Reorientation in Virtual Environments using Interactive Portals

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Abstract

Real walking is the most natural method of navigation in virtual environments. However, physical space limitations often prevent or complicate its continuous use. Thus, many real walking interfaces, among them redirected walking techniques, depend on a *reorientation technique* that redirects the user away from physical boundaries when they are reached. However, existing reorientation techniques typically actively interrupt the user, or depend on the application of rotation gain that can lead to simulator sickness.

In our approach, the user is reoriented using portals. While one portal is placed automatically to guide the user to a safe position, she controls the target selection and physically walks through the portal herself to perform the reorientation. In a formal user study we show that the method does not cause additional simulator sickness, and participants walk more than with point-and-fly navigation or teleportation, at the expense of longer completion times.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques

1 Introduction

The probably most natural method to move through real world and virtual environments (VE) alike is physical walking. Compared to virtual navigation techniques, real walking has two distinct advantages: it increases presence [9, 13] and reduces mental load [15].

Real walking can be implemented in a straightforward way by mapping the user's real position directly to her virtual one. However, the physical workspace is limited, while the VE is often significantly larger. Therefore, auxiliary techniques are needed—often, real walking is restricted to maneuvering, while travel is accomplished with a virtual navigation technique.

One way to realize continuous walking are *reorientation techniques* that *reorient* users into safe directions or positions when they reach system boundaries, such that they can continue walking. This can, for example, be done by simulating a 360° virtual turn while having the user do a 180° real turn [14, 6]. However, a possible disadvantage of such methods is that real and virtual motion are usually decoupled (e.g., by applying *rotation gain*), which can lead to simulator sickness [4, 5]. Furthermore, the system starts the reorientation on its own, which may surprise or confuse the user.

In this work, we introduce a novel approach to reorient users in VEs based on interactive portals, to facilitate real walking in limited workspaces. The process is initiated by users themselves, and causes no additional simulator sickness. Here, when users approach workspace boundaries, they are warned by a barrier tape. Using a pointing device and raycasting-based selection, they can place a portal at their desired target location. Another portal is opened automatically, and positioned in a way to guide the user away from system boundaries. By physically walking through the portal, the user arrives at the selected target location; visual continuity is preserved by a live view through the portal (see Fig. 1). This approach also allows travel over larger distances, such that only one reorientation is necessary to get to the desired location by real walking.

We evaluated our method in a user study among 26 subjects, comparing the approach to two standard navigation techniques (point-and-fly and teleportation).

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Figure 1: A user is reoriented into the center of the CAVE by walking through a portal.

2 Related work

Several approaches have been developed to prevent users from reaching physical boundaries while walking. An important class of these is based on the fact that real and virtual motion can be decoupled to some extent without the user noticing, as the visual sense usually prevails over vestibular and proprioceptive cues [1]. Studies found that the virtual translation in walking direction can be increased or decreased by up to 22% without the user noticing [11]. Similarly, virtual rotation can be amplified or reduced, rotating a user 49% more or 20% less in the real world than in the VE [12]. These weaknesses of the human sensory systems are exploited in *redirected walking* techniques [8] to continuously and imperceptibly steer the user away from physical boundaries.

However, these techniques usually need very large tracking areas (with a radius of more than 15 m [11, 12]) to be truly imperceptible. Still, users eventually collide with system boundaries if they repeatedly choose a path that conflicts with the system's prediction. When the redirection fails, *reorientation techniques* can guide the user in a safe direction or position.

These techniques are necessary as reset mechanism for redirected walking, but can also be used exclusively, or in combination with other navigation techniques. Whenever the user is about to reach physical boundaries, she is *reoriented* to a safe place, e.g., the opposite wall or the center. This can be done by forcing the user to walk backwards until reaching a safe position (*Freeze-Backup*) or to do a 180° real turn while simulating a 360° turn (*2:1 turn*) [14, 6]. However, these techniques cause a distinct interruption while the reorientation is performed. Furthermore, virtual and real motion are decoupled, which can lead to simulator sickness [4, 5]. Peck et al. [7] try to minimize this effect by constantly applying small rotation gains to prevent the user from reaching boundaries, and if that fails, supporting reorientations with larger gains with distractors.

