InfinityWall – Vertical Locomotion in Virtual Reality using a Rock Climbing Treadmill

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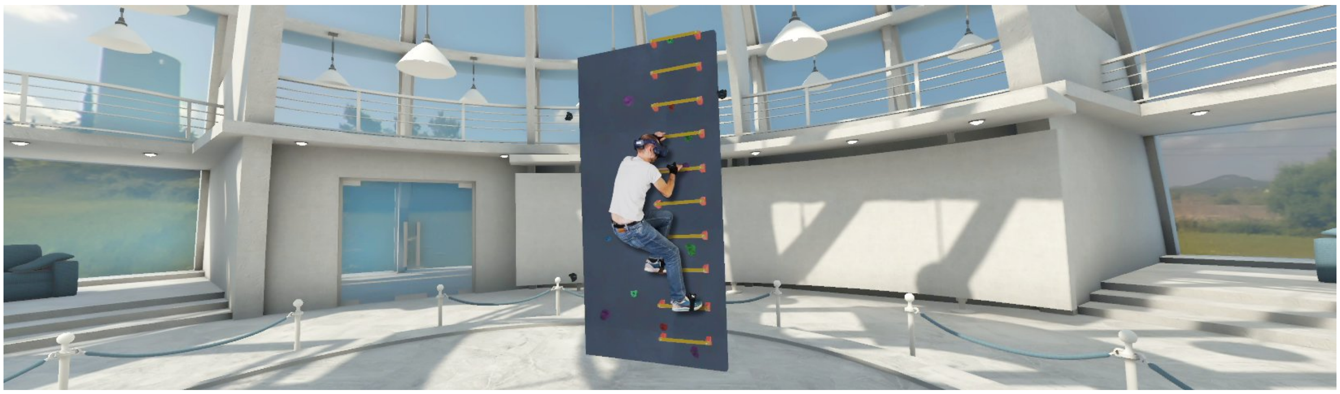

Figure 1: Virtual Reality rock climbing on a physical climbing treadmill. This allows for continuous climbing while wearing a head-mounted display. With the system presented in this work, we implemented different virtual scenarios. In this showcase application, the climber is placed into a virtual showroom.

ABSTRACT

Current commodity Virtual Reality (VR) hardware allows for free, even wireless roaming, however it is still confined by a finite tracking space. To overcome this issue, past research has introduced different methods for vertical locomotion, ranging from walking on a treadmill to interaction paradigms such as teleportation. Recently, researchers have integrated rock climbing on a physical wall into VR experiences. The space available is naturally confined by the dimensions of the wall. Building upon this, we present implementation details and future research directions of a VR system for vertical locomotion on a rock climbing treadmill.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; *User studies*; *Visualization techniques.*

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1 INTRODUCTION

With the ongoing improvement of commodity virtual reality (VR) headsets, their ability to create immersion increases continuously. This includes not only the increased resolution of the employed screens but also the tracking methods that allow for free, even, and untethered movements, within a room-sized tracking space. Using either inside-out or external tracking allows users to roam freely within a space only restricted by the tracking technology used or the physical space available. To overcome the spatial limitations, different methods and technologies have been applied in the past (see [7, 10] for a more extensive overview). From a user interface perspective, *Point & Teleport* is a well known method, which allows the users to select the desired location with their controller and teleport themselves via a push of a button [8]. In doing so, the user actively acknowledges the physical borders of the space available, which might break immersion. Other methods change the user's perception of the virtual space into tricking them into staying inside the available physical space [5, 19, 20] or control their walking direction using electronic muscle stimulation to reach the same goal [4].

As an alternative, physical apparatuses have been proposed which aim to conceal the aforementioned limitations: Unidirectional treadmills allow the users to walk or run in any given direction while remaining in the same physical location [15, 25]. Similarly, movable floor tiles, reminiscent of shelf robots in large warehouses, foresee the user's movements and transport them back to a neutral position [15]. While walking or running is probably the most prevalent type of locomotion inside a virtual environment (VE), other forms have been presented as well, including climbing "infinite" stairs [9], jumping [24], scuba diving [14], and rock climbing [17, 22, 23].

For rock climbing in a VE, the space restrictions present a number of special challenges. Firstly, an artificial climbing wall has finite dimensions, and secondly, with increasing elevation, safety measures have to be employed to avoid injury in case of a fall (e.g. a thick mat or a climbing rope). With the increasing popularity of rock climbing, new technologies have been introduced in this sport: Multiple vendors offer so-called climbing treadmills. These have a vertical conveyor belt with attached hand and food holds (see Figure 2). The mechanics involved move the belt in sync with the climber, allowing for an infinite, albeit repetitive accent, since the climber will be presented with the same holds starting with each new rotation of the belt. While these machines are commercially available, an integration of VR is not available yet.

