Augmented Virtual Studio for Architectural Exploration

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Abstract—**Immersive virtual environments and natural 3D user interfaces have shown great potential in the field of architecture, especially for exploration, presentation and review of designs. In this paper we propose an augmented virtual studio environment for architectural exploration based on a mixed-reality head-mounted display environment. The proposed system supports (1) real walking through large virtual building models, (2) visual feedback about the user's body and (3) display of real-world objects in the virtual view based on color transfer functions. We describe the locomotion user interface for immersive exploration, as well as a mixed-reality 3D user interface for interaction with virtual designs.**

Keywords-3D user interfaces; virtual environments; mixed reality; architectural exploration; redirected walking

I. INTRODUCTION

Immersive virtual environments (IVEs) provide a versatile platform for communication and exchange of architectural design proposals, and show great potential to improve exploration and design of architectural models over traditional and analog media. Immersive exploration of three-dimensional architectural scenes provides architects, clients and decision makers with an excellent spatial impression of a planned construction. In head-tracked head-mounted display (HMD) setups or immersive projection environments, such as CAVEs, users can explore virtual scenes from a realistic point of view with freedom of movement, allowing users to explore models at real scale by walking [23, 36] or flying [4] through the virtual space. Though real walking is considered the most intuitive and basic exploration metaphor, which allows natural exploration of virtual models, the user's movements are restricted by the range of tracking sensors as well as physical obstacles in the laboratory environment. To account for the limited interaction space, various locomotion interfaces have been proposed that enable unrestricted walking in virtual environments (VEs), while compensating and limiting the user's displacement in the real world, e. g., walking in-place [9, 20], locomotion simulators [14] and omni-directional treadmills [25]. Despite the technological achievements of those interfaces, real walking is still considered more natural, which is closely related to the user's sense of feeling *present* in the VE [31].
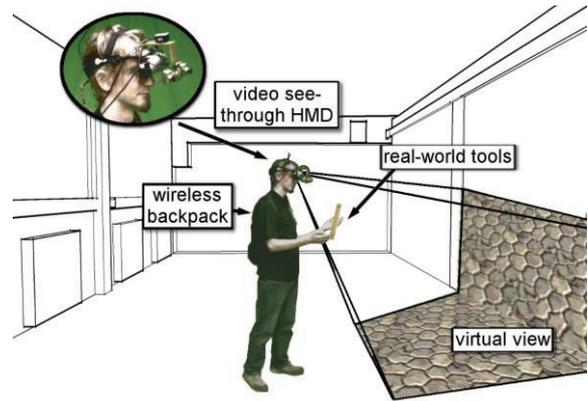

Figure 1. Illustration of the virtual studio environment: The frustum on the right illustrates the user's view of a virtual scene, while the video see-through HMD captures real-world tools and objects, which are displayed in the mixed-reality view on the HMD; the left inset shows a modified eMagin Z800 HMD with attached cameras and sensors.

Cognition and perception research provides us with a different approach to allow unrestricted walking, not based on hardware devices, but rather on psychological studies stating that a human's visual sense usually dominates proprioception and vestibular sensation in case the senses disagree [3]. Razzaque et al. [20] proposed a virtual motion manipulation technique for real walking environments, showing that visual domination can be exploited in IVEs to *guide* users on different walking paths in the real world than they visually experience, e. g., a user can be visually influenced to walk a circular path in the real world, while walking a straight path in the VE. Different extensions of this approach have been proposed [8, 28], providing system designers with redirection and manipulation techniques, and sensory thresholds for imperceptible manipulations. Though research shows that redirected walking works in virtual reality (VR) laboratories that offer a large walking area (approximately 50m×50m [28]), in smaller laboratories usually multiple techniques have to be combined [19, 28], or information about the virtual scene structure has to be exploited. In previous work we showed that architectural building models can be subdivided into regions, which can be separately explored by real walking in the laboratory

space, whereas imperceptible redirection (adapted to features of architectural models) provides the means to walk from one region in the VE to another [5]. This effectively allows users to explore large buildings room by room. Successive exploration of rooms—or room-sized spaces—has the advantage of limiting reorientation spatially to doorways or similar features in architectural scenes.

