Redirected Walking

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Abstract

Redirected Walking, a new interactive locomotion technique for virtual environments (VEs), captures the benefits of real walking while extending the possible size of the VE. Real walking, although natural and producing a high subjective sense of presence, limits virtual environments to the size of the tracked space. Redirected Walking addresses this limitation by interactively and imperceptibly rotating the virtual scene about the user. The rotation causes the user to walk continually toward the furthest wall of the lab without noticing the rotation. We implemented the technique using stereo graphics and 3D spatialized audio. Observations during a pilot study suggest that the technique works: Redirected Walking causes people to change their real walking direction without noticing it, allows for larger VEs, and does not induce appreciable simulator sickness.

1. Introduction

Locomotion is an important interaction technique in virtual environments. Real walking is better than flying or walking-in-place, in terms of presence, ease of use, and naturalness[1]. However, a serious limitation of real walking is that users cannot move through virtual environments that are larger than the working area of the tracker - the user loses tracking and/or runs into a wall of the lab. The goal of the technique we call Redirected Walking is to allow users to really walk through very large virtual spaces.

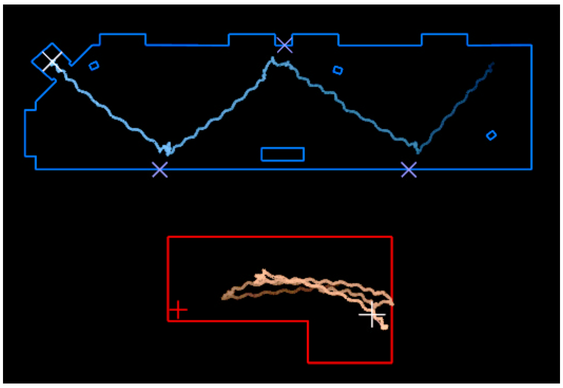

Figure 1: *Overhead views of the path taken by the user in the virtual environment (above in blue) and the laboratory (below in red). Note how the user walked in a zigzag pattern through the VE while walking back and forth within the tracker space. The tracker space and VE are drawn to scale. Crosses denote waypoints.*

The technique is inspired by the fact that a person wearing a blindfold and instructed to walk in a straight line, unknowingly walks along an arc instead. In 1994 Michael Moshell and Dan Mapes, at the University of Central Florida[2], attempted to manipulate VE users into unknowingly walking along an arc while thinking they are walking straight. Simulator sickness and limitations in VE systems, particularly tracker technology, thwarted them. General improvements in VE systems and the development of accurate, low latency, wide-area trackers suggest that Redirected Walking may now be feasible. Observations from our pilot user study give initial confirmation of this feasibility: Redirected Walking does cause people to change their actual walking direction without noticing, allows for larger VEs, and does not appear to cause unacceptable simulator sickness.

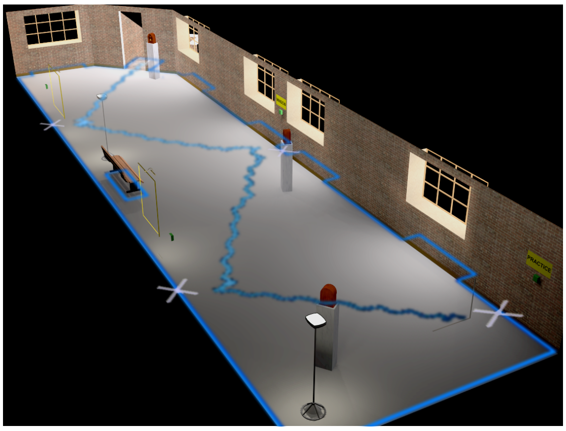

Figure 2: *The user's path superimposed onto the virtual env.*

2. The Technique

Redirected Walking works by interactively rotating the virtual scene about the user, such that the user is made to continually walk towards the farthest "wall" of the tracker area. The user does not notice this rotation because the algorithm exploits the limitations of human perceptual mechanisms for sensing position, orientation and movement. The amount of rotational distortion injected is a function of the user's real orientation and position in the lab, linear velocity, and angular velocity.

In the extreme, Redirected Walking could cause the user to walk in a large circle in the lab, while she thinks she is walking in a straight line in the virtual environment. Theoretically, if we had enough tracker area for the complete circle, we could present a virtual environment of infinite extent. Given a tracker of limited size, there is a trade-off: the more rotational distortion (resulting in the user walking in tighter arcs), the larger the virtual environment we can present. However, the more rotational distortion, the more likely it is that the user will detect the rotation.

