Walking in Circles: Combining VR Redirection Techniques

Kunsh Singh
Ultimate User Interface Lab
University of Vrginia
Charlottesville, United States
bca2nk@virginia.edu

Seongkook Heo
Ultimate User Interface Lab
University of Virginia
Cbharlottesville, United States
seongkook@virginia.edu

***Abstract*—Real walking for virtual environments has been seen to increase immenseness over controller or joystick influenced movements. Many existing redirected walking techniques seek to exclusively use continuous redirection techniques such as translational gains and curvature gains, or discrete redirection techniques such as redirecting based on eye blinks, but few seek to combine the two. We present a novel solution that combines both continuous and discrete redirection techniques in order to attempt to preserve the natural feel of redirected walking in a smaller environment. Using both techniques in smaller thresholds may decrease simulator sickness.**

Keywords—virtual reality, vr, redirected walking, locomotion techniques, human computer interaction

I. INTRODUCTION

Humans have been known to have poor sense of direction without visual cues. Blind walking in the real world leads people to walk in slightly curved paths when attempting to walk in a straight line. We have seen that in virtual environments (VEs), we lose sight and thus our sense of direction similar to real blind walking. [1;2] Thus, if we rotate the virtual world at a rate that counteracts the physical rotation of a participant, we can create the illusion that the world is much larger than it actually is — this phenomenon is known as redirection. The redirection factor controls the proportion of rotation of the VE as per the distance traveled by the user in continuous redirection. In sizable environments with enough redirection factor, we observe that redirection can create enough curvature in a person's movement to move indefinitely in a circular shape: this is known as one-dimensional infinite walking. Such circular movement is known as *steer-to-center* when the circular movement is based upon the center of the VE, while *steer-to-orbit* is when the circular movement is based around another point in or outside of the scene. Infinite walking can be extended into two-dimensional infinite movement if we adaptively redirect when the person reaches the edges of the virtual environment, known as *curvature gains*.

II. BACKGROUND

Redirected walking in virtual environments employs techniques to subtly manipulate a user's physical movement in the real world while maintaining the illusion of unhindered motion in the virtual world. This method addresses the challenge of limited physical space, enhancing the immersion and sense of presence within the virtual environment. The core of redirected walking techniques revolves around the strategic application of rotational gains and translational gains, which adjust the user's perception of the VE subtly enough to remain unnoticed [3]. Applying such redirection at a rate proportional to the user's movement is known as *continuous redirection.*

Studies have shown that effective redirected walking requires a balance between perceptibility and the user's ability to adapt to virtual manipulations. The threshold of detection varies, influenced by several factors including the individual's awareness and the nature of the virtual environment. For instance, Boiling et al. [4] and Razzaque [5] identified specific thresholds for rotational and translational gains beyond which users begin to notice the manipulation, potentially breaking the immersion.

Moreover, the integration of *discrete redirection* techniques, such as saccadic redirection, which exploits natural eye movements to adjust the scene, enhances the feasibility of redirected walking in even smaller physical spaces without user awareness. This approach, when combined with continuous techniques, can potentially reduce the onset of simulator sickness, a common drawback associated with prolonged exposure to virtual reality environments.

The ongoing development in redirected walking research seeks to refine these techniques to allow for more naturalistic user experiences in virtual reality. The ultimate goal is to create a seamless integration of physical and virtual spaces, enabling users to explore expansive virtual worlds within the confines of their limited physical environments without compromising the immersive quality. The following study attempts to shrink the physical space size requirements by combining discrete and continuous redirection techniques from prior literature.

III. METHODS

A pilot study with 8 participants (3 female, 5 male) was taken, with 6 individuals having slight visual impairments or aliments, or more nearsighted than 20/40 vision without glasses. Continuous redirection with steer-to-orbit (STO) and discrete redirection using blinks were used to rotate the world, and thus cause the participant to redirect.

