



Exploring Rock Climbing in Mixed Reality Environments

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Abstract

While current consumer virtual reality headsets can convey a strong feeling of immersion, one drawback is still the missing haptic feedback when interacting with virtual objects. In this work, we investigate the use of a artificial climbing wall as a haptic feedback device in a virtual rock climbing environment. It enables the users to wear a head-mounted display and actually climb on the physical climbing wall which conveys the feeling of climbing on a large mountain face.

Author Keywords

Virtual Reality; Passive Haptic Feedback; Mixed Reality; Rock Climbing.

ACM Classification Keywords

H.5.1 [Information interfaces and presentation (e.g., HCI)]: Multimedia Information Systems - Artificial, augmented, and virtual realities; H.5.2 [Information interfaces and presentation (e.g., HCI)]: User Interfaces - Haptic I/O

Introduction

Rock climbing exists as a sport since the 1890s and was founded in the Saxon Switzerland region [5]. Since then climbing has undergone a broad development from a dangerous extreme sport to an easily accessible leisure activity

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with 25 million people climbing regularly¹. Climbing gyms with artificial walls are on the rise and can be found in every major city. They offer the climber a safe opportunity for some hours of after-work climbing without much preparation. The walls are equipped with holds of different shapes and colors, some being as easy to grab as a rung of a ladder, others which only fit a single finger. This allows the creators of climbing routes to set routes for different levels of difficulty. Lately, artificial rock climbing was extended by computer systems which aim to enhance the experience of the climber. This includes augmenting artificial climbing walls with projections that allow for interactive games or training assistance [4, 14]. Rock climbing also found its place in computer games ranging from simple smart-phone games to more sophisticated virtual reality (VR) experiences like *The Climb*², which enables the climber to explore remote areas with a scenic view in an immersive virtual environment (VE) through a head-mounted display.

The increasing power and decreasing price of powerful graphics cards, display technology, and tracking solutions made immersive VR available and affordable for the masses and thus paves the way for new game concepts and novel types of applications and interactions. However, the degree of immersion is determined by the expression of the three feedback dimensions: visual, auditory and haptic. While today, the visual and auditory feedback are already very sophisticated, realistic haptic feedback is still one of the next big challenges for VR and a very active field of research. Insko et al. [3] presented a concept of passive haptics, a low-cost approach which can provide realistic haptic impressions. Here, physical objects in the user's real environment, called proxies, are spatially registered with virtual counterparts and provide natural haptic feedback when the user

¹<http://www.ifsc-climbing.org/index.php/media-centre/key-figures-2>

²<http://www.theclimbgame.com/>



Figure 1: Visualization of the virtual reality climbing system. The integrated field camera of the HTC Vive was used to capture the view that the climber would have seen.

touches them. This feedback can drastically increase the user's sense of presence and enhance spatial learning [3].

While *The Climb* comes closest to climbing in VR, it is lacking exertion and haptic feedback. In this work we explore rock climbing in VR and discuss potential applications. For this, we developed a prototype of a VR climbing system, using a $3 \times 4 \text{ m}^2$ artificial climbing wall and a HTC Vive equipped with a Leap Motion for hand tracking. We propose to use the artificial climbing wall as a haptic proxy for a virtual rock, which enables the user to climb in a VE while still having both realistic haptic feedback and exertion (see Figure 1). To allow bystanders to participate and observe the climber in the VE, we additionally integrated a projection-based mixed reality feature. Therefore, the virtual rock environment is projected onto the physical climbing wall (see Figure 6).

Our system facilitates the creation of several applications: training for dangerous situations like falling rocks or sud-

den appearances of wildlife in a safe environment or giving climbers with a disability or those who suffer from altitude sickness the feeling of climbing outside while climbing an easier route inside. Another application would be to map different VEs to a single climbing wall, which would be especially useful for climbing treadmills, which present the climber with the same holds every couple meters of climbing.

With this work, we contribute a) a VR climbing system that provides haptic feedback and exertion, b) a collaborative projection-based mixed reality experience, and c) an easy calibration method for incorporating a virtual model of a physical scene into a virtual environment to allow for realistic haptic interaction.

