A Taxonomy for Deploying Redirection Techniques in Immersive Virtual Environments

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ABSTRACT

Natural walking can provide a compelling experience in immersive virtual environments, but it remains an implementation challenge due to the physical space constraints imposed on the size of the virtual world. The use of redirection techniques is a promising approach that relaxes the space requirements of natural walking by manipulating the user's route in the virtual environment, causing the real world path to remain within the boundaries of the physical workspace. In this paper, we present and apply a novel taxonomy that separates redirection techniques according to their geometric flexibility versus the likelihood that they will be noticed by users. Additionally, we conducted a user study of three reorientation techniques, which confirmed that participants were less likely to experience a break in presence when reoriented using the techniques classified as subtle in our taxonomy. Our results also suggest that reorientation with change blindness illusions may give the impression of exploring a more expansive environment than continuous rotation techniques, but at the cost of negatively impacting spatial knowledge acquisition.

Keywords: Virtual environments, redirection, taxonomy

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; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1 INTRODUCTION

Natural interaction is vitally important for creating compelling virtual reality experiences, particularly locomotion, which is one of the most common and universal tasks performed when interacting with 3D graphical environments [1]. The most natural locomotion technique, real walking, has been shown to provide a greater sense of presence when compared to alternative techniques that do not employ realistic body motion, including walking-in-place and virtual travel metaphors (e.g. flying) [18], and has also been shown to provide benefits for memory and attention [16]. Despite these advantages, natural walking remains a challenge for practitioners that utilize immersive head-mounted displays, as physical space limitations will ultimately restrict the size of the virtual environment that can be explored.

Redirection is a promising solution that relaxes the space restrictions of natural walking by manipulating the user's route in the virtual environment, causing it to deviate from the real world path [13]. These techniques can be used to allow considerably larger virtual environments to be explored using natural body motions within a relatively confined physical workspace. To better understand how

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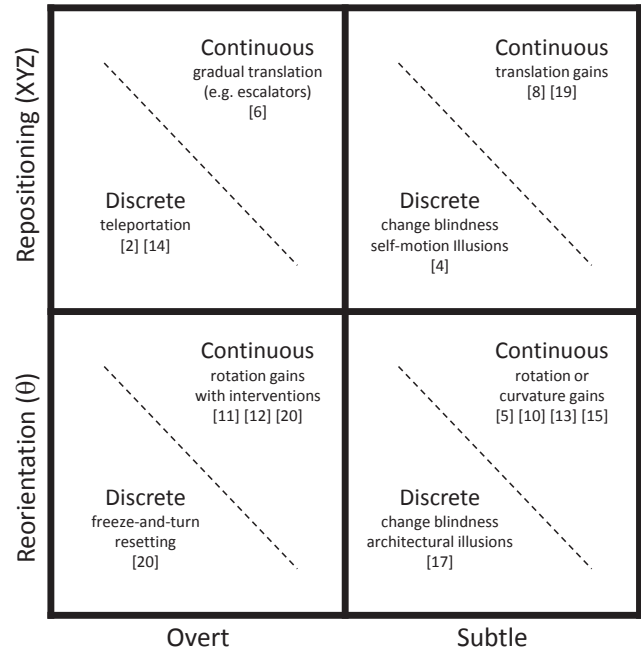
Taxonomy of Redirection Techniques

Figure 1: Taxonomy of redirection techniques for supporting natural walking through immersive virtual environments. The vertical axis distinguishes how the technique is applied in the environment. The horizontal axis provides a ranking in terms of noticeability to the user. The division in cells represents distinct implementation strategies for each type of technique.

these redirection techniques may be employed in practice, it is useful to provide a classification scheme that maps the spectrum of available methods. Steinicke et al. previously described one such taxonomy for redirection techniques that manipulate locomotion gains, based on the type of gain being applied (translation, rotation, or curvature) [15]. However, recent work has yielded an assortment of innovative redirection techniques with similar goals, but drastically different implementations that do not neatly fit into previous conceptual frameworks. As such, we have developed a new taxonomy that is organized to allow practitioners to select and apply one or more redirection metaphors based on a variety of criteria relevant to virtual environment design. Additionally, we conducted a user study of three techniques selected from the taxonomy and collected data on participants' breaks in presence and spatial knowledge acquisition during redirection.