In order to determine the effectiveness of combining discrete and continuous redirection techniques in a smaller physical environment, we utilize a 4x4 meters physical space and observe redirection over 18 trials with randomized IV, each occurring a maximum of 3 times. The 6 IV levels were used included a control with no redirection, 3 IVs with fully continuous redirection (3 degrees/m or 0.075 redirection factor, 6 degrees/m or 0.15 redirection factor, 12 degrees/m or 0.3 redirection factor) and 2 IVs with both continuous redirection and discrete redirection with blinks (3 degrees/m or 0.075 redirection factor, 6 degrees/m or 0.15 redirection factor), however, realized curvature of path may differ. Trials that redirect solely with continuous redirection were deemed “no-blink” trials since they did not redirect based on blinks, while trials that combined both were considered to be “blink” trials. We gauge perceptibility and naturalness of redirection in the virtual environment using a 1-question perceptibility questionnaire score (PQ); we determined perceptibility the question “Did you feel any weirdness while you were walking?” on a 4-point Likert scale (0 = not weird, 1 = slightly weird, 2 = moderately weird, 3 = very weird). This was done as opposed to a simulator sickness questionnaire due to the nature of this being for a pilot study, such that we did not want to induce excessive burden on time for participants.

Participants were not given any prior knowledge that their virtual environment would rotate to create redirection; participants were tasked with walking on a designated line in the virtual world starting from a consistent spot in the real world denoted with black tape in a “X” shape on the floor. In the virtual world, participants were given a visual aid of a straight line on the floor of the scene. One trial was completed once the participant reached the border of the play space, such that the real world was slightly bigger than the play space in order to ensure the participant did not collide any real world walls. The real area was cleared around the player before each trial.

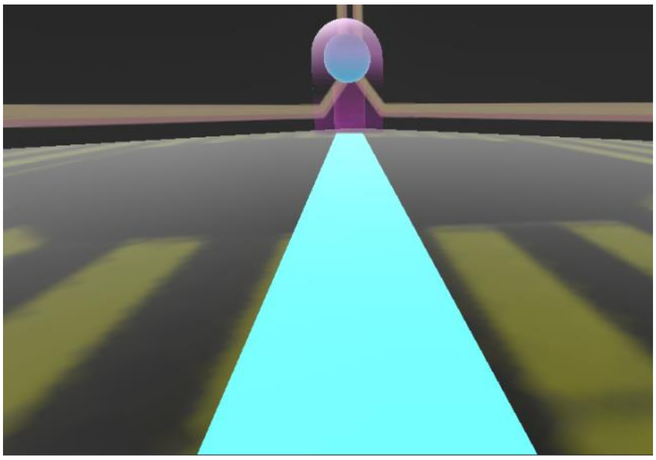
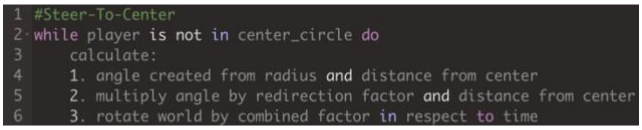


Figure 1: Virtual environment

A. *Steer-To-Center Algorithm*

The steer-to-center algorithm is a method of redirection that actively rotates the virtual world in an increasing magnitude as the user travels further from the center of the play space. These larger factors of redirection attempt to push the user toward the center of the play space, thus keeping them physically away from boundary while virtually allowing them to infinitely walk. The STO algorithm extends this exact redirection algorithm for any point that is not the center.

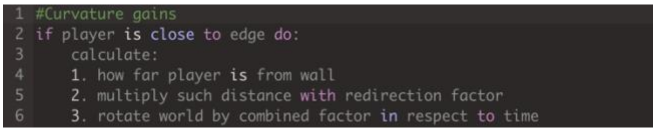


```
#Steer-To-Center
while player is not in center_circle do
    calculate:
    1. angle created from radius and distance from center
    2. multiply angle by redirection factor and distance from center
    3. rotate world by combined factor in respect to time
```

Figure 2: Steer-to-center psuedocode

B. *Curvature Gains Algorithm (Unused)*

The curvature gains algorithm prevents users from hitting the boundaries of the virtual environment by rotating the world by an increasing amount the closer the individual gets to the boundaries in order to keep the individual in perpetual motion, thus supporting two dimensional redirected movement. In a real-world scenario implementing such redirected walking, curvature gains would allow for further movement dynamics.

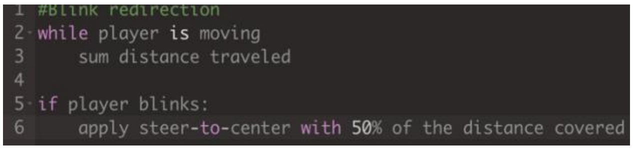


```
#Curvature gains
if player is close to edge do:
    calculate:
    1. how far player is from wall
    2. multiply such distance with redirection factor
    3. rotate world by combined factor in respect to time
```

Figure 3: Curvature gains psuedocode

C. *Blink Redirection*

The blink redirection proposed in the following paper works uniquely from previously researched methods. In the following methodology, the blink redirection works by accumulating the amount the world should rotate as the user travels without actually applying any rotations to the virtual environment. Then, once the user blinks, we rotate the scene 50% of the accumulated factor. The blink redirection code is shown below.



```
#Blink redirection
while player is moving
    sum distance traveled

if player blinks:
    apply steer-to-center with 50% of the distance covered
```

Figure 4: Blink redirection psuedocode

IV. DISCUSSION

To ensure redirection was taking place, the trajectories of each participant’s walking path was mapped. Equations 1-4 demonstrates the steps taken to calculate the interpolated and smoothed trajectory of walking for each redirection factor.

