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Natural Walking Interfaces to Improve Immersive Training in Virtual Reality

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1 Introduction

Virtual reality (VR) allows users to be placed in a computer-generated environment and provides realistic visual feedback through motion tracking, high refresh rates, and a stereoscopic display [16]. VR presents a new opportunity to provide immersive experiences with applications to job training, entertainment, social interactions, and therapy and rehabilitation. One important aspect of providing users with a comfortable, immersive virtual experience is granting users the ability to freely explore the virtual environment (VE) [5, 6, 30]. Due to the importance of exploration for virtual experiences, it is crucial that we develop locomotion interfaces that provide the best user experience.

Research has shown that locomotion interfaces that allow users to explore VEs using natural, everyday walking are often preferred due to improvements in the user's sense of presence [34] as well as benefits to their performance on tasks in the VE [14, 28]. Despite these benefits, achieving natural walking in VR is difficult because the user's desired path through the VE might correspond to a path in the physical environment (PE) that yields a collision with an obstacle or exits the tracked space boundaries. Redirected walking (RDW) is a locomotion interface that mitigates this problem while allowing users to explore VEs using natural walking [26, 27].

Prior research has shown that RDW has promise as a natural, easy-to-use locomotion interface for VR [20, 24], but two major constraints still limit its effectiveness and practicality *outside* of controlled lab environments. First, current RDW algorithms do not work well when the size and layout of the PE are significantly different from that of the VE [2, 38]. This is because as the size and shape of the PE and VE differ more, the likelihood that a valid path in the VE corresponds to an invalid (collision-yielding) path in the PE increases. This problem is exacerbated for small PEs where free locomotion is difficult (e.g. a living room). The second condition that is challenging for RDW is when the layout of the PE changes dynamically or is not fully known at runtime. If the user's physical surroundings are constantly changing or the positions of physical obstacles are unknown, it is difficult for the redirection algorithm to reason about the user's surroundings and steer them on a collision-free path.

My dissertation makes progress towards creating a RDW system that is usable outside of controlled lab environments by mitigating the restrictions imposed by these two constraints. This is achieved using multiple innovations. First, we build upon the concept of *alignment* to develop new RDW algorithms that take into account both the physical *and* virtual environment to optimally steer the user away from physical obstacles [36, 37]. Additionally, we introduce new RDW algorithms that are built using a new formalization of the RDW problem based on motion planning [37]. This mathematical formalization allows us to leverage techniques from robot motion planning and computational geometry to develop steering algorithms that are more easily generalizable to different environment layouts without requiring us to update the algorithm implementation [38]. To further improve the usability of our RDW algorithms in dynamic, unknown environments, we propose to augment the traditional RDW pipeline with data about the user's PE that is computed in real time using computer vision. Finally, by taking into account the user's subjective perception of their virtual surroundings, we also improve the usability of RDW for a range of users in a range of VR system and VE configurations by developing new methods to accurately estimate how much redirection can be applied before users begin to feel symptoms of simulator sickness. Thus, my dissertation asserts that *knowledge of the user's physical and virtual surroundings and estimations of their subjective level of comfort can be effectively used to enable safer and more comfortable exploration of large virtual environments using natural walking.*

2 Results

2.1 Project 1: Smart Distractors for Improved Virtual Locomotion

The first result of my research completed while supported by the Link Fellowship is a project titled "Persistent Distractors for Natural Locomotion in Virtual Reality" which is currently under review at the IEEE Virtual Reality 2024 conference.

Natural exploration of VEs is especially challenging since the PE is usually significantly smaller than the VE. The greater this size difference, the more likely it is that a valid path that the user wants to travel on in the VE will correspond to an invalid physical path that yields a collision with a physical obstacle [38]. The two main approaches that enable natural walking and mitigate this simultaneous navigation problem are manipulated virtual architecture [7, 8, 31, 32, 33, 35] and redirected walking (RDW) [24, 26, 27]. With manipulated virtual architecture, the layout of the VE is modified [8, 31, 35] or the virtual geometry is warped [7, 33] to fit within the user's physical space. A downside of this approach is that it cannot be applied to applications where the precise layout of the VE is a hard constraint that cannot be manipulated (e.g., a virtual real estate tour). With RDW, subtle rotations and translations are injected into the user's virtual movements, which causes the user to subconsciously walk on a physical path that has a different shape than its virtual counterpart. One downside of RDW is that the benefit it provides scales with the size of the PE—RDW requires a large amount of space (and time) in order to significantly alter the user's physical trajectory such that they can be reliably steered away from obstacles [2, 23]. Considering that most people's living spaces, where they are likely to want to use VR, are quite small ($20 - 28\text{m}^2$ [9]), the utility of RDW is limited in the kinds of situations where a VR locomotion interface is most needed.