Related Work

The Reality - Virtuality Continuum

Milgram and Colquhoun [9] introduced the Reality - Virtuality continuum, a taxonomy that classifies systems based on their real and virtual aspects. It spans a continuous space of *Mixed Reality* between the two poles *Reality* and *Virtuality*. The experience we introduce here can be classified as *Augmented Virtuality*, as the user's stimulation is primarily virtual (visuals & audio), augmented with passive haptic feedback.

Passive Haptic Feedback in VR

The concept of passive haptic feedback is an established way of introducing haptic feedback to immersive VEs [1, 3, 7, 8, 11]. Here, proxies (i.e. physical counterparts representing virtual objects) are used to provide tactile and kinesthetic feedback. Often, proxies are low-fidelity props made out of cheap and available material such as styrofoam, cardboard, or wood. However, concepts that utilize existing objects in the real surrounding as proxies, exist

as well, e.g. the concept of *Substitutional Reality* [11].

Through spatial registration with virtual counterparts, these proxies provide tangibility for objects in the VE. Insko [3] showed that passive haptics can enhance the user's sense of presence. We utilize this to enhance climbing on an artificial climbing wall.

Interactive Climbing Walls

In the past, rock climbing has been investigated in the context of human computer interaction. Liljedahl et al. [6] presented *Digiwall*, a climbing wall which featured translucent, instrumented holds that incorporated LEDs and capacitive sensors, enabling different interaction models. Ouchi et al. also used sensor-embedded climbing holds to model play behavior on an instrumented climbing wall [10]. A similar system that augments the climbing wall by instrumentation was presented by Fiess and Hundhausen [2]. In their work they build a climbing wall out of translucent material. A LED-wall placed behind the climbing wall surface acted as a display that covered the whole climbing wall. As in the work of Liljedahl et al. [6], the authors also included capacitive sensors to allow for interactive climbing games.

While the systems described above rely on heavy instrumentation of the climbing wall, including wiring or replacing the surface with translucent material, some research projects approach the augmentation of climbing walls by projections from behind the climber. Kajastilla et al. introduced *The Augmented Climbing Wall* [4], which is a combination of a normal climbing wall, a depth-camera, and a projector. With this, the authors implemented several interactive games and new ways to highlight custom routes which are usually indicated by the color of the holds. Similar to that, Wiehr et al. proposed a mobile, self-calibrating camera-projection unit which could be placed in front of an arbitrary bouldering wall [14]. Besides playing games and

creating new routes via an augmented reality smart-phone app, the system allows for the recording and playback of in-place video, projected directly on the climbing wall.

In contrast to the direct instrumentation and the augmentation via projection, the system proposed in this work augments the climbing wall in three dimensions by utilizing the possibilities of current VR headsets. The use of VR entails a lot of opportunities that go beyond illumination of holds or projections on the climbing wall. The main reasons for that is that the augmentation is not only limited to the surface of the climbing wall, but can span areas as far as the eye can reach. Furthermore, it gives the opportunity to alter the representation of the reality by removing elements like holds from the wall or adding new details like weather conditions, animals, or falling rocks in the VE.

Concept

In the following, we describe the general concept of our VR climbing system and its theoretical classification. We extended Milgram and Colquhoun's [9] Reality - Virtuality continuum, by introducing the *Climbing Reality Continuum* that classifies climbing activities and applications based on the authenticity of the climbing experience. Figure 2 shows the resulting two-dimensional design space combining the *Reality - Virtuality* continuum and the *Climbing Reality* continuum.