Redirected walking has been previously known to require at least 6x6 meters for minimal immersion, and by combining both continuous and discrete redirection techniques, we hoped to improve immersion for smaller room sizes, thus enabling redirected walking for room sizes smaller than 6x6 meters. Lesser physical space needed for redirected walking would allow for redirected walking

A. *Calculations*

Figure 5 demonstrates the average trajectory of the participants’ walking path averaged over the redirection factors used. To effectively calculate this we take the following steps.

I. Data Processing and Normalization

To analyze the movement of the participants navigating virtual environments, data smoothing and interpolation was employed in order to standardize the resolution of the trajectory data across trials, facilitating a comparative analysis of movement dynamics.

Prior to interpolation, the raw trajectory data, representing the positional coordinates of participants (denoted as x, z), were subjected to a preprocessing routine. This included the calculation of the cumulative distance traveled by participants, serving as a basis for the uniform resampling of the trajectory data. The cumulative distance D was computed as follows:

$$D = \sqrt{\Delta x^2 + \Delta y^2} \qquad (1)$$

such that Δx and Δz represent the differential changes in the x and z coordinates respectively across sequential time points in a given trial.

To achieve a consistent representation of trajectories, a spline-based interpolation method was applied. This involved fitting a univariate spline of order 2 to the positional data, relative to the cumulative distance traveled. The objective was to interpolate the trajectories onto a common set of distance markers, thereby standardizing the data representation across all trials.

$$Sx\,(d),\ Sz\,(d) = UnivariateSpline(D,x,z,k = 2) \qquad (2)$$

where D denotes the cumulative distance vector, k = specifies the spline order, and the method used for interpolation was *scipy.interpolate.UnivariateSpline*.

The interpolated trajectories were further normalized to ensure that each path's initial position coincided with the origin (0,0). This was achieved by subtracting the initial coordinates from the entire trajectory, aligning all paths for a coherent aggregation. The normalized paths for each experimental condition were averaged, yielding a representative trajectory for the condition. The averaging process was as follows:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} S_x^i(d),\ \bar{z} = \frac{1}{N}\sum_{i=1}^{N} S_z^i(d) \qquad (3)$$

where N denotes the number of trials under the same redirection factor and blink status, and $\bar{x},\ \bar{z}$ represent the averaged coordinates along the interpolated path.

II. Data smoothing with Quadratic Regression

The vertex (x_v, y_v) of the approximating parabola is determined first, since it is vital in estimating the geometry of the circular path that would be walked by the user if we extended the curve. We use a quadratic regression over the path of the user to determine a, b, and c for the following equations:

$$x_v = \frac{-b}{2a}, \qquad y_v = ax^2 + bx + c, \qquad a < 0 \qquad (4)$$

The a term is constrained to be less than 0 to ensure the curve concaves downward, and thus all walking trajectories are comparable since they are directionally similar.

The computation shown below is for the midpoint of the chord connecting the two points on the quadratic regression representing the start and end points of the walking path respectively, $p_1 = (x_1, y_1)$, and $p_2 = (x_2, y_2)$. The chord length d is derived using Equation 1, and the midpoints (m_x,m_y) is obtained by averaging the points p_1 and p_2.

$$m_x = \frac{x_1 + x_2}{2}, \qquad m_y = \frac{y_1 + y_2}{2} \qquad (5)$$

III. Calculation of Radius and Theta

To determine physical space requirements for redirected walking determined by the walking trajectories of each individual, we can use the radius computed below. From Equation 4, we determine the vertex of the parabola and add additional constraints to ensure the vertex we are computing is between p_1 and p_2.

