Infinite Walking in Virtual Reality

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***Abstract*— The objective of this project is to design and develop a minimal viable product that allows users to freely explore a virtual scene that is considerably larger than a room-scaled tracked space. In this paper, we propose a redirected walking (RDW) technique combined with a user interface (UI) to avoid user-obstacle collisions. Via an HTC Vive headset and two base stations, our method redirects users towards the center of the tracked space by manipulating the virtual scene. Our application also displays a spatial UI to instruct the users to turn around when they are close to the boundary of the tracked space. This method is evaluated based on mathematical calculations and user studies. A user study is set up in a room of 2.1×2.9 meters. This study shows that our system successfully prevents users from hitting a wall and the design of the UI appears intuitive to users.**

I. INTRODUCTION

Current Virtual Reality (VR) systems use outside-in optical tracking systems to locate and track a user in a physical space. There are many videos and games coming out to the market. The most popular customer devices are HTC Vive and Oculus Rift. Both of them use a camera to track the position of the user when the user moves in the virtual world. However, in most situation, the real room space is limited and the virtual world is large. If the control-display ratio is 1, the user will have risk bumping into the wall. Thus, most of the games are designed to let the user move to the destination immediately, which is called teleport. The disadvantage of this method is that it will destroy the feelings of immersion. Thus, this method is not the best choice to be applied to a random exploration. We will propose our own method in this paper, which will not only let user move randomly but also make the user have real feelings of walking. One way to solve this problem is to change the control display ratio according to the distance to the wall. However, if we dont know the destination, it is hard for us to map the virtual distance to the real distance in a limited room. Another way we figured out is to redirect the user. If the user is walking continuously, we will redirect the user to walk in a circle. However, the limitation of this method is that if the room is not big enough, mapping a short straight line to the circle will let user feel dizzy. Thus, in a small room, we will not change the radius of the circle to be small artificially. Instead, we made a user interface to warn the user when they get close to the wall. This userinface is composed by two parts, one is an arrow letting user turn around in place, the other one shows the progress of rotation. In this way, a user can randomly explore the virtual world and because they are actually walking in the room, and their walking will not be limited by technology. This study aims to design the scene implementing the redirecting technology and gather data for our method to test the performance (Fig. 1).

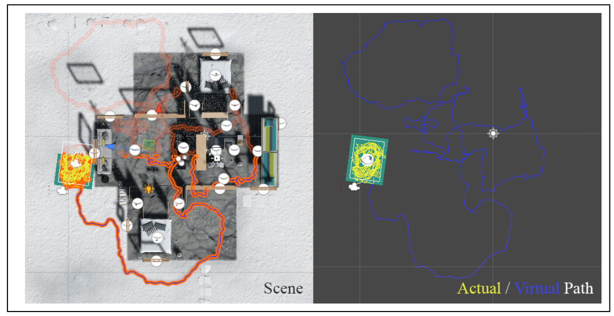

Fig. 1. An example trace with the actual and the virtual path marked on the map.

II. PRIOR WORK

Real walking experience in infinite virtual environments (VEs) has been a challenging goal in VR research. Much effort has been put in the field using different locomotion techniques to overcome the limitation of the tracking space in the real world. Among them, redirected walking (RDW) is a broadly used approach that enables users to walk on paths in the physical world that are different from the paths they perceive in the virtual scene [1]. Typically, RDW techniques subtly manipulate the viewpoint of users to reposition or reorient their walking direction. Some popular redirection techniques include steering algorithms [2] [7] [8] [10] [11] and stop-and-go techniques [12] [13] [14].

Steering Algorithms. Razzaque et al. [6] introduced the traditional approach of Redirected Walking by slightly rotating the users view to one direction while he or she walks on a straight path in the VE. They further proposed three steering algorithms: steer-to-center, steer-to-orbit and steer-to-multiple-targets[11]. The basic idea of that is to always redirect the user to one or more certain locations in the physical tracking space while the user explores freely in the virtual scene. Steinicke et al. [10] improved Razzaques technique by introducing manipulations by means of gains. Recently, a method that constraints walking in the VE to curved paths have been introduced [7]. It pre-defines several curves mapping the curved paths in the VE that are fitted in the tracking space and connected at specific intersections at which the user can turn. Ideally, the user staying on these paths should never hit the boundaries. Our approach is based on the steer-to-orbit algorithm to redirect the user to walk on a circular path orbiting the center of the tracking space.

