An Overview of Redirected Walking Approaches and Techniques in Virtual Reality

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Abstract

One major obstacle to the ideal of virtual reality is the physical constraints of the user's location, primarily its limited size. A commonly proposed solution is using redirected walking, defined as manipulation of the user's experience to alter their walking path, to keep the user within a confined physical space without causing any perceivable sensory distortion for the user. This paper discusses various redirected walking approaches which have been proposed, including predictions of user movement via navigation meshes and simulated users, and subtle redirection techniques using blink-induced change blindness and avatar manipulation.

Keywords: Virtual reality, VR, redirected walking, eye blinks, psychophysical experiments

1 Introduction

The dream of virtual reality is the ability to freely navigate a very large, or even infinite, virtual space while believing that you truly occupy it, walking wherever you want. Unfortunately, while a virtual space may be infinite (or effectively so), the real physical space in which the user stands is not. This presents an unfortunate situation where the user has to break immersion and relocate, or else run into a wall. While some sources solve this problem by suspending the user within a specialized piece of hardware such as a harness to keep them in one location, this hardware is large, cumbersome, expensive, and generally impractical for personal use [5]. Another, more promising, approach is redirected walking, which seeks to subtly manipulate the user in order to cause them to avoid walking into a wall in the first place, ideally without them noticing any such manipulation. Newer research shows that this can be achieved with commercial-grade hardware in conjunction with specialized software that helps determine when and how the redirected walking techniques should be deployed. [5]

This paper aims to provide a basic overview of some recent redirected walking research. In Section 2, I provide a brief background on the field as it stands, including common terminology and a description of the problems that redirected walking solves. Section 3 will cover an overview of path prediction algorithms which aim to best determine when various redirected walking algorithms should be applied, while section 4 describes newer approaches for actual redirection based on blink detection. Finally, I summarize the findings discussed throughout the paper and provide suggestions for future research.

2 Background

In this section, I provide information as on the field as it stands, starting with definitions of terms, followed by a discussion of the general concept of redirected walking, including an explanation of the method's general benefits and generalized functionality.

2.1 Common terms

VR, or virtual reality, refers to any technology which fully immerses the user in a virtual environment. In practical usage, and for the scope of this paper, it refers to technology using headsets which completely cover the eyes and, using a small monitor for each eye, display a three-dimensional image of a virtual space to the user. User head movement alters their visual perspective as though they were physically situated in the displayed space, allowing them to look around manually. Typically other motions are tracked, allowing the user to interact with simulated objects or walk around freely. Within the virtual space, the user may be represented by an avatar

While using virtual reality, the user may experience varying levels of avatar embodiment. In the context of virtual reality, embodiment refers to the idea that the user *is* their physical avatar, rather than merely indirectly controlling it. High levels of embodiment are very desirable, as it increases immersion in the fictional environment and decreases the cognitive load involved in VR usage. Embodiment is very easy to trigger to lesser or greater extents; it can be most strongly generated with a full virtual avatar.

Redirected walking, or RDW, refers to various techniques used to alter the user's walking behavior without their awareness, specifically in order to constrain their physical motion within a limited space while allowing for free traversal of a much larger virtual space. Various approaches are employed to subtly alter the user's actual physical movement without altering their perceived movement or movement within the virtual space, by using different subtle sensory illusions or manipulations. In the ideal case, RDW could allow a VR user to move totally freely within their virtual space while staying within a very small physical space while maintaining total embodiment.

