can be assigned. Furthermore, arbitrary virtual geoobjects, which are part of the plan, can be imported into the editor and be modified there. When the city planner finishes the editing process the virtual geoobject can be transferred to the virtual 3D city model. Thereupon, another city planner can arrange the virtual geoobject in a very immersive way using the VR system technologies described in Section 3.2.

4.2 Arrangement of Virtual Geoobjects in VR-based Environments

Although VR environments provide the possibility to manipulate virtual objects in an intuitive manner, e.g., by using *virtual hand* or *virtual pointer metaphors* (Mine 1995), these concepts are often limited, because the cognitive effort for an interaction is definitely higher in VR than the effort for the corresponding interaction in the real world. In addition, it is often difficult to perform precise interactions because of tracking errors and hand tremors. For example, it is hard to select small or distant objects. Thus, generic interaction tasks need to be enhanced. In order to advance such generic interaction tasks we proposed the *improved virtual pointer* (IVP) metaphor, which avoids most disadvantages of current interaction metaphors (Steinicke, Ropinski and Hinrichs 2005). This approach allows a city planner to select a desired geoobject with a virtual pointer without requiring an exact hit. While a straight ray is used to indicate the direction of the virtual pointer, an additionally visualized bendable ray points to the closest selectable geoobject or item (Figure 4). After selecting the desired geoobject, manipulations can be performed similar to the manipulations of physical block models. The movements of the virtual input device are transferred by advanced mapping approaches to the selected geoobject, which supports also the manipulation of distant objects outside the immediate reach of the city planner (Steinicke, Ropinski and Hinrichs 2005). Due to this mapping strategy virtual geoobjects can be arranged very comfortably and intuitively.

To reduce the cognitive effort for such 3D interactions, we have integrated *3D widgets* into the manipulation process. 3D widgets provide an easy way to manipulate objects with six degrees of freedom by constraining the simultaneously manipulated degrees to one. These widgets provide handles for translation, rotation, and scaling of virtual geoobjects. Thus, six DoF manipulation tasks can be decomposed to a sequence of simple two-dimensional interactions.

Furthermore, we support interaction with multimodal feedback. For example, when a selection is possible, e.g., the selection ray hits a virtual building, the users perceive a slight vibration and an acoustic feedback. The intensity of both signals depends on the position of the virtual building with respect to the planner's position.

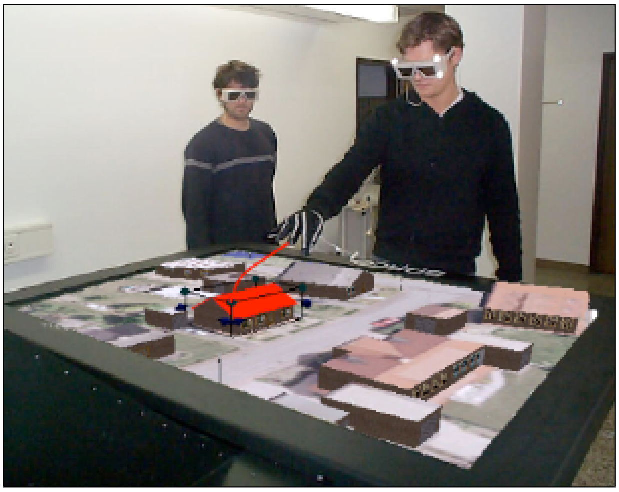

Figure 4. Virtual 3D city model and improved virtual pointer. The image has been manipulated to illustrate the stereoscopic effect

5. EVALUATION

We have evaluated the VR-based interaction concepts in a usability study performed within the context of the 3D residential city planner project. The 15 subjects chosen for the test series were familiar with residential planning environments. Most subjects were geoinformatic students, but also landscape ecologists, computer scientists and mathematicians participated in the usability study.

During the test series the subjects had to accomplish several selection and positioning tasks, i.e., randomly marked virtual buildings had to be selected and arranged in a development plan by using different interaction metaphors. These metaphors included the IVP metaphor and a simplification, called *Sticky-Ray metaphor*, the *ray-casting technique*, and the *sticky-finger technique* described in (Steinicke, Ropinski and Hinrichs 2005, Bowman and Hodges 1997, Pierce *et al.*1997). We have evaluated the time needed for each subtask and the accuracy achieved with a particular metaphor.

