

Moving Towards Generally Applicable Redirected Walking

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Walking is the most natural way of moving within a virtual environment (VE). Mapping the user's movement one-to-one to the real world clearly has the drawback that the limited range of the tracking sensors and a rather small working space in the real world restrict the users' interaction. In this paper we introduce concepts for virtual locomotion interfaces that support exploration of large-scale virtual environments by *redirected walking*. Based on the results of a user study we have quantified to which degree users can unknowingly be redirected in order to guide them through an arbitrarily sized VE in which virtual paths differ from the paths tracked in the real working space. We describe the concepts of generic redirected walking in detail and present implications that have been derived from the initially conducted user study. Furthermore we discuss example applications from different domains in order to point out the benefits of our approach.

Virtual Reality, Virtual Locomotion Interface, Generic Redirected Walking

1. Introduction

Walking is the most basic and intuitive way of moving within the real world. Taking advantage of such an active and dynamic ability to navigate through large-scale virtual environments (VEs) is of great interest for many 3D applications demanding locomotion, such as urban planning, tourism, 3D entertainment etc. Although these domains are inherently three-dimensional and their applications would benefit from exploration by means of real walking, VR-based user interfaces are often not supported.

In many existing VR systems, the user navigates with hand-based input devices in order to specify direction, speed as well as acceleration and deceleration of movements [25]. Although advanced visual simulation often requires a good sense of locomotion in order to increase the user's presence in the virtual world, most of these systems do not provide a real sense of walking. An obvious approach to enable users to explore a virtual world by real walking is to transfer the user's movements to corresponding movements in the VE by means of a simple one-to-one mapping. Apparently this technique has the drawback that the limited range of the tracking sensors and a rather small working space in the real world restricts the users' movements. Therefore, virtual locomotion interfaces are needed that support walking over large distances in the virtual world, while physically remaining within a relatively small space [23]. Many hardware-based approaches have been presented to address this issue [1][13][14]. Unfortunately, most of them are very costly and support only walking of a single user, and thus they will probably not get beyond a prototype stage. However, cognition and perception research

suggests that more cost-efficient alternatives exist. It is known since decades that visual perception usually dominates proprioceptive and vestibular senses [24]. If the visualization stimulates the user appropriately it should be possible to guide her/him along a path in the real world that differs from the path the user perceives in the virtual world. 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 being able to walk in the virtual world in any direction without restrictions.

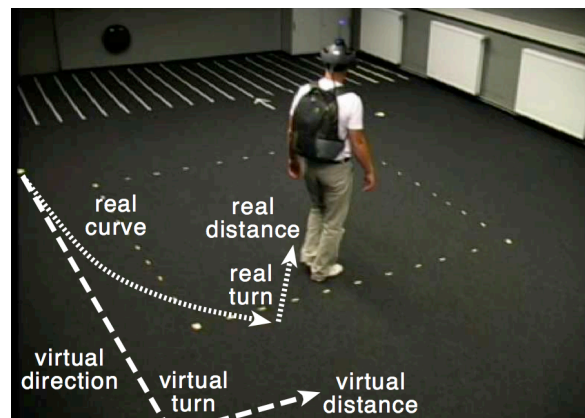


Figure 1 Virtual Locomotion Scenario: a user walks through the real environment on a different path with a different length in comparison to the perceived path in the virtual world.

In this paper we present an evaluation of redirected walking and derive implications for the design process of a virtual locomotion interface. For this evaluation we have extended current redirected

walking by *generic* aspects. We have extended the concepts described in [18] to curvatures as well as to motion compression. Furthermore, in contrast to previous approaches we have conducted a pilot user study to derive optimal parameterizations for these techniques. Virtual locomotion interfaces based on implications derived from our evaluation allow users to explore 3D environments by means of real walking in such a way that the user's presence is not disturbed by limited interaction space or physical objects present in the real environment. Our approach can be used easily in any fully-immersive VR-setup providing user tracking as well as stereoscopic projection, no special hardware is needed in order to support walking or haptics. For these reasons we believe that these techniques make immersive exploration of VEs more natural and thus ubiquitously available.