2.2 Potential solutions to constrained space

As noted in the introduction, the discrepancy between virtual and real space causes multiple potential issues. Various approaches have been considered for this, each with their pros and cons. The simplest solution, and one which is used by many VR games, is to simply disable free movement entirely. Instead, the user either navigates the environment via usage of a control stick or via some in-game method of teleportation, or the game contrives a reason whereby the player character is immobile. Unfortunately, teleportation or controller-mediated movement hurt embodiment, and preventing character movement entirely is only appropriate in limited circumstances. Other programs opt to simply sacrifice embodiment and immersion entirely, and pause gameplay to ask the user to reorient or recenter themself within their physical space. [5]

Another approach, which is based on hardware rather than software, is to use a specialized harness which allows the user to run above a multi-directional treadmill while artificially suspended in place. Unfortunately, the specialized hardware required is not generally commercially available, and the harness still damages immersion [5]. Therefore, redirected walking could be considered the best solution in many cases, as it can strongly maintain embodiment, and as a purely software-based solution, remains available to all consumers and users even when specialized hardware might be unavailable or overly expensive.

3 Path Prediction

Of course, in order to redirect the user away from obstacles or boundaries, it's necessary to understand when said collision is going to occur in the first place. Ideally, this can be predicted slightly ahead of time; in order for redirection to be seamless, it needs to occur slowly, meaning the user needs to start to be redirected before they're too close to a collision with the obstacle or boundary in question. This may require beginning RDW well before the user is actually close to said obstacle. As such, the program needs to predict the user's path ahead of time in order to determine which obstacles they would actually need to be redirected away from, and similarly, in which direction the redirection should be applied to avoid simply routing the user into a new obstacle.

A naive method of path prediction is to simply assume the user will continue to move in a straight line from their current path, but this presents difficulties if the user abruptly changes their behavior, likely in response to some factor in the simulated environment (such as turning to the side to pick up an item or avoid an enemy). Therefore, more advanced prediction algorithms are desirable in order to more accurately account for user movement.

If the user's movement within the virtual space can be predicted by analyzing its physical properties, their movement in real space can correspondingly be predicted. By being able to anticipate when a user will change in direction abruptly due to an in-simulation event or object, such as abruptly diverting to pick up an item, the user can be redirected more appropriately. For example, if a user is walking alongside a physical wall, it would be useful to anticipate if the user would abruptly turn towards the wall and then collide, and thus begin preemptively redirecting them away; on the other hand, if the user is likely to turn away from the wall naturally, redirection may not even be needed. Of course, if the user's movement is in response to the virtual environment, it becomes necessary to in some way connect the virtual space to a set of location-based movement predictions.

3.1 Charting the Space

A relatively simple method of predicting theoretical user movement relative to a virtual space is to set up a navigation mesh to chart the virtual space and provide likely travel routes. A navigation mesh is a representation of a navigable space as a mesh of polygons which permit navigation between polygons which share an edge, as illustrated in Figure 1. Navigation meshes are most commonly used for video games and programs to aid AI systems in navigating a space by having them move from point to point along the provided lines. However, this approach has also been used for various redirected walking approaches; by overlaying a navigation mesh over a virtual space and approximating the user's position at one of the relevant points, weights can be assigned to the various paths leading away from that point, which are in turn used to predict the user's future movements and rotations in order to account for them in the redirection. Typically, the paths being generated at any given moment are limited to a maximum length from wherever the user's current location is. [2]

While this approach does help with predictive RDW, it comes with its own set of costs. Creating the navigation mesh and associated weights for a virtual space is difficult and time-consuming, and typically created for each new environment independently. A proposed solution is to automate the creation of paths within these meshes. Azmandian et al. present a variety of algorithmic approaches to the generation of navigation meshes for various spaces. Their approach involves locating the user on the map, generating a tree of all potential paths from that location by connecting the user's specific location (rather than just the polygon they're in) to nearby polygons in the mesh, and using a modified version of Dijkstra's algorithm to search that tree for a list of the paths which travel greater distances or move to or along points of interest (as opposed to those which simply travel in circles or zigzag a lot for no reason). The algorithm was modified with

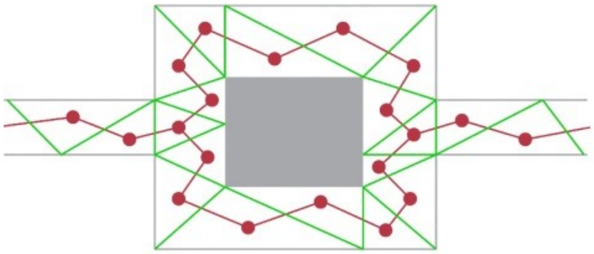


Figure 1. An example of a navigation mesh. The space is divided into polygons, with each containing a central point, and navigation routes shown as edges connecting the polygons. [2]