When users are immersed into a virtual world by wearing a HMD, real world information is blocked out by the HMD, and users do not perceive visual stimuli from their physical surroundings. As a consequence, a user cannot see her hands and body, or other physical objects. Mixed reality approaches, e. g., based on optical- or video see-through HMDs, provide means to augment or combine information from the real and virtual world. Between virtual and augmented reality in the mixed reality continuum [18] the term *augmented virtuality* refers to primarily virtual spaces that are augmented with real objects. One example of such environments is given by virtual video conferencing systems [24], in which cameras capture real-time views of users and display them in a VE. *Virtual studios* provide a similar approach. Using color-based (usually blue- or green-screen) background segmentation in the camera images [11], all areas of the images that show the specific color can be replaced by a rendered view to a virtual scene. Such virtual studios are primarily used for movies or TV productions in order to display real actors in virtual or remote environments, whereas the actors are not immersed in the displayed virtual scene [33]. Virtual studios are also applied for VR-based training applications that require users to be able to see their own body and real-world equipment [7] in a video see-through HMD setup (see Fig. 1).

In this paper we present an augmented virtual studio environment, which incorporates real walking, providing users with a platform for natural immersive exploration and augmented visual feedback from the real world. The remainder of this paper is structured as follows. Section II gives an overview of related work. Section III describes the augmented virtual studio. Section IV concludes the paper and gives an overview of future work.

II. RELATED WORK

Virtual studios are used in movies and television for seamless combination of computer-generated imagery with actors or real-world objects. In modern television studios position and orientation of the camera can be tracked and used to adapt the perspective of a virtual camera to that of the real-world camera. The rendered image from the virtual camera and the captured image from the real-world camera can be processed and combined in real-time to a final image, which provides a consistent viewing experience for the observer. In virtual studios discrimination between those parts of the images that should show the real world and those showing the VE is accomplished via a color keying approach such as *chroma keying* [34]. Therefore, it is required that the background of the studio is uniformly colored, e. g., painted in green or blue, and that lights provide diffuse

illumination. Thus all areas within the real-world view masked with the specific color of the background can be replaced with the corresponding virtual scene. Assuming a VR laboratory with a uniform (or nearly uniform, cf. [6]) background, this allows to augment video see-through HMDs in real-time with digital data, similar to the approach used in television studios. For instance, the uniformly colored background in the camera images can be replaced with the view to a virtual world, allowing a user to see her body in a virtual world when she looks down. Besides displaying the user's body, such studios allow to display arbitrary objects from the real world mixed in the view of a virtual scene. Until now, virtual studios have been primarily applied in military training [2, 7, 15, 17], where users are required to be able to see their own body and equipment in virtual training environments.

For immersive exploration it is essential for users to be able to explore large virtual scenes in the VR laboratory. As described in Section I, direct implementations of real walking in IVEs are limited by the size of the VR laboratory or tracking range. To provide users with a larger exploration range in the VE than the real walking space in the laboratory permits, Interrante et al. [13] developed the *seven league boots* metaphor, which modifies the mapping of traveled distances between the real and virtual world, and up-scales the traveled distances in the intended walking direction in the VE. Thus users can explore a larger virtual space in a VR laboratory. However, this technique does not allow unrestricted walking. *Redirected walking* [20, 28] denotes a technique, which is based on slow rotations of the virtual scene around the user, which are imperceptibly compensated, and which result in the user walking circular paths in the laboratory. Though redirected walking in theory allows unrestricted exploration of virtual scenes, in typical VR laboratories the technique is applicable only with limitations. This is due to the fact that the necessary intensity of manipulations scales with the room size, resulting in perceptible and in times distracting manipulations in case of a small laboratory. To account for this limitation, Peck et al. [19] evaluated reorientation techniques that are based on the approach to integrate graphical or auditive instructions or "distractors" into the virtual scene, to make users turn away from obstacles in the real world, before they can continue walking in the intended direction in the virtual world, i. e., resulting in a stop-and-go walking style.

To allow exploration of large architectural scenes in the limited space of a typical VR laboratory, we proposed the *Arch-Explore* [5] user interface, which incorporates different redirected walking techniques [20, 28]. Therefore, virtual scenes are manually or automatically subdivided into regions of the size of the VR laboratory, which can be explored by real walking, whereas the user is turned around in the real world when she tries to walk from one virtual region into another, e. g., when she walks through a door from one room into another. For the work reported in this paper we implemented the Arch-Explore user interface in our virtual studio environment, and adapted the interface to the newly introduced aspect of visual feedback from the real world.