The remainder of this paper is structured as follows. Section 2 summarizes previous related work. In Section 3 we present a pilot study we have conducted in order to quantify to which degree users can be *redirected* without the user noticing the discrepancy. Based on the results of this study we discuss implications for the design of a virtual locomotion interface supporting *generic redirected walking* which is described in Section 4. Section 5 shows example applications and discusses the benefits of our approach for different domains. Section 6 concludes the paper and gives an overview about future work.

2. Previous Work

Currently locomotion and perception in virtual worlds are in the focus of many research groups. Early hardware-based technologies such as treadmills or similar devices allow users to walk through VEs [3]. Most of these approaches do not support omnidirectional walking, i.e., the user is not able to change the physical walking direction easily. Hence, various prototypes of interface devices for walking have been developed, including torus-shaped omnidirectional treadmills, motion footpads, and robot tiles [1][15][14][13]. All these systems have in common that they are very costly and hardly scalable since they support only walking of a single user. For multi-walker scenarios, it is necessary to instrument each user with a separate device. Moreover, most of the described technologies are only applicable to HMD setups, other systems such as CAVEs or curved projection walls are not supported. Although these hardware interface devices represent enormous technological achievements, most likely they will not get beyond a prototype stage in the foreseeable future. Hence there is great demand for alternative approaches.

As a solution to this challenge, traveling by exploiting walk-like gestures has been proposed in many different variants, giving the user the impression of walking, for example by walking-in-place, while physically remaining almost at the same position [12][23][21]. However, as a matter of fact real walking is a more presence-enhancing locomotion technique than any other navigation metaphor [23].

Redirected walking [18] is a promising solution to the problem of limited tracking space and the challenge of providing users with the ability to explore the VE by walking. With redirected walking, the virtual world is imperceptibly rotated around the center of the user's head. Thus, when the user explores the potentially infinite VE, s/he unknowingly walks along curved paths within the limited tracking area. This approach is also applied in robotics when controlling a remote robot by walking [6][22].

In our approach we have extended these redirection concepts by combining motion compression [22] respectively gain, i.e., scaling the real distance a user walks, rotation compression respectively gain, i.e., scaling the real turns, and different amounts of curvature, i.e., bending the user's walking direction such that s/he walks on a curve. The phenomenon that users do not recognize small differences between a path in the VE and a path in the real world is based on principles from perceptive psychology: Perception research has identified essential differences between cognition as well as estimation of features in VR in contrast to their counterparts in the virtual world [24].

For example, many researchers have described that distances in virtual worlds are underestimated in comparison to the real world [11][10]. Furthermore, it has been discovered that users have significant problems to orient themselves in virtual worlds [19]. In this context Burns et al. have investigated how visual perception can dominate over *proprioception* [4]. They have introduced a shift between the visual representation of the user's arm and its pose in the physical space; up to a certain degree users have not noticed this shift. This approach focuses on the user's arm and has not been applied to walking.

In summary, substantial efforts have been put in to allow a user to walk through a large-scale VE while presenting continuous passive haptic stimuli, but until now this challenge could not be addressed adequately.

3. Pilot Study for Generic Redirected Walking

As described in Section 1, in order to enhance the user's presence it is essential that s/he can walk through the entire scene without any constraints