Stop-and-Go Techniques. Most steering algorithms is unable to prevent the user from hitting a boundary of the tracking space no matter how well they are designed. In this case, the user needs to be stopped and reset, i. e. the user must be turned to a direction without obstacles to go into in the tracking space. Williams et al. [12] introduced the three methods: freeze-backup, freeze-turn, and 2:1-turn. Freeze-backup means that the virtual position of the user seen in the VE is frozen at the physical border, and he or she should walk backward until there is enough empty physical space in the front. For Freeze-Turn, the orientation of the user is frozen, and he or she should turn until there is space ahead. Lastly, in the 2:1-turn method, the user turns 180 degrees in real world while seeing a 360-degree turn in the VE. Similarly, the RDW toolkit [14] applies a stop-and-go approach that rotates the user when a boundary is reached. Other design includes assigning the point to stop and restart some meaningful metaphors, like a turning bookshelf [13]. We propose to handle the extreme situation where the user is approaching the boundary with a stop-and-reset design derived from the freeze-turn method. It varies from [12] in setting the threshold of when the user is safe to keep walking.

While one focus of some RDW techniques is to reorient users without noticing, another important goal is to keep users safe during the immersive interaction in room-scale VR settings. Previous research proposed to manipulate the control-to-display ratio, known as the go-go technique [5], to enhance the interaction experience and the sense of control [9]. Other studies have been carried out to examine how to prevent collisions in VEs [3]. However, there is no systematic approach for the safety purpose yet. Hence, our goal is to develop a software system combining previous RDW algorithms to enable users to walk safely and naturally in the VE within a limited physical space. The proposed method is designed to work in various kinds of VEs.

III. METHOD

Our method is mainly composed of two RDW algorithms and a user interface showing the user how to act when reaching the boundary. With redirected walking, the user walks in a tracked room that is much smaller than the VE in the same distance as physically as virtually. As a result, the user can explore the VE by actual walking in a safe way and overcome the limitation of the size of the physical space.

A. Redirecting Method

Redirected Walking techniques enable the user to walk on a path in the real world that may be different from the one in the virtual world by rotating the virtual scene in some specific ways. In our method, we incorporate two categories of redirected walking techniques, the steering algorithm and the stop-and-go algorithm. While the user will be steered to walk in orbit when walking along the same direction, she will be warned to stop and spin in place when she gets too close to the physical obstacle, i.e. the wall in our case.

1) Steer-to-Orbit: Among different types of steering algorithms, we choose to implement the steer-to-orbit algorithm proposed in [11] due to following two reasons. First, compared to "bending" algorithms like [7], there is no need to predefine paths in the VE for the steer-to-orbit algorithm. It aligns with our wish to let the user have unrestricted walking experience. Secondly, compared to other steering algorithms, including steer-to-center and steer-to-multiple-targets, steer-to-orbit makes better use of the limited physical space. Under the assumption that the user tends not to change the direction where she is heading, the steer-to-orbit approach enables the user to walk on a smooth path for a longer time.

The steer-to-orbit algorithm tries to steer the user to walk onto a circular path orbiting the center of the tracked space (Fig. 2 Left). After the user is walking on the orbit (2 Right), she can continue walking on the orbit as long as she walks straight in the virtual world. Once she makes a turn away from her heading direction, she will be steered to go back to the orbit. In order to realize the redirection, the angular velocity at which the virtual scene rotates is manipulated. While the user is turning away, the system increases the angular velocity of the virtual scene to reduce her turning away from the orbit center. Therefore, the user is steered back onto the orbit after the turning. The user should then be redirected to walk in a circle without noticing and be able to walk an infinitely long time without collision.