In this paper, we will present the implementation of a system that allows for climbing on a physical climbing treadmill while being immersed in a virtual environment. While we implemented this system for the Climbstation [16], the general concept is applicable for a generic model. In addition to the technical implementation details on how to replicate the system, we propose future study directions.

Figure 2: The Climbstation is a climbing treadmill that allows for continuous climbing with a slant from -15 to 45 degrees. We used the Vive VR system to allow for physical climbing in a VE. Vive trackers attached to the frame of the climbing wall track the position and slant of the wall. Three Lighthouse systems were employed, two in front of the wall and one above the wall pointing towards the floor. In the back of the wall, a spring loaded wheel with a rotary encoder measures the position of the belt.

2 RELATED WORK

First examples of actual rock climbing in a VE have been presented in the past by Tiator et al. [23] as well as Kosmalla et al. [17]. Both systems included a virtual model of a physical climbing wall placed in a virtual surrounding. Using different tracking methods, e.g. Magic Leap or Vive Trackers, the climber's extremities were integrated into the VR. This allows the user to climb naturally by grabbing and stepping on holds that were present in both the virtual and physical world.

While these works demonstrated the general feasibility of rock climbing in a VE, subsequent studies investigated certain aspects of this augmented version of the sport. Schulz et al. [22] studied the role of physical props in VR climbing environments. They compared actual, unaugmented climbing in 10m height, fully immersive virtual rock climbing as described above, and virtual climbing using controllers, similar to the VR game "The Climb" [11]. Using the VR setup including physical climbing increased the anxiety and sense of realism perceived by the study participants. Kosmalla et al. [18] investigated the importance of virtual hands and feet while climbing in a VE. This was done by letting participants climb in a VE while hiding or displaying their respective extremities. Subjective reports suggested that the inclusion of feet is more important than having a hand visualization.

All works presented above have the restriction in common that actual climbing in the VR is constrained by the available trackable space. In the following, we will present how the approaches outlined above can be transferred to a climbing treadmill.

3 IMPLEMENTATION OF THE VR CLIMBING SYSTEM

For this work, we used a Climbstation [16], a rotating climbing treadmill. It features a climbing surface of 1.5m by approximately 3m with a total belt length of 6.4m. The belt is mounted on a number of aluminum extrusions that run in rails on either side of the climbing treadmill. The extrusions have nuts integrated in them on which standard climbing holds can be fastened. Using its actuators, the climbing wall can be tilted while climbing within the range of +15° to −45°, allowing for slab climbing or climbing on an overhang. The climbing treadmill has a digital control system that automatically adjusts the speed of the belt according to the climbers accent, on contrast to a running treadmill where the speed is prescribed by the machine. Sensors at the top and bottom of the wall will break or accelerate the belt when the climber is about to reach either end of the wall. While we implemented the system for this specific model, it can be easily adapted for models of other manufacturers. As VR hardware we chose the HTC Vive Pro, leveraging their Lighthouse Tracking System with absolute positions for the HMD (Head Mounted Display) and wireless trackers (also see Video Figure[1]). Unity 3D was used as the game engine. In their terminology *GameObjects* are virtual objects that are placed in a *Scene*. If they are placed in the hierarchy of another GameObject, they will follow the translation and rotation of this parent.

To integrate the physical climbing wall into a VR experience, several steps have to be performed, which are described in more detail below. To begin, the location and configuration (i.e. the tilt of the wall as well as the position of the belt) has to be continuously monitored. For this, we used multiples Vive trackers to follow the frame of the climbing wall and custom hardware to measure the position of the belt. Afterwards, a virtual model of the climbing wall and its holds has to be created. This includes tooling to digitize climbing holds and to align the virtual models according to their physical counterparts. As a third step, the virtual model from step one has to be aligned according to the data acquired in step two. Finally, a visual representation the user's hands and feet has to be integrated into the VE.

3.1 Monitoring the Configuration of the Climbing Wall

To represent the physical climbing wall in a VE, its configuration (i.e. position of the wall itself, slant, and position of the belt) has to be tracked. The position and tilt of the wall was acquired by mounting three Vive trackers on the border of the frame: two on the top of the frame in equal height and one in the bottom left of the frame. To keep the trackers in place on the frame, we designed custom mounts that feature a quick release mechanism (see Figure 2) and flexible dampers to reduce vibration during movement of the belt and change of tilt. This should mitigate possible sensor drift [2]. While we originally planned for a wireless use of the trackers, long USB cables and an active USB hub appeared to be more practical.