Main Results: In this work, we focused on enabling natural walking to explore large VEs when the user is located in a small PE, which we considered to have an area of approximately $20 - 28\text{m}^2$ [9]. We developed a new natural walking locomotion interface that leverages *persistent distractors*—elements of the virtual environment that the user continually interacts with over the course of their virtual experience. Our interface consists of two main components, a "safe zone computation" module and a "distractor behavior modification" module. When an interaction between the user and a persistent distractor is initiated, our method computes the regions of the physical space that the user can be guided towards without colliding with any unseen physical obstacles, which we label as *"safe zones."* After a safe zone has been chosen, the next step is to compute and execute a behavior for the persistent distractor that will influence the user to alter their virtual trajectory such that they are guided towards the chosen safe zone. In this manner, we are able to guide the user along virtual trajectories that decrease the chance of a physical collision. Our method is general enough to be applicable to any physical and virtual environment as long as the physical safe zones can be computed and an appropriate distractor behavior can be executed to guide the user to a safe zone. To evaluate our interface, we conducted three experiments and compared against a common benchmark for generalized redirected walking (steer-to-center [14]) paired with randomized distractor behavior. Quantitative results of our study indicated that when steered using our distractor-based algorithm, users were able to walk on average 1.6m further ($\sim$20.3% increase) before being forced to stop and reorient due to an imminent collision in the PE. Qualitative results indicated that participants found the distractor-driven algorithm to be engaging and that they were unaware that they were being explicitly guided around the PE. In summary, our main contributions are:

- A new VR locomotion algorithm that is based on continually integrating the virtual content into the path-planning system in the form of *distractors*. Unlike RDW, our algorithm causes users to overtly change their *virtual* trajectory such that it is less likely to yield a physical collision. We achieve this by computing candidate safe regions of the physical space and modifying the behavior of persistent distractors that the user engages with to guide them along collision-free trajectories. By overtly changing the virtual trajectory, it is easier to avoid physical obstacles in small physical environments where there is insufficient space for RDW to be effective.
- Three user studies that compare the effectiveness of our algorithm against a classic redirection algorithm (steer-to-center) with unoptimized distractor behavior. Results of our studies show that distractor-guided navigation allows users to travel an average of 1.6m further ($\sim$25.8% increase) before incurring

a collision with an obstacle, and that it can yield more immersive and comfortable experiences for users.

2.2 Project 2: Sensitivity to Radial Optic Flow Motion Artifacts in Stereoscopic Displays

The second project that was carried out (partially) under the support of the Link Fellowship is a project titled "Perceptual Thresholds to Radial Optic Flow Distortion in Near-Eye Stereoscopic Displays" which is also under review for publication at the IEEE Virtual Reality 2024 Conference.

VR displays allow users to interact with computer-generated environments in a way that is natural and immersive. Unique to VR is the feeling of presence, wherein the user feels that they are truly in the virtual environment that they are perceiving through the head-mounted display (HMD) [29]. Some important factors that contribute to this feeling of presence are a high-resolution, high refresh rate stereoscopic display [3, 13]; a wide field of view (FOV) [21]; and low-latency position tracking to render perspective-correct views of the virtual content [13]. These features improve the level of immersion provided by the HMD [29], and poor implementations of these features may introduce visual artifacts such as the screen door effect [19], screen tearing and flickering, chromatic aberration [39], and motion artifacts. Although these artifacts can break a user's sense of presence in the virtual experience, limits of the human visual system (HVS) mean that beyond a certain threshold, these artifacts are imperceptible [10] (though they may still impact the user experience [11]). For example, prior work suggests that a total system latency of $50 - 70$ms is tolerable for gaze-contingent foveated rendering [1], a measurement that informs HMD manufacturers on how responsive the eye tracking and rendering systems need to be. Thus, in order to understand how good the display, optical, and rendering systems of an HMD need to be to produce a sufficiently-immersive experience, it is important that we study the perceptual thresholds of the HVS for different types of visual artifacts.

In this work, we mainly study human sensitivity to radial optic flow patterns in wide FOV stereoscopic displays, with applications to distortion correction for varifocal HMDs. Varifocal HMDs are of interest because they are able to provide accurate focus cues as the user shifts their gaze around the scene to look at objects at different depths. In particular, varifocal HMDs allow users to see a clear, sharp image of the virtual content when it is very close to the user's head position in the virtual environment, which can help them to complete tasks that require very close proximity and a clear image of the virtual content (e.g. virtual surgery tasks). This ability to provide accurate focus cues mitigates the vergence-accommodation conflict (VAC), a problem which can reduce image quality and cause eye strain and fatigue after prolonged use of the display [15, 17]. One side effect of varifocal HMDs is image distortion that occurs when the system's focal power changes. In particular, changes in the focal power cause the virtual image size to change (i.e., image *magnification* or *minification*). To the user, this is perceived as a motion artifact in the form of *radial optic flow* (i.e., the retinal image appears to expand/contract and objects appear to move closer to/further away from the observer), and can manifest as a sensation of self-motion in the world. To eliminate this artifact, we can apply the inverse of this distortion to the rendered image so that the two distortions (from the applied distortion and the change in focal power) cancel each other out and there is no perceived distortion [4, 18]. In order to know how accurate the inverse distortion needs to be to prevent perception of the radial flow artifact, we need to understand how sensitive users are to radial optic flow.