The *Climbing Reality* continuum spans from pure *virtual climbing* on one end to *classical rock climbing* on the opposite end. Due to the similarity to classical rock climbing, artificial climbing walls are located in between both ends, close to the classical rock climbing end. On the opposite, games that require the user to use a standard game controller (like a Xbox controller) to climb, are located close to the virtual climbing end as the interaction strongly abstracts

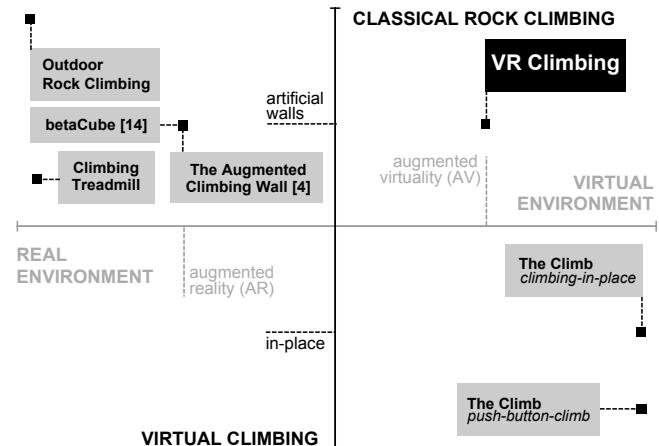


Figure 2: 2D continuum spanned by the *Climbing Reality Continuum* (vertical axis) and the *Reality - Virtuality Continuum* [9] (horizontal axis) with some examples. Our VR climbing system is located in the upper right quadrant.

from classical rock climbing. With regard to the VR locomotion techniques investigated by Usoh et al. [13], this type of interaction is closely related to *push-button-fly*. Thus we call it *push-button-climb* (e.g. playing *The Climb* with a game controller). If the game, however, allows the user to climb by grabbing virtual grips with motion-tracked controllers, and moving the arms to virtually pull up her body, the interaction is more related to actual climbing. Due to the similarity to the VR locomotion technique *walking-in-place*, we call this type of interaction *climbing-in-place* (e.g. playing *The Climb* with motion-tracked controllers). *Climbing-in-place* is located between *push-button-climb* and climbing on artificial climbing walls in our continuum.



Figure 3: To register the physical wall with its virtual counterpart, the Vive controllers are used to set the position of the calibration points.

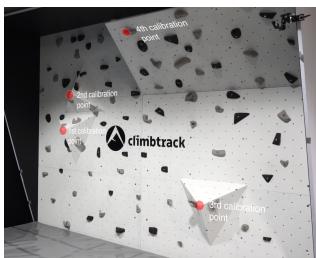


Figure 4: The physical climbing wall used in our prototype. The marked calibration points are analog to the ones seen in Figure 5.



Figure 5: 3D Model of the climbing wall within the virtual environment. The spheres depict the calibration points.

Previous work and existing concepts can be categorized in this design space as depicted. The upper right and the lower left quadrant of the design space are so far left understudied. While applications that involve a form of virtual climbing in real environments are rather abstract, the combination of real physical climbing and immersive VEs promises interesting applications. Thus our goal is to explore this part. For this, our prototype system has to meet two main criteria: The user should be immersed in a VE while having the realistic physical impression of climbing. To meet these requirements, our system includes a head-mounted display (HMD) and an artificial climbing wall.

As an optional addition, the system can utilize a projector placed in front of the climbing wall to generate a projection-based *Augmented Reality* experience for bystanders watching the climber. By projecting the virtual rock, we intend to help climbers to get familiar with the VE (see [12]) and to provide a smooth transition into it. In addition, the projection allows bystanders to observe and guide the climber (see Figure 6).

Implementation

Setup

The setup of our VR climbing prototype consists of an artificial climbing wall with 4m in width and 3m in height that included an overhanging panel and three volumes (see Figure 1, lower right image). To catch the climber in case of a sudden fall, a thick mat covers the floor in front of the climbing wall. For the VR headset, we opted for the HTC Vive, since it allows for free movement within a certain area and high quality position tracking. The HTC Vive system³ consists of the headset itself, two controllers, and two lighthouses that are needed for tracking. In our setup, we placed the lighthouses to the right and left of the climbing

³<https://www.vive.com/>

wall in approximately 2.5m height. For the hand tracking, we mounted a Leap Motion controller on the headset. The current prototype does not feature a tracking for feet yet. In the future, the tracking could be integrated by using additional optical tracking (e.g. OptiTrack) or Vive tracking pucks which were not available at the time of this work. Unity was used as development environment which runs on a ZOTAC NEN Steam Machine.