2 TAXONOMY / PREVIOUS WORK

Figure 1 illustrates the taxonomy, which is based on each redirection technique's geometric applicability, noticeability to the user, and content-specific implementation details. Redirection tech-

niques may be broadly divided into two categories based on their geometric applicability, in other words, how they help make the desired virtual space fit within the actual tracked volume. *Repositioning techniques* manipulate the correspondence between points in the real and virtual worlds to compress a larger virtual space into a smaller physical workspace. *Reorientation techniques* attempt to rotate the user's heading away from the boundaries of the physical workspace. Ideally, the user would not notice redirection techniques, so that the virtual reality implementation remains as invisible as possible. As such, our proposed taxonomy distinguishes between subtle and overt methods. *Subtle* techniques are designed specifically to be imperceptible when the magnitude of the manipulation is beneath a certain detection threshold. In contrast, *overt* techniques will be easily noticed by users when they are applied. While the subtlety of techniques can most likely be mapped to a continuum, this course binary categorization is nonetheless conceptually useful for our taxonomy. This distinction implies a logical ranking: in general, subtle techniques are preferable to overt ones, since the latter have greater potential to disrupt the natural process of walking through the environment. Finally, in terms of implementation, techniques may either be *discrete* (applied instantaneously) or *continuous* (applied over time), which is a potentially important factor as practioners seek to balance the implementation of these techniques with the narritive and timing demands of their content.

2.1 Repositioning Techniques

Overt Continuous Repositioning. A simple repositioning can be achieved by continuously translating the virtual environment about the user's position. This allows the user to walk to areas in the virtual environment that were not previously accessible within the confines of the physical workspace. This may be disorienting if the virtual world is translated unexpectedly, and may make the virtual environment appear unstable. This disruption can be mitigated by coupling the translation with known metaphors associated with motion, such as elevators (e.g. [7]), escalators (e.g. as demonstrated with [6]), moving walkways, or vehicles.

Subtle Continuous Repositioning. A continuous repositioning can be applied in a subtle manner by applying translation gains to the user's physical locomotion, effectively scaling walking motions to cover greater distances in the virtual environment [19]. This method can be improved by estimating the user's intended direction of travel and scaling translations only in that direction, which reduces exaggeration of the oscillatory head bob and sway from walking motions [8]. This technique remains subtle so long as the gains applied are small enough to avoid detection. Steinicke et al. conducted a psychophysical study of detection thresholds, and found that travel distances could be downscaled by 14% or upscaled by 26% without becoming noticeable to the user [15].

Overt Discrete Repositioning. Discrete repositioning techniques may be achieved through instantaneous translation, effectively teleporting the user to a new location in the virtual space. This technique is potentially disorienting if the user is not expecting the virtual position to be manipulated. To mitigate this problem, researchers have leveraged the concept of portals from popular science fiction to provide an environmental grounding for teleportation [2]. In fact, users have reported greater levels of presence when portals were used to teleport from a transitional virtual replica of the real environment into an unfamiliar environment, compared to entering the unfamiliar environment immediately [14].

Subtle Discrete Repositioning. Given the abrupt translation required for a discrete repositioning, it seems difficult to apply this technique in a subtle manner. However, recent research has found that inter-stimulus images or visual optic flow effects in the periphery of the user's view can be used to mask abrupt translations in the environment [4]. These small discrete updates can be repeated periodically as the user walks, allowing travel distances to be scaled

similar to the continuous techniques.

2.2 Reorientation Techniques

Overt Continuous Reorientation. Resetting is a conceptually simple method of reorienting the user that requires an intervention when the user reaches the boundaries of the physical workspace. During the intervention, the user is instructed to turn around, during which a rotation gain is applied. For example, for every one degree of turn in the real world, the virtual environment is rotated two degrees, so that after a 180 degree physical turn (pointing back into the workspace) the virtual environment has rotated by 360 degrees, restoring the user's original heading in the virtual world [20]. Since issuing explicit instructions to the user may break presence, one suggested mitigator has been the use of visual distractors to elicit head turns during the intervention, thereby providing an opportunity to apply rotation gains [11]. It is important to note that while the continuous rotation gain itself may not be detectable, interventions are obvious to users, and so we classify the overall method as an overt technique.

