Bookshelf and Bird: Enabling Real Walking in Large VR Spaces through Cell-Based Redirection

Run Yu*, Wallace S. Lages*, Mahdi Nabiyouni*, Brandon Ray*,
Navyaram Kondur*, Vikram Chandrashekar*, Doug A. Bowman*

Center for Human-Computer Interaction, Virginia Tech, Blacksburg, VA, USA

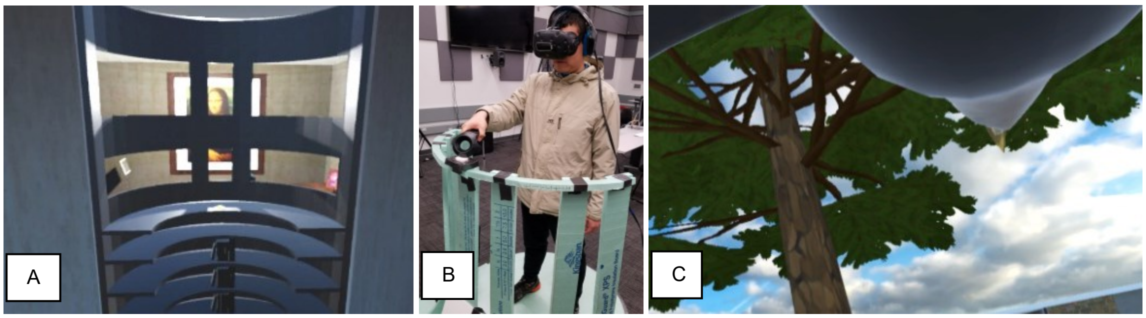

Figure 1: The bookshelf and bird techniques. A) The bookshelf uses a virtual rotation to allow the user to proceed to an adjacent room; B) The user standing on the physical prop and touching the button that activates the Bookshelf redirection; C) The bird translates the user to another cell while maintaining the correct relationship between the user, the physical workspace, and the virtual cell.

Abstract

We present two novel redirection techniques to enable real walking in large virtual environments (VEs) using only "room-scale" tracked spaces. The techniques, called Bookshelf and Bird, provide narrative-consistent redirection to keep the user inside the physical space, and require the user to walk to explore the VE. The underlying concept, called cell-based redirection, is to divide the virtual world into discrete cells that have the same size as the physical tracking space. The techniques then can redirect the users without altering the relationship between the user, the physical space, and the virtual cell. In this way, users can always access the entire cell using real walking.

Keywords: Locomotion, virtual reality, walking, redirection

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, Augmented, and Virtual Realities

1 Introduction

Real walking, as a locomotion technique for virtual reality (VR), can help enhance presence and overall user experience [1]. However, its use in practical applications has been challenging [2]. Since virtual environments (VEs) are often much larger than the physically available, motion-tracked space, a direct one-to-one mapping between walking and viewpoint motion is not possible without other enhancements. Even though many techniques have been developed, they all involve tradeoffs, and a general-purpose solution has yet to be found [2].

One option is to use travel techniques that do not require physical walking movements [2]. A typical example within this category is teleportation, where the user is moved instantaneously to another point in the VE without actually moving in the physical space [3]. This allows the user to travel beyond the limits of the physical space and still use real walking when the destination is within reach. Although seemingly effective, this approach tends to discourage users from real walking, since it is possible to teleport to any point. Furthermore, users can lose awareness of the physical space when an arbitrary translation is combined with real walking. For instance, she could end up in a corner of the physical space, leaving teleportation as the only navigation option if the destination lies beyond the direction of that corner. Thus, teleportation often makes the user *more* aware of the limitations of the physical environment, which breaks the VR experience.

Another category of solutions preserves natural walking motion but manipulates the virtual movement. Typical redirected walking (RDW) techniques (e.g., [4]) apply continuous rotation and/or translation gains to the user's movement to keep him within a limited space. Such techniques can fool the user into thinking that they are walking great distances. Unfortunately, for the illusion to be convincing, this technique requires a large physical space [5].

Other variations of RDW separate redirection from real walking. Instead of altering the perceived motion during walking, they require an explicit, discrete redirection when the user approaches the boundaries of the physical space. For example, the system may "freeze" the virtual world and ask the user to turn around, after which a normal one-to-one walking mapping is resumed [6]. These redirection techniques can be used with small physical spaces, but often break the flow of the VR experience.

