Supporting Free Walking in a Large Virtual Environment:
Imperceptible Redirected Walking with an Immersive Distractor

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ABSTRACT

Redirected walking, a technique in which the user's orientation in the physical space is constantly and imperceptibly changed from their orientation in the virtual world, has been shown to be an effective technique when only a limited physical space is available. Unfortunately, previous efforts have restricted redirected walking applications to operate under the constant supervision of researchers to prevent the users from leaving the tracked area. In addition, Virtual Environments (VE) used in these applications were often limited to narrow hallways, mazes or predefined waypoints, while the performance of redirected walking in a large, open VE is not well explored. In this paper, we introduce the idea and implementation for an *imperceptible redirected walking* system that supports the illusion of free walking in a large, open virtual environment with minimal amount of physical interventions, by integrating the distractor into the user's main immersive activity in the VE. We demonstrate this new approach with two user studies of an immersive interactive game. Our study indicates that for the majority of the subjects, the illusion is maintained of unconstrained walking in a very large area (a full-size basketball court, 50 feet x 95 feet), even while they were limited to a physical area of a mere 6% of the size of the basketball court (16 feet x 16 feet tracked area). Our result demonstrates that the illusion of free walking is created, since a majority of them was not interrupted by the researchers and did not realize they were redirected, and the 34 subjects took vastly different routes to reach the distant goal (See Figure 2). We believe that this technique demonstrates a more immersive way of designing redirected walking application and shows possibility of bringing redirected walking applications out of the monitored lab environments. Our result may provide insights for the designers of immersive experiences to create other redirected walking applications for consumer VR systems with room-size tracking.

CCS CONCEPTS

•Computing methodologies → Virtual reality; •Human-centered computing → User studies;

KEYWORDS

Redirected Walking Immersive Distractor Virtual Environments Experimentation

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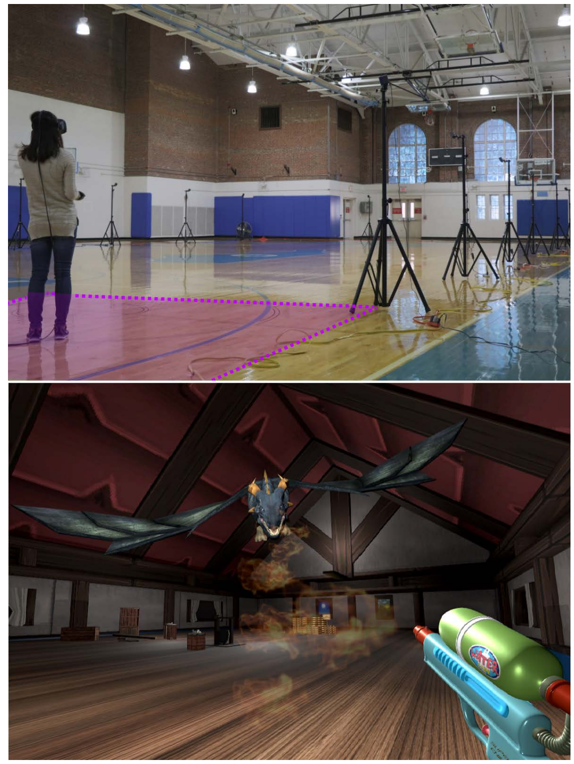

Figure 1: Our experiment setup on a full-size basketball court (top) and the view of our virtual environment from the position of the user (bottom). A 16 feet by 16 feet square marked by the red region was the actual tracked area. The tracking equipment mounted around the entire basketball court was used to give an illusion to the subjects that they would be able to walk freely in the entire area.