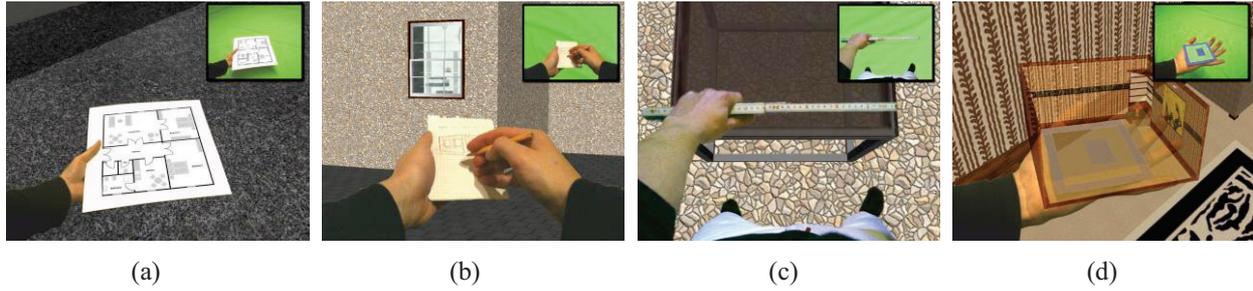(a)   (b)   (c)   (d)

Figure 2.   Augmented virtuality environment: (a) user reading a floor plan while being immersed in the virtual model, (b) user taking notes on a sheet of paper, (c) user measuring the size of virtual objects using a real-world ruler, and (d) hand-held marker used to display a *worlds in miniature* model of the user's virtual surroundings. Insets show the real-world view.

III.   AUGMENTED VIRTUAL STUDIO

In this section we describe the virtual studio environment, in which we combine two approaches:

1. Augmentation of a user's virtual view with real-world feedback using a video see-through system. We display elements of the real world in the view of the virtual scene, which are classified and segmented using color transfer functions. Since this enables users to perceive physical components in virtual scenes, users can compare virtual objects' measures using references from the real world. Previous research motivates that real-world feedback can enhance distance estimation in architectural scenes, spatial cognition and the user's sense of feeling present in the displayed VE.

2. Real walking allows users to explore virtual architectural scenes similar to real-world constructions. We make use of information about the structure of the virtual scene, specifically to detect coherent spaces that can be explored in the limited laboratory space, and incorporate redirection to enable users to explore large-scale VEs by walking. We adapted the visual augmentation system to account for region information from the redirected walking implementation.

In the following subsections we describe the augmented virtuality system for mixed real and virtual feedback; then we describe optical marker-based interaction and go into detail on the real walking implementation.

A.   Augmented Virtual Views

As illustrated in Fig. 1 and 2, a video see-through HMD, which captures in real-time images of the real world in the user's view direction, allows to display parts of these images as insets in the user's view of a virtual scene. In such augmented virtuality setups the virtual view is updated with respect to the tracked position and orientation of the HMD, such that the virtual and real views are aligned. The HMD, cameras and sensors can be attached to a laptop in the user's backpack, which can be used for rendering of a virtual scene, and exchange of tracking data with outside-in tracking systems using wireless LAN. On the laptop the camera images and rendered virtual frames can be mixed in real time. Therefore, the camera images can be segmented using color transfer functions, such that certain real-world objects can be displayed, whereas others can be hidden from the user.

To combine real and virtual views in real time, virtual studios make use of color-keying approaches, which allow to classify pixels (x, y), $0 \leq x < width$, $0 \leq y < height$ of the camera images according to provided color information into background and foreground. Using color transfer functions we can specify (depending on the color space) the mapping of colors to intensity values $r_{xy} \epsilon [0,1]$, which we define as the likelihood that the pixel belongs to the foreground. In case we choose the HSV color space, the transfer function assumes the form $f{:}[0,1]^3 \rightarrow [0,1]$, $f(h,s,v) = r$. Usually transfer functions can be evaluated separately (or sequentially) for the input dimensions without losing much of expressiveness. These functions can be precomputed for a given step size and stored in lookup tables, which allows intuitive specification and efficient computation on graphics hardware. After this initial step, we sum the computed intensity values for each pixel (x_0, y_0) in a 5×5 neighborhood and assign the pixel to the foreground if and only if the sum exceeds a certain threshold $\tau \geq 0$: $\sum_{x=x_0-2}^{x_0+2} \sum_{y=y_0-2}^{y_0+2} r_{xy} > \tau$

