Arch-Explore:
A Natural User Interface for Immersive Architectural Walkthroughs

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Abstract

In this paper we propose the *Arch-Explore* user interface, which supports natural exploration of architectural 3D models at different scales in a real walking virtual reality (VR) environment such as head-mounted display (HMD) or CAVE setups. We discuss in detail how user movements can be transferred to the virtual world to enable walking through virtual indoor environments. To overcome the limited interaction space in small VR laboratory setups, we have implemented redirected walking techniques to support natural exploration of comparably large-scale virtual models. Furthermore, the concept of virtual portals provides a means to cover long distances intuitively within architectural models. We describe the software and hardware setup and discuss benefits of Arch-Explore.

Keywords: 3D user interfaces, virtual environments, locomotion, architectural walkthroughs, redirected walking, passive haptic feedback.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1 Introduction

Three-dimensional models play an important role in architectural design, since they allow architects, decision makers and customers to review, communicate and present design proposals [3]. These models give an excellent impression of space and geometry and allow to visually verify compliance with design constraints and regulations. There are various analog and digital approaches for architects to present their design ideas. For instance, planners as well as architects commonly use physical 3D block-models that represent miniaturized city entities such as buildings and streets. The physical block-models are complemented by digital models which are used for the generation of images and fly-through animations. Constructing analog models is a time-consuming task, and in terms of changeability these models are less flexible than their digital counterparts. In this context, VR systems promise great potential to improve the exploration of architectural models. Perception and cognition research suggest that interactive exploration, as supported for example by immersive virtual environments (IVEs), improve the perception of space and geometry [11]. Stereoscopic visualization of three-dimensional data in combination with tracking systems often allow an improved understanding of complex data sets. Tracking of head motions enables users to control the view in the virtual world in a natural way. By contrast, passive animations and fixed view directions reduce the capability of the human mind to build up a mental model of the considered architectural entities. In HMD or CAVE setups with position and orientation sensors users can move through virtual worlds on a one-to-one scale using the most basic and intuitive exploration technique, i. e., real walking. Apparently this technique has the drawback that the users' movements are restricted by the limited range of the tracking sensors and a rather small workspace in the laboratory environment. Despite these limitations, real walking is superior to other locomotion techniques in terms of the users' sense of "feeling present" in the virtual environment (VE) [29]. Some setups even provide passive haptic feedback, so that users can sense virtual objects by touching their real-world counterparts such as walls to get a better feeling for the displayed scene [7].

Interaction can be implemented almost naturally in IVEs [22], however, perception in the virtual world differs from perception in the real world. For instance, subjects tend to underestimate egocentric distances [8, 10, 17], visual speeds [1] and traveled distances [5] during walking in IVEs. The limited field-of-view (FoV) and various side-effects of uncomfortable VR equipment may have an impact on this perception phenomenon. Redirected walking techniques have been proposed which allow walking over large distances in the VE, while a large displacement of the user in the real-world can be avoided. Hence, without the requirement of exhaustive hardware technology, the users remain in a limited laboratory area, while they can explore arbitrarily large virtual worlds [21, 25]. Redirected walking techniques are based on psychological experiments, which state that usually vision dominates proprioception and vestibular sensation when these senses disagree [2]. Therefore in real walking setups, where users perceive the VE visually, one can insert additional manipulations to the tracked motions which are applied to movements of the virtual camera. When these manipulations are below the perception thresholds, users unknowingly compensate for these changes in their real-world path of travel. For instance, if users walk straight ahead for a long distance in the virtual world, small rotations of the virtual camera redirect them to walk unconsciously a circular arc in the opposite direction in the real world. This allows to guide users on paths through the real world that differ from the paths perceived in the VE. If the induced rotations are small enough, users get the impression of being able to walk in the virtual world in any direction without restrictions.

In this paper we present the *Arch-Explore* user interface, which incorporates architectural miniature and true-to-scale exploration in a single setup. Support for both demands is essential for communication of architectural design proposals. The Arch-Explore is a real walking user interface, which adapts redirected walking for architectural scenes. We describe a virtual miniature model environment, which provides architects with benefits comparable to physical block-models and combines these with the possibility to explore the models also from an interior view. Therefore, we take advantage of features in indoor environments and enable exploration of large-

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IEEE Symposium on 3D User Interfaces 2009
14-15 March, Lafayette, Louisiana, USA
978-1-4244-3965-2/09/$25.00 ©2009 IEEE

scale virtual models in a room-sized VR laboratory. We describe how subjects can walk through architectural models while passive haptics indicate certain restrictions of the model as introduced, for instance, by physical walls.

