Beyond Sight: The Role of Kinesthetic Feedback in Redirected Walking within Virtual Reality

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***Abstract*—In this paper, we introduce a method and device aimed at enhancing the spatial efficiency of redirected walking (RDW) in virtual reality (VR) by modulating haptic perception alongside traditional visual cues. RDW is a technique that enables users to explore expansive virtual spaces by subtly manipulating their virtual perception, giving the illusion of vast navigation within a confined physical space. A key focus is the difference between the haptic and visual perceptions of virtual objects. Using active haptic feedback, our device allows users to feel a virtual wall during redirection, even when its haptic representation differs from what they see. We also present an algorithm that accurately determines the position between a user's hand and the virtual wall, ensuring reliable kinesthetic feedback. This research highlights the potential benefits and challenges of manipulating both the visual and kinesthetic senses in VR environments.**

I. INTRODUCTION

Redirected walking (RDW) in virtual reality (VR) is a technique that manipulates visual perceptions to allow users to navigate expansive virtual terrains within the confines of a limited physical area. Capitalizing on the brain's adaptability to minor sensory mismatches, RDW guides users in desired directions, maintaining immersion. However, while RDW has been transformative, its reliance solely on visual cues can pose challenges, especially when aiming to maintain a balance between increased sensory mismatch and the risk of cybersickness.

Building on the traditional RDW framework, our research presents an novel approach that goes beyond mere haptic feedback. We introduce the capability for haptic perception manipulation, mirroring the established visual manipulation in RDW. Utilizing an advanced algorithm and a kinesthetic cue device, our method actively simulates kinesthetic sensations, replicating the shape and hardness of virtual walls during interactions. This synergistic manipulation of both visual and haptic perceptions is posited to amplify the RDW experience. By harmonizing these sensory perceptions, we aspire to deepen user immersion, and enhance spatial navigation of RDW in VR.

II. RELATED WORK

A. Redirected Walking Techniques

Redirected walking (RDW) serves as a pivotal tool in virtual reality (VR), enabling users to traverse vast virtual environments within confined physical spaces. Central to RDW are steering algorithms, designed to subtly guide users' paths to maintain immersion within the virtual environment [1].

One method of RDW involves curvature gains, which introduce a perceived curvature in the virtual realm, inducing users to walk on a curved physical path while perceiving it as straight within the virtual environment [2]. This method is adept at optimizing limited physical spaces. However, excessive curvature gains can be discernible, potentially leading to user discomfort.

A second method uses rotation gains, which subtly magnify the user's rotation to reorient their walking direction. The main advantage of rotation gains is the ability to explore larger virtual spaces without realizing the actual physical trajectory [3]. However, its primary limitation arises when users do not exhibit any rotation in their path, necessitating interruptions in the VR experience.

B. Haptic Feedback in Redirected Walking

Although early RDW studies primarily emphasized visual stimuli, the integration of haptic feedback has garnered increased attention. The premise that cybersickness arises from sensory mismatches has ignited explorations into the potential of haptic cues to fortify illusionary thresholds [4].

Matsumoto et al. delved into this with the "Unlimited Corridor" technique, integrating visuo-haptic interactions for a more immersive experience in compact spaces. Their system paired a straight virtual wall with a tactile physical counterpart, enhancing redirected walking effects [5]. Building upon this, a subsequent study introduced a handle-based interaction method, comparing it against the wall-based approach and highlighting the potential of haptic feedback in RDW [6].

C. Challenges and Limitations in Current RDW Research

Despite RDW's evolution, challenges persist, including the necessary physical space, sensory perception disparities, and inherent physical constraints of specific RDW methods. This paper introduces a novel technique and device, emphasizing an algorithm that leverages active haptic feedback, aiming to refine RDW's visual recognition thresholds.

III. ACTIVE KINESTHETIC FEEDBACK DEVICE

A. Device Overview

Figure 1 shows our active kinesthetic feedback device. It integrates a user-arm frame, a controller chip (ESP32), a positional servo motor, and dual power sources, emphasizing cost-effectiveness, portability, and reproducibility.

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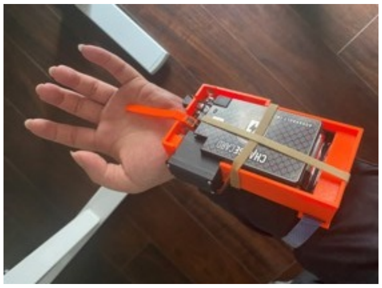

Fig. 1. The active kinesthetic feedback device.