Fig. 3 shows the effects of applying a color transfer function using the hue value of the HSV space to classify pixels. The foreground with the user's hand and floor plan in the real-world view is significantly different from the uniform green background, such that the foreground pixels can be segmented and displayed in the user's view of a virtual scene.
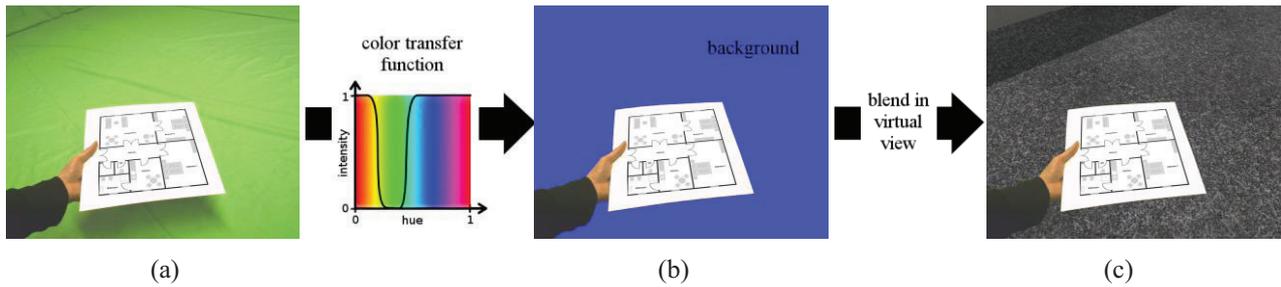
Figure 3.   Illustration of the color transfer process: (a) shows the real-world view, (b) the segmented image after applying the color transfer function, and (c) shows the mixed-reality view displayed to the user.

Color-based segmentation works effectively as long as the colors of foreground and background objects can be distinguished, which usually requires the background to have a uniform color. Previous work [6] showed that color-based classification and segmentation of certain real-world objects can be accomplished even in typical VR laboratories. However, in the following we assume the background to be colored significantly different from all foreground objects, i. e., we assume the laboratory to be colored uniformly in green or blue. This allows us to simplify discrimination of foreground and background pixels and provides us with freedom to apply color-keying for the differentiation of certain foreground objects.

1)   Visual Body Feedback: The cameras of the video see-through HMD capture the real world in accordance to the position and orientation of the virtual view. Hence, the user is able to look down at her body in the real world and see a spatially stable representation of herself in the virtual world displayed on the HMD (see Fig. 2 (c)). Recent studies motivate that the ability to see one's own body can enhance the user's sense of presence [6] and performance in distance judgment tasks [22], which are both essential for architectural exploration. In contrast to full-body motion tracking systems, which usually require the user to wear a motion capture suit and only provide a generic virtual avatar, virtual studios allow to display the user's actual body in a VE.

As illustrated in Fig. 2, architects, clients or visitors immersed in architectural scenes may use a variety of real-world tools, such as notepads and pencils to take notes, rulers and tape to measure distances, or the like. This provides users with affordances that are similar to those during exploration of architectural constructions in the real world. Real-world objects can be displayed to the user, as long as they do not have the same color as the surroundings, i. e., it would be impossible to see green ink on a notepad if the color used for the background is green. Fig. 2 lists typical uses of real-world tools during immersion in architectural scenes.

2)   Selective Augmentation: In some situations it is reasonable that the user may not want to use real-world objects directly, such as using a hand-held ruler to measure distances, but rather indirectly as spatially stationary elements. For instance, a user may place objects in the interaction space to mark locations of objects. Such stationary objects are normally only intended to be used in a single room or region of a virtual construction, whereas displaying those objects at all times to the user may reduce the user's ability to get an unconfined impression of other regions of the architectural model. Since virtual models are usually much larger than the interaction space in the VR laboratory, use of such stationary objects should not limit the ability of the user to explore the model. Therefore, since one affordance of the color transfer functions described above is to enable successive use of more than one function, we can enable or disable use of certain color transfer functions, which results in conditional visual feedback of the corresponding color-keyed objects. For some real-world objects it makes sense to hide them entirely from the user's view if she explores a different region of an architectural model, however, for larger obstacles we suggest displaying them semi-transparent. Fig. 4 illustrates use of a color transfer function to display or hide real-world objects from the user's view, displaying only those markers that are relevant for the current region of the architectural model.
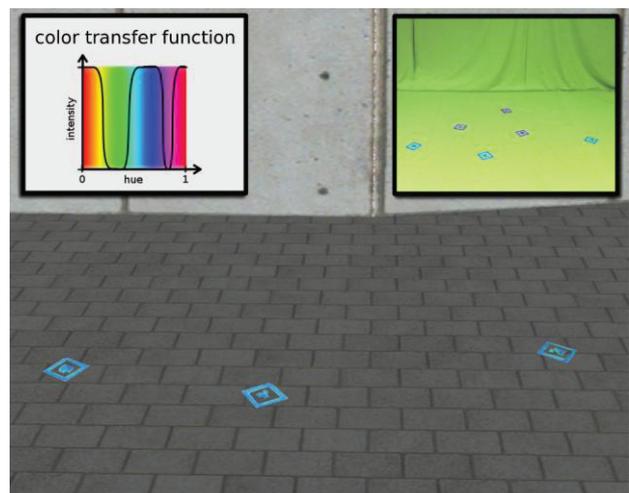