The remainder of this paper is structured as follows. Section 2 summarizes related work. Section 3 introduces the Arch-Explore user interface and describes in detail the redirected walking implementation for true-to-scale models. Section 4 describes the used hardware and software setup. Section 5 concludes the paper with preliminary self-reported feedback about the presented Arch-Explore user interface and gives an overview about future work.

2 Related Work

In order to communicate design proposals, architects and urban planners commonly use physical block-models, which are made of paperboard, wood or plastics. Their measures vary in terms of their application, for instance, urban planning models are built on a 1:2000 to 1:500 scale, individual buildings on a 1:200 to 1:50 scale, and details are shown ranging from 1:20 to 1:1 [12]. Different desktop- and VR-based user interfaces have been proposed to support exploration of digital 3D models at such scales. In IVE setups, downsized models are often used as 3D maps of the displayed VE, e. g., as insets [4], while users explore the model from an egocentric perspective at true scale. Hand-held models like the *Worlds in Miniature* (WIM) metaphor [28, 33] have been used to augment an immersive HMD view with a hand-held miniature copy of the VE. Other interfaces allow users to navigate through virtual models of nested scales, e. g., by magnifying a human body until users can see blood cells rushing through the veins [14].

Miniature models are also used in hands-free walking setups, for instance, the *Step WIM* [15], which allows users to walk through virtual environments at different scales by performing gestures with the feet. It has been shown that walking setups are superior to hand-based navigation in architectural scenes [29, 34]. Although Interrante et al. have shown that distance estimation and space cognition require virtual surroundings of real size [10], many IVE setups allow users to walk through arbitrarily scaled virtual models. *Real walking* through VEs can be supported simply by transferring the user's tracked head movements to identical camera positions and orientations in the virtual world [30]. As mentioned above, the drawback is that the movements are limited by the tracking sensor ranges and space restrictions of the user's physical surroundings.

Redirected walking [21] and reorientation techniques [20] make use of imperceptible manipulations – basically rotations and translations – applied to tracked head motion, which users subconsciously compensate by reorienting or repositioning themselves in the real world. The main objective is to redirected users imperceptibly such that they remain in a limited tracking space while a much larger virtual world can be explored by real walking. Therefore, different techniques have been proposed. The most basic approach is to scale translational movements, so that walked physical distances can be transferred to larger or shorter covered distances in the virtual world [31, 32]. Using this technique, unintended lateral shifts can be prevented by scaling only movements in the main walking direction [9]. Reorientation techniques imperceptibly rotate the displayed scene around the user's position in the virtual world. Most approaches require users to stand still or turn in the real world. When small rotations are applied in such a situation, the user can be reoriented, for example away from physical obstacles in walking direction, before they can continue to walk [13, 20, 21]. Other approaches apply rotations while users are walking [6, 21, 26]. As mentioned above, when users want to walk straight in the virtual world, small rotations of the virtual camera cause them to imperceptibly compensate for this manipulation by walking a circular arc in the opposite direction in the real world (see Figure 1).

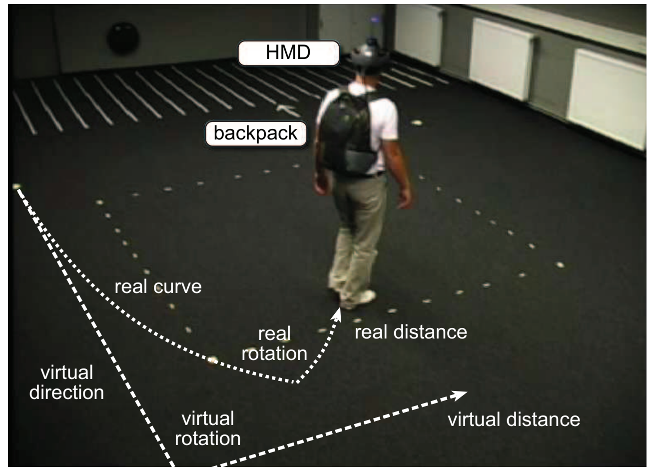


Figure 1: Illustration of redirected walking techniques (adapted from [24]): user walks in the real world a path that differs from the visually perceived path in the VE.

Steinicke et al. have presented a practical taxonomy of redirection functions [25], analyses of human sensitivity to these manipulations [24, 26], as well as a path prediction and mapping algorithm, which allows to guide users on paths in the real world that may differ from the walked paths in the VE [25]. Other work has focused on combining passive haptics [7] with redirected walking, so that users are redirected to proxy props in the real world that they can touch when they approach virtual objects [13, 25]. The main problem with these approaches is that a large VR laboratory setup of at least $50m \times 50m$ floor area is required in order to allow imperceptible manipulations [21, 24]. Peck et al. have proposed to use visual distractors [20], which distract users and hence allow stronger manipulations of the virtual world without them noticing. This approach, however, injects small moving objects into the virtual world that intendedly distract users. For this reason virtual distractors are unfeasible for professional architectural exploration.