While existing reorientation techniques make unlimited real walking through VEs possible, we see the necessary decoupling of physical and virtual motion as a disadvantage. Techniques like *Freeze-Backup* or *Freeze-Turn* [14] also cause distinct interruptions by freezing the simulation. Furthermore, the reorientation is initiated by the system, which might be confusing to some users, as the environment suddenly starts acting differently (e.g., when rotation is amplified). Our approach therefore focuses on these two aspects: reorientation without introduction of simulator sickness, and without changes in the VE that the user did not initiate.

Virtual portals for (limited) navigation in VEs have already been employed by Steinicke, Bruder et al. who used them to travel from a transition room to the actual VE [10]. The technique was applied for architectural walkthroughs, where users could travel into rooms of the model and back using portals [2]. However, the focus of their technique is not on navigation, but on increasing presence and performance through transitional environments—the virtual portals are not used for continuous real walking or user reorientation, and are not placed freely by the user.

3 Method

In short, our approach works as follows: Upon reaching workspace boundaries, the user is warned—in our implementation, a barrier tape fades into view. To continue walking in the desired direction, the user can then create a portal to her target location (*target portal*) using a pointing device and raycasting selection. After that, another portal (*start portal*) is placed automatically in a way that ensures that the user is guided away from physical boundaries when walking through (e.g., towards the workspace center). By physically walking through the portal, the user arrives at the (virtual) target, while at the same time moving towards a safe (real) position.

We identify several possible advantages of this approach over reorientation techniques like *Freeze-Turn* or *2:1-Turn* [14]. First, the reorientation is initiated by the user (even if it may not be perceived as a reorientation to her), avoiding unexpected environment changes. Second, neither an external interruption of the simulation, nor the application of a rotation gain are necessary. We assume that this way, it is easier for users to mentally stay within the context of the VE, and to retain an immersive effect. Furthermore, by not decoupling virtual and real rotation, possible additional causes of simulator sickness are avoided. It is also easier to use the technique in CAVE-like environments, where the decoupling of real and virtual motion is usually noticed much more strongly, due to the fact that in contrast to HMD setups, the own body and parts of the real environment can be seen and used as reference. Third, by letting the user select the target location, multiple reorientations for targets that are farther away than the size of the workspace can be avoided.

Users can create portals at any time, not only when directly at a workspace boundary. The distance to the target portal is not limited, which makes navigation over greater distances possible in reasonable time and without several reorientations. Therefore, when the user knows that the target is too far away to be reached by walking within the available physical space, she can directly create a portal. This is done by pressing a button on a pointing device and selecting the target using raycasting, during which a preview of the target portal is displayed. When a ground position is selected, the portal is placed at that position, facing the user. When targeting a position on or close to a wall or larger obstacle, the portal is placed in front of that obstacle (at a distance of 1.20 m in our implementation) and aligned with it. To facilitate the selection of far-away destinations, a world-in-miniature (WIM) model can be opened on the ground with a second button, and used for portal placement with the same raycasting metaphor.

In our implementation, portals appear as stone arcs standing on the ground, with an inner height of 2.15 m and a width of 0.92 m, allowing for a comfortable passage (see Fig. 1). A live view through the portal to the target preserves visual continuity and provides for a seamless transition when walking through, which can be realized using a multi-pass rendering approach. The start portal smoothly rises from the ground to avoid startling the user. If it does not appear within 45° of her view direction, a sign appears in front of the user and indicates a left, right or U-turn using an arrow.

The start portal is placed in a way to maximize the physical interaction space after using it. This results in two base cases, depending on the user's target selection. We assume a rectangular workspace here, but the placement can be generalized to arbitrarily shaped areas. If there are no obstacles close to the target portal, the start portal is placed in the center of the tracking area. This placement maximizes the physical interaction space available after passing through, assuming that the user's next walking direction at the target location is not known. For very large tracking areas, it might be beneficial to move the portal closer to the user to avoid unnecessary walking, but in our case, this corresponded to a maximum distance of less than 2.50 m from the user.

If the target portal is located in front of a wall or obstacle, the start portal is placed in front of the closest workspace boundary, at the same distance. As the target portal is aligned with the virtual wall, the (real) boundary coincides with the virtual wall after using the portal. Assuming that the user does not intend to walk through that wall, this maximizes the physical interaction space, as no space is lost in the direction of the virtual wall.