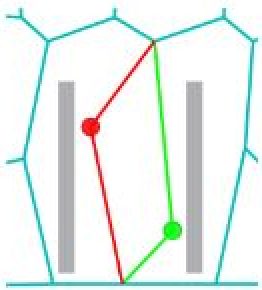
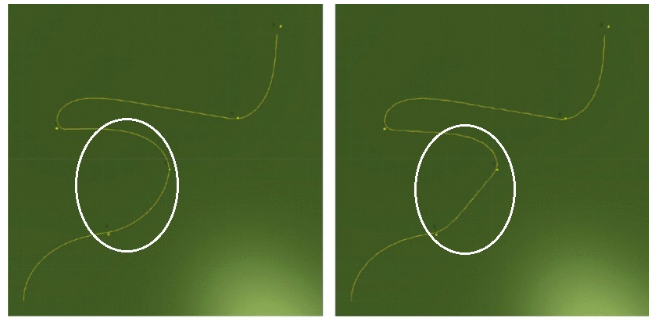


Figure 2. An example of generated paths changing when the user moves from the green point to the red point. The more distant parts of the potential likely paths are unchanged [2]

a maximum length of generated paths and a record of node connections along the nodes traversed. This allows for rapid generation of potential navigational paths relative to the user, with the additional advantage that, due to the fact that the meshes and paths are being generated on the fly, they can be remade in response to unusual user movement, as shown in Figure 2. The results can be automatically inserted into the prediction mesh, and were found to be reasonably similar to those generated by hand, and with a negligible increase in computation time when performing the generation; their specific algorithm generated search paths to a distance of 20 meters, with each graph taking 7.5 milliseconds to generate. This fast generation allows the mesh to be updated on every computation cycle. [2]

3.2 Specific Path Prediction

While using a navigation mesh to predict movement is powerful, it frequently fails to account for the fact that humans are not machines and thus do not walk in perfectly straight lines. Hutton and Suma present an approach for more accurately simulating human movement. They noted that, especially at higher velocities, humans tended to make a sharper curve



(a) Smooth path (b) Path with noise

Figure 3. Walking path predictions with and without noise. The noise level is exaggerated for illustration; note the change in the circled region from a smooth curve to direct linear movement. Based on [4].

and then walk in a straight line towards their target, rather than rotating gradually. They also noted that human walking includes some amount of noise which could be included in the predictive models, primarily originating from a combination of natural variations in gait and slight sinusoidal head motions. [4] These factors could be combined with existing navigational meshes to create an even more accurate prediction of user behavior, as shown in Figure 3.

A secondary benefit of this research is the ability to generate "ghost walkers", or simulated human figures to navigate an arbitrary space. This allows researchers to, given an arbitrary virtual space, generate and view a simulated person's actual predicted traversal route, rather than simply providing a generalized mesh of probabilities from any singular given point. In general, this is simply an alternate method of presenting existing predictive information, by attaching a visual representation of spatial traversal to allow for more obvious depictions of the effects of redirected walking techniques. In particular, by combining the simulation of the user's walking path in the *simulated* world with deviations based on the known effects of external walking techniques, observers could see a more accurate depiction of how a hypothetical user would move in real space. Hutton and Suma additionally note that these "ghost walkers" could be used to improve further research in the field of redirected walking, including via a proposed but not-yet-detailed method for evaluating the accuracy of various predictive models [4].

4 Redirection methods

Once user motion is predicted, the actual redirection techniques must be applied. This section describes several methods used, beginning of an overview of general RDW methods and techniques, followed by a description of a technique based on detecting blinks and using them to apply redirection techniques more effectively, and finally discusses a potential RDW approach which manipulates the user's avatar.

