The Holodeck Construction Manual

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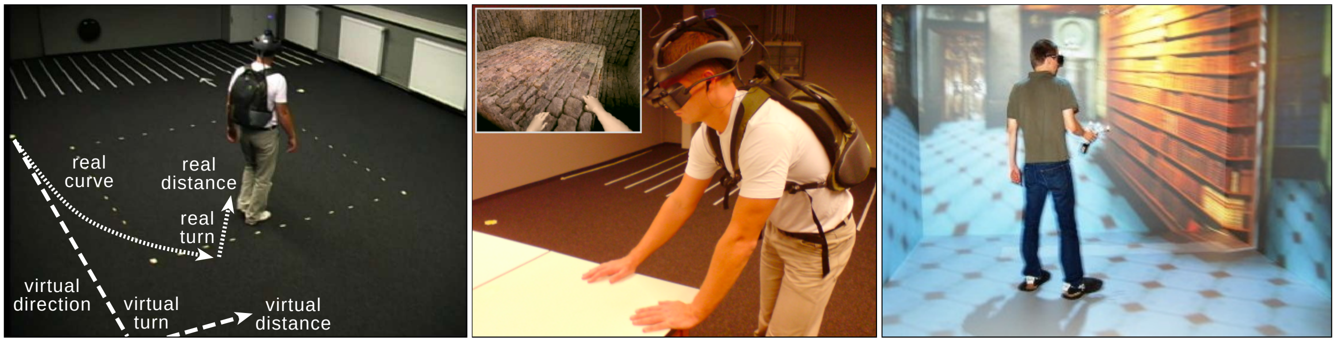

Figure 1: Concepts of the virtual holodeck: (left) a user walking through the tracked interaction space on a different path than the visually perceived counterpart, (middle) a user touching a real proxy object (the user's view is displayed as inset), and (right) a user in a six-wall CAVE in which a virtual room is displayed (by courtesy of CGV of TU Graz).

1 Introduction

Immersive virtual reality (VR) systems allow users to interact in virtual environments (VEs), where presence is limited to the virtual world; the physical surrounding cannot be perceived. Movie as well as scientific literature have reported about several of these interfaces that enhance presence of users in a VE, for example, the holodeck on the U.S. enterprise. Some of these immersive environments inspired researchers to provide at least a notion of an *ultimate display*, where the user cannot tell real from virtual [Sutherland 1965]. As shown in Figure 1 (right) in a six-wall CAVE the user is located in a cube on which sides stereoscopic content is projected from the back [Cruz-Neira et al. 1992]. Tracking of the user's movements can be performed from outside, for example, by infrared-based approaches [Vorozcovs et al. 2005]. The most intuitive way of moving through such a scenario as well as through our real world is to perform *real walking*. Unfortunately, those setups provide only a limited interaction space in contrast to the potentially infinity VE. However, omnidirectional walking along arbitrary distance is essential for presence in VEs. Therefore, virtual locomotion interfaces are needed that support walking over large distances in the virtual world, while physically remaining within a relatively small space [Usoh et al. 1999]. Many hardware-based approaches have been presented to address this issue [Bouguila et al. 2002; Bouguila and Sato 2002]. Unfortunately, most of them are very costly, while providing only a single user a notion of walking, and thus will probably not get beyond a prototype stage.

In this paper we suggest a different approach based on perceptive psychology exploiting that the human's visual sense may vary from the proprioceptive and vestibular senses without the person noticing a discrepancy. Hence it get possible to direct the user on a physical path which may differ from the perceived path in the virtual environment. For instance, if the user wants to walk straight ahead for a long distance in the virtual world, small rotations of the camera *redirect* her/him to walk unconsciously in circles in the real world. If the induced rotations are small enough, the user gets the impression of walking in the virtual world in any direction without restrictions [Razzaque 2005; Jerald et al. 2008]. In contrast to [Razzaque 2005] we have extended *redirected walking* concepts by combining motion compression, which scales the real distance users walk, rotation compression and gains, which make the real turns smaller or larger, and curvature gains, which bend the user's walking direction such that s/he walks on a curve (see Figure 1 (left)). Furthermore we introduce the new concept of *dynamic passive haptics* which extends passive haptics [Insko et al. 2001; Kohli et al. 2005] in such a way that *any number* of virtual objects can be sensed by means of real *proxy objects* having similar haptic capabilities, i. e., size, shape and surface structure see. Dynamic passive haptics provides the user with the illusion of interacting with a desired virtual object by redirecting him/her to the corresponding proxy object (see Figure 1 (middle)). The mapping from virtual to real objects is not constrained to one-to-one. Since the mapping can be changed dynamically during runtime, a small number of proxy objects suffices to represent a much larger number of virtual objects. Based on these strategies we present a construction manual for a virtual holodeck, where users can walk omnidirectional and touch any objects in the VE by means of touching an associated proxy object.