Figure 4.   Selective display of real objects: The right inset shows the real-world view, and the left inset the applied color transfer function, whereas the main image shows the resulting mixed-reality view displaying the blue, but not the purple markers.

B. Interaction

Besides mixing real and virtual views, video see-through HMDs also afford well-established optical marker tracking. Using image-based tracking software, such as ARToolKit Professional [1], position and orientation of markers can be tracked. This results in a two-step tracking system: While the absolute position and orientation of the HMD is tracked in the virtual studio (usually with an outside-in tracking system), ARToolKit supplies the relative position and orientation of markers as captured from the HMD-mounted cameras.

ARToolKit markers are usually colored in black and white, however, it is as well possible to use markers colored in two different colors. For instance, if the background of the virtual studio is colored in green, then the markers can be adapted to this color, leaving one color that can be used to distinguish different markers. Fig. 4 illustrates selective display of markers in blue (and green) or purple (and green) using color transfer functions.

For detected markers we compute the absolute position and orientation, i. e., we map the relative to absolute coordinates in the VR laboratory, and map those to the corresponding coordinates in the currently explored region of the architectural model. Using such markers, assigned and aligned three-dimensional models can be positioned in architectural scenes (see Fig. 4 (d)). This allows users to experience an architectural model from an ego-centric perspective in the virtual studio, while being able to arrange components in the environment via ARToolKit markers. For instance, this allows users to furnish rooms of a virtual building model using ARToolKit markers. Since we can selectively display or hide color-keyed ARToolKit markers from the user's view, this allows to display markers only in a specific region of a virtual model, providing users with consistent and persistent use of markers.

In addition, we evaluate attaching ARToolKit markers to physical tools, which allows to track their position and orientation, and can be used for tool-specific interaction metaphors within the VE. Tracking position and orientation of physical objects, such as the floor plan shown in Fig. 2 (a), allows to augment this information, which shows potential to support architectural exploration and design. We further evaluate using ARToolKit markers to provide users with a *worlds in miniature* (WIM) [30, 37] view of segmented parts of a virtual scene as illustrated in Fig. 2 (d). Miniature models play an important role in architectural design. Architects and urban planners use physical or digital miniature models of various scales, e. g., 1 : 2000 to 1 : 500 for urban planning models, and 1 : 200 to 1 : 50 for buildings, with details shown in 1 : 20 to 1 : 1 [16]. During immersive exploration of virtual architectural constructions at one-to-one scale such miniature models provide additional views to the environment from the outside, which not only provide users with a three-dimensional map of the surroundings, but also support generation of a mental map of the environment.

C. Region-based Redirection

Usually real walking setups apply a one-to-one mapping from the (tracking) coordinates of the VR laboratory to those of a virtual scene, which provides a user with a close to life exploration metaphor for a limited interaction space. In order to provide a larger virtual interaction space and motivated by psychological studies in IVEs, stating that users tend to underestimate traveled distances in VEs [10], some IVEs up-scale translational movements, so that walked distances in the real world result in larger displacements in the VE [13, 35], i. e., a one-to-n mapping, with $n > 1$ meters displacement for each meter in the real world. However, in order for users to perceive a spatially stable mixed reality view, it is necessary to revert to a one-to-one mapping in the virtual studio environment. Furthermore, it is not possible to apply redirected walking as proposed by Razzaque et al. [21], since continuous manipulation of the virtual scene would be easily perceptible by users by comparing real and virtual motions in the mixed reality view.