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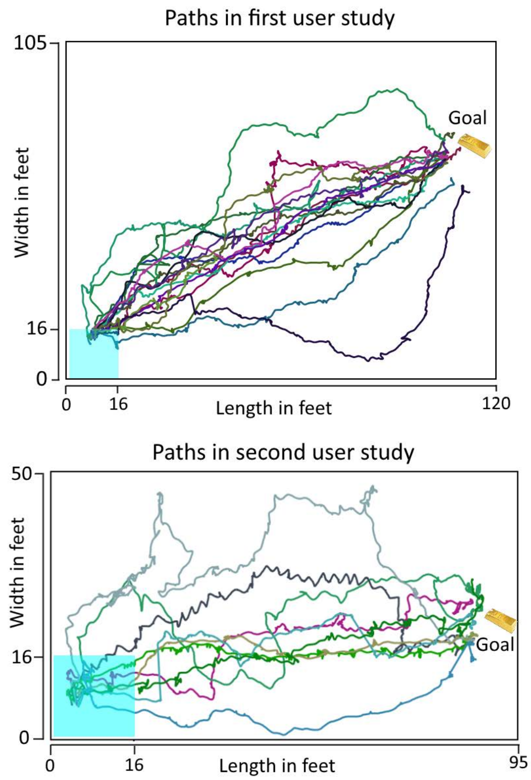

Figure 2: Visualization of the walking paths from the two studies. Each subject's path is marked by a unique color. The blue square at the lower-left corner denotes the size of the tracked area, in which the subjects actually walked. The figure indicates that the subjects did walk in varying paths, although the paths converge at the destination.

1 INTRODUCTION AND RELATED WORK

Redirected walking, pioneered by [3], has been demonstrated to be a promising way to allow the user to physically navigate in a larger VE than the available physical area. By interactively rotating the virtual scene about the user, the technique of redirected walking manipulates the user's route in the virtual environments, causing it to deviate from the real world path. When redirected properly, the user does not notice this rotation due to limitations of human perceptual mechanisms for sensing position, orientation and movement. Physical-walking locomotion interface combined with redirected walking shows the potential of faithfully and feasibly stimulating physical navigation of large virtual environments without causing noticeable simulator sickness.

As consumer VR systems that support accurate room-size tracking, such as the HTC Vive, become more affordable, whether redirected walking techniques can be brought out of the lab environment and integrated into regular use of VR applications without compromising immersion becomes a key concern. This goal faces the challenge of designing redirected walking systems to be free from the needs of supervision and intervention from researchers. Unfortunately, many previous redirected walking systems are limited in this aspect as they rely on methods such as training, giving verbal warning or turning off the display to prevent the users from walking out of the tracked area ([1], [2], [3], [8]). This makes redirected walking inseparable from others' assistance, which may occasionally disrupt the users' sense of presence.

Besides the concern of intervention in redirected walking, relatively free walking in a large, open VE is also barely seen in previous redirected walking systems. Many experiments instructed users to walk along a predefined path ([3], [4], [5]), while others confined the users in narrow virtual space ([2], [7]). [1] demonstrates an experiment that supports free navigation in a large, open VE, but at the expense of using a very large tracked area (nearly 1000 m^2). Specified paths and maze-like VE structures have the advantage of increasing the predictability of the users' walking directions or head rotations at specific locations of the VE. However, the requirement for a specially structured VE also imposes a limitation for designers of virtual experiences. It was left unexplored how well redirected walking could support free navigation in a large, open virtual environment.

In this paper, we present a redirected walking system to address the two problems described above. Our core contribution is to integrate a distractor into the immersive activity that the users perform in a large, open VE, in which they can choose to walk towards a distant destination along many possible paths. The idea of distractor originates from Peck's design of Improved Redirection with Distractors (IRD) algorithm, in which she used a moving sphere and a hummingbird to move back and forth in front of the users ([2]). The design was weakened by the necessity of training and verbal instructions given to the users to look at the distractor during the VR experience. Our design provides an improvement over the original design in its ability to maintain the sense of presence: the users do not need to be trained or instructed to look at the distractors, or to be aware of its assisting role. They would be redirected when they are simply performing the VE tasks. Besides the distractor, we also integrate an immersive "deterrent", introduced in [2], in a similar manner to the experience to further prevent the users from crossing the boundary before they are redirected. The deterent can be virtual objects that occupy the space near an edge of the tracked area. We speculate that if the distractor and the deterrent are well integrated into the context of the immersive experience, the level of immersion can be kept at a maximum level. We further speculate that this system would work in a large, open VE, and that the users are able to choose their own route to walk towards a distant goal. Our system may demonstrate the potential of redirected walking applications to create an illusion of free walking in any VE and to be used in an unsupervised environment, such as one's home. Distractor and deterent, if designed properly, could be integrated into many meaningful VR applications. For example:

- virtual house tours in which the distractor could be a house agent who distracts the users by introducing each part of the house, and the deterents could be people or pets who live in the house.
- virtual tourism in museums and landmarks in which the distractor could be a museum guide, and the deterents could be other tourists.

- interactive games in which the distractor could be moving enemies, and the deterents could be movable traps.

2 SYSTEM

We designed a redirected walking system that integrates a distractor and a deterent into an immersive interactive game. In the immersive interactive game, the user, armed only with a water pistol, attempts to walk in a large virtual area to a distant goal, a pile of gold, which is guarded by a fire-breathing dragon (see the bottom figure of Figure 1). The dragon only appears to stop burning up the user if it gets sufficiently drenched by water from the water pistol. The system implements both a redirection algorithm and a distractor algorithm to redirect the users imperceptibly. The two algorithmic components operate independently of each other. The redirection algorithm merely tries to inject rotational distortion to the users' head rotation so that the users are redirected back to the tracking center. Because the users may not turn their head frequently enough to achieve adequate redirection, the distractor is triggered whenever the user approaches the edge of the physical tracked area until sufficient redirection is accomplished.

Our redirection algorithm is a modified version of the steer-to-center IRD algorithm proposed by [2]. We redirect the user's walking path by continuously and imperceptibly rotating the VE around the user, which was shown to optimally reduce incidence of breaks in presence compared to other redirection methods [6]. For simplicity, we set the prediction of the user's future movement to always point to the goal destination, as we expect that the users are unlikely to move in a reverse direction.

The distractor algorithm is devised to both redirect the user impercetibly and prevent the user from leaving the tracked area. The choice of "distractor," virtual objects or characters that are part of the experience, must consider its capability of attracting attention and stimulating head rotation while remaining as an integrated part of the VR tasks. The advantage of choosing a dragon in an interactive game representation is that the users are compelled to look at it while it rotates around the user. To minimize its interference of navigation, the distractor is only active when redirection is most needed. The action of distracting is therefore determined by a "trigger on" condition and a "trigger off" condition. First, a "safe circle", whose radius was heuristically determined to be 3 feet for a balance between effectivness and frequency of distraction, is placed at the center of the tracked area. The distractor is triggered on if 1) the user is outside the circle and 2) the direction to the goal does not intersect the safe circle. It is triggered off if the above condition is false. In our implementation, the dragon will start breathing fire towards the user once it is set active. At the same time, it rotates around the user within the field of view. Its breathed fire is temporarily distinguished if the user manages to hit the dragon with water.

Additionally, to further prevent the user from leaving the tracked area, a deterent is placed at the edge of the tracked area that is closest to the user when the distractor is active. Our design of deterent is rendered as a wall of fire on the ground when the dragon is breathing fire. If the user walks into the fire, the display will immediately turns red to prevent the users from advancing further.

3 USER STUDIES

We designed and conducted two IRB approved user studies to test two hypotheses about the performance of our system:

(1) Our system is able to redirect the subjects in a large, open VE to walk to a distant goal without the need to instruct them to turn their heads, to stop them at any moment, or to give them any special instruction about redirected walking, and thus it minimizes interventions from the physical world during the immersive experience and creates the illusion of free walking in a large virtual environments.
(2) Our system allows the subjects to travel along different paths to the goal.

We designed the user studies to keep the fact of redirected walking hidden until the subjects completed the study. This is because we believe prior awareness of redirection may affect the subject's perception of whether they have really walked in a large virtual environment. It may also affect the subjects' response to the distractor given that they know it serves a special purpose. We conducted the studies on a full sized basketball court in order to provide the subjects with the illusion that they are able to walk in the entire area. The illusion can be shown to be maintained if the subjects report at the end of the study that they are far away (>= 30 feet) from their starting position.