2 Pilot Study and Implications

We have performed a pilot study in order to quantify how far the appearance of the virtual world may deviate from that of the real environment without the user noticing the difference, i. e., how visual perception dominates proprioceptive and vestibular cues [Burns et al. 2005]. A total of 8 (7 male and 1 female) subjects participated in the study. The users' paths always lead them clockwise or counterclockwise around a table which is represented as virtual block in the VE (see Figure 1 (middle)). The participants were equipped with a HMD backpack consisting of a laptop PC with a GeForce 7700 Go graphics card and battery power for at least 60

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minutes (see Figure 1 (left and middle)). We used the WorldViz Precise Position Tracker.

In order to support *generic* redirected walking concepts as well as *dynamic* passive haptic strategies, we have modulated the real and the virtual environment by means of the following independent variables:

- **Rotation compression/gain factor** s_{rot} describes the compressing/streching of a user's head rotations, i. e., when the user rotates the head by α degrees the virtual camera is rotated by $s_{rot} \cdot \alpha$ degrees.
- **Amount of curvature** s_{cur} denotes the bending of a real path. While the user moves the camera rotates continuously enforcing the user to walk along a curve determined by a segment of a circle with radius r, where $s_{cur} := \frac{1}{r}$. The curve is considered for a normalized distance of $\frac{\pi}{2}m$. In the case that no curvature is applied $r = \infty$ and $s_{cur} = 0$.
- **Motion compression/gain factor** s_{mot} denotes the scaling of translational movements, i. e., 1 unit of physical motion is mapped to s_{mot} units of camera movement in the same direction.
- **Object compression/gain factor** s_{obj} denotes a uniform scaling transformation applied to virtual objects or the entire VE.

We have used the above variables in our experiments and have evaluated how they can be modified without the user noticing any changes. Detailed information about the experiment can be found in [Steinicke et al. 2008a]. Based on the results we are able to introduce thresholds which allow sufficient redirection such that the user neither perceives redirected walking nor dynamic scaling of objects. We formulate the following guidelines:

1. Rotations can be compressed/gained up to 30%,
2. distances can be downscaled to 15% and upscaled to 45%,
3. users can be redirected such that they unknowingly walk on a circle with a radius up to $3.3m$,
4. objects/VE can be up-/downscaled up to 40%.

Indeed, perception is a subjective matter but with these guidelines only a reasonably small number of walks or objects are perceived as manipulated. Based on these guidelines we can determine how much space the physical environment must provide such that users can walk on a circle without recognizing. Furthermore, a shift of direction has to be supported such that a collision with the physical setup is prevented.

3 Setup Requirements

Regarding Guideline 2 (see Section 2) users can physically walk on circle with radius $3.3m$ when visually perceiving a straight distance. In this case users usually do not observe discrepancies between proprioceptive or vestibular senses and the visual sense. Hence a CAVE with a diagonal of approximately $7m$ including an additional security area is sufficient to enable virtually straight waking, but shifts in directions are constrained in such a scenario. In oder to enable an almost omnidirectional walking without the user observing discrepancies between movements in the physical world and mappings to the virtual camera, we suggest to provide an additional space around the circle by extending the radius by a factor of three. According to a prototype setup such an area provides sufficient space for redirection concepts and support for passive haptics. With corresponding path prediction approaches and concepts for the transformation of virtual paths to real counterparts and vice versa, the user can be guided through the CAVE such that collisions with a reasonably number of physical obstacles can be prevented [Steinicke et al. 2008b]. However, if the user towards a physical obstacle rigorous rotations can be performed according to Guideline 1. Furthermore, the user's movements can be accelerated or arrested with respect to Guideline 3.

Consequently, a virtual holodeck must contain the following components. As illustrated in Figure 2 it requires a six wall CAVE with passive stereoscopic back-projection and six passive back-projection walls which maintain polarization for stereoscopic display. Each wall should measure at least $20 \times 2.5m$.. The entire cube must be built such that a projection from each sides gets possible. One wall must be portable or provide a door such that user can enter the virtual holodeck. Tracking the user's movement can be done optically by means of outside-in tracking as described in [Vorozcovs et al. 2005]. Hence no cameras are located within the holodeck. With increasing numbers of active markers which project IR light to the walls the number of required tracking cameras can be reduced. At least six cameras capturing the walls from outside are required to provide precision tracking data. In such a setup at least one user is able to move through the VE by means of omnidirectional walking.