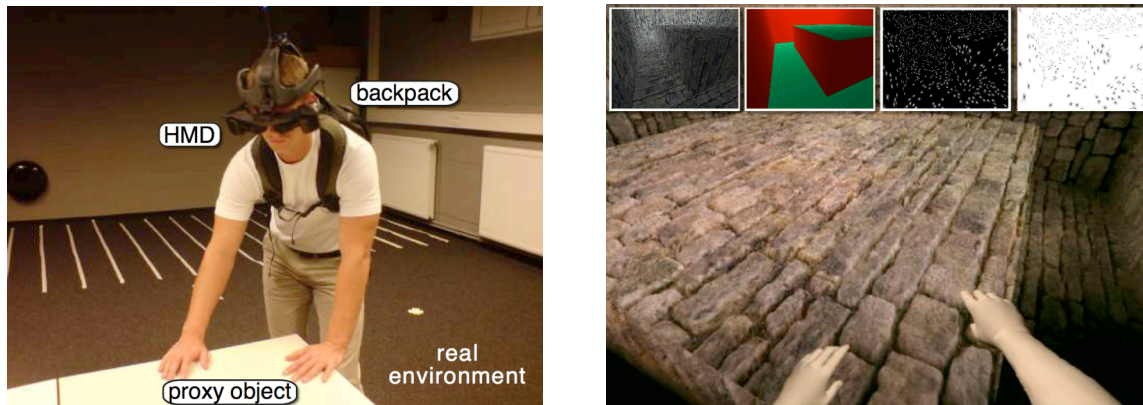


Figure 2. (left) the user touches a real proxy object of (right) the virtual object seen from the user's perspective. Alternative visualizations are displayed as insets: (from left to right) textured, Gouraud-shaded, textured with white circles on black surfaces, and vice versa.

enforced by limited tracking space and that s/he can touch obstacles presented in the virtual world. When using redirection concepts it has to be ensured that users are guided in such a way that they do not collide with objects of the physical environment or with each other. In this section we present a pilot study in which we determine preliminary limits and perceptual thresholds that indicate how much paths in both worlds can differ when redirecting users without letting users notice the difference.

3.1. Experimental Design

3.1.1. Test Scenario

In our experiments movements of the users are restricted to a $10 \times 7 \times 2.5 \text{ m}$ tracking range. In the center of a $6 \times 6 \text{ m}$ area we placed a square table of size $1.5 \times 1.5 \times 1 \text{ m}$. The user's path always leads him/her clockwise or counterclockwise around the table which is represented as virtual block in the VE (see Figure 3 (a) and 3 (b)).

As illustrated in Figure 3 the virtual room in which the user walks measures $x_1 \times y_1 \times z_1 \text{ m}$ and the square block in the center measures $x_2 \times y_2 \times z_2 \text{ m}$. The room and the block can be scaled uniformly. The visual representation of the virtual environment can be changed continuously between different levels of realism (see Figure 2 (right) (insets)). For example, we can apply different levels of *optical flow*, which gives indications about the motion of objects within a visual representation. In order to quantify how optical flow influences our concepts we apply textures to the surfaces of the virtual room which only contain small circles. The number, size and lifetime of the circles can be changed: many circles that do not disappear provide plenty of optical flow, whereas few circles with short lifetimes provide only little optical flow (see Figure 2 (right) (insets)).

3.1.2. Participants

A total of 8 (7 male and 1 female) subjects participated in the study. Three of them had experience with walking in VR environments using an HMD setup. We arranged them into three groups: 3 “*expert users*” (EU Group) who knew about the objectives and the procedure before the study, and 3 “*aware users*” (AU Group) who knew that we would manipulate them, but had no knowledge about how the manipulation would be performed. Subjects of both groups were asked to report if and how they realized any discrepancy between actions performed in the real world and the corresponding transfer in the virtual world. 2 “*naive users*” (NU Group) had no knowledge about the goals of the experiment and thought they had to report any kind of tracking problems. The entire experiment took over 1.5 hours (including pre-tests and post-questionnaires) for each participant.

3.1.3. Tasks

We have performed some preliminary interviews and tests with the participants in which we revealed their spatial cognition and body awareness by means of distance perception and orientation tests. For instance the users had to perform simple *distance estimation tests*: After reviewing several distances ranging from 3 to 10 m the subjects had to walk along blindfolded until they estimated that the distance seen before has been reached. Furthermore they had to rotate by specific angles ranging from 45° to 270° and rotate back blindfolded ten times. In both experiments we measured the differences between given and performed distances and rotations respectively. One objective of the study was to draw conclusions if and how body awareness may affect our virtual locomotion approach. We have performed the same tests before, during and after the experiments.