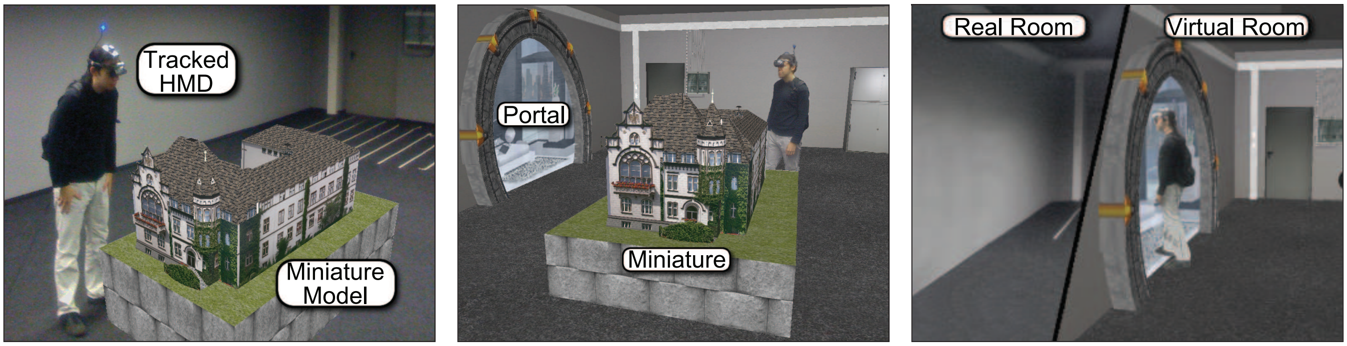
3 Arch-Explore User Interface

The Arch-Explore user interface combines two main approaches to architectural exploration in IVE setups:

1. Architectural 3D models are displayed as miniatures in a real walking setup, which allows architects and urban planners to examine them like physical block-models in the real world. We display the virtual model in a virtual replica room that resembles the physical laboratory environment. Since users are familiar with this environment – they see the laboratory before the VR experience starts – users can compare measures of the displayed models with real-world features, and distance estimation as well as space cognition is improved.

2. Real walking allows natural exploration of the interior of architectural designs at true scale. We overcome most of the aforementioned problems of real walking user interfaces by integrating redirection techniques for long-distance traveling.

Both strategies are combined using virtual portals to walk intuitively from the virtual replica room with the 3D architectural model into certain rooms of the model at true scale; users can return from the interior of the architectural model back to the virtual replica room at any time. In the following subsections we will first describe the virtual replica room as well as virtual portals. Afterwards, we will describe the real walking user interface for the exploration of the interior of 3D models.



(a) (b) (c)

Figure 2: Illustration of the immersive architectural exploration environment: (a) A user views a digital miniature building model in an HMD setup; (b) a portal opens to a room in the architectural model. Image (c) illustrates walk distance compression, where a user reaches a wall in the displayed VE earlier than in the real world.

3.1 The Virtual Replica Room

We use a virtual replica room to support users in the Arch-Explore working environment for two reasons. First, the virtual replica room provides a known environment for the exploration of downsized architectural models as mentioned above. Second, it has been shown that the user's sense of presence increases when the VR experience starts in a virtual replica of the user's real environment [27].

Such a virtual replica room is modeled and textured to mirror the physical VR environment, i. e., the laboratory room. Users are in the VR laboratory when they are immersed in the IVE system, e. g., by wearing an HMD with markers or sensors for position and orientation tracking. Tracking systems allow to provide users with a view of the virtual replica room model from the same position and with the same orientation as in the real world, which leads to minimal disorientation and transition effects when immersing users in the IVE system [23, 27]. Furthermore, the virtual replica room allows users to calibrate the VR equipment, e. g., by adjusting the HMD and orientation sensor until the virtual replica room is correctly aligned with the physical surroundings. First-time users can familiarize themselves with the displayed VE and VR devices, for example, by walking to virtual walls and touching their real world counterparts.

Once the users are familiar with the virtual replica room, downsized architectural 3D models are displayed in the center of the room. Miniature models give an improved impression of the size and dimensions of architectural constructions, in particular in the context of their surroundings. The miniature models can be displayed with available neighborhood information on pedestals in the virtual room. Hence, users can walk around them and examine them from all sides like they would do with physical block-models. Besides the possibility to change the visual appearance of virtual block-models easily, users can move their head even into the displayed 3D model and view it from inside when using VR-based models instead of physical block-models. Figure 2(a) illustrates how virtual miniature models can be explored in a tracked HMD setup.