In this paper, we describe two novel redirection techniques called *Bookshelf* and *Bird* (Figure 1). Both are explicit redirection methods that maintain a consistent mapping between physical and virtual spaces after the redirection. Bookshelf allows the user to go from one room to the next by virtually rotating her on a spinning bookcase. After the virtual rotation, the destination room is on the same side as the physically available space. The Bird technique translates the user to another cell by lifting him over ground obstacles in the virtual world. It automatically drops him in a virtual location corresponding to his location in the physical space. These two techniques guarantee that the current cell is

*{runyu | wlages | nabiyoun | branr94 | kvnav16 | vikramc | bowman}@vt.edu

2017 IEEE Symposium on 3D User Interfaces (3DUI)
March 18-19, 2017, Los Angeles, CA, USA
978-1-5090-6715-2/17/$31.00

always mapped exactly to the physical workspace, keeping the entire cell accessible via real walking.

These designs require an environment that can be divided into discrete cells the same size and shape as the tracked area, and they constrain the redirection to ensure a “perfect” mapping between virtual and physical space. Thus, they are limited to applications that support a flexible environment design (e.g., in gaming or education applications). However, because they are based on understandable metaphors, Bookshelf and Bird (and techniques in the same family) can enhance the narrative of a VR experience.

Our contributions include:

(1) Two novel redirection techniques that enable walking through a large VE in a narrative-consistent manner

(2) A generalization of these techniques into a concept called “cell-based redirection,” which is a powerful design tool to facilitate real walking in VR given limited physical space

2 RELATED WORK

Suma et al. present a taxonomy of redirection techniques based on three characteristics: whether the alteration is subtle or overt, whether the redirection is repositioning or reorientation, and whether this happens continuously or discretely [7].

The original RDW falls in the category of subtle redirection, in which the key is to hide the change from the user by leveraging the limitations of human perception [4]. Following this idea, Steinicke et al. described thresholds of translation, rotation and curvature gain that keep the alteration from being perceived by the user [5]. To lower the chance of collision, customized RDW based on path-finding algorithms exist, but these techniques cannot guarantee that the illusion will be unnoticeable given a small physical workspace and large virtual worlds [8].

More similar to this paper’s techniques are the ones that create overt redirection. Williams et al. introduced explicit, discrete redirections that reset the user’s position or orientation at the boundaries of tracking space [6]. They either ask the user to move back or turn around in reality while her view of the VE is frozen, or require her to physically turn 180 degrees while presenting a 360-degree virtual turn (this is called “2:1-Turn”). These techniques use brute force “stop to reset” actions that are separate from the intended narrative, which is likely to disrupt the user experience significantly. Peck et al. added visual distractors so that the VE can be repositioned or reoriented while the user is paying attention to something else [9]. This is similar to our approach, except that the user must be instructed to stop and pay attention to the distractors, which could break the narrative flow.

Freitag et, al. introduced a “portal” based design, which asks the user to specify a destination when they approach a physical boundary [10], then positions a portal that guides the user to walk away from the boundary as they teleport to the destination. This has similarities to our Bird technique, but we argue that continuous movement is more understandable than teleportation and will result in less disorientation [11].

The prior work most similar to ours is the Arch-Explore system [12]. In this system, architectural spaces are also divided into cells (rooms), and redirection is applied when users are transitioning between cells. However, in order to allow real walking through arbitrary architectural models, Bruder et al. apply different walking scale factors depending on the size of the room, and use large rotation and curvature gains as the user walks through a door between rooms. These features could lead to issues with distance perception, discomfort, and disorientation. In contrast, our techniques always use a 1:1 scale for walking and use only one type of overt rotation redirection, which we believe will reduce disorientation and discomfort. The techniques in Arch-Explore are applicable when the VE design is prescribed, while our techniques take advantage of situations where VE design is flexible.

3 NOVEL REDIRECTION TECHNIQUES

The Bookshelf and Bird techniques rely on the virtual world being broken into a 2D grid of cells, with each cell having the same size as the physical motion-tracked space. The Bookshelf technique allows the user to travel between adjacent indoor cells, while the Bird is used to move between cells that are out in the open.