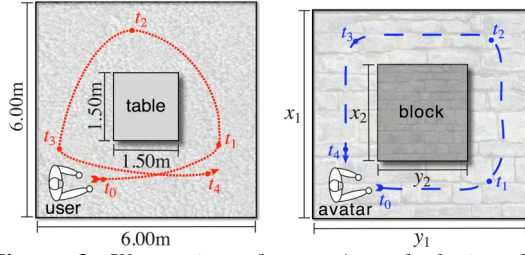


Figure 3. Illustration of a user's path during the experiment showing (left) path through the real setup and (right) virtual path through the VE and positions at different points in time t_0, \dots, t_4 .

In order to support generic redirected walking concepts we have modulated the real and the virtual environment by means of the following independent variables:

3.1.4. Independent Variables for Redirected Walking

- **Rotation compression/gain factor** s_{rot} describes the compression or gain 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 in order to stay on a straight path in the virtual world. The curve is determined by a segment of a circle with radius r , where $s_{cur} := 1/r$. The resulting curve is considered for a normalized distance of $\Pi / 2$ m. In the case that no curvature is applied $r = \infty$ and $s_{cur} = 0$ whereas if the curvature causes that the user has rotated by 90° clockwise after 1 meter the user has covered a quarter circle and $s_{cur} = 1$.
- **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. In contrast to [12] this mapping is applied to movements in any direction and not restricted to the intended walking direction.

We use the above variables in our generic redirected walking concepts, and we have evaluated how they can be modified without the user noticing any changes. The sequence and also the amount of change altered for each subject in order to reduce any falsification caused by learning effects. After a training period we used random series starting with different amounts of discrepancy between real and virtual world. We used a simple up-staircase design by slightly increasing the difference each 5 to 20 seconds *randomly* until subjects reported visual-

proprioceptive discrepancy - this meant that the perceptual threshold had been reached. Afterwards we performed further tests by altering the differences around the perceived threshold in order to verify the subjective values and to diminish potentially biased results. Indeed this simple methodological procedure has its limitation in terms of the validity of the derived thresholds, but indicates a first impression of a possible threshold. All variables were logged and comments were recorded in order to reveal in how far subjects perceive a difference between the virtual and the real world. The amount of difference is evaluated on a four-point Likert scale where (0) means no distortion, (1) means a slight, (2) a noticeable and (3) a strong perception of the discrepancy.

3.2. Setup

The tests were performed in a laboratory environment that provides the following technical infrastructure.

3.2.1. Visualization Hardware

In the experiments we used an Intel computer (host) with dual-core processors, 4 GB of main memory and an nVidia GeForce 8800 for system control and logging purposes. The participants were equipped with a HMD backpack consisting of a laptop PC (slave) with a GeForce 7700 Go graphics card and battery power for at least 60 minutes (see Figure 1). The scene was rendered using DirectX and our own software with which the system maintained a frame rate of 30 frames per second. The VE was displayed on two different head-mounted display (HMD) setups: (1) a ProView SR80 HMD with a resolution of 1240×1024 and a large diagonal optical field of view (FoV) of 80° , and (2) an eMagin Z800 HMD having a resolution of 800×600 with a smaller diagonal FoV of 45° . During the experiment the room was entirely darkened in order to reduce the user's perception of the real world.