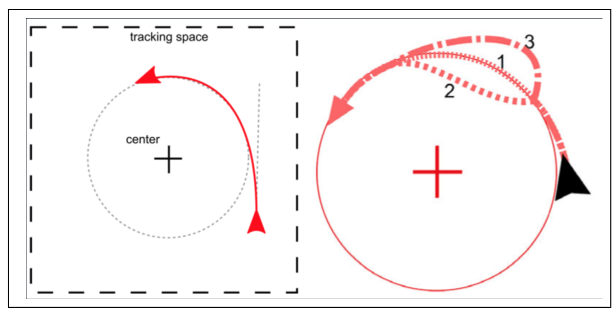

Fig. 2. Left: The user is steered to walk on a circular orbit. Right: Once the user is on the orbit, she will be redirected to keep walking on it when she makes no turning (path 1). When she turns away (path 2 and 3), the system steers her back to the orbit. [12]

2) Freeze-Turn: Ideally, as the steer-to-orbit algorithm being successful, the user can walk without touching the boundary. However, there are always extreme situations such as that the user unexpectedly turns away from where she is heading. In addition, steer-to-orbit fails when the tracking space is too small. It results in the case that the user runs into the boundary before being steered onto the orbit. Hence, we handle these extreme cases with the stop-and-go method. We implement a revised version of free-turn proposed by [12].

When the user is detected to be close to one boundary (Fig. 3), our system indicates that she is in danger and should stop and reset. The user is notified to turn around. When she is turning around, the virtual scene shown on the display of her headset is frozen until she is 100 degrees away from the normal vector to the wall. At this point, the scene is unfrozen and the user is free to keep her walking.

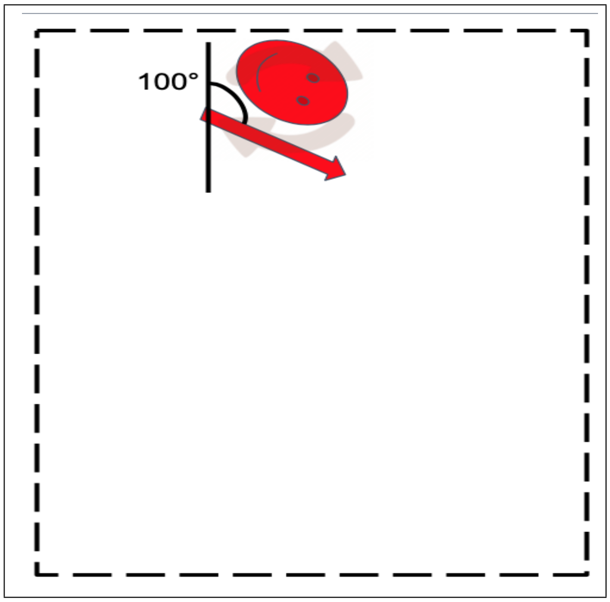

Fig. 3. When the system detects the user approach the boundary, it indicates that the user should turn around to have space to continue walking.

We choose the threshold of turning away to be 100 degrees because we consider a 10-degree angle from the wall to give the user enough safe space to continue her exploration. Admittedly, it is not the optimal solution. It would save the user efforts if the angle could be calculated such that the user has the largest available space to walk in the VE. However, as we propose that our system should work in various VEs. We manually set the threshold given that we know nothing about the VE in advance.

B. User Interface Design

The user interface consists of two parts: the warning (red) and the progress percentage (yellow)(Fig. 4). The warning sign contains a 360arrow and the phrase spin in place. It was designed to remind users to turn around when they see this UI. The progress bar reflects the percentage of degrees the user has completed before the UI disappears in real time.

Fig. 4. A screen shot of out "spin in place" warning. Above the rotating arrow, the completion of the turning is shown so that the user knows when she is safe to continue.

IV. Experiment

This section introduces the devices, the room-scale tracking space and the virtual environment we use to experiment our system.

A. Device

Our VR program is developed in Unity for HTC Vive to do the experiment.

B. Tracked Space

We use the physical space tracked by two camera stations as shown in Fig. 5. It is a rectangle room with 2 m in width and 3 m in length.