Subtle Continuous Reorientation. Redirected walking was the first technique to introduce an imperceptible gain to head rotations in order to guide the user away from the boundaries of the physical workspace [13]. The detectability of rotation gains have been studied in the context of both head turns [9] and full-body turns [3]. A recent comprehensive study found that users can be physically turned approximately 49% more or 20% less than the perceived virtual rotation without noticing [15]. Alternatively, it is also possible to dynamically apply a continuous rotation as the user travels forwards, resulting in a curvature of the walking path [5] [13]. However, experimental results have indicated that imperceptibly redirecting a user along a circular arc requires a very large workspace with a radius of at least 22 meters [15].

Overt Discrete Reorientation. In addition to continuous techniques, resetting can also be applied in a discrete manner. In their freeze-and-turn implementation of resetting, Williams et al. freeze motion tracking and instruct the user to rotate away from the boundaries of the physical workspace [20]. After the user completes the physical rotation, the virtual view is unfrozen and motion tracking resumes. While the discontinuity introduced by freezing and unfreezing the motion tracking will be obvious to the user, resetting remains useful as an emergency "failsafe" technique to prevent the user from exiting the workspace.

Subtle Discrete Reorientation. In a drastically different implementation from other reorientation techniques, researchers have proposed instantaneously changing the location or orientation of architectural features, particularly doors, in a virtual scene at runtime [17]. The technique is based on change blindness, a phenomenon that can be observed when users fail to notice alterations to a visual scene that occur outside of their visual field. While studies have shown that this illusion can be leveraged to reorient the user in a very subtle way, with only one out of 77 users noticing the scene change, change blindness techniques are largely limited to interior environments with doorways that can be manipulated, and would often not be geometrically applicable in sparse, open environments such as outdoor scenes.

2.3 Redirection Controllers

Each redirection technique imposes its own set of limitations, making it difficult or impossible to provide unlimited free exploration with a single technique. Therefore, to employ redirection in practical virtual environments, *redirection controllers* must maintain awareness of the user's state in real and virtual space, and invoke repositioning and/or reorientation techniques in order to facilitate walking through the virtual world. A fairly restrictive example is a waypoint-based controller, which reorients users as they walk between predefined locations, usually along a zig-zag or "S" curve

path (e.g. [13]). More sophisticated controllers have attempted to dynamically optimize continuous reorientation techniques, for example, by adjusting curvature gain levels based on the user's walking speed [10]. Redirected Free Exploration with Distractors is perhaps the most generally applicable redirection controller developed to date, which continuously steers the user towards the center of the tracked area and invokes overt continuous reorientation when the user approaches the boundaries of the physical space [12].

Developing automated redirection controllers that utilize a wider range of available techniques will be an important step towards making redirection more generally applicable for practical settings. One example of an implementation that makes use of both discrete and continuous techniques is Arch-Explore, a system for architectural walkthroughs that combines repositioning using discrete portals and continuous translation, rotation, and curvature gains for reorientation in a semi-automated manner [2]. We believe the taxonomy presented in this paper will provide a useful starting point for the design of future redirection controllers that make use of multiple repositioning and reorientation techniques in tandem.

3 USER STUDY

Based on the taxonomy presented in Section 2, we selected three existing reorientation techniques and asked participants to self-report whenever they experienced a break in presence. We hypothesized that continuously collecting data on these breaks in presence as participants were redirected would be a useful metric for measuring the "subtlety" or "overtness" of each technique.