3.2.2. Tracking System and Communication

We used the WorldViz Precise Position Tracker, an active optical tracking system that provides sub-millimeter precision and sub-centimeter accuracy. With our setup the position of up to eight active infrared markers can be tracked within an area of approximately $10 \times 7 \times 2.5$ m. The update rate of this tracking system is about 60 Hz, providing real-time positional data of the active markers. The positions of the markers are sent via wireless LAN to the laptop. For the evaluation we attached a marker to the HMD, but we also tracked hands and feet of the user. Since the HMD provides no orientation data, we used an Intersense InertiaCube2 orientation tracker that provides full 360° tracking range along each axis in space and achieves an update rate of 180 Hz. The InertiaCube2 is attached to the HMD and connected to the laptop in the backpack of the user.

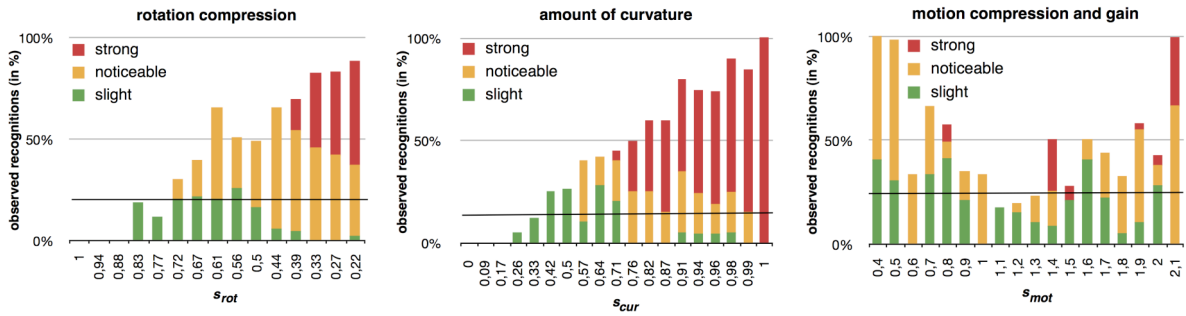


Figure 4. Evaluation of the generic redirected walking concepts for (a) rotation compression factors s_{rot} , (b) amount of curvature s_{cur} and (c) motion compression respectively gain factors s_{mot} . Different levels of perceived discrepancy are accumulated. The bars indicate how much users have perceived the manipulated walks. The EU, AU and NU groups are combined in the diagrams. The horizontal lines indicate the thresholds as described in Section 4.1.

All computers including the laptop on the back of the user are equipped with wireless LAN adapters. We used a dual-sided communication: data from the InertiaCube2 and the tracking system is sent to the host computer where the observer logs all streams and oversees the experiment. In order to apply generic redirected walking and dynamic passive haptic concepts, i.e., altering the variables explained in Section 3.1.4 the experimenter can send corresponding control inputs to the laptop. The entire weight of the backpack is about $8kg$ that is quite heavy. However, no wires disturb the immersion, no assistant must walk beside the user to keep an eye on the wires. Sensing the wires would give the participant a cue to orient physically, an issue we had to avoid in our study. The user and the experimenter communicated via a dual head set system only. In addition acoustic feedback within the virtual scene can be applied via the headset but was only used for ambient noise in the experiment such that an orientation by means of auditory feedback in the real world was not possible for the user.

3.3. Analyses of the Results

The results of our pilot study allow deriving appropriate parameterizations for generic redirected walking for typical VR setups as the one we used in the study. In Section 4 we present some guidelines for the usage of these techniques that have been derived from the results, which are discussed in detail within this section.

In Figure 4 the results have been summarized. In the Figure the number of walks that have been reported as manipulated are combined. The colors indicate how strong the manipulation has been perceived, i.e., slight, noticeable, strong.

3.3.1. Rotation Compression and Gain

We tested a total of 147 different rotation compression and gain factors for all participants.