Some special cases have to be accounted for. To avoid startling the user, the start portal is placed at least 0.80 m from the user, and moved away from her to fulfill this requirement, if necessary. Furthermore, the placement should be plausible, and the portal visible and reachable, so it is moved to the closest position where it can be placed on even ground, within sight and without obstacles between it and the user. If it is aligned with a system boundary, the adjustment is only applied parallel to it, or another boundary is chosen.

4 User Study

After fine-tuning the details of the technique in an informal pilot study among six expert users, we conducted a controlled user study to determine whether user performance using real walking and reorientation by interactive portals is comparable to that of standard navigation techniques. The main goal of this study was thus to determine how novel users perform with the technique at simple tasks, and to find possible weaknesses and starting points for improvements. To quantify the consequences and effectiveness of the actual reorientation process (e.g., effects on spatial orientation and a detailed simulator sickness evaluation), we plan to compare the method to existing reorientation techniques in a future study.

We chose a within-subjects design and performed two experiments in sequence, in both of which users had to navigate to a series of waypoints and operate a virtual button located there. Experiment E1 compared our approach to point-and-fly navigation and teleportation. In experiment E2, we tested how much influence the portal target selection process itself ("aiming") had on participants' performance by letting the selection ray "snap" to the target.

The study took place in a back-projected, five-sided (four walls and a floor) CAVE-like environment with a floor area of 5.25 m$\times$5.25 m, and a height of 3.30 m. Stereo images were generated at a frequency of 60 Hz per eye, the shutter glasses and input devices (an A.R.T. Flystick2 and a lightweight tracking body for the other hand) were tracked opto-electronically at 60 Hz.

We hypothesized that users walk more with our approach, as physical walking is optional in the comparison techniques. Furthermore, they would also take longer on average to reach a target than when using teleportation, as physical walking takes some time. We hypothesized that the reorientation will cause some users to lose orientation at least temporarily, but will not induce any simulator sickness. In E2, we hypothesized that users are faster with the easier target selection, but do not walk significantly more or less.

The VE consisted of a large park with a parking lot, framed by buildings. It contained some static occluders such as immobile cars and trees and had a size of 200 m$\times$128 m. During all navigation in all conditions, the user was constrained to the ground. For all conditions, we also added the Magic Barrier Tape (MBT) as conceived by Cirio et al. [3] which we shaped octagonally and placed at a distance of 0.80 m from the walls and 1.50 m from the corners. The tape indicates the edges of the reliable tracking area and also allows small-scale navigation by pushing a hand against it in the desired direction. We included it for two reasons: first, the portal reorientation technique needs a method to inform the user that she is about to reach a CAVE wall when walking. To avoid any influence of this information missing in the other techniques, we made it available in all conditions. Second, tracking is sometimes unreliable close to the walls. On the one hand, the tape thus prevents users from coming too close for this being an issue, and on the other hand allowed for small positional corrections when the target was incorrectly judged by participants to be in the reliable tracking area.

In total, 26 individuals (6 female, 20 male), aged 20–32 (mean 25, $SD = 2.6$) participated in the study. All had normal or corrected-to-normal vision and could walk without problems. All participants were unpaid volunteers and naïve to the purpose of the experiment. The total procedure took 45–60 minutes per participant. One participant had to abort the experiment early due to severe simulator sickness, and was omitted from evaluation. Due to technical difficulties, no measurements were taken for another participant, leaving 25 fully answered questionnaires and 24 complete measurements.

After an explanation of equipment and procedure, participants could try out all techniques (including the MBT and WIM) until they felt comfortable with them, and completed one unrecorded waypoint assignment for each technique. This was followed by experiment E1 and E2 in succession.

In E1, we tested three conditions in counter-balanced order:

Point-and-fly (F)—the user could move by pointing the Flystick in the desired direction and pressing a button. The speed depended on the horizontal distance between glasses and Flystick, using the same relation as the MBT. It was capped at 10 m/s at a distance of 0.49 m. A WIM model was available on the second button, but did not provide any interaction.

Teleportation (T)—a target could be selected by raycasting into the world or WIM model in the same way as with the portal target selection. During the teleportation, the world shortly faded to gray, which we found to avoid unnecessary discomfort.

Walking with reorientation by portals (P)—as described in Section 3.