To test our first hypothesis, we analyzed the reported estimated walked distances by the subjects and whether intervention by the research administrator was required for the subject. If a subject did not require intervention and reported an estimated walked distance of at least 30 feet from the starting point, we regard the first hypothesis as successfully proven in the individual study.

To test the second hypothesis, we collected data of tracked positions recorded by the computer. We visualize the paths of each subject and compute the percentage of the VE covered by the paths, for which we subdivide the VE into 3 feet x 3 feet floor tiles and find the percentage of the tiles that at least one subject has stepped in.

In addition, we also evaluate the effectiveness of our designed distractor by measuring the percentage of time distraction is required during the experience, average rotational distortion applied during distraction and the subjects' report on whether they find the distractor interrupting their experience.

3.1 Experiment Design

We designed two user studies to evaluate our redirected walking system. The second study is an improved version of the first study. The first study recruited 24 subjects and used a medieval-style hall of size 105 feet x 120 feet as the VE. A desktop PC rendered the VR program and was connected to the HMD with an approximately 20-feet long cable. A pile of wrapped cable, similar in appearance, was attached to the cable in use to hide its actual length. The second study, with 10 subjects, improved the design by replacing the desktop PC with a VR backpack (MSI VR one), as we observed that tethering in the first user study led some subjects to question whether they have really walked far from the starting point. We also remodeled the VE to be an outdoor scene with size 50 feet x 95 feet in the second study in order to match the size of the basketball court.

Both the studies were described to the subjects as an evaluation of an immersive VR game. No training was included in either of the

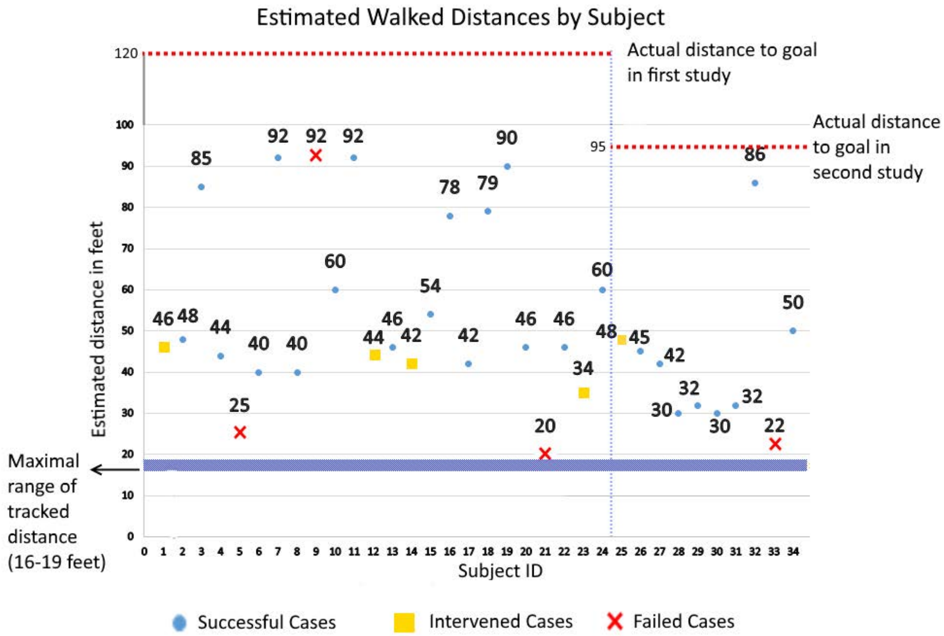

Figure 3: The reported distances from the 34 subjects in the two studies. The three cases shown by different markers correspond to path patterns shown in figure 4. The maximal actual distance that can be tracked from the starting point is approximately 16 feet (along the horizontal direction). As we observed that the subjects were tracked when they were 2 to 3 feet away from the boundaries, we extend the maximal range of actual distances to 19 feet.