To make Redirected Walking usable for trackers of limited area, we can get around the above trade-off by forcing the user to look around at strategically placed waypoints in the VE. While the user is rotating herself to look around, we can get away with more rotational distortion. The VE is rotated so that a direction which was previously out of tracker range is now safely within the tracked area. The distance between adjacent waypoints must be less than the length of the tracking area. Figures 1 and 2 illustrate the waypoints. While the need for waypoints imposes a major constraint on the VE, we believe that many tasks, such as the fire drill discussed below, naturally lend themselves toward waypoints.

3. Theory

Humans rely primarily on vestibular, visual, and auditory cues for balance and orientation[3]. Humans also use these senses to determine whether they themselves are moving (self-motion) or if the objects around them are moving (external-motion). Previous research suggests that keeping multiple cues consistent increases the chance that the user will perceive rotation as self-motion as opposed to external motion[4]. If Redirected Walking maintains consistency between visual, aural, and vestibular cues, the user should not sense the world moving arbitrarily around her. The goal is to maximize the probability that all of the user's perceived motion is self-motion.

Each ear's semi-circular canals act approximately as three orthogonal rotational rate gyros; they sense the high-frequency components of a person's angular movement. The visual and auditory systems sense low-frequency components. Because our VE system does not employ devices that induce vestibular cues, such as a motion platform, we avoided injecting high-frequency rotational distortion.

Even while standing still, the user unknowingly rotates her head and torso with the virtual scene. We hypothesis the user's own balance mechanisms are responsible for this[3]. While walking, in attempting to stay on a virtual trajectory that she perceives as straight, the user unwittingly veers in the direction of the induced rotation. At the waypoints, the rapid turning while looking around causes substantial vestibular stimulation. Against this high background an additional vestibular stimulation that would be noticed while walking is unnoticeable. Therefore the user does not notice the increased rotational distortion we inject while she is looking around.

For Redirected Walking to be successful, the user must register and respond to the continuously updated orientation of the VE, without recognizing it as externally induced. Furthermore, the rotational distortion must not increase the simulator sickness of the user. Because the technique keeps the visual, auditory and vestibular cues consistent, the added rotation should cause users to change direction, but be unnoticed. Since simulator sickness is believed to be caused by discrepancies between visual and vestibular cues[5], we believe Redirected Walking does not cause an increase in simulator sickness. We carried out a pilot user study to test the feasibility of the technique.

4. Pilot User Study

We explored the viability of the Redirected Walking technique with an observational, 11 subject, pilot study. Specifically, we wished to know if we could induce enough rotation to turn users and enable large VEs, while keeping the rotational distortion low enough that users would not notice the distortion nor suffer any increase in simulator sickness. We found that Redirected Walking satisfies these criteria. The details and quantitative data from the user study are presented as a technical report[6].

4.1 Task.

The task was a simulated fire drill. Subjects wore a head-mounted display with stereo headphones that presented the visuals and spatialized audio. Subjects were immersed in a virtual room approximately twice the size of the tracker area. Even in our large, 4m by 10m, tracking area, Redirected Walking cannot imperceptibly cause the user to walk in a complete circle, so we exploited waypoints to increase the size of our virtual environment.

Four buttons mounted on the virtual walls served as waypoints. Subjects were asked to push the virtual buttons, in order, using a tracked hand controller. Each button triggered an auditory and/or visual response related to the fire drill scenario: 1) practice, 2) sound the alarm, 3) close the windows, and 4) activate the fire suppression system.

4.2 Path in the Virtual Environment.

Buttons were located eight meters apart in both virtual and real space; participants had to really walk in order to travel between them. After pushing all four buttons, subjects were instructed to leave the virtual room through a doorway. The path took the subject through the virtual room in a zigzag pattern. The subjects had to stop at each waypoint to push the buttons. Subjects were instructed to walk calmly. They were instructed not to wander aimlessly about the room but to locate the next button before walking towards it.

4.3 Path in the laboratory.

As the subject turned to see the next button we inserted large amounts of distortion by scaling the user's rotation rate. After the subject turned, the next virtual button was almost lined up with the furthest wall of the lab. Any small misalignment that remained was then made up once the subject started walking, by applying rotational distortion proportional to the subject's walking speed. This yielded the arced paths seen in the lower portion of Figure 1.