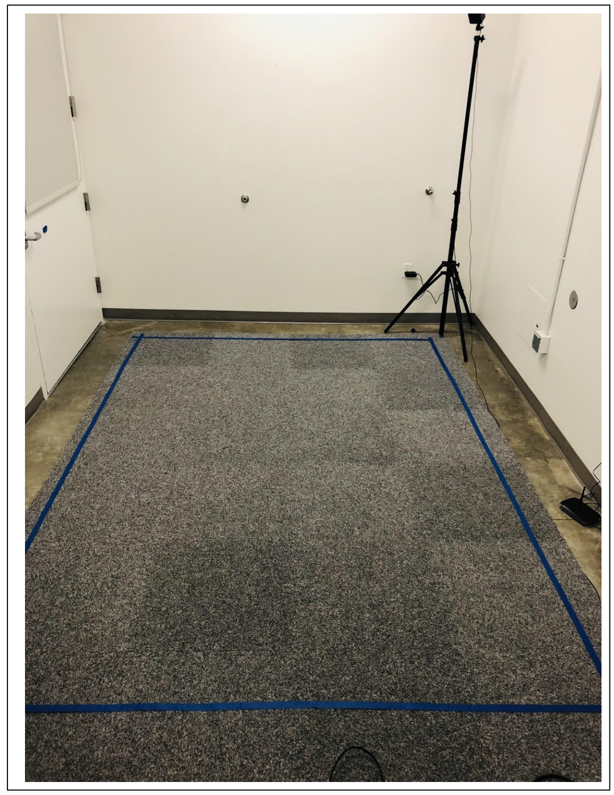

Fig. 5. Our tracked space.

C. Virtual Environment

We design the VE so that we can test our method for different styles of scenes and different tasks of exploring them. Therefore, our environment is made up of a one story house with rooms of different functions and a wide outdoor snowfield.

The house (Fig. 6) covers an area of 10 m by 10 m. Inside, there are five rooms: two bedrooms, a living room, a bathroom and a kitchen. There is not too much furniture in the living room, offering a spacious place for walking without obstacles. However, the arrangement of the room is not too obvious. For example, the bedrooms are partly visible from the perspective of the living room and the bathroom is hidden behind the kitchen cupboard. The arrangement of the rooms is somehow interesting to explore.

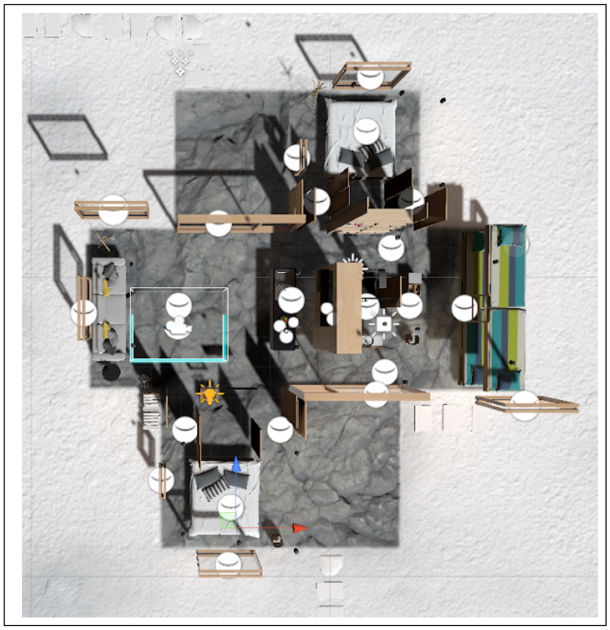

Fig. 6. The floor plan of our house.

Outside the house, there is a snowfield (Fig. 7) with many trees covered in snow. In the distance, there are mountains surrounding the boundaries. Because the area of the snowfield is significantly larger than the house as well as our tracking space, we consider it as an infinite VE.

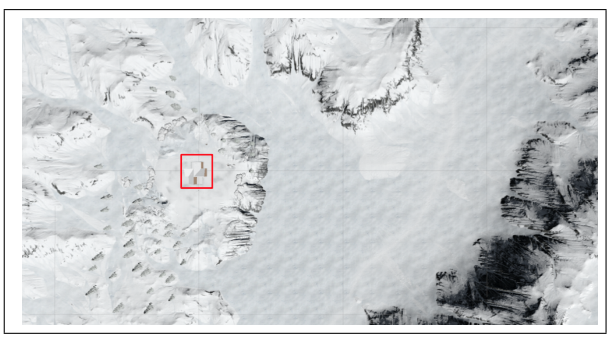

Fig. 7. A top of the virtual world. The house is marked by the red square.