experiments. Before the start of the study, the subjects were only instructed to walk slowly and informed that the goal of the game was to reach the pile of gold at the far side of the VE, while they defend themselves against a dragon. Several virtual objects were placed along the direct path to the goal in the VE, so the users may walk in varying paths. Once the study started, a researcher followed behind the subjects to ensure safety. If the subjects left the tracked area, they were told to stop and walk one step back. The subject was then marked as intervened in the research data. After the subjects reached the goal, they were asked to answer a question about their estimated walked distance on the basketball court, while they were still in the virtual environment wearing the headset. The subjects were also asked to complete a questionnaire in regard of their experience. When the subjects completed the study, we revealed to them the actual purpose of the study.

3.2 Subjects

The subjects were university students or employees who were at least 18 years old and had no difficulty walking without aid. 34 subjects participated in the experiments. All of them were given the same instructions. After the completion of the experiment, the collected data revealed to us that none of the subjects were familiar with redirected walking.

3.3 Software and Hardware Equipment

The subjects wore an HTC Vive Headset (90 Hz refresh rate, 1080 x 1200 resolution per eye, about 110° field of view). The Vive uses inside-out sensors both on the Head-mounted display (HMD) and the two controllers anchored by two diagonally placed "lighthouse" signal generators in a room-size space. Our tracking boundaries were configured to be a 16 feet by 16 feet square, although the users would be tracked if they were 1 to 3 feet away from the tracked area. One Vive controller was used to represent the water pistol. The immersive game application was driven by the Unity game engine with SteamVR library support.

4 RESULT AND DISCUSSION

4.1 Successful Rate and Walking distance estimation

Figure 3 shows a plot of the reported distances by the subjects from the two studies. It also shows three types of outcomes for each individual study: successful case, intervened case and failed case. In the successful case, the subjects were not intervened by the research administrator. The experience maximized immersion in this situation. In the intervened case, the subjects left the tracked area occasionally and were intervened. However, the subjects did not realize that they were redirected and thus they may still have the illusion of freely walking in a large space. In the failed case, the subject noticed redirection due to certain failures.

The results show that in the first study, the successful rate is 17/24, or 71%. In the second study, the successful rate is 8/10, or 80%. Most subjects (87.5% in the first study, 90% in the second study) estimated that they were at least near the middle of the basketball court when they completed the studies, and they were genuinely surprised after taking off the headset and finding that they were very close to where they started. Redirection, however, failed to remain imperceptible for 3 subjects in the first study and 1 subject in the second study. In the first study, two of them noticed that the cable was too short when they passed the physical tracked space, and thus stated that they couldn't have walked too far. The other subject pulled the cable off from the PC when she passed the tracked space, and thus took off her headset. She still reported a high number with the awareness of redirection (subject ID 9 in Figure 3). Since the three failed cases were related to tethering, the use of VR backpack in the second study has prevented this kind of failure. However, one subject in the second study noticed extra rotation when turning his head, even though he was not intervened during the study (subject ID 33 in Figure 3).

4.2 Variation of Paths

The visualization of the subjects' walking paths in the virtual space are shown in Figure 2. While the subjects never received instructions on how they should walk towards the goal, the paths they took in both studies showed significant variations. If each VE is subdivided into 3 feet x 3 feet floor tiles, we found that about 27.6% of the VE of the first study was covered by the paths, and 23.8% for the second. The result shows the potential that redirected walking algorithm could support relatively free walking in a large, open VE. If a crude prediction of the subjects' walking direction is known, some deviations in the paths from the estimated direction were shown to be tolerated. In our case, the subjects were allowed to walk towards directions that were at most 90°deviated from the direction towards the goal. Since all the subjects attempted to walk forward towards the goal, the redirection did not fail, although it became less effective the more the walking direction differed from the estimated direction.