3.1 Study Design

We chose to focus on reorientation techniques since they are more commonly used and cited in the literature than repositioning techniques, and tested one approach from each of the three parts of the taxonomy that were most used in practice, i. e., excluding overt discrete manipulations. We conducted a within-subjects study with all participants experiencing the following three conditions:

SCR: Subtle Continuous Reorientation

To implement this technique, we applied rotation gains as users walked around a partially-opened virtual swing door connecting two virtual rooms, as proposed by [2]. The detectability of these manipulations depends mainly on the discrepancy between a manipulated virtual rotation $\alpha_{virtual}$ compared to a rotation of a user in the real world α_{real}, expressed via rotation gains: $\alpha_{virtual} = g_R \cdot \alpha_{real}$, for $g_R \in \mathbb{R}$ [15]. In this notation, $g_R = 1$ would imply an exact 1:1 mapping from real to virtual rotation; therefore, manipulations become less noticeable as g_R approaches 1. To compare this technique in both optimal and non-optimal cases, we compared results between two different situations: reorientations achievable with $g_R >= 0.59$ and reorientations requiring $g_R < 0.59$, (cf. [2]).

SDR: Subtle Discrete Reorientation

We implemented the change blindness reorientation technique to manipulate the location of virtual doorways, as was done in [17]. To compare this technique in both optimal and non-optimal cases, we conducted an informal pilot test to determine the magnitude of scene changes that can be feasibly applied. Thus, we compared results between two different situations: reorientations achievable with door movement distances $<= 1$m and reorientations requiring distances > 1m.

OCR: Overt Continuous Reorientation

We implemented rotation gains with distractors using an animated virtual hummingbird and a gain of 1.5 of the user's head rotation, as suggested by Peck et al. [11]. Since this technique is overt and cannot be applied without the user noticing, it did not make sense to discriminate between optimal and non-optimal cases.

3.2 Methods

A total of 22 people participated in the experiment (16 male, 6 female). Participants were university students between the ages of $21-30$ ($M = 24.4$), and had normal or corrected-to-normal vision. The graphical environment was presented on a ProView SR80 HMD manufactured by Kaiser Electro-Optics (1280×1024 resolution, 60Hz refresh rate, $80°$ diagonal field of view) with an opaque cloth attached to block peripheral vision of the real world. The position of the HMD was tracked with an infrared LED and an active optical tracking system (Precision Position Tracker PPT X8 from WorldViz), which provides sub-millimeter precision and an update rate of 60Hz. Orientation tracking was achieved with an InterSense InertiaCube 3 fixed to the top of the HMD. The virtual environment was rendered at 60 frames per second using OpenGL on PC with Intel Core i7 processors, 6GB of RAM, and nVidia Quadro FX 4800 graphics card.

At the beginning of each session, participants were guided into the laboratory room wearing a blindfold to avoid exposing them to the physical workspace. They were instructed to explore a virtual environment consisting of a series of offices arranged in a randomly generated layout. The experimental task required participants to collect a one dollar bill from an avatar in each room, then proceed towards an adjacent office via a color-identified door. Avatars were matched to a student coworker in the laboratory, who assumed the corresponding pose to provide passive haptic feedback. Participants were instructed to announce verbally whenever they experienced a break in presence (BIP), which we described to them as the feeling that the virtual scene or interaction appeared implausible. After the VR session, subjects sketched the path they traveled through the VE by drawing a virtual floor plan on a sheet of blank paper, excluding furniture or avatars. The maps were evaluated separately for each transition between rooms, to which a score of either $+1$ was assigned if the path information between entering and leaving the room roughly matched the actual door layout (i. e., the unmodified door layout in the case of SDR), or 0 otherwise. The total map score was computed as sum of the scores for the separate transitions for each subject, and varied between $0-10$. Furthermore, we asked subjects to label the sides of a square map with their estimation of the dimensions of the physical walking area in the laboratory. The total time to complete the study was approximately one hour.

3.3 Results

Figure 2 shows the pooled BIP probabilities in each of the five conditions. The results were treated with a repeated measures analysis of variance (ANOVA) with a significance level of $\alpha = .05$, which was significant, $F(4,84) = 76.43$, $p < .01$, $\eta_p^2 = .78$. Pairwise comparisons with Bonferroni-adjusted α values indicated that SCR optimal ($M = .13$, $SD = .13$) and SDR optimal ($M = .21$, $SD = .28$) had lower BIP probabilities than all other conditions, $p < .01$, but were not significantly different from each other, $p > .99$. Additionally, OCR ($M = .91$, $SD = .14$) had higher BIP probabilities than SCR non-optimal ($M = .70$, $SD = .18$), $p < .01$, but was not significantly different from SDR non-optimal ($M = .86$, $SD = .19$), $p > .99$.