4.1 Basic Principles

One of the core concepts behind redirected walking is to take advantage of the way in which the human brain processes sensory information, and use it to obscure subtle alterations. There are many quirks in human information processing to take advantage of, the most relevant being change blindness. Change blindness refers to the phenomenon whereby people are oblivious, or "blind", to significant changes in their environment, such as the movement of a prominent image on a computer screen. Interestingly, and somewhat counterintuitively, this phenomenon is actually stronger with naturalistic, complex stimuli, such as people being unaware of the position of walls and doors around them moving, or even being unable to detect when the person they're talking to changes. This phenomenon is strengthened in certain directions of rotation or translation by specific eye movements and blinks, either voluntary or involuntary [5]. These lapses in perception can be exploited in order to alter the user's behavior to align with their perceptions.

4.2 Change Blindness for Redirection

A typical method of user manipulation is to manipulate the user's environment, via either environmental cues or subtle alteration of the user's perspective. A common method of doing this is via subtly rotating or translating the user's orientation in the virtual environment, making it so that in order to traverse a straight line within the simulated space, they necessarily traverse a curved path in real life. Typically, however, in order for the adjustments to be unnoticed, they need to be very small.

However, if changes occur while the user's eyes are closed, slightly larger rotations or transpositions can occur without them noticing. By detecting eye blinks and only rotating the environment mid-blink, the user can be more significantly redirected, with the angle of user walking rotation increased by up to 50% more than via standard redirection without taking advantage of blinking [5].

In their 2018 article, Langbehn et al. show that when a user blinks, they can be translated 4-9 cm or rotated by 2-5 degrees within the virtual space without noticing any visible change. Since this can be performed cumulatively with every single blink, users can be dramatically rerouted without noticing. [5] Doing this requires detecting eye blinks and timing the changes accordingly. Langbehn et al. suggest doing this with preexisting eye-motion tracking built into commercial VR headsets, as it already tracks eye blinks for various other purposes with varying levels of efficacy. After the eyes are closed for 300 ms, the system detects a blink and induces the visual rotation (see Figure 5). [5]

In the initial testing, 16 participants were asked to stand still and blink consciously in response to a prompt. With each blink, the user's viewpoint would be rotated. Using a forced-choice two-option trial where the participants were

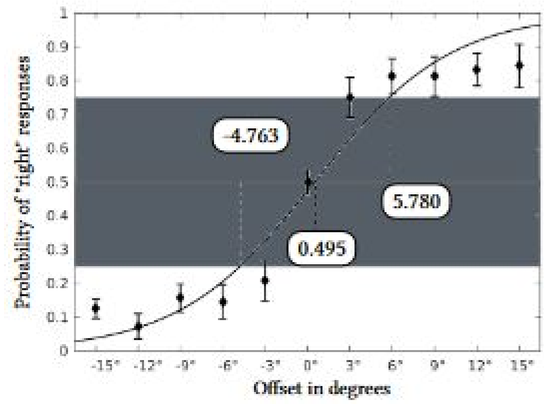


Figure 4. Langbehn et al.'s results regarding rate of user change identification in their fixed-choice test for horizontal rotation. The x-axis is the number of degrees by which the user was rotated to their right, while the y-axis is the probability of the user stating that they were rotated to the right. The gray area shows the range in which the rate of correct rotation identification was considered low enough for the technique to be considered undetected. [5]

required to select whether they rotated or moved left or right, they found that the participants were able to correctly identify a change of about 5 degrees less than 75% of the time (see Figure 4 for a more specific description of rotation and detection chance), providing a statistically significant chance that they were effectively guessing rather than accurately perceiving the change. [5]