3.1 The Bookshelf Technique

Movies and games sometimes feature a false bookshelf or fireplace that, when activated, can spin around its vertical axis, taking a person standing next to it into an adjacent, secret room. The Bookshelf technique uses this metaphor (Figure 1A).

When the user intends to travel to the next cell connected by a wall, he can step onto the platform attached to the bookshelf and push a yellow button. Once activated, the bookshelf will rotate itself (along with the user) by 180 degrees in the virtual scene, placing the user in the virtual room on the other side of the wall. Since no such rotation happens in reality, the user is actually still standing in the same lab space facing the original side of the real wall (Figure 2A-C). The destination virtual room is now reoriented to lie on the same side as the physically available lab space (Figure 2C). The user can then simply turn around and walk to traverse the virtual room, which is perfectly mapped to the physical motion-tracked space (Figure 2D). Note that this requires the bookshelf to be placed in the middle of the wall. Repeating this redirection between each pair of adjacent cells enables the user to traverse a much larger area than the physically available space without breaking the narrative of the game.

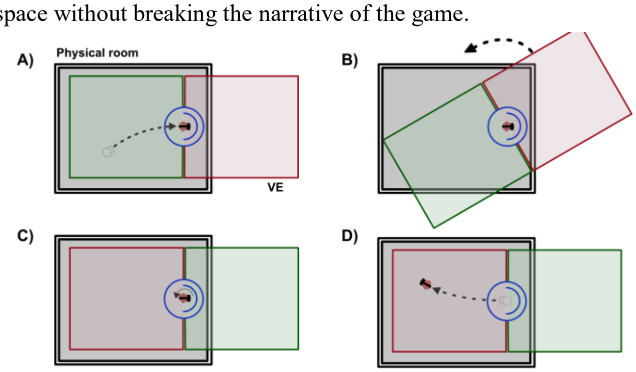

Figure 2: Redirection in the Bookshelf technique. The black rectangle indicates the tracked physical room, while the red and green ones indicate two virtual rooms. A: The user starts from the green room, steps onto the bookshelf, and activates redirection; B: The bookshelf rotates with the user in the virtual world while he stands still in reality; C: The physical space now lies on the same side as the red virtual room, and the user turns around to face it; D: The user steps off the bookshelf to walk through the red virtual room.

To be effective, the Bookshelf needs to convince the user that he is indeed rotating. We help create this illusion in several ways. First, the metaphor itself is accessible and familiar from popular media. Second, part of the virtual bookshelf is made of translucent glass (Figure 1A), so the user can see the next room during the reorientation. This provides visual feedback that makes the perceived rotation more convincing. Third, we provide spatial sound in both cells, and use a subwoofer to create vibration-based haptic feedback as the bookshelf turns.

In order to re-map the physical space to the new cell, the bookshelf needs to rotate continuously for 180 degrees. If the user steps off the bookshelf during the rotation, he would perceive himself as being rotated for no reason and perhaps going through virtual walls, which breaks the VR experience. To discourage this from happening, we dim the display while the bookshelf is rotating to create a “cut scene” effect, which makes the user feel like an observer. We also built a physical prop to give the user a tangible platform to stand on, which is expected to make him reluctant to step off it during rotation. Finally, the button that activates redirection is placed so that the user is required to stand on the bookshelf platform before activation (Figure 1B).

A potential issue with the Bookshelf is cybersickness created by visual-vestibular mismatch during the virtual rotation. To minimize this effect, we designed a semi-circular bookshelf that places the user close to the pivot point of the rotation, resulting in reduced virtual translation during the bookshelf movement. The dimming of the view is also designed to reduce perceived optical flow, and thus to reduce cybersickness.

3.2 The Bird Technique

The Bird technique (Figure 1C) is designed for outdoor scenes, where cells are separated using low obstacles. Instead of relying on redirection through rotation, the Bird translates the user to a new cell. The player first selects a target by looking at the ground plane of the desired destination cell. We cast a ray from the user’s eye point in the direction his head is facing, and the system selects the cell whose ground plane is intersected. A semitransparent sphere appears on the ground in the selected cell to provide visual feedback. Once satisfied with the choice, the user calls the bird by pushing a button on a hand-held controller. The bird approaches the player, grabs and lifts him, flies to the new cell and then descends to drop him there. Once the user perceives no more movement, he is free to walk around in the destination cell.