Interrante et al. have shown that distance estimation in virtual environments that are known from the real world, is better than distance estimation in unknown environments [10]. We assume that this effect is transitive, i. e., the users' familiarity with the measures of the virtual replica room model may lead to a better understanding of the measures of the architectural miniature models displayed therein.

3.2 Virtual Portals

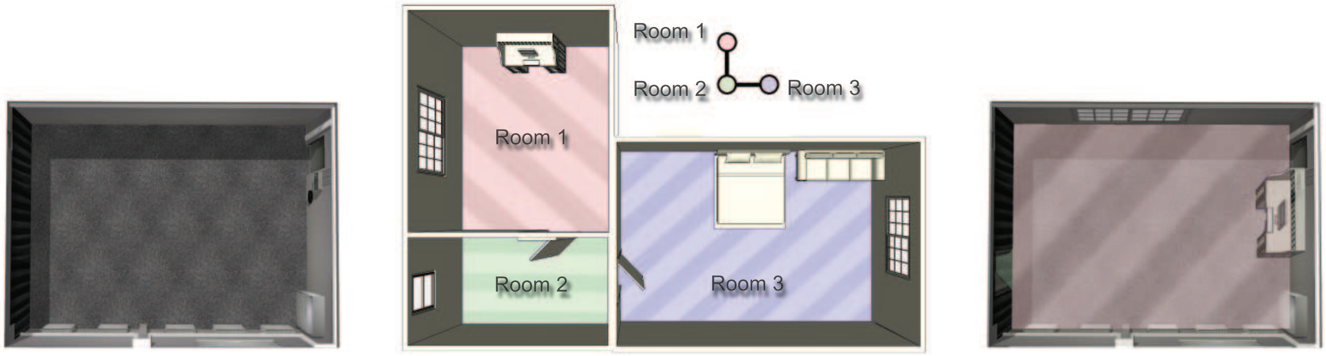
Virtual portals are three-dimensional doorways that connect one virtual location with another and can be entered by users in order to get to that place and back. Besides connecting different locations in the same VE, portals can also provide doorways between different VEs. Such portals are used in conjunction with the virtual replica room as means for users to travel from the virtual replica room, which shows the downsized 3D model, to a place *within* that specific model (see Figure 2(b)). By walking through such a virtual portal or doorway, users can leave the virtual replica room and enter a previously selected room from the miniature model that was displayed in the center of the virtual replica model. Afterwards, the room can be explored at real scale of the architectural model. The transition between two rooms is intuitive, since users just walk from one room through a doorway into another room. The implementation of virtual portals is based on the intention to present the Arch-Explore virtual working space to users as a persistent and continuous world in order to minimize breaks in the users' subjective sense of "feeling present" [23]. Furthermore, virtual portals require real walking, which is the most natural way of traveling in the real world.

We equip users of the Arch-Explore user interface with a *Nintendo Wiimote* controller, which they can use to choose a location in the displayed miniature model. After selecting a room, a virtual portal appears on one wall of the virtual replica room. By walking through the virtual portal users can enter the selected room and view it at true-scale. Figure 2(b) shows a user that has opened a portal on a wall of the virtual replica room, which shows a view to a room in the displayed miniature model. As mentioned above, by walking through that portal the user can walk into the selected room.

Once users have walked through the frame of the portal, they are in a room in the architectural 3D model. In order to allow a realistic exploration of these rooms, we fade out the just crossed portal behind users after a few seconds. When users want to get back to the virtual replica room, they can again use the Wiimote controller, e. g., by pressing the 'Home' button, and a virtual portal appears. By walking through the portal users can get back to the virtual replica room.

Motion Compression

Visualizing portals on walls of the virtual replica room raises one practical concern: Since the walls in the virtual room model are aligned with the walls in the real-world laboratory, users cannot simply walk through a visualized doorway on one of the walls, because they would collide with the physical wall. To overcome this



(a) (b) (c)

Figure 3: Schematics illustrating the segmentation and fitting process: (a) top-down view of the tracked VR laboratory space, (b) segmentation of a simple virtual building model into three rooms and (c) fitting of the coordinates of Room 1 by a clockwise 90° rotation to the VR laboratory coordinate system.

limitation, we make use of walk distance compression [26]. Sensitivity analyses have shown that users are incapable of detecting differences between walked physical and virtual distances, when the virtual translations are decreased or increased by up to 22% compared to the real world [24]. We adapted these findings to scale user movements that are directed towards a portal on one of the walls of the virtual replica room.