As a solution, we subdivide large architectural models into regions of approximately the size of the VR laboratory, which can be explored using a one-to-one mapping, whereas we apply redirected walking when the user is about to walk from one region into another, and we restrict visual feedback from stationary real-world objects (cf. Sec. III A. and III B.) to situations when no redirection is applied.

1) Regions: Using a naive subdivision scheme, we would segment the virtual world into a regular raster of spaces of the size of the VR laboratory. However, since this approach often produces real walking areas that are too small, or spaces blocked by obstacles, we enhanced this approach by using information about the architectural scene. Therefore, we segment architectural models into spatially enclosed regions—usually rooms—which we then subdivide into smaller regions of the size of the VR laboratory if necessary. Following this approach, users have to be redirected when they leave one room and enter another, but they do not have to be manipulated during exploration of a room—with the exception of very large rooms. We believe that this approach applies redirection in the right situations, supporting the notion of traveling between rooms.

2) Redirection: As described in the Arch-Explore user interface [5], architectural features can be exploited for redirection. For instance, if a user walks through a narrow gap between two rooms, such as a door, redirection is often less perceivable than during straight walking. Consequently, we identify passages that connect segmented regions and initiate rotations of the virtual scene around the user. To account for different types of passages and architectural conditions, we represent passages by circles or rectangles—so-called redirection zones—and apply redirection such that the user performs a 180° turn in the real world gradually between the time she enters and leaves the zone. When the user enters one
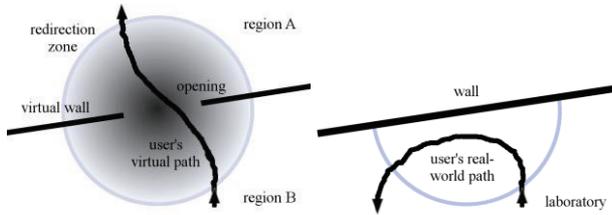
Figure 5. Illustration of a circular redirection zone: The left image shows a user's virtual path and the right her real-world path. The color gradient on the left illustrates gradual scene rotations around the user due to applied redirection manipulations.

of those zones and proceeds to walk through to the other side, we slowly rotate the virtual scene around the user, which she compensates by turning around in the real world. Fig. 5 illustrates this redirection scheme. The perceptibility of the applied manipulations depends on the types of passages and attention of the user, however, informal studies motivate that even when users perceive the manipulations, those gradual changes were preferred over stop-and-go reorientation techniques [36]. When users enter a redirection zone, we disable color transfer functions, i. e., we display the virtual world exclusively. Since redirection zones are of limited and controllable size, we believe that this method is applicable.

D. Virtual Portals

Inspired from TV series and movies, for instance, MGM's *Stargate*, but also 3D games such as the first-person action video game *Portal*, we incorporated the concept of virtual portals (introduced in [5]). 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 openings between different VEs, such as concurring design proposals for architectural constructions. In the context of the virtual studio environment we primarily use portals as a means for users to travel from one region into another. Such "shortcuts" are useful, since those regions do not have to be adjacent to each other, which allows users to cover long distances in the VE.

Virtual portals between two virtual regions are implemented consistently with the interaction concept described in Sec. III B.: With ARToolKit markers users can specify portals from one region to another. The surface of an opened portal remains bumpy until the user specifies the target region with a second ARToolKit marker (illustrated in Fig. 6). After that, users can take a look through open portals into the region on the other side, and get to that place by walking through the portal's frame. Via virtual portals users can walk between arbitrary regions as if they were adjacent to each other.

The transition between two rooms is intuitive, since users just walk from one room through a doorway into another room. Another reason for the usage of virtual portals is based on the intention to present the virtual studio's working space to users as a persistent and continuous world in order to minimize breaks in the users' subjective sense of presence [26]. Furthermore, virtual portals require real walking, which is the most natural way of traveling in the real world and supports the notion of getting to another place. Recent experiments have shown that virtual portals can enhance the user's sense of presence [27], and enable users to transfer space perception skills from one environment to another, since the portals preserve spatial coherence between the two environments [29].

Besides the affordance to enter different virtual regions through a portal, we can also use portals as interactive *magic lenses* [32]. For instance, users can switch between and compare various architectural models with different appearances. A portal object can also be attached to an ARToolKit marker, such as used for the world in miniature in Fig. 2 (d). Thus the user can move and view through the frame of the portal the world behind the portal. As illustrated in Fig. 6 (b), this can be used to review different design options.