In the case of a head-mounted-display environment with the same interaction space, but without projection on CAVE walls, even dynamic passive haptics can be provided. Regarding the number and variance of virtual objects in the VE, a certain number of proxy objects suffers to map all virtual objects. Considering a real box that measures $x \times y \times z$ units in the physical space according to Guideline 4 such a proxy object can be exploited to provide passive haptic feedback for boxes measuring $(\alpha \cdot x \times \beta \cdot y \times \gamma \cdot z)$ units, where $\alpha, \beta, \gamma \in [0.6, ..., 1.4]$. Thus, a single proxy object can even be used to provide passive haptic feedback for multiple virtual objects. Hence, in order to map arbitrary 2D boxes with edge lengths between x_{min} and x_{max}, it can be shown by structural induction that the number of required two-dimensional proxy boxes is given by $\frac{n \cdot (n+1)}{2}$ with $n = log_{\frac{7}{3}}(\frac{x_{max}}{x_{min}})$. In this case symmetry of boxes is considered since the user can be guided to the boxes from different directions. In order to support 3D boxes, i. e., boxes with different heights, symmetry cannot be exploited and the number of required boxes increases to $n \cdot \frac{n \cdot (n+1)}{2}$. Indeed, some real-world constraints such as the projection walls can be exploited to provide passive haptic feedback, for instance, for virtual objects such as walls of a virtual building. Hence the number of required proxy objects can be decreased.

When the user approaches a virtual object in the VE and it can be predicted reliably, the user has to be guided according to the Guidelines 1.–4. to the associated proxy object. Then, the user can touch the proxy object that is visually perceived with a different size, but the user cannot observe a discrepancy according to Guideline 4. A single proxy object can even be used to provide passive haptic feedback for multiple virtual objects. For example, as illustrated in Figure 2 the VE displayed to the user walking in the holodeck may consist of several chairs, tables and cubes which measure $[0.6, ..., 1.4]$ times the sizes of the physical proxy objects.

4 Conclusion

In this paper we have presented a construction manual for a virtual holodeck based on a pilot study and its implications. The challenge of natural traveling in limited tracking space has been resolved sufficiently by redirected walking approaches and dynamic passive

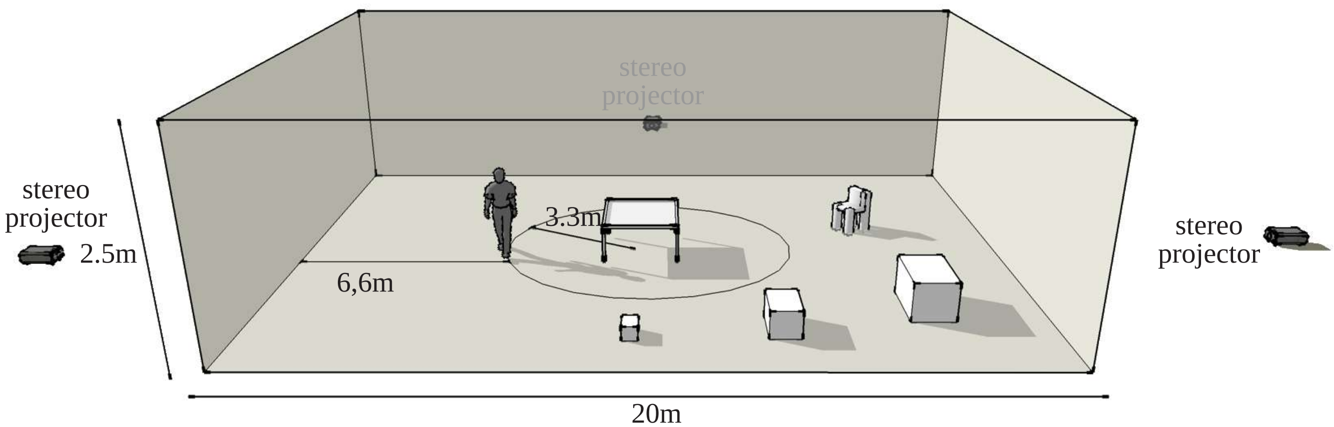

Figure 2: Illustration of the virtual holodeck: (a) a user walking through the holodeck on a circle and several objects are exploited as proxy objects in order to provide dynamic passive haptics.

feedback provides the user with the possibility to touch virtual objects respectively associated proxy objects. The setup is sufficient to enable at least a single user omnidirectional walking with passive haptic feedback. Even multiple users may interact in such an environment, but this has to conducted in further tests.

In the case of collisions which could not be prevented by redirection with respect to the guidelines presented in this paper, the concept of virtual distractors may be applied [Peck et al. 2008]. Such distractor objects should focus the user's attention enforcing him/her to perform a rigorous rotation. For example, a virtual clingone may attack the user which has to focus on the enemy while we rotate the virtual scene in the backgound. Consequently, the user is required to perform a rigorous rotation which enforce the user to walk towards away from the physical obstacle that has been in the user's previous direction.

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