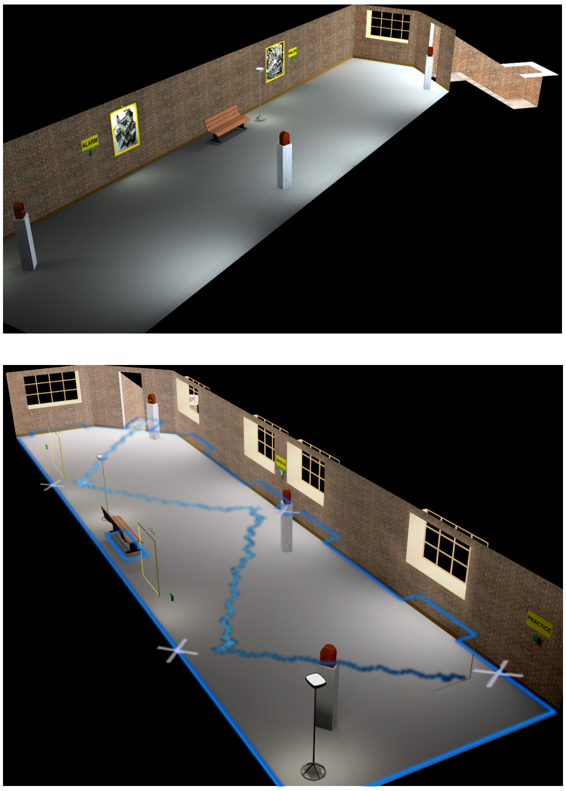

Figure 3: *Two views of the virtual environment. The user pushed the green buttons below the four yellow signs on the walls. In the lower view, a user's path is superimposed. The waypoints are denoted with white crosses.*

Figure 4: A user's view in the headset as she walks toward the button to close the windows. An antique radio, used for presenting pre-recorded instructions, is in the foreground.

Figure 5: A user's view in the headset as she walks toward the button to sound the alarm.

4.4 Computation of Rotational Distortion.

Our algorithm employed three separate components of rotational distortion. During development, we discovered that even while the user was standing still, we could slowly rotate the virtual scene and the user unwittingly turned in the same direction without noticing the distortion. Because of this, we injected a small, baseline amount of constant rotational distortion, even when the user was standing still. Second, we used a component of rotation related to the user's walking speed. Third, when the user turned herself, a higher frequency motion, we injected additional rotation proportional to the user's angular velocity.

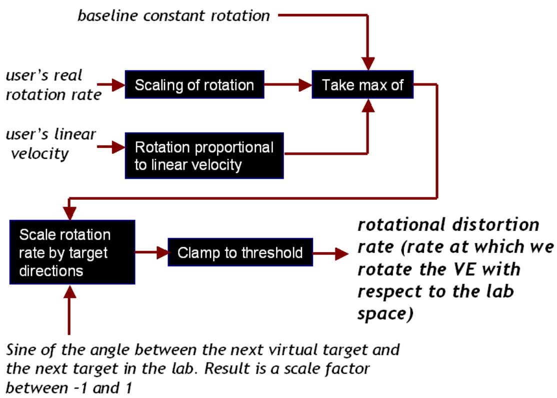

Figure 6: *The algorithm for computing the rotational distortion rate*

The rotational distortion we injected in any frame was the maximum of the above three components: constant rotation, rotation proportional to user's linear velocity, and rotation proportional to the user's angular velocity.

We then scaled this distortion rate by a "direction coefficient." The direction coefficient told us how much and in which direction we needed to steer the user. This coefficient was dynamically calculated by computing the sine of the angle between the user's direction in the VE and the direction we desired her to take in the lab. As implemented in the study, the desired direction was the direct path to the next waypoint. Finally, we compared the scaled combined rate to a threshold for imperceptible angular distortion. If the distortion rate exceeded the threshold, it was clipped to the threshold value. The threshold was set so that the rotations were imperceptible to all of our algorithm testers.

4.5. Hardware.

For this study, subjects wore a Virtual-Research V8 head mounted display, with a 60 degree diagonal field of view and a 4:3 aspect ratio. A veil prevented the subjects from seeing the laboratory. Stereo visual imagery was generated at 30Hz using one IR2 graphics pipe and one R12000 processor of an SGI Onyx2 Reality Monster. A custom wide-area optical tracker[7 8] provided position and orientation of the user's head and right hand at 70 Hz. End-to-end latency, including tracker filtering, network delays and image generation was measured at 50 to 115ms. Spatialized audio was generated by an Aureal AU8830A2 A3D 2.0 processor sound card in a Dell PC. They were presented through Sennheiser HD250 II sealed, circumnaural headphones.

Figure 7: *A user wearing the HMD and the wide area tracker*

5. Observations

5.1 Room size and walking direction.

The subjects were unfamiliar with our building and did not see the lab before entering the virtual environment. All of them were surprised, upon removing the headset, when they saw the actual size of the lab. All subjects reported that the virtual environment was larger than the lab space. Subjects were also surprised to learn they had been walking back and forth between the ends of the lab, rather than zigzag through the lab.

5.2. Sound.

Consistency of the auditory and visual cues makes it more likely that the brain will interpret the rotation as self-motion[4]. For this reason we believe a full 3D spatial sound model to be an important component of a VE using Redirected Walking.

The sounds were plausible in both content and source location. We also aimed to eliminate the sound related breaks-in-presence reported in Usoh 1999[1]. These were caused by awareness of lab noises and by instructions coming from a disembodied (experimenter) voice.