The three Vive trackers are used to align the virtual climbing surface to its physical counterpart. To achieve this in an automatic manner, we used the process described in [17]: three or more points that are easily identifiable on the physical wall as well as on the virtual model are obtained and by means of Singular Value Decomposition, the optimal rotation and translation is found to align the corresponding points. Running this algorithm continuously will render the virtual frame at the correct position and slant.

To obtain the three points on the virtual model, the climbing wall is brought to an upright position, perpendicular to the floor with the trackers attached. While running the Unity editor, a (later invisible) cuboid *(belt container)* is manually aligned to the plane that is held by the position of the three trackers. Within the hierarchy of this cuboid, reference points in form of GameObjects are placed for each tracker. Additionally, the cuboid will later on hold the model of the belt itself with its climbing holds. With this, we have a virtual model of the frame with three reference points that spatially correspond to the physical climbing wall. To address the individual Vive trackers, we used the Vive Input Utility Unity package [1]. First trials have shown that placing the two Vive Lighthouses in front and next to the climbing wall and one mounted on the ceiling pointing towards the floor results in a robust tracking of all trackers and the HMD. The Lighthouse mounted on the ceiling allows for

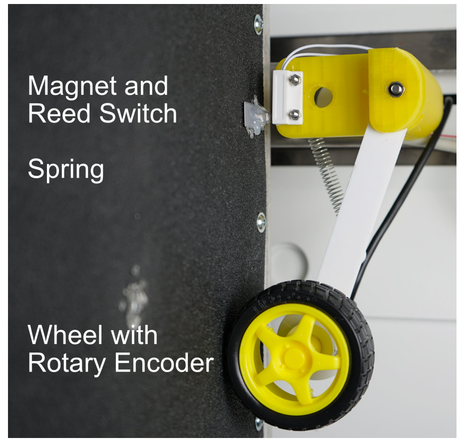

Figure 3: We designed a spring loaded arm that presses a wheel onto the belt of the climbing wall. A rotary encoder mounted to the wheel measures the rotation while a reed switch detects the start of a new revolution of the belt by means of a single magnet glued to the belt.

both arms pointing upwards while climbing, which would usually result in covering too many sensors of the HMD.

After having established the spatial configuration of the frame, the position of the belt has to be monitored. While the Climbstation has a machine readable interface, the resolution of the belt distance is rather coarse (approx. 5cm per tick), which does not allow for a precise representation in VR. To overcome this issue, we designed and 3D printed a frame holding a spring loaded wheel that presses on the belt of the climbing wall (see Figure 3). A rotary encoder (WISAMIC 600p/r) driven by a Wemos D1 Mini was attached to the wheel to readout the rotations. To reduce drift induced by slipping of the wheel and also to introduce a zero position, a small magnet was glued to the belt which is detected by a reed switch.The current tick count of the rotary encoder and status of the reed switch is printed to the serial output every 16ms which is in turn consumed by the

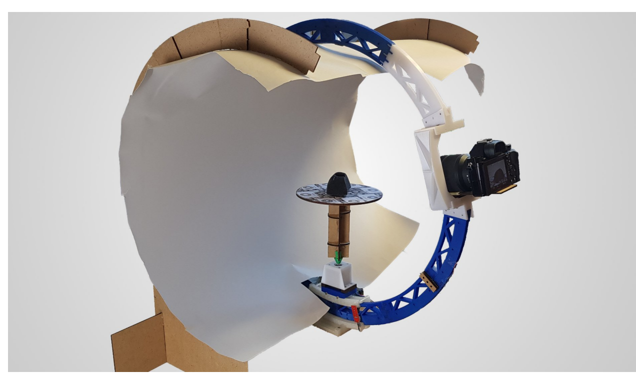

Figure 4: We used an open source photogrammetry rig that allows one to take a set of pictures from an object from different angles. These pictures were used in Meshroom to reconstruct 3D models of the climbing holds.