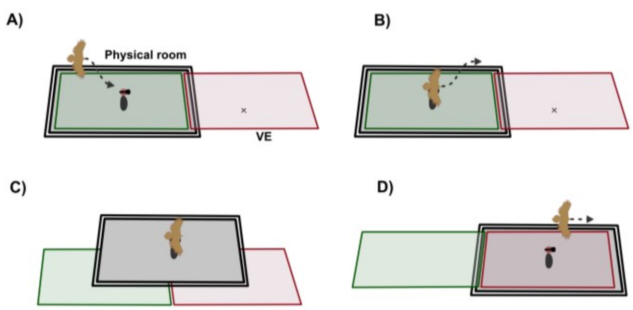

Figure 3: Redirection in the Bird technique. The black rectangle indicates the tracked physical room, while the red and green ones indicate two virtual cells. A: The user starts from the green cell and selects the red cell as the target. B: The bird approaches and picks him up; C: The bird lifts him and flies to the destination cell; D: The user is dropped at the corresponding position in the destination cell as his previous location in the original cell.

Although this sounds similar to teleportation, it differs in two key respects. First, the Bird does not drop the user at an arbitrary point in the destination cell, but rather translates the user from her position in the current cell to the corresponding position in the destination cell (Figure 3). This means that the physical boundaries are still aligned with the virtual edges of the cell, and the user can thus walk to any location in the cell. Second, the Bird uses a rapid but continuous virtual movement, rather than an instantaneous repositioning as in teleportation or a portal-based technique. This not only provides a physically plausible metaphor, but also may help the user maintain spatial orientation [11].

To maintain consistency with the overall narrative, the Bird technique is applied in outdoor parts of the scene. The boundaries between cells are low obstacles (e.g., plants, rocks, or streams) instead of walls, so the user can see the destination region and will not pass through objects when carried by the Bird.

3.3 Demonstration

We built a simple “treasure hunt” game using these two redirection techniques. The game was implemented in Unity3D and is displayed in an HTC Vive head-mounted display. The display and the Vive controller are tracked by the Vive’s Lighthouse tracker in an area of about 5m x 5m. The user’s goal is to find words that compose a sentence that reveals the location of a treasure. The scene is a house with 8 rooms, some of which connect to an indoor yard with 5 regions. Each room and each region in the yard is a cell with the same dimensions as the physical workspace. The entire virtual scene spans over 325 square meters. Some rooms are connected by bookshelves and the yard is segmented by a small water channel and bushes (Figure 4).

The player can traverse the environment using a combination of walking and the Bookshelf/Bird techniques. Each cell contains a clipboard that reveals the next word in the secret sentence when the user walks close to it. The full sentence directs the user to return to a particular room, where the treasure appears.

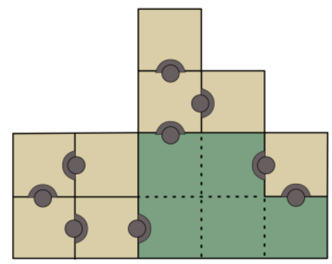

Figure 4: Layout of the “treasure hunt” VE. It has 8 rooms (yellow cells) and a yard (green cells), with 9 rotating bookshelves.

We have not yet run a formal evaluation, but we demonstrated both the whole game and the individual techniques to a number of users and collected informal user feedback.

4 Discussion

4.1 User Experience

In our experience with the game demo, no users have had any difficulty in learning how to use the Bookshelf or Bird. Players naturally use real walking to move around within each cell. During the session, they seemed to easily recall the locations of previously visited landmarks and which cells have not yet been traversed. Many users felt surprised that they could explore such a large space. Users seemed convinced that they were walking through a virtual scene much larger than the motion-tracked area.

The Bookshelf and Bird metaphors were believable and effective in our experience. One of the users asked, “Wait… was I really being rotated just now?” after she experienced the bookshelf interface and took off the head-mounted display. When carried by the Bird from one cell to another, most users remain still during the flight. Some people express fear the bird will drop them before landing, which also indicates strong immersion.