V. User Study

This section describes how the user study was designed, executed, and evaluated.

A. Recruitment

There were no requirements for users to have previous experience with a specific VR system or experience with VR at all. Users were recruited with the aim of having diverse groups with regards to prior VR experience and gender. Age diversity is preferred. All users were students of the University of California, Berkeley. Users ages ranged from 20 to 26 years old and 60% of them were male.

B. User Test

There were two rounds: the pilot round and the regular round. The pilot group had 7 unique users and the regular group had 13 unique users, so 20 users in total for the study. Some adjustments had been made after the pilot round had finished. Users participated in the pilot tests were not allowed to participate in regular tests.

Each test was conducted by two moderators with one user. The user was instructed to stand in the center of the tracked space and put on the headset. One moderator briefly explained the virtual environment to the user. Users were given instructions to turn around if they are close to the boundary of the tracked space. However, they were not told about the design of the UI and how to interact with it. They had not seen our housing scene either before tests started.

Once the user informed the moderator that they understood the instructions, the moderator started the application. The user remained in place but was allowed to look around the scene in order to get comfortable with virtual reality. Once the user was ready to go, the moderator announced the tasks and started the timer. The tasks given were:

1) Start from the center of the living room (fixed for all users) and walk to the apple on the kitchens desk.
2) Explore the scene for 3 more minutes.

An average user was expected to finish task 1 after being redirected for 2 - 3 times.

C. Data Gathering

Qualitative data was gathered from the following sources:

- Observations made during the test:
  - Did the user realize that the scene is frozen during rotation?
  - How did the user react to the user interface(the warning of bumping into the wall)?
  - How long does it take for a user to get the apple?
  - Did user bump into the wall?
  - Is this user get stuck at the corner?
- Questionnaire after the test:
  - Age
  - Gender
  - How do you feel about the UI reminding you to spin in place?
  - Do you feel comfortable with the redirection?
  - Are you willing to participate open house tour in this virtual way? Any further suggestions?

These results were then compiled and analyzed. Trends in participant reactions and responses (if statistically significant) determined whether the user is limited by the technology and whether our technology has future potential. (i.e. If the user bumped into the wall or got stuck at the corner, or are they willing to make virtual house tour). For areas where the results could not be statistically validated, such as if users feel dizzy, how comfortable are they with the warning, these result needed to be observed and argued for by the author. To complement the qualitative data, which was the primary source, quantitative data was gathered in the form of time to complete each task. This data was gathered with the purpose of establishing a baseline for the other data. If a user is very skilled at the game, it stands to reason that they would be faster than a less skilled user and they will be more comfortable with the VR environment and interaction with the virtual world.

VI. Results

This section presents sample results from the user study. We had made modifications to the user interface after the pilot testers had taken the user study. Therefore, this section excludes the pilot users. Users aged between 21 - 24 and 62% of the them are male.

A. Task Performances and Questionnaire Responses

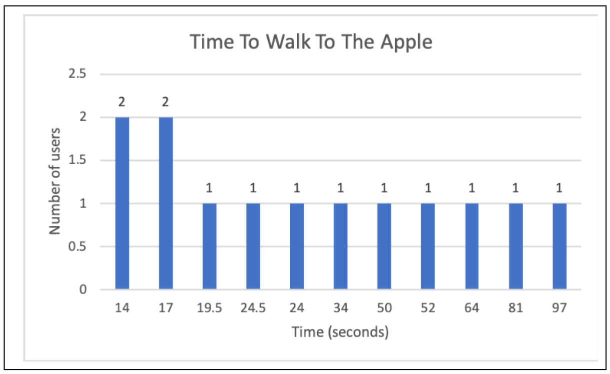

Fig. 8. Time for users to walk to the apple.