[1]https://umtl.cs.uni-saarland.de/research/projects/infinitywall.html

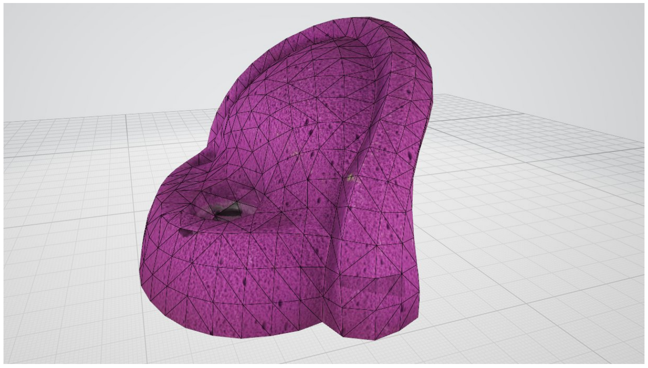

Figure 5: Having exact representations of the climbing holds helps to establish a strong and precise grip on the first try. The number of polygons of the models had to be reduced to give a smooth, high FPS experience during climbing in VR.

Figure 6: To visualize the hands and feet of the climbers, Vive trackers are attached to the climber's hands and feet. A spatially registered template is used for calibration, i.e. to align the virtual models to the physical trackers.

Unity application. To convert ticks to meters, an initial calibration has to be performed once for the setup. This is done by mounting a Vive tracker to the belt, with which the distance traveled between two fixed but arbitrary points can be meassured. Simultaneously recording the tick count of the rotary encoder allows for calculating a fixed scaling factor to convert from ticks to meters.

3.2 Modeling the Climbing Wall

While the belt of the climbing wall can be modeled as a simple plane or cuboid, the climbing holds need a more sophisticated representation. Climbing holds come in different shapes and sizes, ranging from tiny footholds with the size of a matchbox, holds that can only accommodate the tip of a finger, to large holds that can be grabbed with the climbers's whole hand. The holds are mounted with bolts that are screwed into existing threads integrated into the belt of the climbing wall. To prepare the climber in the VR for the upcoming holds, the virtual models should allow for an assessment of the holds topology before grabbing it. This reasoning is based on feedback from preliminary experiments in which only very low fidelity models were used. Using these rough models resulted in the climber trying to grab the hold and immediately readjusting their grip since the visual representation did not match the actual physics of the hold. We used an open source turntable[21] design to acquire pictures with a DSLR camera of the individual climbing holds which we then used to create 3D models via photogrammetry (see Figures 4 and 5). Meshroom[3] was used for the creation of the 3D models. After cleaning the resulting model from artifacts and the turntable base, we reduced the number of polygons using Instant Meshes[26], followed by a re-texturing of the now decimated model with Meshroom. The individual models were converted into pre-configured GameObjects with the origin placed on the ground plane and in the center of the bolt hole.

To represent the climbing holds in the VR, a virtual belt in form of a cuboid is placed within the *belt container* and is moved according to the readout of the belt senor described above. After each full rotation of the belt, it will reset itself to the initial (null) position. Within the hierarchy of this belt, the virtual holds need to be initially positioned. To facilitate this process, we implemented a simple editor. Once the climbing wall has been set up (i.e. physical holds are already mounted), the procedure is as follows: First, the position of the physical hold has to be defined. This is done by placing the bottom of the Vive controller directly on the head of the bolt. A press on a button confirms this position. To obtain the position on the belt (remember: the origin of the virtual holds is located on its ground plane), the end of the Vive tracker is placed on the belt, next to the hold to obtain the exact plane of the belt. In doing so, the position of the thread is obtained. After establishing the base position of the hold to be placed, the user is guided through the process of selecting the corresponding virtual model of the climbing hold. Holds are grouped by color and can also be identified with their number that was established during the digitizing process. After selecting the corresponding virtual hold, the correct orientation of the hold can be set by rotating the Vive controller followed by a press of the trigger to confirm. Finally, the virtual hold is placed within the hierarchy of the virtual belt. To save the setup of the holds, the local position, local rotation, and hold ID are stored in a file.

3.3 Visualisation of Hands and Feet

To visualize the climber's hands and feet in the VE, we created a 3D model of a climbing shoe through photogrammetry and used a rigged hand model obtained from the Unity Store. Trackers are mounted to the hands and feet with commercially available straps. To align the virtual models with the users hands and feet, we followed the procedure described in [18]: A Vive tracker is mounted on a wooden template that is represented as is in the VE. Initially, the GameObject holds the 3D models of the climber's shoes as well as their hands (see Figure 6). When placing either feet or hands on the respective position, the 3D models are attached to the GameObjects of the Vive trackers, resulting in a visual representation of the users extremities in the correct location and orientation. While other works (e.g. [23]) have implemented finger tracking using additional sensors and/or gloves, we trigger an animation of a closing hand when the virtual hand comes into close proximity to a hold ($10cm$), resulting in a somewhat realistic behavior.