These actions would allow for notable increases in the efficacy of various redirection techniques. By synchronizing actions with blinks, translations can be increased by as much as 10% without being noticed relative to previous RDW techniques. Similarly, when a user voluntarily rotates themself within the virtual world, the extent to which they rotate in the real world can be altered by more than 60%, allowing a perceived rotation of 90 degrees to cause the user to rotate anywhere from 67 to 139 degrees in reality. Likewise, while walking a curved path within the simulation, the user can rotate as much as 43% more than intended without noticing, as shown in Figure 6. These greater rotation gains allow the user to be redirected much more quickly, reducing the quantity of space necessary to allow for perceived infinite traversal. [5]

A follow-up confirmatory study was performed to ensure that horizontal rotations (i.e. equivalent to the user turning their head left or right) would remain undetectable and could be effectively combined with previous redirection techniques. 5 subjects were instructed to walk down a curved hallway in a virtual simulation, following the same path a total of 10 times each. During this time, previous rotational gain techniques were applied. Additionally, at two separate moments, they were prompted to blink. During one of the blinks, the

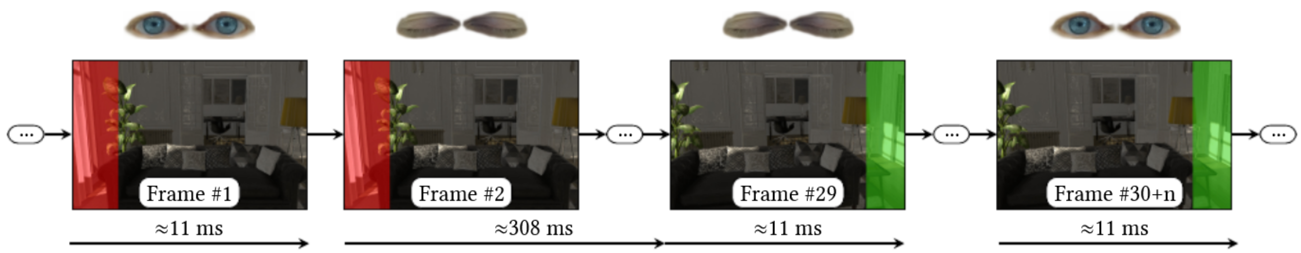


Figure 5. An example of blink detection and view alteration. On frame 1 the user's eyes are open. After 1 frame (about 11 ms), the user has closed their eyes. After the eyes are closed for more than 300 milliseconds, on frame 29, the program determines that the user is blinking and alters their view, by removing the red section on the left and adding the green section on the right. On any later frame, when the user opens their eyes, they see the image depicted on the far right. [5]

subject's perspective would be rotated by 5 degrees, while during the other it would remain unchanged. Via the same forced choice method, subjects were then asked which of the blinks had the rotation applied. Of the total 10 trials performed, 25 of the 50 responses were correct, strongly implying that the subjects were guessing randomly due to being unable to perceive the rotation. [5]

While previous studies had been done using eye motion tracking to induce rotations or translations at points when the user would be unable to effectively see them, this has the significant advantage of requiring only standard, commercially available hardware and software, whereas previous methods required specialized hardware for high-definition and high-frame rate eye tracking in order to detect involuntary rapid eye motions called saccades, rendering them less feasible for practical use [5]. Additionally, this blink-based approach has also been confirmed not to increase rates of VR-induced disorientation or sickness [5].

The most significant potential issue with the study is that it involved conscious and voluntary, rather than involuntary, blinking on the part of the participants. As the authors themselves admit, it's unclear whether these would have different detection thresholds [5]. On the other hand, the participants in question were actively expecting and attempting to analyze the redirection, which would in turn increase their sensitivity to various changes they might otherwise be oblivious to, implying that the actual threshold used for changes could even be higher in practical use.

Additionally, both trials had very small test groups, using 16 participants for the initial tests, and only 5 for the confirmatory follow-up experiment. These small numbers reduce the statistical power of the trials, as it doesn't strongly control for variations in user ability or perception.

