Abstract
Real walking in virtual reality (VR) is a promising locomotion technique since it offers multi-modal feedback to the user. Unfortunately, the virtual environment (VE) is limited by the available space in the physical world. So far, several techniques were developed to overcome this problem, e.g. redirected walking (RDW) and the use of impossible spaces. RDW subtly manipulates the viewpoint of the user to reorient her walking direction. Impossible spaces are based on subtle changes of the VE to reuse the same physical space for different virtual spaces. In this research demonstration, we show how these two approaches of redirected walking and impossible spaces can be combined. In particular, for our implementation we focus on the use of curved corridors that benefits both methods.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction techniques

1 INTRODUCTION
Natural exploration of immersive virtual environments (VEs) by real walking is an important challenge of VR research. While real walking is the most presence-enhancing locomotion technique [8], it is limited by the available space in the physical world. Hence, there is a need for novel locomotion techniques, that exploit the benefits of real walking but keep the user inside the borders of the tracking space. One approach is RDW that guides the user in the physical world on a different path than she perceives visually in the VE [3]. Typically, the user walks straight in the VE, whereas she walks on an arc in the real world. This is implemented by manipulating the virtual viewpoint of the user and rotate it slightly clockwise or counterclockwise. The user will unconsciously correct such a manipulation by walking in the opposite direction. Previous research has shown that a manipulation, which results in a walked arc with a radius of $22m$ is unnoticeable [4].

We discovered that it is even more difficult to detect a manipulation when the virtual path is curved as well [2], and introduced a RDW method that enables infinite walking in room-scale VR based on virtually curved paths [1]. For this, several curves are fitted into the tracking space and connected at specific joint points. The curves have visual representations in the VE and the user is advised to walk on these paths. Each curve can have a different gain which enables the user to explore a VE that is reasonably larger than the available space in the physical world. At the joint points, the user is able to change walking direction and continue on a different path.

Another approach to implement real walking in VR is to use impossible or flexible spaces [10], i.e., self-overlapping or changing architectural layouts. Instead of the user’s viewpoint, in these spaces, the VE itself is manipulated with the goal to enlarge the explorable virtual space. Such a manipulation can be done by e.g. moving walls or doors when the user is looking somewhere else [6] to exploit the same real world space for different virtual rooms. It was shown that virtual rooms may overlap by more than 50% before users detect the manipulation [7]. Moreover, curved corridors between the overlapping rooms are more beneficial than right-angled corridors in terms of manipulation detection [9].

In this research demonstration, we show how these two approaches can be combined in order to achieve a novel user experience that enables a user to literally go beyond borders.

2 DEMONSTRATION
This research demonstration combines two techniques to enable natural walking in a restricted tracking space:

- **Redirected Walking** using bending gains when users walk on virtually curved paths, and
- **Impossible Spaces** with subtle overlapping rooms.

This is done by using a curved corridor that connects three virtual rooms $A$, $B$ and $C$ (cf. Figure 2). The virtual rooms overlap by approximately 50%. As soon as the user opens the door to one of the three rooms, all other rooms are hidden, so she can not directly see the actual overlap of the different rooms. When walking through the corridor a subtle redirection gain is applied that forces the user to walk on an even more curved path in the physical world. The redirection is turned off when the user enters a room. Hence, she can explore the room with a one-to-one mapping. When the user leaves a room the bending gain is turned on again, and she can continue walking down the corridor until she enters the next room. The design of our RDW method [1] allows it to connect several curved corridors to further extend the size of the VE. The redirection and the bending of the corridor is designed in such a way that these rooms always fit into the tracking space. The entire virtual environment can be explored by real walking within a tracking space of $4 \times 4m$. 

Figure 1: A curved corridor in a science-fiction inspired spacestation.
Additionally, there are virtual tables in the rooms which are related to a physical table in the real world to provide passive haptic feedback [5]. Due to the redirection and the overlapping it is possible to use just one physical table that serves as a proxy object for several virtual tables.

Using a curved corridor supports the illusion of this demonstration in two ways:

(i) Applying bending gains to an already curved path is less obvious compared to curvature gains applied to a straight path [2].

(ii) The detection of overlapping spaces is more difficult if a curved corridor connects these spaces [9].

The visual appearance of the demonstration is a virtual space station inspired by science-fiction literature or cinematography (cf. Figure 1) that could be used, for instance, in a VR game context. However, this concept might be applied for different application domains, including virtual museums, archaeological visualizations, tourism, or training.

3 Conclusion

This research demonstrates the combination of RDW and impossible spaces to enable real walking in VR. For both techniques we use manipulations below the detection thresholds [2, 7] and both techniques benefit from the use of a curved corridor. We hypothesize that the size of the explorable VE can be increased significantly when using both techniques in combination to exploit a single technique alone. Qualitative feedback that we collected during an informal preliminary user study suggests that the overlapping of the rooms could not be detected. Most of the participants did not even recognize that the physical table was the same in both virtual rooms.

REFERENCES


1https://youtu.be/MjSL7-nFw1Y