When portals are opened, we ensure that they are opened on the wall of the virtual room model farthest from the user's current position. Hence, when we scale the users' walked distance in the virtual replica room towards the wall with the portal, e. g., by the factor 1.22, they reach the virtual wall earlier than the corresponding real world wall. By injecting such slight deviations between traveled physical and virtual distances, users can imperceptibly be manipulated, so that they can walk through a portal in one of the virtual walls without colliding with a wall in the real world. Figure 2(c) illustrates the effect of this walk distance compression. In the virtual world the user reaches the portal, but in the physical world the user is almost in the center of the room.

3.3 Real Walking Indoor Exploration

Real walking IVE setups allow users to explore architectural indoor scenes like they do in the real world. By mapping tracked positions and orientations of the user in real-time, users get the impression of walking through a virtual world. In case of a one-to-one mapping, this allows users to explore a room-sized VE (see Section 3.1). However, even with scalings of one-to-n, i. e., one meter in the real world results in a translation of n meters in the VE (see Section 3.2), the explorable virtual space is limited, since the topology of virtual and real room are usually different. Redirected walking in theory provides the means to overcome this limitation and enable exploration of large-scale VEs. The main problem with this technique, however, is that the physical walking area has to be larger than typical room-sized VR setups (about $50m \times 50m$ [21, 24]). The Arch-Explore user interface allows exploration of large-scale 3D models even in typical VR laboratory environments by using global knowledge about architectural models and integration of adapted redirected walking techniques.

In the following subsections we describe the segmentation and fitting process, which allows users to explore arbitrary virtual rooms or room-sized volumes in 3D building models naturally. We describe the redirected walking techniques, which allow users to walk from one virtual room to another.

3.3.1 Virtual Room Segmentation

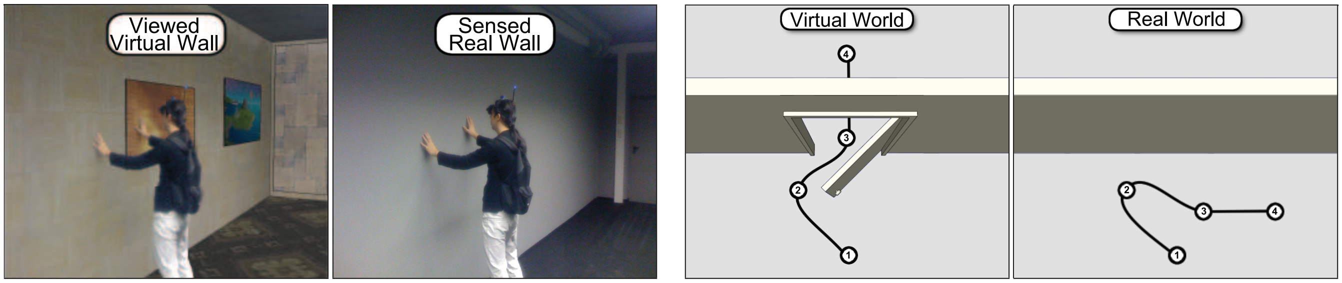
In most practical cases, the measures of 3D building models exceed the available size of the tracked working volume in the VR laboratory. In order to allow exploration of these virtual models, we divide them into smaller coherent volumes of space. In this paper we describe in detail virtual rooms, which are connected via virtual doors, however, the proposed techniques are not limited to this case.

Currently, we identify rooms and doors in architectural models manually. Although this is possible in reasonable time, this process can be automated. Segmentation of architectural interiors is standard practice in computer graphics to speed up rendering by occlusion trees. The *cells-and-portals* partitioning scheme is one example for space partitioning approaches [18]. With this technique 3D models are divided into coherent polyhedral volumes called "cells", which can only be "seen" or accessed from adjacent cells through openings in cell boundaries called "portals". Various cells-and-portals algorithms exist that can be used to automatically subdivide virtual building models into room-sized cells (cf. [16, 19]). Figure 3(b) illustrates the segmentation of a simple three-room building.

3.3.2 Virtual Room Fitting

As described in Section 3.1, the virtual replica room can be explored intuitively by real walking in the VR laboratory. The users' physical tracking positions are mapped to the corresponding identical positions in the virtual model, which allows users to walk to walls in the virtual replica room and touch their physical counterparts. This is not always possible with rooms in arbitrary building models (Figure 4(a) and (b)). Their shape as well as their size may differ from the (usually rectangular) VR laboratory space. The process we refer to as "fitting" derives mappings from the shape and size of the physical tracking space and coordinate system to that of virtual rooms. Since it is desirable for users to get passive haptic feedback when touching a virtual wall, this fitting enables us to align at least some virtual and physical walls such that when the users walk towards a virtual wall we redirect them to a real-world wall. This also enables exploration of virtual rooms larger than the physical laboratory by using small or non-perceivable manipulations.