Results from task performances show that the mean time for users to finish Task 1 (walk to the apple) is 39 seconds. However, we can observe that the variation is large. Some users finish the task in less than 20 seconds while some other users take longer than 1 minutes to finish it (Fig. 8). This variation could be explained by the responses collected in the questionnaire. The first question was "how do you feel about the UI reminding you to spin?." Most users thought that the instruction given by the moderator is sufficient enough for them to understand and react to the UI. It was intuitive for them to turn around when they saw the red warning. However, some users took extra time to figure out what the warning meant before they reacted. One pointed out that the "spin in place" warning could be more obvious. Another suggested that although it was easy to observe "while it can be more clear, such as spinning speed and clockwise." Two users were confused by the percentage shown. The application started to cause dizziness after users had been playing in the scene for approximately 3 minutes. The second question was "do you feel comfortable about the redirection?" It took a shorter time for users to spin when they got used to the redirection than when they first started. Thus, most users began to feel dizzy when they began to turn very fast during redirections. The last question was designed to gain more insights about the potential use of such applications ("Will you consider using VR to take a virtual house tour in the future?") Our experiment theme was designed to demonstrate a virtual house tour. Users were positive about involving VR experiences in future house tours. One user suggested that it would be better if the physical experience were also included. Lastly, many users suggested that the cable connecting the headset to the computer is interrupting their immersive experience. 90% of the users thought a reasonably larger tracked space would improve this system.

B. Test Observation

Most users who had previous experience with VR understood the warning which is turn in place, and after being redirected, most of them can find the previous direction, and get close to the apple quickly. Some of the users who dont have previous experience in the VR system misunderstand the warning. Some of the users cannot find the previous direction because they turned too quick, the angle that they turned has exceeded the threshold of scene freezing. Thus, they wasted lots of time finding the apple every time after being redirected. We also observed that for the users who have lots of difficulties in reaching the apple, in their second task, they seemed to be more comfortable with our technique. Another observation is that for a small room, setting a rotation angle threshold is not enough, because it is easy to be redirected to another boundary and user has to turn in place again.

Moreover, there are also some limitations in setting the room. For the room which has a large glass as the wall, always lead to the wrong calibration of tracking space. Thus, we should avoid using a camera to track the user in an environment which has lots of reflection.

VII. Method Criticism

After a series of user test, we found that there are still lots of details have disadvantages and needed to improve. Firstly, the threshold of rotation angle should be set as a dynamic parameter. This improvement will solve the problem that user getting stuck in a corner in a significant way. No matter user get close to a wall in which angle, the rotation angle should lead the user to turn to the center of the room. In this way, they will not get to another boundary quickly. Secondly, some of the users commented that getting through the object was weird. When considering solving this problem, we first need to make the virtual world compatible with the real world. If we change the wall objects to be meshes so that users cannot get through them, we should also have some design standards for the scene to avoid trapping a user in a dead corner between a virtual wall and a physical wall. Thirdly, we freeze the scene when the warning appears to make the user easier to find their previous direction. Some of the users didnt notice this character but some of them feel confused about this technique. Last but not least, the warning reminds users to turn in place. Some of them ask us which direction to turn when taking user test. Our warning should be more clear to let users know, both directions work.

VIII. Conclusion

Our current technology is composed of two parts, the first part is redirecting the user to orbit, which let user walk in a circle instead of walking in straight line. Thus, the user will not have risk bumping into the wall. The other part is using the user interface to remind the user to turn in place, which is a baseline to avoid bumping into the wall. In our user test, we set a scene which is a house with beautiful details. We also test the potential application of VR system and our technics. From the result of the user test, we can conclude that infinite walking has a promising future in applications with a large map and an immersive virtual tour.

IX. Future Work

Many users expressed the desire to change the object in the virtual world to be mesh and others demanded intuitively change of scene, and they wanted to walk a long distance before getting closer to the boundary. They also wanted this technology to be less dizzy.

As discussed in the method criticism, the most important algorithm needed to be changed in the future is that we should set the redirection angle to be dynamic, which always redirect users to go to the center of the room. Another problem to be solved is the compatibility of the virtual world and the real world. If we change the redirection angle when user gets closer to the wall and this direction is not compatible with the virtual world, then left space will be narrow down.

Due to time constraints, we only did user tests for twenty people, thus, in the future, we would like to do more tests to figure out the disadvantages of our current algorithm. Moreover, our questionnaire can be more concrete, to evaluate users feelings about redirection, the time it takes to deal with the user interface. A more reliable questionnaire could also provide a more useful method to compare different techniques.

Appendix

Video Demo: `https://youtu.be/hS1753LknZ4`

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