Figure 4 (a) shows the corresponding factors applied to a 90° rotation. The bars show the amount as well as how strong turns were perceived as manipulated. The degree of perception has been classified into not perceivable, slightly perceivable, noticeable and strongly perceivable. It points out that when we scaled a 90° rotation down to 80° , which corresponds to a compression factor $s_{rot} = 0.88$, none of the participants realized the compression. Even with a compression factor $s_{rot} = 0.77$ subjects rarely (11%) recognized the discrepancy between the physical rotations and the corresponding camera rotations. If this factor is applied to physically rotate almost 30° more when they perform a 90° virtual rotation. The subjects adapted to rotation compression and gain factors very quickly and they perceived them as correctly mapped rotations. We performed a *virtual blindfolded turn test*. The subjects were asked to turn 135° in the virtual environment, where a rotation compression factor of $s_{rot} = 0.7$ had been applied, i.e., subjects had to turn physically about 190° in order to achieve the required virtual rotation. Afterwards they were asked to turn back to the initial position. When only a black image was displayed the participants rotated on average 148° back. This is a clear indication that the users sensed the compressed rotations close to a real 135° rotation and hence adapted well to the applied rotation compression factor.

3.3.2. Amount of Curvature

In total we tested 165 distances to which we applied different amounts of curvature as illustrated in Figure 4 (b). When s_{cur} satisfies $0 < s_{cur} < 0.17$ the curvature was not recognized by the subjects. Hence after $3m$ we were able to redirect subjects up to 15° left or right while they were walking on a segment of a circle with radius of approximately $6m$. As long as $s_{cur} < 0.33$, only 12% of the subjects perceived the difference between real and virtual paths.

Furthermore, we noticed that the more slowly participants walk the less they observed that they walked on a curve instead of a straight line. When they increased the speed they began to careen and realized the bending of the walked distance. This might be exploited by adjusting the amount of curvature with respect to the walking speed, but this issue has to be quantified in further studies.

One user who did not participate in this particular study recognized each time a curvature gain had been applied. Indeed the user supposed a manipulation even when no gain was used, but he identified each bending to the right as well as to the left immediately. The spatial cognition pre-tests showed that this user is ambidextrous in terms of hands as well as feet. However, the results for the evaluation of motion compression and gain as well as rotational gain factors show that his results fit into the findings of the other participants.

3.3.3. Motion Compression

We tested a total of 216 distances to which different motion compression and gain factors were applied (see Figure 4 (c)). As mentioned in Section 1 users tend to underestimate distances in VR environments. Consequently subjects underestimated the walk speed when a motion gain factor below 1.2 was applied. On the opposite, when a motion gain factor satisfied $s_{mot} > 1.6$ subjects recognized the scaled movements immediately. Between these thresholds some subjects overestimated the walk speed whereas others underestimated it. However, most subjects stated the usage of such a factor only as slight or noticeable. In particular, the more users tended to careen, the less they realized the application of a motion gain or compression factor. This may be due to the fact that when they move the head sideward the motion compression factor also applies to corresponding motion parallax phenomena. This may have the effect that users adapt more easily to the scaled motions. One could exploit this effect during the application of motion compression or gain factors when corresponding tracking events indicate a careening user.

For this experiment we also performed a *virtual blindfolded walk test*. All subjects were asked to walk 3m in the VE where motion compression and gain factors between 0.7 and 1.4 were applied. Afterwards they were asked to turn, review the walked distance and walk back to the initial position, while only a blank screen had been displayed again. Without any factors applied to the motion users walked back on average 2.7m. For each motion compression factor the participants walked too short which is a well-known effect because of the described underestimation of distances but also due to safety reasons, after each step participants are less oriented and thus tend to walk shorter so that they do not collide with any objects. However, on average they walked approx. 2.2m for a motion gain factor $s_{mot} =$

1.4, approx. 2.5m for $s_{mot} = 1.3$, approx. 2.6m for $s_{mot} = 1.2$, and approx. 2.7m for $s_{mot} = 0.8$ as well as for $s_{mot} = 0.9$. When the motion compression factor satisfied $0.8 < s_{mot} < 1.2$ users walked approximately 2.7m back on average. For these factors users adapted to the redirected walking concepts.