Circumaural headphones blocked ambient lab noise and delivered sounds to the user. The sound model included plausible environmental sounds coming from plausible locations; these help drown out lab noises. Experimenter instructions were pre-recorded and delivered in the headphones. The apparent sources of the instructions were the radios in the virtual room.

Our observations of the benefits of sound came not from users' comments, but rather from their lack of comments on the auditory component of their virtual experience. None of the 11 subjects reported hearing noises from the lab or sound-related breaks-in-presence.

5.3 Tracker size requirement.

We saw an as yet unquantified relationship between the size of the tracker area, the size of the virtual environment, the task, and the successful application of Redirected Walking. In an early testing phase we used a narrower tracked space (3m x 12m) and no testers successfully finished the fire drill. The technique failed either because the testers walked into the real walls when we used low rotational distortion rates, or they were aware of the rotations. When one meter was added to the width of the tracked area, almost every tester could complete the task without noticing the rotational distortion. Even a modest increase in tracked area allowed us to successfully use Redirected Walking to portray a much larger virtual environment.

5.4 Preventing Failures.

Occasionally during the algorithm development phase, testers came to be on paths taking them out of the tracker area or into a lab wall, due to tracker failures or mistuned parameters. We learned that when this happened we could momentarily distract the user in a way that allowed her to complete the task without running into walls. When the user was about to run into a (real) wall we played instructions from the virtual radio telling her to stop walking, then to look left and right. As the user turned her head, the algorithm had an opportunity to turn the virtual scene so that the direction of travel in the virtual world came to be within the tracked area. The user then resumed the task. To our satisfaction, the testers reported that they stopped and then continued walking in the same direction, when in fact they turned 90 degrees or more in the lab!

6. Comparison to other Techniques

In addition to flying[9], walking-in-place[10 11] and redirected walking, there are several other techniques that allow users to explore VEs that are larger than the tracked space. Among these are unicycles[12] and bicycles[13], single and multi axis treadmills[13 14 15 16 17], and leaning gestures[18 19].

Each of these methods has it's own advantages and disadvantages. Real walking provides multi-sensory cues: visual, vestibular and proprioceptive[20]. Treadmills provide realistic proprioceptive cues of walking. However, they work by canceling the user's motion (like walking on slippery ice) and thus may not provide vestibular cues[11]. Furthermore, single axis treadmills are disorienting while the user is turning in the VE[13]. Leaning gestures are mechanically simple and do provide some vestibular cues, but do not provide the proprioceptive cues of walking.

We believe Redirected Walking can provide consistent and realistic visual, vestibular and proprioceptive information to the user. To its' disadvantage, redirected walking requires a larger tracker space than any of the other techniques. It either requires that the tracked space be much larger, so that user can be made to walk in a full circle; or it requires the VE to have pre-defined waypoints. Also, redirected walking cannot present uneven or hilly terrain, as can some of the gimbaled treadmills[16].

7. Future Work

Redirected Walking has potential. We will perform a formal study to prove the efficacy of the technique. Redirected Walking can be both tuned and extended. We speculate that Redirected Walking will work better with a higher frame rate and improved measurement of linear and angular velocity. We intend to find out how much of each constituent type of rotational distortion, as a function of user linear and angular velocity and acceleration, we can inject imperceptibly.

In the current version of the algorithm we exploit only rotational distortion. We speculate it is also possible to distort the user's walking speed without her noticing. In order to do this we need to measure linear acceleration and make the linear-vestibular, visual, and auditory cues consistent.

We would like to explore how much the Redirected Walking technique relies on the consistency of the visual and auditory signals. Can we replace spatialized audio with non-spatialized audio and get the same results?

Finally, we would like to determine the minimum tracked area in which we could imperceptibly walk a user in a complete circle. This would allow us to achieve the ultimate goal of Redirected Walking: real walking as a means of locomotion in virtual environments of unrestricted size.

Acknowledgements

We thank Frederick P. Brooks, Jr. for help designing the study and writing this paper, Henry Fuchs for suggesting the use of waypoints, Mark Hollins for valuable discussion on vestibular perception and Michael Meehan for feedback regarding the pilot study. We express gratitude to Bill Chung and the Vertical Motion Flight Simulation Laboratory at the Nasa Ames Research Center for explaining and demonstrating techniques used in motion simulators to induce vestibular cues. We also thank Greg Welsh for help editing video, and Kevin Arthur, Bill Baxter, Stephen Brumback, David Harrison, Kurtis Keller, John Thomas and Greg Welsh for hardware support. Finally we thank Michael Zyda and Rudy Darken for informative discussion on various locomotion techniques. This work was supported by NIH National Center for Research Resources, Grant Number P41 RR 02170.

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