As described in Section 3.2, small discrepancies between traveled physical and virtual distances cannot be detected by users. *Translation gains* are used to describe those manipulations of virtual camera translations [25]. Assume that $T_{real} = P_{cur} - P_{pre}$ defines the translation between the current user position P_{cur} and the



(a) (b) (c) (d)

Figure 4: In (a) and (b) the user gets passive haptic feedback about a virtual wall by touching a real-world wall. In (c) a typical path is shown that users follow when they walk through a swing door from one room into another in the virtual world. The example in (d) shows how much the walked path in the real world can deviate from the virtual path (c) when redirection techniques are applied.

previous user position P_{pre} as detected by the tracking system. Translation gains g_T are defined as the ratio between virtual and physical translations, i. e., $g_T := \frac{T_{virtual}}{T_{real}}$, with $T_{virtual}$ the virtual and T_{real} the physical translation. Experimentally validated thresholds show that virtual translations can unnoticeably be scaled by up to +/-22% compared to the real world [24]. This means that a physical position change of one meter should be mapped to a virtual translation in the interval $I_T := [0.78m, 1.22m]$.

Let $(x_r, y_r, z_r) \in \mathbb{R}^3_+$ denote the VR laboratory room size in meters and $(x_v, y_v, z_v) \in \mathbb{R}^3_+$ the size of the minimal non-axis-oriented bounding box of an arbitrary virtual room. For our purposes the y-height of the virtual and physical room can be neglected, which means that gain factors are only needed for the xz-ground plane. If the virtual room is larger than the physical laboratory, the users' movements are upscaled to cover the entire virtual room. If the virtual room is smaller, real-world movements are compressed when mapped to the VE. Differences between physical and virtual walk distances cannot be perceived in case the ratio between the virtual and real room size complies with $\frac{x_v}{x_r} \in I_T$ and $\frac{z_v}{z_r} \in I_T$, respectively with $\frac{x_v}{z_r} \in I_T$ and $\frac{z_v}{x_r} \in I_T$ if the virtual room has been fitted by a 90° rotation to the VR laboratory coordinate system.

This simple fitting strategy allows exploration of most virtual rooms in a typical room-sized VR laboratory with passive haptic feedback for at least some virtual walls. However, in some cases virtual rooms are too small or too large to be reasonably explored in the limited VR lab space. In case the virtual rooms are too small to be explored using the entire physical lab space, we combine them with adjacent virtual rooms to form larger cells. If the virtual rooms are much larger than the VR laboratory, we either subdivide the virtual rooms into smaller cells or apply higher translation gains. Although this results in noticeable manipulations, users can still explore rooms in a natural way. According to previous findings, translation gains up to $g_T = 2.0$ are still not considered as overly distracting by users [26].

The described fitting process can be performed automatically at run time. Figures 3(c), 4(a) and 4(b) illustrate how a virtual room of a different size can be explored from within a VR laboratory room.

3.3.3 Virtual Doors

As described above, 3D building models can be segmented into separate rooms, and users can explore them by real walking. Virtual doors and openings enable users to walk over from one virtual room into another. Again the practical problem shows that virtual doors are located in virtual walls, of which some are aligned with walls in the real world to provide passive haptic feedback. Hence, users have to be reoriented when they approach a virtual door. To reorient users away from a physical wall, we make use of *curvature gains* [25]. These gains exploit the fact that when users walk straight ahead in the virtual world, iterative injections of reasonably small camera rotations to one side force them to walk along a curve in the opposite direction in the real world in order to stay on a straight path in the VE (cf. Section 2). Curvature gains $g_C \in \mathbb{R}$ define the ratio between translations and applied virtual scene rotations, i. e., they describe the bending of the users' walk path in the real world. The bending is determined by a segment of a circle with radius r, as illustrated in Figure 5. Curvature gains are defined as $g_C := 1/r$, with $g_C = 0$ if $r = \infty$.

If the injected manipulations are reasonably small, users will unknowingly compensate for the virtual rotations and walk along a curved path. Curvature gains $g_C \in [0, 0.045]$ are considered imperceptible for users [24]; curvature gains up to $g_C = 0.64$ are noticeable, but still not overly distracting [26].

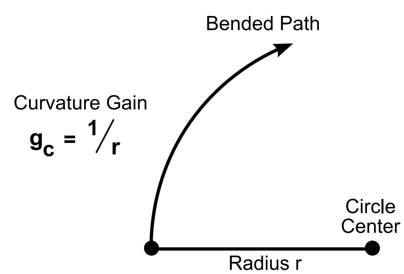


Figure 5: Curvature gains and path bending.