The task was the same for each condition, and consisted of a series of waypoint-reaching assignments. In each assignment, the participant had to reach five waypoints in a row, marked with a red button on a marble pole. Reaching a waypoint was confirmed by touching this button with either hand. To avoid an influence of search time, the button was clearly marked by a large arrow-shaped indicator from above, and a yellow-marked path on the ground. The next button could appear in one of five configurations: at a distance of 5 m, 20 m or 80 m, and for the latter two, occluded by an obstacle or directly visible. Each assignment contained each configuration once, in random order. In E1, each participant completed four assignments per condition. After each condition, a questionnaire was answered, rating a series of statements on a five-point Likert scale.

In E2, we tested the influence of the raycasting-based target selection. Two conditions were compared in counter-balanced order, where one (P) was identical to condition P in E1, while in the other (PA), the selection ray snapped to the target within an angular distance of 2° to its center. Three waypoint assignments were completed per condition.

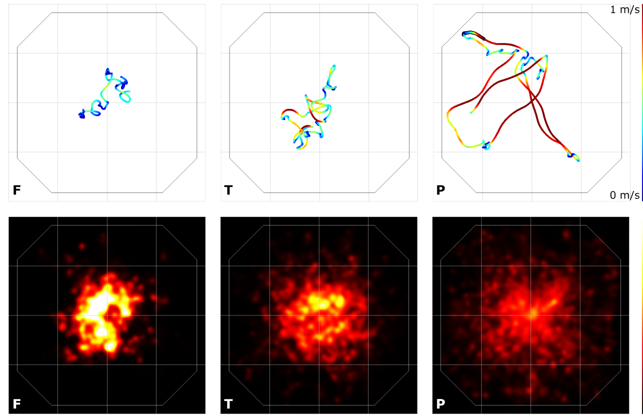

Figure 2: **Top:** Typical real world movement paths for a waypoint task in E1. **Bottom:** Heat maps of the users' positions in the CAVE during E1. The octagon shows the position of the MBT, the grid size is 1 m.

5 Results

All measurements refer to single waypoint assignments (5 waypoints). For all statistical tests, a significance level of $\alpha = 0.05$ was used. When evaluating questionnaires, the values 1 ("strongly disagree") to 5 ("strongly agree") were assigned to the answers and significant differences were determined using Wilcoxon signed-rank tests. Due to the counter-balanced order of conditions, we did not test for order or learning effects. More results and visualizations can be found in the supplemental material.

Walking distance—In E1, users walked on average 5.1 m ($SD = 1.6$ m) per waypoint assignment in condition F, compared to 8.8 m ($SD = 1.9$ m) in condition T and 19.5 m ($SD = 3.6$ m) in P. Welch's t-tests revealed all these differences to be significant ($p < 0.001$). Fig. 2 shows visualizations of representative paths. In E2, users walked significantly less in condition PA ($M = 14.9$ m, $SD = 2.8$ m) than in P ($M = 18.2$ m, $SD = 3.1$ m, $p < 0.001$).

Time—In E1, participants took on average 37.1 s ($SD = 6.5$ s) per waypoint assignment in condition F, 31.7 s ($SD = 6.0$ s) in T and 50.6 s ($SD = 11.0$ s) in P. Welch's t-tests showed significant differences between all pairs ($p < 0.001$). In E2, participants were significantly faster in condition PA ($M = 38.0$ s, $SD = 7.8$ s) than in P ($M = 47.2$ s, $SD = 9.5$ s, $p < 0.001$).

Space usage—As all waypoint assignments started with the user close to the CAVE center, the deviations from that point can be compared. In condition F, participants spent 90% of the time within a radius of 0.90 m around their center of residency. In condition T, this number decreases to 69%, and further to 50% in condition P. See Fig. 2 for a heat map visualization of user positions.

MBT usage—In E1, the MBT was used on average for 0.2 s ($SD = 1.0$ s) in condition F, 0.8 s ($SD = 1.6$ s) in T and 4.1 s ($SD = 4.5$ s) in P. Welch's t-tests showed significant differences between all pairs ($p < 0.001$). In E2, the MBT was used significantly less in condition PA ($M = 1.3$ s, $SD = 2.2$ s) than in P ($M = 2.7$ s, $SD = 3.4$ s, $p = 0.003$). Only for the shortest distance of 5 m, the MBT was sometimes used exclusively (E1: 17% of cases in T and 57% in P, E2: 42% in P, 28% in PA).