4.3 Effectiveness of the Distractor

On average, the distractor was active in 48 percent of the time the subjects spent in the first study, and 45 percent in the second study. The subject's head orientations were distorted on average 31 degrees in the first study and 26 degrees in the second study when the dragon was attacking. When the dragon was not attacking, the averages were only 8 degrees in the first study and 7 degrees in the second study. In the first user study, the subjects were asked in the questionnaire whether they found the distractor interrupting their experience. 17 out of the 24 subjects at least disagreed that the dragon was interrupting and stated that it was an integrated part of the game.

Figure 4 shows three recorded walking paths from the first study in both the physical tracked area and the virtual environment, each corresponding to a case described above. The lines are marked in red in each of the visualized paths if the distractor was active. In the physical tracked space, the subjects' paths when the distractor was active contain most of the sharp turns from the tracking boundaries, because the distractor led the subjects to be redirected much more effectively when they were close to the boundaries. In the virtual environment, the visualized paths show that each active phase of distractor, indicated by a small segment of red line, enabled the subjects to continue walking towards the goal for a certain distance without

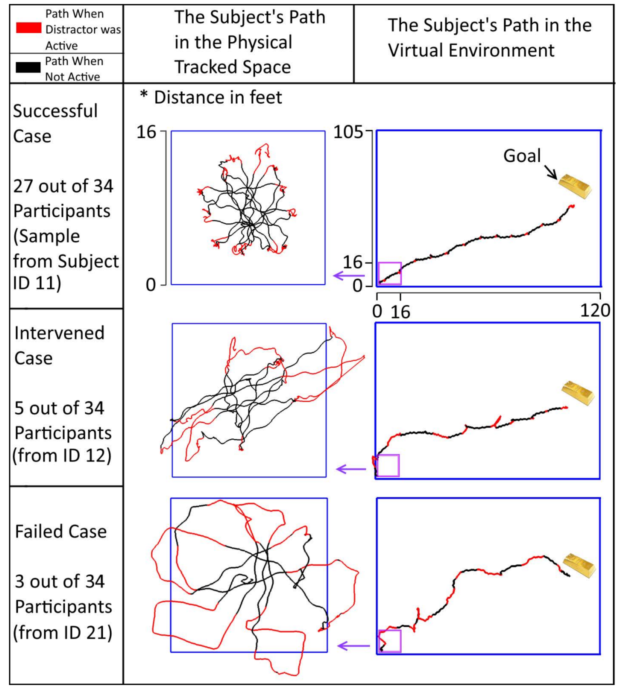

Figure 4: Path visualizations of the three different cases discussed in section 4.1

being distracted. An interesting observation from the visualized paths is that the subjects in the intervened and failed cases tend to continue walking when the distractor was active, while the sampled subject in the successful case walked very little under the same condition. Thus it appears that the distractor was more effective in cases where it managed to stop the subjects from walking when it was active.

5 CONCLUSION AND FUTURE WORK

We introduced a redirected walking system that aims to create the illusion of free walking in a large, open VE. By using a moving distractor that is integrated into the immersive activities of the VR experience, we hypothesized that our system is able to minimize the need for physical interventions, and thus provide an example for integrating redirected walking techniques into regular use of VR applications. We evaluated our technique with two user studies by recording the subjects' perceived walked distance in the VE, the variation of their walking paths and whether the subjects were intervened by research administrators. Our results show that in both studies, at least 70% of the subjects were redirected impercetibly, without the need for research administrators to intervene. Moreover, our results show that the subject's walking paths varied greatly in the large, open VE without causing failures. Overall, the results suggest that our system created the illusion of free walking in a large, open VE most of the time.

The major limitation of our system is that it always assumes the users would walk towards the goal, and thus entirely free walking (walk towards any direction at any time) is not supported. Free walking is only possible if the future walking direction of the users can be estimated within certain accuracies. In a large, open virtual environment, this task becomes most difficult as no constraint of walking direction can be inferred from local structures of the VE. Reliable prediction of the user's future walk direction remains an open question for future studies. Another problem with our design of distractor and deterent did not effectively turn or stop some users due to their intrusive nature. Future studies and designs of redirected walking applications can create immmersive distractors that attract and redirect the users in a more effective way.

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