Repeated measures ANOVAs testing the within-subjects effect of reorientation technique were performed for both the sketch map grades and physical room size estimates. Significant results were observed for the map ratings, $F(2,42) = 17.26$, $p < .01$, $\eta_p^2 = .45$. Pairwise comparisons indicated that sketch maps were rated lower in the SDR condition ($M = 6.68$, $SD = 2.08$) compared to both SCR ($M = 8.95$, $SD = 1.89$), $p < .01$, and OCR ($M = 8.91$, $SD = 1.48$), $p < .01$. The ratings were not significantly different between SCR and OCR, $p > .99$. The results for the room size estimations were also significant, $F(2,42) = 88.29$, $p < .01$, $\eta_p^2 = .81$. Pairwise comparisons indicated that the length of a wall in the square physical room were estimated to be the longest when reorienting with SDR ($M = 12.43$m, $SD = 3.36$m), compared to the shorter estimates in
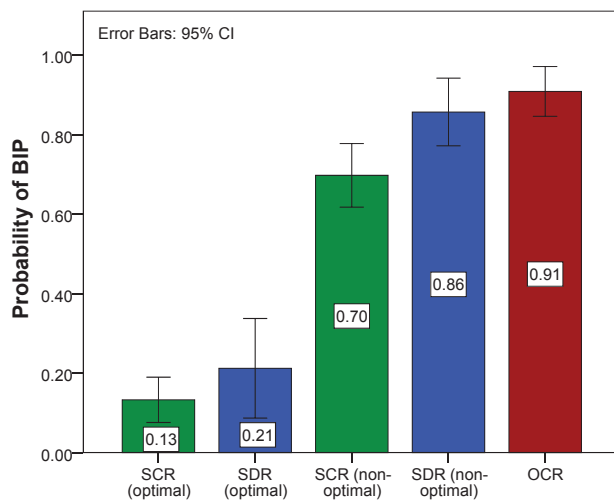
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Figure 2: Results showing the pooled probability of a reported a break in presence for each condition. Subjects reported significantly fewer breaks during reorientation using the SCR and SDR techniques when they were applied optimally.

both the SCR ($M = 6.72$m, $SD = 1.38$m), $p < .01$, and OCR conditions ($M = 5.05$, $SD = 0.74$m), $p < .01$. The difference between the estimates in the SCR and OCR conditions was significant, $p < .01$.

3.4 Discussion

Self-reported breaks in presence seem to be a useful metric for discriminating between subtle and overt redirection techniques. The results from the study confirmed that reorienting the user with subtle techniques (SCR and SDR) is preferable, but primarily when they can be applied optimally. However, even when this is not possible, it may still be beneficial to employ a technique such as SCR in non-optimal conditions. This is supported by the observation that even though the SCR non-optimal caused a fairly high incidence of self-reported BIPs, it was still lower than the OCR condition. However, overt techniques generally have the advantage of being more generally applicable, and so any automated redirection controller should include at least one to prevent failure cases, when the user would otherwise exit the physical workspace.

On average, subjects estimated the physical workspace to be much larger when exploring the environment in the SDR condition, compared to both other conditions as well as th. This interesting result suggests that change blindness architectural illusions may be more effective at giving the impression of exploring an expansive environment. However, this advantage is not without a cost, since subjects also received lower sketch map grades compared to the other two techniques. This is not particularly surprising, since the environment model was dynamically changing, and the sketch maps grades were calculated as compared to the original, unmanipulated environment layout. This suggests that these architectural illusions may not be appropriate for practical use in applications where acquiring accurate spatial knowledge is important.

4 CONCLUSION

In this paper, we introduced a novel taxonomy that maps the spectrum of available redirection techniques. In the future, this taxonomy may be used to inform the design of virtual environments, and provides the theoretical foundation for the development of automated redirection controllers that can dynamically apply a variety of techniques based upon the needs of the system and the current state of the user.

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