Next, we use the sagitta s and chord length d to determine the radius r. Finally, θ is recomputed to determine the actual redirection in walking path experienced by the participant.

$$r = |y_v - m_y|, \qquad s = \frac{d^2}{8 \cdot s} + \frac{s}{2} \qquad (6)$$

$$\theta = 2\sin^{-1}\left(\frac{d}{2 \cdot r}\right) \qquad (7)$$

B. Analysis

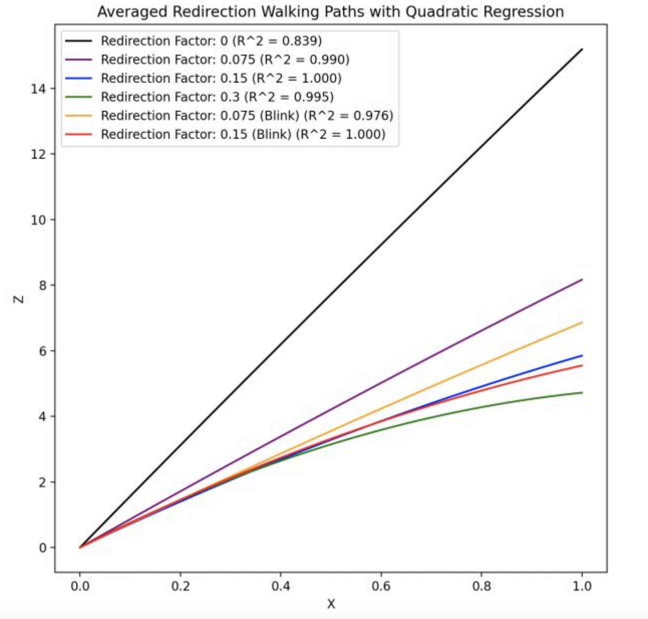


Figure 5: Average of participants walking trajectories

Figure 5 displays the averaged redirection paths of participants. Samples of position in the VE were taken at a frequency of 100 Hz. We smooth the walking paths with quadratic regression and interpolate them with 500 points to show how the path changes with different redirection factors, including two conditions involving blink-induced redirection. The curves are differentiated by color, each representing a unique redirection factor. Notably, the redirection factors of 0.15 (both with and without blinks) exhibit a perfect fit (r^2=1.000).

From the graph, it is evident that higher redirection factors, such as 0.3, result in a steeper slope. This indicates a greater change in virtual path per unit of real movement, facilitating infinite walking in smaller physical spaces by making more efficient use of the available area. Additionally, 0 redirection is very similar to y The blink trials, highlighted in orange and red for redirection factors of 0.075 and 0.15 respectively, show a slightly less steep increase compared to their non-blink counterparts but maintain high regression values, suggesting that combined redirection is effective at increasing redirection, but not enough to reach the next redirection threshold (ex. 0.075 redirection factor + blink is not analogous to curvature of 0.15 redirection factor).

We recalculate the following redirection degrees using Equation 7 of the participant proportional to Table 1 below. These likely differ from the true redirection we attempt to setup, since humans do not perfectly redirect as observed by others in prior literature, similar to the reason why people do not walk directly linearly especially when blindfolded.

Redirection Factor	Degrees
0.075	4.803
0.075 + blink	6.350
0.15	7.008
0.15 + blink	7.293
0.3	11.818

Table 1: Participant path curvature degrees

As per Equation 6, we calculate the optimal radius and average it across all participants for each redirection factor. We double each as well as add an additional 0.5 size buffer considering space between wall in order to determine optimal size of physical space. We determine a square space for optimal physical space because we assume a circular path for infinite walking. Calculated physical space requirements for each redirection factor shown in Table 2, such that the dimension represented is one side of a square space.

Redirection Factor	Physical Space Requirement
0.075	9.03m
0.075 + blink	7.74m
0.15	7.30m
0.15 + blink	7.19m
0.3	6.54m