3.3.4. Further Observations

Although most participants had walked over 45 minutes using the HMD setup, only two participants had problems with cyber sickness. In order to determine if our camera manipulations caused the sickness we performed a post-test for these users two days later. Both participants got sick again although neither generic redirected walking nor dynamic passive haptics had been applied. Users reported problems in both HMD setups; the heavier ProView SR80 HMD tended to cause sickness faster than the eMagin Z800 HMD. Cyber sickness occurred after approximately 5-10 minutes with the ProView SR80 HMD, while using the eMagin Z800 HMD caused problems after approximately 15-20 minutes. In both cases both users reported problems after approximately the same time period regardless whether our concepts had been applied or not. Indeed cyber sickness is an important issue in VR but it is not further considered within the scope of this paper since it seems not to be caused by our concepts. However, this needs to be proven in a further study. Additionally, users felt uncomfortable due to the weight of the setup and the tightness under the HMD. However, they definitely preferred to wear a backpack than to take care about wires during walking.

The effect of different visual appearances had no significant influence on the evaluation. But in environments with only little optical flow subjects tended to realize redirected walking less than in environments with plenty of optical flow. Furthermore, objects could be scaled more in environments with only little optical flow while the users did not perceive the discrepancy. This can be exploited by delaying necessary rigorous manipulations until less optical flow is provided. A significant relation between spatial cognition and the ability to perceive redirected walking could not be derived from this study. The phenomenon of the user who reported each occurrence of curvature gains correctly (see Section 3.3.2) has to be studied in further experiments. There was no significant difference in the evaluation between the EU group, AU group or the NU group; even when we tested the experts, they hardly recognized the application of generic redirected walking. 3 users (2 from the NU group and 1 from the AU group) reported several jittering and latency effects during the tracking update process, but did not realize the application of redirected walking. We have verified this by showing them the VE where no manipulation has been applied

and they remark jittering and latency errors with the same amount. Due to the fact that these users were not familiar with VR-based technologies such reports are not unexpected since they were not aware of these typical VR-related issues.

4. Implications for Virtual Locomotion Interfaces

In this section we describe implications for the design of a virtual locomotion interface with respect to the results obtained from the pilot study described in Section 3. For typical VR setups we want to ensure that only reasonable situations cause the user to perceive a manipulation. As mentioned above the simple up-staircase design of the study involves drawbacks and we acknowledge these limitations such as potentially biased results. However, at least the pilot study gives indication about thresholds and limitations of generic redirected walking for the first time.

4.1. Virtual Locomotion Interface Guidelines

Based on the results from Section 3 we formulate some guidelines in order to allow sufficient redirection. These guidelines shall ensure that with respect to the experiment the appliance of redirected walking is perceived in less than 20% of all walks. The horizontal lines in Figure 4 show the threshold that we defined for each subtask in order to ensure the desired rate of recognized manipulations

- 1, Rotations can be compressed or 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,

Indeed, perception is a subjective matter but with these guidelines only a reasonably small number of walks from different users is perceived as manipulated.

4.2. Verification of the Guidelines

In a post-test two weeks later we have applied these guidelines to a simple test scenario where only a rectangular virtual room of variable size has been used. Four users (3 of them have not participated in the pilot study) were told to walk within this environment. An essential objective was to keep the user in the tracking area and to prevent collisions with physical objects that were not in the immediate vicinity of the user in the virtual world. When the user potentially left the tracking area, while virtually being located in the center of the room, we determined the angle of intersection between the user's path and the boundary of the tracking area.

Corresponding camera modifications were performed to redirect the user on a circle segment with respect to the guidelines 1-3 such that the user was guided away from the wall back into the interior of the room. Less than 15% of all redirected walks were perceived as manipulated when the guidelines 1-3 were satisfied. The application of object compression or gain factors was reported less than 5% for this scenario.