Cybersickness is still an issue for some users with one or both techniques. The most severe sickness is reported when someone tries to step off the bookshelf while it is rotating, which only happens when physical prop is not used.

4.2 Cell-Based Redirection

On the surface, Bookshelf and Bird seem to have limited applicability, since they use highly specific metaphors. However, they are actually instances of a family of techniques we call “cell-based redirection” (CBR). CBR techniques divide the VE into discrete cells, with each having the same size and shape as the tracked space. Each cell is fully accessible by real walking and is perfectly aligned with the physical space. Users move between adjacent cells by invoking redirection through reorientation (e.g., Bookshelf) or repositioning (e.g., Bird). The key characteristics of CBR are that natural 1:1 walking is used within each cell, and that redirection is consistent with the narrative of the VE.

Other metaphors can be used within the CBR family to support different narratives. For example, a revolving door could be used in the place of the Bookshelf to rotate the user into an adjacent room. Similar to the Bird, a “sky hook” system could be presented where the player is carried to other rooms by grabbing onto a hook that’s attached to a rail above. Elevators, escalators, or any other vehicle-based metaphor could be applied to carry the user between cells in such interfaces, as long as the new cell is re-aligned with the real-world workspace after the transition.

Table 1 provides a comparison between CBR and some existing techniques. Unlike prior approaches to redirection, CBR combines several desirable qualities: it requires the user to walk physically, never applies a scale factor to physical walking or turning movements, is practical for room-scale spaces, maintains the fit between the physical tracking space and the virtual space, and provides metaphors that can be consistent with the VR narrative.

4.3 Limitations

Obviously, the most important downside of CBR is that it does not apply to arbitrary VE layouts since the VE must be divided into room-sized cells. To seamlessly embed the redirection into the experience, one has to find metaphors that are appropriate for the environment and consistent with the narrative, which may be difficult depending on the application. For example, placing objects like bookshelves in a VE for architectural planning may not be acceptable since it alters the building’s interior appearance. Overall, CBR is more applicable if one has freedom in designing the environment and story, such as when building a VR game.

Redirection in CBR must be designed carefully to realize a good user experience. For example, we need to encourage the user to remain on the Bookshelf platform when it is rotating and stand still when he is being carried by the Bird. Furthermore, the player will experience the redirection every time he travels from one cell to another, which may become too repetitive. The designer may need to vary the redirection metaphors, increase the speed of redirection, provide interesting visuals, or present tasks that are performed during redirection to keep the user engaged. Finally, the visual-vestibular mismatch introduced by CBR techniques can cause cybersickness. One needs to carefully implement the visual and haptic display to limit such discomfort.

Compared to teleportation and portals, the user is given less control over the redirection action with CBR techniques, but this constraint guarantees that the system can maintain a perfect mapping between the walkable cell and physical space.

CBR is not meant to be a general-purpose locomotion solution. But given metaphors that are consistent with the application’s narrative, it is a powerful design approach that enables walking in VR far beyond the physical boundaries of the tracked space.

5 Conclusions and Future Work

This paper proposes the Bookshelf and Bird techniques as examples of cell-based redirection in VR locomotion. By mapping discrete cells in the virtual world to the physical workspace, the user can always access the entire cell with real walking while traveling between cells using seamless and believable redirection. Users can walk without worrying about the physical boundaries and can access a virtual space much larger than the physical one.

In the future, we plan to evaluate CBR more formally. We will also explore ways to enhance the user experience during the redirection phase by providing a better sense of safety or decreasing potential cybersickness. Finally, we plan to explore additional metaphors, such as elevators and revolving doors, to expand the applicability of this family of techniques.

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Table 1: Comparison of characteristics of CBR and related previous techniques (✓́ indicates a technique partially qualifies for a characteristic).

	CBR	Teleportation	Traditional RDW	2:1-Turn	Arch-Explore
Requires physical walking to traverse the scene	✓		✓	✓	✓
Does not use translation or rotation gains	✓	✓			
Practical for room-scale physical spaces	✓	✓		✓	✓
Maintains correspondence between real and virtual boundaries	✓			✓	✓́
Redirection can be fit into the narrative of the VE	✓	✓			
Applicable to any VE layout		✓	✓	✓	✓