Virtual Environment

As a first step, we scanned the climbing wall with the help of a Kinect v1 and the *Skanect*⁴ software. After cleaning up the model in Meshlab, we imported the model in a Unity scene. For our prototype, we used a height map of the Matterhorn that was applied to a terrain. The 3D model of the climbing wall was placed at the top of the mountain to give a feeling of height. As an "entry point" for the climber, we added a virtual wooden ledge on which the climber would find herself when putting on the HMD.

As opposed to common VR games where a registration in the physical playing environment is not necessary (except for the position and orientation of the floor), the calibration of the virtual and the physical environment is critical for climbing in VR. The positions of the virtual holds have to match the physical holds exactly, otherwise the climber would grab into the air or hit the climbing wall with her hands.

For this, we implemented a simple calibration method: In the first step we defined four *calibration points* on the climbing wall that are easily identifiable in both the 3D model and the physical wall. In our case, we chose the tips of the three volumes (see Figure 4) and one additional hold. These four points were then registered in the Unity scene by placing

⁴<http://skanect.occipital.com/>



Figure 6: Using a projector, the virtual environment is projected back on the physical climbing wall to reflect the interactions of the player in the VE.

invisible *game objects* at the respective positions on the 3D model of the climbing wall. In a second step we used one of the Vive controllers to register the positions of the calibration points in Vive / physical space. As a result we had four coordinate pairs. In a last step, we calculated the optimal rotation and translation applied to the Vive space using single value decomposition to match the model of the climbing wall. We provide a sample Unity project with a manual on how to create custom virtual environments matching a physical scene on GitHub⁵.

Projection

As an optional feature we used the Microsoft Room Alive Toolkit⁶ and the corresponding Unity Plugin⁷ to create a mixed reality experience. For this, we used a camera projection unit as in the work by Wiehr et al. [14], which was placed in front of the climbing wall. The Unity plugin was used to place a virtual camera in front of the 3D model of the climbing wall, with intrinsic parameters equivalent to those of the used projector. Using the same calibration method as above, we rotated the complete virtual scene so that it matched up with the model of the climbing wall. A network connection between the computer connected to the Vive and a second laptop used for the projection was established. It was used to synchronize the game states, so that the projection would reflect the VE seen by the climber.

Climbing Game

We presented our prototype at our institution's Christmas event. Since we did not expect every user to be a climber, we implemented a small game in which the player had to collect as many presents as possible by touching them with their hands. The player had to step on two marked

⁵<https://github.com/felixkosmalla/unity-vive-reality-mapper>

⁶<https://github.com/Kinect/RoomAliveToolkit>

⁷<https://github.com/Superdroidz/UnityRoomAlive>

foot holds and as soon as she grabbed a third hold with her hand, the game started. To include the audience, we used the projected mixed reality as described above (see Figure 6).

In total, 27 guests tried out the game and from most of them we received positive feedback. A formal evaluation will be conducted as part of future work.

Conclusion & Future Work

In this work, we presented a VR climbing prototype that utilizes a 3D model of an artificial climbing wall and a HMD equipped with a Leap Motion Controller to allow for physical climbing in different virtual environments.

Based on this work, a large number of extensions are possible. Climbing treadmills could be made less monotone by mapping a virtual environment on the revolving belt to convey the impression of climbing a large mountain face, by displaying only a subset of holds that are actually mounted on the treadmill.

A different application could aim at training scenarios where a 3D representation of a climber could be placed in the VE to demonstrate a difficult climbing move. As opposed to 2D projection, this would have the advantage of depth perception and no occlusion when climbing the same problem simultaneously. Other applications could focus on training for dangerous situations such as the simulation of falling rocks. This could also be applied to other domains e.g. a training system for firemen.

For the future, we plan to integrate the tracking of feet, followed by a formal user study. Albeit we did not experience any tangling of the wires of the HMD by the climbers, counter measures like the use of a wireless headset should be investigated.

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