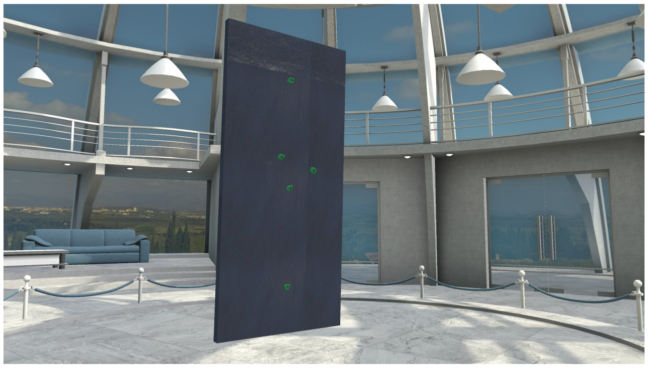

Figure 7: The exhibition room scenario features a minimalistic representation of the climbing treadmill. Similar to climbing routes in a climbing gym, only a subset of the available holds will be displayed. This allows for a more varied climbing experience, albeit the repeating belt.

Figure 8: In the skyscraper scenario the climber is immersed into a futuristic city. In contrast to the exhibition room scenario, the climber will ascent a large skyscraper. The holds of one belt revolution are stitched together to allow continuous climbing.

4 SHOW CASE SCENARIOS

To demonstrate the possible applications of the system, we implemented two initial show case scenarios: a virtual representation of the rotating climbing wall in a virtual exhibition room (see Figure 7) and a skyscraper climbing simulator in a futuristic city (see Figure 7). In the exhibition room demo, we implemented a simple route editor to break the monotony given by the repeating belt. For each repetition only a subset of the available holds is displayed. This is common practice in climbing gyms, with the difference being that holds that belong to a specific route are usually marked by the same color or colored tape next to the holds. Hiding holds that do not belong to the current route/repetition should improve the illusion of a long route and give a better user experience.

While the exhibition room show case demonstrates the capability of replaying a custom route, a feeling of height is not induced since the climber is still displayed near the ground. To leverage the possibilities of VR, we implemented another show case in which the climber scales a sky scraper in a futuristic city. For this, we attached the complete 3D model of the city to the belt GameObject. Whenever the belt moves down, the city is 'pushed down' as well, resulting in a feeling of ascension. With each new revolution, the city model is detached from the belt, the belt position is reset, and the city model is attached again. This allows for continuous climbing up the skyscraper. To decrease the risk of injury when stopping climbing, a piece of virtual floor is faded-in whenever the climber's feet approach the physical floor to bring back a sense of orientation. While we did not a perform a full user study, informal trials have shown that climbing is easily possible, that the location of virtual climbing holds corresponds to the position of their physical counterparts, and that a feeling of height is induced in the skyscraper show case.

The source code, documentation and CAD models of the project, including the two show case scenarios, can be found online[2] .

[2]https://umtl-git.dfki.de/infinityclimb

5 CONCLUSION AND FUTURE WORK

In this work, we presented a system that integrates a climbing treadmill into the VR, allowing for continuous climbing in a VE. This is done by digitizing the physical climbing wall and its holds and continuously aligning this model with the physical climbing wall. Given the implementation details outlined above and sample code, the system should be easily adoptable to other climbing treadmills. While no complete user study was conducted, informal trials have shown the feasibility and robustness of the system.

Building upon these results offers a set of intriguing research opportunities. In future work we aim to explore more usage scenarios by conducting in-depth user studies. As demonstrated in the skyscraper showcase, the sensation of (extreme) heights can be simulated. This could be used to explore new methods for acrophobia or fear of heights treatment [13], investigate height perception in VR climbing [22], or in general to simulate other tasks in (extreme) heights (e.g. [12]). Furthermore, similar to redirected touching [6], redirected grabbing of climbing holds or the effects of overhang perception could be studied in psycho physical experiments. Combining techniques such as redirected grabbing and the possibility of the climbstation to programmatically change the tilt of the wall could allow to climb popular outdoor climbing routes that were previously digitized with a drone, similar to [27]. Future work could also integrate interaction with bystanders. Naturally, bystanders are excluded from the VR experience. Past research has investigated how projection interfaces could be used to allow a bidirectional communication in a similar virtual reality climbing scenario [28]. Building on that that, bystanders could be enabled to highlight, respectively hide climbing holds or change the tilt of the climbing wall. This could be useful for trainer/trainee applications or various (exer)games. Especially playful VEs could increase the motivation and possibly the training effect using such a climbing treadmill.

ACKNOWLEDGMENTS

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