In case users walk a curved rather than a straight path in the VE, *rotation gains* are applied [25]. Those gains describe the ratio between physical and virtual rotations. When the tracking system detects a change of the user's orientation in the real world, the corresponding rotation angles (yaw, pitch, roll) can be scaled when transferred to the VE. Rotation gains $g_R \in \mathbb{R}$ define these mappings, i. e., the scaling from a physical rotation angle R_{real} to a virtual angle $R_{virtual}$, by the quotient $g_R = \frac{R_{virtual}}{R_{real}}$ with $R \in \{yaw, pitch, roll\}$. Rotation gains are used to scale rotations while users are standing or walking. If rotation gains are applied while a user is walking, the bending of the path in the virtual world differs from that of the corresponding path in the real world. If the applied gains for yaw rotations are in $g_R \in [0.59, 1.1]$, they are considered natural by users [24]. For instance, if users turn by 45° in the VE they can imperceptibly be manipulated to turn 69% or 31° more in the real world.

Path Prediction

In order to walk from one virtual room to another, users have to pass a virtual door. These come in various shapes, and usually they leave only a narrow opening for users to pass through. Since users are aware that some virtual walls have physical counterparts, they are likely to maneuver carefully through these doors. This enables sufficiently accurate prediction of the paths users take to enter adjacent rooms.

Path guidance techniques for redirected walking allow us to map such a predicted virtual path to a different path along which users move in the real world [25]. When rotating the virtual camera slightly while users are walking and/or turning as described above, they compensate for these scene rotations by counter-rotations of their bodies, which makes it possible to bend physically walked paths. Figure 4(c) illustrates a path through a virtual swing door and 4(d) shows the bended path in the real world, which avoids collision with a physical wall. Path guidance allows to compute paths with minimal noticeable manipulations.

Seamless Transitions

The previously described path manipulations enable users to walk from one virtual room into another while being reoriented, so that they do not collide with obstacles or leave the physical tracking space. When walking through virtual doors users usually have to be reoriented by about 90° or 180° in the real world so that their orientation suits the virtual room fitting process described in Section 3.3.2. Once users have walked through a virtual door, the coordinate system of the previous virtual room is changed to the fitted coordinate system of the new room with respect to the users' current position. Thus, the users can explore the new virtual room without further reorientations until they leave the room again through another door.

3.3.4 Virtual Portal Shortcuts

In Section 3.2 virtual portals were introduced as means for users to travel between the virtual replica room and rooms in 3D building models. Virtual portals can also be used to walk from one virtual building model room to another. Such "shortcuts" are useful, since these virtual rooms do not have to be adjacent to each other, which allows users to cover long distances in the VE. Virtual portals between two virtual rooms are implemented just like portals to the virtual replica room, as described above. Currently, the Wiimote controller allows users to open virtual portals to all rooms of the building model. Since users can take a look through open portals into the room on the other side, they can toggle through the rooms of the building model until they have found their intended destination. The other option is to open a portal to the virtual replica room and use the downsized building model displayed therein to choose the virtual portal's destination.

3.4 Architectural Characteristics

In the previous sections virtual building models were segmented into virtual rooms, which are connected via virtual doors. These doors serve as transition regions, where users can be reoriented considerably. In general, architectural models do not have to consist of virtual rooms and doors in order to be explored using the Arch-Explore user interface. The presented concepts can be adapted for other architectural entities with different characteristics as well. In these cases, 3D models are segmented into arbitrary volumes of space, which are divided by regions that suit the reorientation process described in Section 3.3.3. All regions in architectural models that allow sufficient prediction of the paths users take in order to walk from one part of the 3D model to another can be used to redirect users. These regions can be analyzed for their quality, i. e., the likeliness that users might detect the applied redirected walking manipulations. This allows a segmentation of architectural models, which is based on a trade-off between the size of separated virtual volumes and the perceptibility of reorientations at the transition regions. Hence, the virtual volumes can be explored by real walking in the limited VR laboratory space, just like the virtual rooms described above. The transition regions are used to reorient users when they are about to walk out of the tracked lab space.

The fitting process in Section 3.3.2 allows to register virtual with real-world walls, and users get passive haptic feedback when they touch displayed walls. This is widely applicable, since partition walls can be set up in VR laboratories in case the tracking space does not cover the entire laboratory room. Kohli et al. have shown that visual and haptic feedback about surfaces may differ without users perceiving inconsistencies [13]. This is not limited to real-world walls. If the physical lab space contains proxy props [25], i. e., typical architectural indoor objects like door frames and tables, virtual 3D models can be segmented into adapted virtual volumes and fitted in the laboratory space to register these real with virtual objects of similar haptic characteristics.