Simulator sickness—While the majority of participants did not report simulator sickness, the rating for the statement "I felt dizzy/headaches/other discomforts during the test" was significantly higher in condition F ($p = 0.005$), where 9 out of 25 participants agreed or strongly agreed to the statement. There were no significant differences between condition T (24 "(strongly) disagree") and P (25 "(strongly) disagree").

Loss of orientation—The statement "I lost orientation while navigating" was disagreed most often with in condition F (median "strongly disagree"), followed by T (median "disagree") and P (median "neither agree nor disagree"). All these differences were significant ($p \leq 0.028$ for all pairs).

6 Discussion

The results show that participants walked significantly more with the portal technique than with the comparison techniques. This was expected, as it was the only technique that strictly required physical walking. It should be noted that not the complete distance to the target had to be covered, but only the distance to the portal, and from the portal to the target—as most targets were far away, most participants immediately placed a portal as they saw that it could not be reached without leaving the workspace. Experiment E2 shows that participants walked about 3.30 m less with supported aiming. We did not expect this result, as simplified aiming does not reduce the distance to any target. In fact, this difference seems to have been due to initially unnoticed, inaccurate placement of the target portal, such that two portals were necessary to reach the target. This underlines the importance of an adequate target selection technique, but may also be partly due to the fact that participants had no extensive training with the technique and 20 out of 26 had actually never used a VR system before. With aiming assistance—when precise selection was not necessary—participants walked about 15 m per assignment, or 3 m to reach any one target. We believe that this is enough to convey the feeling that the target was reached on foot, but not so much as to become too fatiguing or time-consuming.

Corresponding to our hypothesis, simulator sickness was significantly stronger with the point-and-fly technique. We attribute this to the fact that the other techniques did not rely on virtual motion that can lead to simulator sickness due to conflicts of different senses [4, 5]. As none of the participants reported any simulator sickness or discomfort effects with the portal technique, we conclude that reorientation and frequent turning were no cause for discomfort. However, as no in-depth simulator sickness evaluation was done, these results should be rechecked more thoroughly in further studies.

Users reported loss of orientation more frequently with the portal technique. We expected this result, as it was the only reorientation technique under comparison. However, it is unclear whether this loss of orientation was only temporary, and whether it actually affected user performance. We are therefore interested to see in a follow-up study how our approach compares to existing reorientation techniques regarding spatial orientation. A contributing factor might have been the fact that most of the VE looked similar and symmetrical, and that there were no obvious direction cues. Some users stated that it was sometimes hard to perceive the change of location when passing a portal, and suggested that this could be mitigated by some kind of distortion effect on the portal view.

As expected, participants took longer per task with our approach. We identify several possible reasons for this: First, physical movement takes some time (although of course, the time for point-and-fly techniques strongly depends on the speed). Second, users lost time trying to aim precisely (in E2, condition PA was on average 9 s faster), an effect that was less pronounced with teleportation, as users often just teleported several times instead. Third, some participants also involuntarily activated the MBT when using portals close to CAVE walls, as it was about the same height as their hands. Deactivating the MBT in these cases might have avoided these errors that often made the creation of another portal necessary.

In the 5 m conditions, participants sometimes used the MBT exclusively. One reason for this is that they just started walking and unexpectedly reached the workspace boundaries, where the MBT only had to be used to cover the remaining distance. In other cases, they seemed to want to save the effort to walk and aim: the ratio was less with more training (condition P in E2) and aiming assistance (PA). As this (unexpected) usage might have distorted some results, future studies should examine the technique without the MBT.

7 Conclusion

In this paper, we have proposed, evaluated and discussed reorientation by interactive portals as a new approach to support continuous real walking through VEs. Contrary to existing techniques, the reorientation is initiated by the user, and no decoupling between virtual and real motion is necessary. Study participants reported no simulator sickness effects with the technique.

In future work, we will investigate sound as additional direction cue to improve user orientation, as well as visual cues. We also hope to improve user performance by speeding up the part of the interaction not related to physical walking. Furthermore, we plan to compare the approach with existing reorientation techniques regarding performance, spatial orientation and simulator sickness.

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