Main Contributions: We conducted an experiment to measure human observers' sensitivity to expanding radial optic flow in a wide FOV stereoscopic display, motivated by the advent of varifocal HMDs with focus-tunable optics. To understand the viability of masking the flow artifact during blinks, we measured this sensitivity before, during, and after self-initiated blinks. Our experiment makes use of recent developments in HMD distortion calibration [12] and adaptive psychophysics [25]. In particular, we used a stereoscopic, wide field-of-view, eye-tracked display simulator [12] to emulate the radial optic flow distortion effect in a well-controlled environment. Since our experiment modified both the magnitude of the optic flow effect *and* the delay in the flow onset (relative to blink timing), we used an adaptive psychophysical paradigm [25] to reduce the number of trials needed in our experiment. In a psychophysical user study, we collected eye tracking data and subjective perceptual responses to radial optic flow from 12 participants. Our results show that users are extremely sensitive to image magnification artifacts during normal viewing of the virtual content, and that blinks can be an effective method of masking this artifact that yields a $10\times$ decrease in sensitivity to radial optic flow compared to without blink masking. In particular, we find that:

- Visual sensitivity to image magnification during normal viewing (no blink suppression) is about $0.1\% - 0.2\%$ change in image size.
- The maximum image magnification that can be hidden during a blink without the user noticing is about 2%, with some inter-observer variability ($1.14\% - 2.54\%$).
- Visual sensitivity to radial optic flow begins to recover ~ 70ms after the first detected frame of the start of a blink, and ~ 50ms before the first detected frame of the end of a blink.
- Our results have implications for varifocal HMD design and engineering. Results suggest that the error margins on radial optic flow correction in normal viewing conditions are *very* low and that discrete varifocal systems are an attractive paradigm for implementing varifocal HMDs, since the radial flow artifact can be reliably masked using blinks, as long as it occurs over a short enough time window.

2.3 Project 3: Physiological Signals During Walking in VR

The third project that I worked on while supported by the Link Fellowship is an ongoing project titled "Physiological Signals as an Indicator of Comfort During Locomotion in Virtual Reality." I will submit this project to the ACM SIGGRAPH conference in January 2024.

When users explore virtual environments using RDW, their perception of their surroundings is unstable since RDW injects additional rotations and translations into the virtual environment during locomotion. When these injected motions are too strong, the user will consciously perceive them and they will usually feel some discomfort in the form of motion sickness symptoms. Traditional methods for avoiding this motion sickness involve a long calibration process wherein the user is exposed to varying amounts of redirection and they give an answer about whether or not they perceived the motion that was injected into the virtual environment. This calibration process does not scale well since it requires multiple hours to complete, a person's sensitivity to redirection changes depending on the virtual content being viewed, and overall sensitivity to redirection varies across the human population, i.e., there are individual differences in sensitivity.

In order for RDW to be a practical technology, it is important that the amount of redirection applied is well-calibrated to avoid making the user feel uncomfortable. To help make this achievable, my project studied how different physiological signals changed as a function of the strength of redirection applied during locomotion, so that we can investigate the viability of using physiological signals as a proxy for user discomfort in VR. That is, if there are correlations between the user's discomfort level (as the strength of redirection increases) and their physiological signals, it is possible to monitor these signals in real time and adjust the level of redirection being applied if we see a pattern in the user's physiological data that is correlated with feelings of discomfort. In this project, the physiological signals we chose to monitor are position data and gaze data since these data streams are readily available on most VR devices. So far, I have completed an initial study that showed that as we increase the strength of redirection, users' postural stability decreases when they rotate in place where they stand. Although this rotation-in-place maneuver is not a typical movement seen in regular walking, it is a commonly-used paradigm for measuring users' sensitivity to RDW since it is easy for users to complete and causes the injected rotations from RDW to be more easily noticeable. Results from this initial study did not show any correlations between the strength of RDW and users' gaze data, although we believe this is due to the somewhat unnatural motion task we had users complete during the experiment. The next step in this project is to look for correlations between gaze data and redirection strength in a more natural setting that is representative of how RDW may be applied. In our second experiment, users will walk around in virtual reality while following and maintaining their focus on a moving visual target. During this walking task, we will slowly increase the strength of redirection and study how their gaze data changes over time. Our hypothesis is that as the strength of redirection increases, users' gaze will become more and more unstable over time since the target they are focusing on will move around more and more in their field of view, requiring more frequent eye movements to maintain focus on the target.