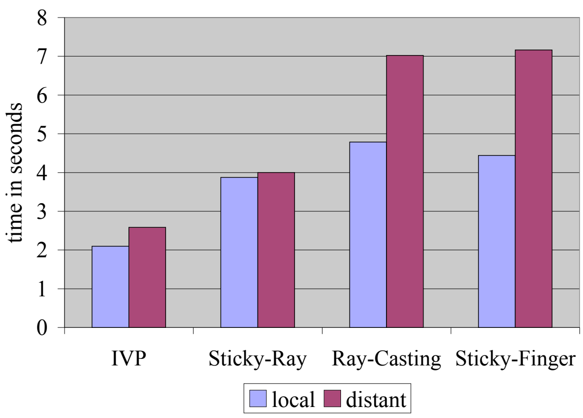

Figure 5. Results of the usability study

The most significant results are illustrated in Figure 5. This chart shows the time needed for a selection subtask when using the different metaphors. The results clearly show that the IVP metaphor improves efficiency and that selections are performed faster for local object selection, i.e., selection in the immediate reach of the user, as well as for distant geoobjects. Performing the required manipulations was more accurate and precise using the described approach. Moreover, the participants have evaluated the IVP metaphor as the most intuitive, ease to use and easy to learn metaphor in comparison to the other approaches. Although a significant performance increase could not be observed, the participants felt convenient and confirmed during interaction processes when receiving multimodal feedback.

6. CONCLUSION AND FUTURE DIRECTIONS

We have proposed a hybrid system environment for city planning tasks. Due to the fact that this system has been developed with co-operation partners from the domain of city planning their demands could be fulfilled so that they are motivated to use the application to develop new building plans. The user studies have proven the usability and benefits of the proposed VR-based concepts.

Currently, the land surveying and land registry office evaluate a prerelease version and the urban development, city planning and transport planning office will test the software system in a real planning process involving the proposed hybrid system setup soon. When these field studies are finished, modifications of the actual application or integration of further functions will be accomplished.

REFERENCES

Beck, M, 2003. Real-Time Visualization of big 3D City Models. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXIV(5/W10).

Bowman, D and L Hodges, 1997. An Evaluation of Techniques for Grabbing and Manipulating Remote Objects in Immersive Virtual Environments. In *ACM Symposium on Interactive 3D Graphics*, pp. 35–38.

Dodge, M, S Doyle, A Smith, and S Fleetwood, 1998. Towards the Virtual City: VR & Internet GIS for Urban Planning. In *Workshop on Virtual Reality and Geographical Information Systems*.

Döllner, J, H Buchholz, F Brodersen, T Glander, S Jütterschenke, and A Klimetschek, 2005. SmartBuildings - A Concept for Ad-Hoc Creation and Refinement of 3D Building Models. In *Proceedings of the 1st International Workshop on Next Generation 3D City Models*.

Döllner, J and K Hinrichs, 2002. A Generic Rendering System. *IEEE Transaction on Visualization and Computer Graphics* 8(2), 99–118.

Dorfmüller-Ulhaas, K, 2002. *Optical Tracking - From User Motion to 3D Interaction*. Ph. D. thesis, Technische Universität Wien.

Krüger, W, C Bohn, B Fröhlich, H Schuth, W Strauss, and G Wesche, 1995. The Responsive Workbench: A Virtual Work Environment. *IEEE Computer* 28(8), 42–48.

Mine, M, 1995. Virtual Environments Interaction Technqiues. Technical Report TR95-018, UNC Chapel Hill Computer Science.

Pierce, J, A Forsberg, M Conway, S Hong, R Zeleznik, and M Mine, 1997. Image Plane Interaction Techniques in 3D Immersive Environments. In *ACM Symposium on Interactive 3D Graphics*, pp. 39–44.

Steinicke, F, T Ropinski, and K Hinrichs, 2005a. A Generic Virtual Reality Software System's Architecture and Application. In *Proceedings of the 15th International Conference on Artificial Reality and Telexistence (ICAT05)*, pp. 220–227.

Steinicke, F, T Ropinski, and K Hinrichs, 2005b. Multimodal Interaction Metaphors for Manipulation of Distant Objects in Immersive Virtual Environments. In *13th International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision*, pp. 45–48.

Steinicke, F, T Ropinski, K Hinrichs, and J Mensmann, 2006. Urban City Planning in Semi-immersive Virtual Reality. In *Proceedings of the International Conference on Computer Graphics Theory and Applications (GRAPP2006)*.