Table 2: Redirected walking physical space requirements

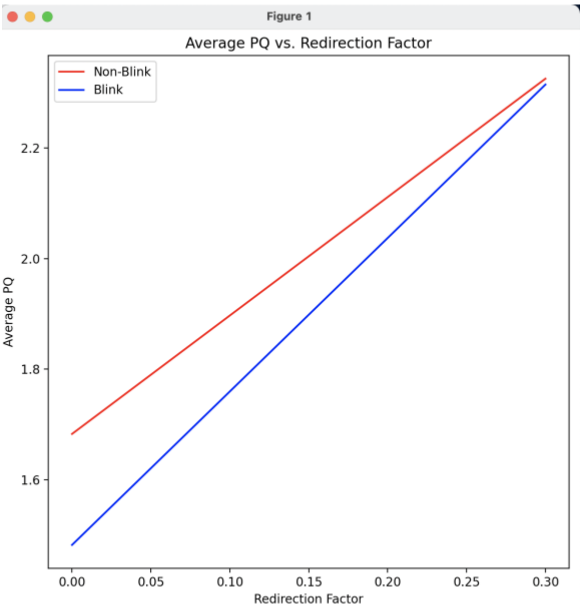


Figure 6: Perceptibility scores of continuous redirection

Figure 6 presents the averaged perceivability scores across all participant trials, with linear regression applied to estimate how changes in redirection factor influence participant perception of being redirected. The linear regression model provides a quantitative measure of the relationship between redirection factor and perceivability, crucial for determining the threshold at which redirection becomes detectable by users. Note that even the control (0 redirection) is not perfectly straight due to this phenomnenon as well as our smoothing, but we observe that our control does not fit to quadratic regression as well as our redirection factors thus.

This graph illustrates that as redirection factors increase, so does the perceivability score, suggesting a direct correlation between the intensity of redirection and user awareness. The combined trials of discrete and continuous redirection methods indicate that lower redirection factors are less perceptible, thereby preserving the illusion of natural movement within the virtual environment.

As highlighted in both Figures 5 and 6, the redirection factor of 0.3 is particularly significant. It represents the point at which redirection remains just below the threshold of general detectability, making it viable for practical application in redirected walking setups. This factor allows for an optimal balance between spatial efficiency and user immersion, requiring an optimal physical space of 6.54m to implement effectively. This space requirement ensures that users can walk indefinitely without encountering physical boundaries, while still maintaining the illusion of a much larger VE. This is in line with prior literature determining 6m x 6m space to be the minimum space required for redirected walking.

C. *Conclusion*

This study has demonstrated the potential of combining discrete and continuous redirection techniques to enhance the immersiveness of virtual reality environments while efficiently utilizing limited physical space. By integrating techniques such as STO and blink-induced redirection, we have explored novel ways to maintain the natural feel of walking within virtual environments that are physically constrained. Furthermore, we realize potential in combining redirection techniques due to lowered perceptibility scores in combined redirection trials.

Future studies combining discrete and continuous redirection techniques may attempt to reduce play area by increasing redirection created by blinks — this pilot study was unsuccessful in reducing the physical space needed for redirected walking, since the blinks did not redirect the play space enough. It should be determined if such combined redirection can preserve an immersive experience in smaller environments previously thought to be not suitable for redirected walking. Additionally, this study combines STO and blink redirection; future research could attempt to combine STC and blink redirection, as well as curvature gains and blink redirection, since both algorithms have been seen to be have greater relative effectiveness in smaller spaces [6].

REFERENCES

[1] Creem-Regehr SH, Willemsen P, Gooch AA, Thompson WB. The influence of restricted viewing conditions on egocentric distance perception: implications for real and virtual indoor environments. Perception. 2005;34(2):191-204. doi: 10.1068/p5144. PMID: 15832569.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Massoglia, Crystal, "Blind Direct Walking Distance Judgment Research: A Best Practices Guide", Open Access Master's Report, Michigan Technological University, 2021. https://doi.org/10.37099/mtu.dc.etdr/1223 K. Elissa, “Title of paper if known,” unpublished.

[3] Hayes, A. (2022). Will virtual reality connect or isolate students? In M. V. Albert, L. Lin, M. J. Spector, & L. S. Dunn (Eds.), Educational Communications and Technology: Issues and Innovations (pp. 139-150). Springer, Cham. https://doi.org/10.1007/978-3-030-84729-6_9

[4] Bolling L, Stein N, Steinicke F, Lappe M. Shrinking Circles: Adaptation to Increased Curvature Gain in Redirected Walking (2019). IEEE Trans Vis Comput Graph. 25(5), 2032-2039. doi: 10.1109/TVCG.2019.2899228. Epub 2019 Feb 20. PMID: 30794515.

[5] Razzaque, S. (2005). Redirected Walking—ProQuest [University of North Carolina at Chapel Hill]. https://www.proquest.com/openview/fb76f9b62be494669530d

[6] Azmandian, M., Grechkin, T., Bolas, M., & Suma, E. (2015). Physical space requirements for redirected walking: How size and shape affect performance. Proceedings of the 25th International Conference on Artificial Reality and Telexistence and 20th Eurographics Symposium on Virtual Environments, 93–100.