3 Significance and Impact

The findings of my work have multiple implications for future work in virtual reality. The first project on smart distractors lays the foundation for interaction-based RDW interfaces for VR. A core aspect that makes VR interesting is the ability to *interact* with the virtual environment—users in VR are often engaged with some component of the virtual environment and this usually occupies most of their attention. The next logical step for us to develop more sophisticated and effective RDW locomotion interfaces is to develop algorithms that take advantage of this constant engagement by *manipulating* the virtual content the user is interacting with such that it also helps them avoid collisions in their physical surroundings. Indeed, as VR technology becomes more advanced and widespread, it is crucial that the algorithms underlying the technology are able to adapt to different virtual contexts. My work on persistent distractors is a step in this direction, since my algorithm relies on understanding what content the user is interacting with and modifying its behavior in a *realistic* fashion that preserves the user's sense of immersion in VR while also guiding them along collision-free paths.

The second project, on sensitivity to radial optic flow motion in stereoscopic displays, has implications for both locomotion in VR and near-field interactions in VR. Radial optic flow motion can be mistakenly perceived by users as a sensation of moving forward through their surroundings. This is the same motion pattern that is perceived when users walk forward *and* when we inject redirected walking translations that amplify the virtual distance the user walks. By understanding how sensitive users are to radial optic flow artifacts in VR, we gain a better understanding of exactly how much injected motion can be applied using RDW to help shorten the distance users need to walk in VR. Furthermore, since my work on understanding sensitivity to radial optic flow artifacts has direct implications for the implementation of varifocal HMDs, this work is also important for developing new VR hardware that can allow users to accurately and faithfully interact with objects at a close distance in VR. For example, in surgical tasks it is important for the surgeon to be able to clearly see the patient's body so that they can correctly perform the surgery with high precision. These sorts of near-field tasks like virtual surgery or even reading small text in a book in VR are not possible with current commodity devices due to the vergence-accommodation conflict. My work on sensitivity to radial optic flow in VR provides necessary bounds on how much error can be tolerated when correcting for the radial optic flow artifact that comes along with varifocal HMDs.

The third project on physiological signals for discomfort has implications for understanding how users behave during locomotion in VR and for improving locomotion interfaces based on this behavior. If we are able to accurately estimate how comfortable the user is during virtual reality locomotion, we can adapt the locomotion interface being used to help mitigate any feelings of discomfort. Furthermore, by studying gaze and posture data in virtual reality, we gain a better understanding of the complex dynamics involved in the perception-action loop [22] and may learn how this process differs in virtual reality compared to in the real world.

4 Future Vision

In the future, I expect the VR research community to continue developing new locomotion interfaces to enable natural walking in VR that are adaptable to different virtual contexts and to different user preferences. Hopefully, my work will serve as a basis for how we can build interfaces that are tightly integrated with the virtual content and are able to change depending on the user's internal state. Future work should look to develop locomotion interfaces that are able to parse the user's physical surroundings in real time using computer vision techniques, and integrate this information into the systems' RDW algorithm to enable more effective collision avoidance behavior.

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List of Publications

Below is a list of journal or conference publications that will acknowledge the Link Foundation support. Note that the final citation may change if the papers are not accepted at the venues I submitted them to.

1. Williams, Niall L., Aniket Bera, and Dinesh Manocha. "Persistent Distractors for Natural Locomotion in Virtual Reality." 2024 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). IEEE, 2024.
2. Saeedpour-Parizi, Mohammad R., Williams, Niall L., Philip Guan, Tim Wong, Dinesh Manocha, and Ian Erkelens. "Perceptual Thresholds to Radial Optic Flow Distortion in Near-Eye Stereoscopic Displays." 2024 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). IEEE, 2024.
3. Williams, Niall L., Logan Stevens, Evan Suma Rosenberg, Aniket Bera, and Dinesh Manocha. "Physiological Signals as an Indicator of Comfort During Locomotion in Virtual Reality." ACM SIGGRAPH 2024 Conference Proceedings. 2024.

Impact of the Fellowship

Receiving the support of the Link Fellowship in Link Foundation Modeling, Simulation, and Training was an honor and a great help to making progress on my PhD dissertation research. The additional financial support provided by the fellowship allowed me to dedicate myself more deeply to my research, resulting in a more concentrated and productive effort. This benefit was additionally helpful for me since I joined my PhD lab with *my own* topic, so I had to serve as a teaching assistant for each semester of my PhD before receiving the fellowship. Additionally, this fellowship allowed me to take more risks with my research and pursue riskier research questions that may have been less likely to yield interesting results. I am deeply grateful for the invaluable support provided to me by the Link Fellowship.

Fellow Information

Name: Niall L. Williams
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