Each graphical portal object consists of a frame and a surface (see Fig. 6 (a)). The surface defines the area the user has to pass. In order to ensure that portal objects can be placed in arbitrary models and at arbitrary positions in space we use the following multipass rendering technique.

LISTING I.   RENDERING OF VIRTUAL PORTALS.

```
glEnable(GL_DEPTH_TEST);
glEnable(GL_STENCIL_TEST);

glClearStencil(0x0);
glClear(GL_DEPTH_BUFFER_BIT|GL_STENCIL_BUFFER_BIT);

glStencilFunc(GL_ALWAYS,0x1,0xFFFFFFFF);
glStencilOp(GL_REPLACE,GL_REPLACE,GL_REPLACE);
glColorMask(GL_FALSE,GL_FALSE,GL_FALSE,GL_FALSE);
glDepthMask(GL_FALSE);

// load position and orientation of portal
glLoadMatrix(portalMVM);
renderPortalSurface();

glColorMask(GL_TRUE,GL_TRUE,GL_TRUE,GL_TRUE);
glDepthMask(GL_TRUE);
glStencilOp(GL_KEEP,GL_KEEP,GL_KEEP);
glStencilFunc(GL_EQUAL,0x1,0xFFFFFFFF);

// plane equation derived from portal orientation
glEnable(GL_CLIP_PLANE0);
glClipPlane(GL_CLIP_PLANE0, peq);

renderPortalTargetEnvironment();

glDisable(GL_CLIP_PLANE0);
glDisable(GL_STENCIL_TEST);
glClear(GL_DEPTH_BUFFER_BIT);

glLoadMatrix(portalMVM);
renderPortalFrame();

glColorMask(GL_FALSE,GL_FALSE,GL_FALSE,GL_FALSE);
glLoadMatrix(portalMVM);
renderPortalSurface();

glColorMask(GL_TRUE,GL_TRUE,GL_TRUE,GL_TRUE);
renderCurrentEnvironment();
```

Figure 6. Virtual portals: (a) graphical objects consist of frame and surface, and provide a doorway to another region in architectural models; (b) portals can link different design proposals or be used as a magic lense.

Listing I shows the pseudo-code for the rendering process of virtual portals. First, the depth and the stencil buffer are cleared. Then, the fragments where the surface of the portal will appear are marked in the stencil buffer. The virtual scene, which is behind the portal is rendered from the current viewpoint into those fragments, and a clipping plane is defined such that no object of the portal's target environment appears in front of the portal. Afterwards, stencil tests are disabled and the depth buffer is cleared. We render the portal frame in the color and depth buffer, and the portal surface in the depth buffer. Hence, afterwards, when we render the user's current environment in front of the portal, only those fragments pass the depth test, which are in front of the portal or belong to the non-masked areas of the stencil buffer. Using this rendering process, users can walk around in the virtual scene and view the world behind the portal through the surface of the portal.

In order to provide users with a consistent mixed-reality view, we segment the real-world view twice, once applying the color transfer function corresponding to the region shown in the portal, and once for the region in front. Then, we mix the fragments showing the target environment in the portal with the segmented view of the corresponding region, whereas we mix the remaining pixels with the segmented real-world view of the user's currently explored region.

IV. CONCLUSION AND FUTURE WORK

In this paper we described an intuitive mixed-reality setup and user interface for immersive architectural exploration and design. We described how redirected walking in architectural scenes can be implemented in the virtual studio environment, and how virtual portals provide a means for long-distance travel, as well as a versatile conceptual metaphor for mixed-reality visualization and interaction. In the described mixed-reality environment, real objects and ARToolKit markers can be used to interact with architectural models, whereas color transfer functions allow selective display of real-world elements in the view of a virtual scene.

In a pilot study we evaluated the user interface for a simple home design task, in which users had to explore and furnish a simple virtual building model. Early results suggest that the proposed 3D user interface is intuitive to use and has potential to foster usage of VR technologies in the domain of architectural design. In the future we will pursue 3D interaction more deeply, providing designers and architects with versatile 3D menus and virtual design tools, as well as tracked physical tools [12] for users to interact with a virtual model. Moreover, since current research does not provide a solution to the problem of manipulating the virtual and real view in the mixed-reality continuum consistently, we will further pursue this aspect, aimed at providing a spatially stable view during mixed-reality redirected walking.

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