5. Example Applications

There is a rising demand for applications dealing with complex 3D datasets, which would benefit from the possibility to navigate naturally through the data. Most of these applications do not provide the required interfaces; even other VR-based technologies such as stereoscopic displays or tracking interfaces are usually not supported.

In this section we discuss the application of the concepts presented in this paper in two example applications from different domains, i.e., geospatial visualization and a collaborative 3D entertainment environment. Besides the testbed application we have integrated the virtual locomotion interface into 3D example applications. The integration is based on an extended 3D interceptor library similar to Chromium [8].

5.1. Google Earth

The widely used geographic visualization application Google Earth combines a search engine with satellite imagery, maps, terrain and 3D city models in order to collect and visualize geographic information. Several city and urban governments have supplied their data, or at least use Google Earth as visualization toolkit for their data. By now some city models include 3D buildings modeled up to a LoD 4, which corresponds to textured models of interiors (see Figure 5). Hence, the user is able to virtually navigate worldwide and to explore specific features and landmarks within urban environments. We have integrated our approaches in Google Earth, which enables users to explore a virtual model in a natural way (see Figure 5). When using our generic redirected walking concepts the user is able to perform infinite walking through 3D city models without space restrictions. In the context of tourism it becomes possible to explore a desired destination in a natural way.

5.2. Second Life

The popularity of Second Life has inspired us to discuss the proposed concepts in the context of this virtual world that is entirely built and owned by its residents. When using our concepts a user would be able to walk through the virtual world that is displayed in Second Life in the same way as walking through Google Earth.

Interaction concepts that might result from such a multi-user scenario would allow users to interact

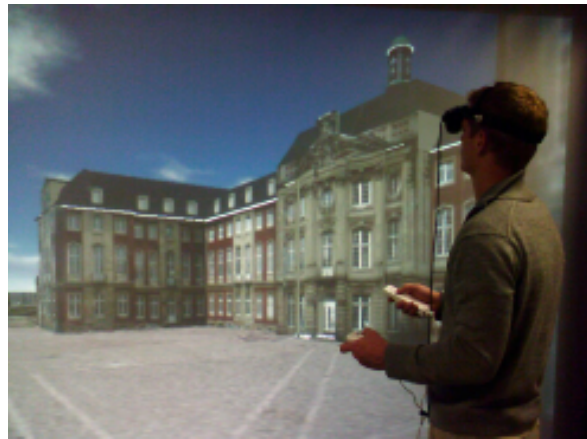


Figure 5. Example applications of redirected walking in the geospatial application domain. The images on the screens show the user's view on the HMD.

physically with each other. Furthermore, real walking increases the user's presence especially in 3D entertainment environments [23].

6. Discussion and Future Work

In this paper we have introduced software-based solutions to provide low-cost virtual locomotion interfaces. The interface has been designed according to guidelines that we have identified on the basis of the results of a pilot study. With our approach it becomes possible to explore arbitrary VEs by real walking. The challenge of natural traveling in limited tracking space has been resolved sufficiently by redirected walking approaches.

Although participants of the user study as well as other users have stated the benefits and usability of our virtual locomotion interface for different application domains, we have identified some issues, which could be improved. According to guideline 3 of Section 4.1 a tracking area of approximately $10 \times 10m$ can provide a single user the notion of an infinitely large VE, where omni-directional walking can be performed. In parts the approach might be usable for single users in projection environments, such as large CAVEs or curved display environments. How many users or physical objects can be added to such a large environment has not been examined within the scope of this paper. According to estimation the tracking area would be sufficient for a reasonably large number of entities such as 2-4 users and 2-4 physical objects. This will be examined in the next study.

The application of the concepts presented in this paper raises further interesting questions; in particular, multi-user scenarios in which several users interact simultaneously may show great potential.

In summary, the introduced virtual locomotion interface seems to be a promising approach to increase the user's presence in virtual worlds. Many

existing applications from different domains could potentially benefit from the possibility to naturally explore virtual environments in an immersive way.

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