The device's 3D-printed frame securely fits onto the user's arm. A tactor is attached to a servo in the device base, and is used to display a force to the user's hand when they interact with the virtual wall. The user's hand position is tracked by the VR headset (Oculus Quest 2). The ESP32 controller chip manages wireless communication between the device and VR headset and processes the hand position data.

IV. Algorithm

A. Initialization Algorithm

At the onset of the experiment, several initial settings are configured. First, the Haptic Wall HW, modeled as a cylindrical barrier with a radius r and height h, is defined. This wall is positioned to the left $\hat{L}$ of the user U. The initial comfortable distance d between the wall's surface and the user is calibrated to ensure that the user could comfortably touch the wall.

Next, the total traveled angle θ is reset to zero. The previous user relative angle θ_p is initialized using the difference in the z and x components between the user and the Haptic Wall, scaled between $-\pi$ and π.

B. Vision Rendering Algorithm

The Vision Rendering Algorithm, executed during every frame refresh, establishes the Visual Wall VW, an infinite straight barrier situated on the Haptic Wall's surface to the user's left, and the Visual Floor VF.

The algorithm initiates by computing the projected vector $\vec{V}$ from the center of the Haptic Wall HW to the user's position U. From this, the projected point P is determined by projecting the unit vector of $\vec{V}$ (denoted as $\hat{V}$) from the center of the Haptic Wall with a magnitude r. Subsequently, the clockwise tangent unit vector $\hat{T}$ on the Haptic Wall's surface at P is calculated using the absolute up direction $\hat{y}$ combined with $\hat{V}$.

To ensure alignment, the quaternions Q_{VW} of the Visual Wall and Q_{VF} of the Visual Floor are matched to the direction of $\hat{V}$. The user's perspective is further refined by evaluating the current relative angle θ_c derived from the z ($\hat{V_z}$) and x components ($\hat{V_x}$) of the projected vector, scaled between $-\pi$ and π. The angular difference between θ_c and θ_p over the frame is reflected to the total traveled angle θ.

The algorithm then computes the user's travel distance td as the product of the total traveled angle θ and the sum of the Haptic Wall's radius r with the initial distance d. To provide the user with a realistic walking experience, the shifting direction vector $\vec{S}$ is introduced, which opposes the user's expected walking direction and is defined by the clockwise tangent unit vector $\hat{T}$, scaled by the magnitude td. Finally, the positions of VW and VF are adjusted by shifting P using $\vec{S}$, ensuring the user feels they are walking straight, though they navigate the Haptic Wall's curve.

C. Haptic Rendering Algorithm

The haptic rendering algorithm begins after the initial calculation of the Visual Wall. If Actual Left Hand AH lies within the Haptic Wall, Haptic Left Hand HH is projected onto the nearest point on the wall's surface. Once HH is determined, the distance between AH and HH is sent to our kinesthetic device.

V. Visions

The fusion of kinesthetic feedback with redirected walking (RDW) has the potential to profoundly influence the future of virtual reality (VR) applications. By bridging haptic and visual perceptions, we envision several key applications for this research:

A. Therapeutic and Rehabilitation Applications

Patients undergoing rehabilitation, especially those with mobility challenges, could use this technology to navigate virtual environments that mimic real-world challenges. The combined visual and haptic feedback could help in gauging their progress and adapting their therapy routines.

B. Architectural and Design Walkthroughs

Architects and designers could use RDW with haptic feedback to guide clients through virtual representations of buildings or spaces. This could allow clients to not only see but also feel elements like barriers, giving them a more comprehensive understanding of the proposed designs.

C. Enhanced Gaming Experiences

The gaming industry is always in pursuit of heightened immersion. Integrating haptic feedback into RDW could redefine gaming, allowing players to feel in-game barriers or obstacles, taking realism to new levels.

References

[1] Razzaque: Introduces redirected walking as a method to allow users to navigate larger virtual environments, subtly altering the user's viewpoint to maintain immersion.

[2] Steinicke et al.: Discusses various redirection techniques, including curvature gains that introduce perceived curvatures in virtual environments.

[3] Langbehn et al.: Discusses the combination of redirected walking with impossible spaces, particularly focusing on the use of curved corridors beneficial for both methods.

[4] Polona et al.: Provides a comprehensive review on cybersickness in modern VR head-mounted displays, highlighting sensory mismatches as a primary cause.

[5] Matsumoto et al. (2016): Introduces the "Unlimited Corridor" technique using visuo-haptic interaction, allowing users to experience an infinite corridor in limited physical space.

[6] Matsumoto et al. (2019): Expands on the "Unlimited Corridor" technique, introducing a handle-based interaction method and comparing its effectiveness to the wall-based approach.