Overall, this redirection approach will require more testing in less artificial conditions for its efficacy to be properly determined, but the information we currently have suggests blink-related redirection will be an effective tool. [5]

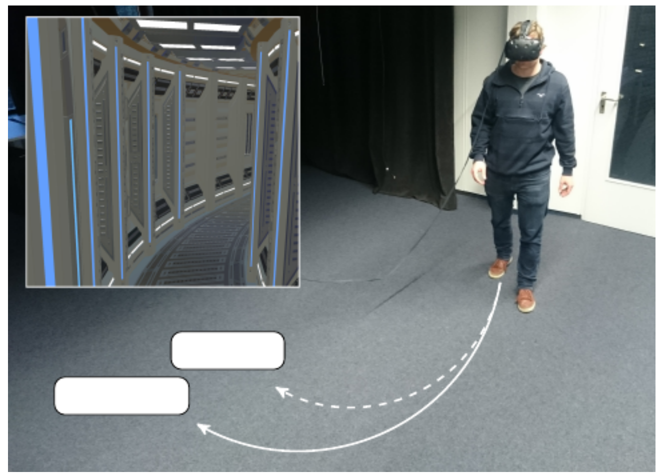


Figure 6. An example of user curve curve angle alteration. The solid line depicts the path the user believes themself to be taking based on the virtual space shown in the top left, while the dotted line shows the actual path the user takes. [5]

4.3 Avatar manipulation

Another potential approach for user redirection is via the user's avatar. Human beings possess a remarkable ability to include external objects as part of their self-visualization, as shown in the "rubber hand illusion" whereby participants stated that they were able to feel a person stroking a rubber hand after an illusion was created to make it seem as though it was their hand [3]. The exact mechanism by which this process occurs is still not entirely clear, with various theories including self-feedback mechanisms in sensory processing and computational factors of the brain attempting to minimize perceived sensory errors via discrepancies such as seeing but not feeling a stimulus. It may also involve motor contagion, whereby people involuntarily mirror the motions of those around them (such as yawning) due to "mirror neurons" [3].

This can be exploited in VR via the "self-avatar follower effect", whereby participants will subtly alter their behavior to synchronize with that of their VR avatar. VR users will frequently, while viewing their simulated avatar, synchronize their movements with its without realizing that they're doing so. This mirroring occurs even in the result of dramatic changes in their avatar's position, despite the strong loss of embodiment that occurs as a result, but is stronger in the case of very gradual changes [3]. While it was mentioned that this approach could be used for redirected walking, Gonzalez et al. did not strongly explore this aspect of their research beyond a brief mention. However, it could still be usable for various forms of motion redirection.

5 Further research

As noted in subsection 4.2, blink-based redirection has currently only been tested in highly artificial conditions. It would be useful to test it in more organic conditions with unprompted blinking and without asking the user to consciously identify and analyze changes.

The self-avatar follower effect has not yet been fully studied, especially regarding its applications for redirected walking. It remains to be seen if it would function in conjunction with change-blindness-induced environmental alterations, or if their combination would somehow disrupt embodiment. Additionally, the self-avatar follower effect was induced either very slowly and gradually during movement or in an abrupt leap designed to break embodiment; it still needs to be determined how the effect would be strengthened or weakened by changes made during blinks or other disruptions of visual perception.

As with many studies, the majority of research done indicated that most if not all participants were neurotypical, as well as primarily male. Various forms of neurodivergence can interfere with or alter sensory processing, including over- or under-sensitivity to specific sensory stimuli, temporary or persistent disruptions of self-image and bodily perception, and over- or under-activation of mirror neurons. Studies on autism in particular have indicated mixed effects on change blindness [1]. Further studies on a more diverse population of participants could strengthen the validity and applicability of these studies' findings.

6 Conclusion

Redirected walking in virtual reality has shown strong potential applicability in increasing the feasibility of full-motion-tracking VR in smaller spaces and making it more accessible to commercial applications. Multiple studies strongly support the ability to seamlessly redirect users via a variety of predictive and manipulative techniques, and in doing so allow for more immersive VR even in small environments. Although much research remains to be done, redirected walking is nevertheless a promising field of study.

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