Hence, architectural characteristics can be used to adapt the concepts described above for different 3D model structures, as well as to enhance the user's VR experience by incorporating compelling passive haptic feedback. However, those implementations depend highly on anticipation or knowledge of typical structures in the specific application field.

4 Implementation

The current implementation of the Arch-Explore user interface is based on an inexpensive real walking HMD setup and a city visualization and urban planning application developed at the Department of Computer Science at the University of Münster.

4.1 Hardware Setup

Users are equipped with a lightweight eMagin 3DVisor Z800 HMD, which has a resolution of 800×600 and a diagonal field of view of 40° at a refresh rate of 60 Hz. We attach an infrared LED to the HMD, which is tracked with sub-millimeter precision and sub-centimeter accuracy at 60 Hz by the optical WorldViz Precision Position Tracker. The position tracking volume covers the whole VR laboratory, which has a size of $9m \times 7m \times 2.5m$. In order to track the user's head orientation, we attach an InterSense InertiaCube2 tracker to the HMD, which provides full 360° tracking range along each axis in space at 180 Hz. We use a Nintendo Wiimote controller for hand-based input as described in Section 3.2. In order to reduce the user's perception of the real world, we can attach an opaque cloth as view blocker to the HMD and stream sound files of recorded city noise over wireless AKG Hearo surround sound headphones.

An Intel computer (host) with dual-core processor, 4 GB of main memory and an nVidia GeForce 8800 GTX graphics card is used for system control and logging. Our software usually maintains a frame rate between 30 and 60 frames per second. Rendering is either done on the Intel host computer, which is then directly connected via cables to the HMD and Intersense, or on a laptop PC which is put into a user's backpack. In the latter case the laptop is connected via wireless LAN to the host computer. The scene is rendered with a GeForce 7700 Go graphics card on the laptop and battery power for about one hour. The weight of the backpack is about 8 kg, which is quite heavy, but compensated by the fact that users do not sense the cables and no assistant has to walk beside them.

4.2 Virtual Environment

We implemented the Arch-Explore user interface using the *Münster in 3D* city visualization and urban planning software, which was developed in cooperation with the "Amt für Stadtentwicklung, Stadt-

Figure 6: Interior view of the city hall of Münster.

planung, Verkehrsplanung" of the City of Münster. Figure 6 shows a typical interior view. The OpenGL-based application allows to render more than $120,000$ buildings, which are generated from real-world cadastral basis data. This enables us to display virtual building models in the context of their surroundings in the virtual replica room as described in Section 3.1. Furthermore, users can take a look out of windows when walking through a building model at true scale and see the streets and buildings in the neighborhood.

5 Conclusions and Future Work

In this paper we have presented the concepts and implementation of the Arch-Explore user interface for exploration of architectural 3D models. With Arch-Explore users can explore virtual building models as downsized miniatures and at true scale by real walking, which suits not only professionals like urban planners and architects, but also potential house buyers. We overcome certain problems of real walking user interfaces by implementing redirected walking, introduced by Razzaque et al. [21], and virtual portals for long-distance traveling. Users can explore large-scale virtual building models by real walking in a typical "room-sized" VR laboratory setup, which is enabled by adapting redirection techniques for architectural indoor environments. Furthermore, the Arch-Explore user interface registers physical with virtual walls, which allows users to get passive haptic feedback when "touching" some walls in the virtual world. Virtual doors and portals enable intuitive navigation and seamless transitions between rooms in large virtual building models while remaining in a comparably small physical space. We propose a virtual replica model of the VR laboratory room to aid the immersion of users in the Arch-Explore virtual working environment and as familiar surroundings for exploration of downsized virtual building models.

Although we have not yet conducted a full-scale user study to compare the Arch-Explore user interface to other architectural exploration systems, we have logged subjective comments of test users in the development cycle. One typical user comment was:

"When I went from [...] to [...], I was redirected, right?"

All users were aware of the means, by which Arch-Explore works. However, we did not provide much detail, so that most users reported a "feeling" of being manipulated at some point in the test, but could not confirm or repeat that. Fewer subjects noticed manipulations when they were engaged in a task, and no one weighted these as overly distracting.

Some users acknowledged the ability to touch virtual walls as a great feature, others were surprised when they felt a real wall in front of them as they deliberately tried to walk through a wall in the VE. We believe that the ability to touch virtual walls increases the users' level of feeling present in the displayed building model. However, others might see it as a restriction not to be able to walk through virtual walls.

In the future we will conduct a user study with architects and city planners in which we compare the Arch-Explore user interface to different IVE and desktop-based systems. We will use the results to design the next stage in the incremental design process of this user interface.

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