Impossible Staircase: Vertically Real Walking in an Infinite Virtual Tower

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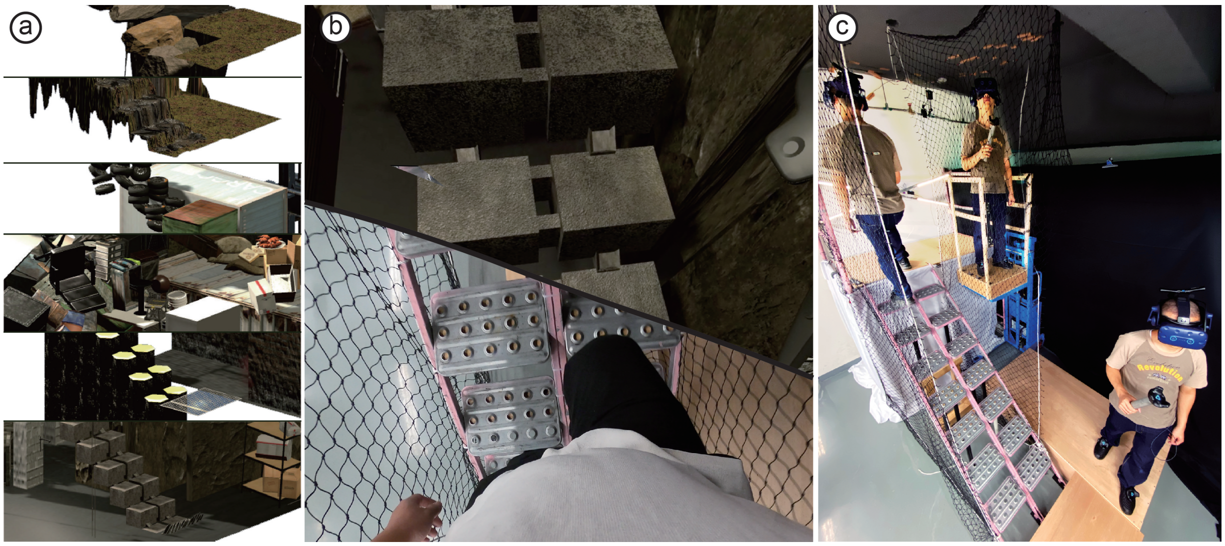

Figure 1: *Impossible Staircase* is a system that allows real walking in an infinite virtual tower. (a) The user goes through levels of various themes in the tower by (b) really walking on the stairway of an one-level scaffold while wearing a head-mounted display. (c) Our system resets the user's position *imperceptibly* to the ground as they stand on a controlled lifter to continue their climbing.

Abstract

We present Impossible Staircase, a real-walking virtual reality system that allows users to climb an infinite virtual tower. Our set-up consists of an one-level scaffold and a lifter. A user climbs up the scaffold by real walking on a stairway while wearing a head-mounted display, and gets reset to the ground level by a lifter imperceptibly. By repeating this process, the user perceives an illusion of climbing an infinite number of levels. Our system achieves the illusion by (1) controlling the movement of the lifter to generate reverse and imperceptible motion, (2) guiding the user through the scaffold with delay mechanisms to reset the lifter in time, and (3) procedural generating overlapping structures to enlarge perceived height of each level. We built a working system and demonstrated it with a 15-min experience. With the working system, we conducted user studies to gain deeper insights into vertical motion simulation and vertical real walking in virtual reality.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, Augmented, and Virtual Realities

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1 Introduction

Recent virtual reality (VR) technology such as Oculus Quest and HTC Cosmos has enabled immersive experiences to be deployed nearly anywhere as long as there is space. To meet the general space requirement, most of the experiences thus are designed under the assumption that the deployed space is empty and flat. To enhance immersion, researchers have proposed approaches such as omnitreadmill [32], redirected walking [21], impossible spaces [29] to enable real walking VR [31] within a controlled space. VRoamer [2] further brings real walking VR to uncontrolled spaces. However, although there has been research focusing on vertical displacement [23] and jumping [6], vertical real walking such as walking on a staircase while wearing a head-mounted display (HMD) only has been briefly mentioned in DreamWalker [33]. In this paper, we look into vertical real walking VR that utilizes a common space configuration in buildings: a staircase and an elevator.

2 Impossible Staircase

We propose Impossible Staircase, a real walking VR system that allows a user to climb an arbitrary number of levels through a staircase in a virtual tower. We introduce Impossible Staircase by illustrating our example virtual experience, *PrisonEscape*. Figure 1a shows an overview of the virtual tower in *PrisonEscape*. The user wears a HMD and sees themselves climbing through what they eventually perceive as a six-level and 40-meter-tall virtual tower by really walking on a stairway as shown in Figure 1b. In reality, they just climb the same 1.4 meter-tall one-level scaffold over and over again as shown in Figure 1c as if they walk on Penrose Stairs [20].

The key component in Impossible Staircase is the lifter that resets the user's position to continue the climbing repetition. Figure 2

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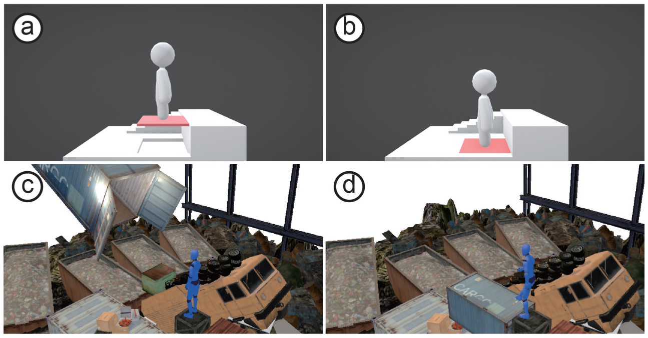

Figure 2: (a)(b) In reality, the user gets reset to the ground by the lifter with imperceptibly acceleration. (c)(d) In the virtual world, the user does not perceive the motion and stands still watching an way-blocking cargo to be moved to the right position to continue exploring the virtual tower.

shows how Impossible Staircase works as the user transits to the scrapyard level in *PrisonEscape*. From the user's point of view, after climbing the stairway, they arrive at this level and see a hanging cargo in front of them blocking their way (Figure 2c). They watch the cargo moving and stand still until the cargo drops, paving the way for them to pass through (Figure 2d). At the same time in reality, they are standing on the lifter, and the lifter is sneakily sending them back to the ground (Figure 2ab). In other words, Impossible Staircase employs delay mechanisms inspired by TurkDeck [3] to buy time for the lifter to reset the user's position. The user then continues their exploration and climbs the same physical stairway again to the next level.

Moreover, Impossible Staircase enables more drastically vertical movement mismatch by changing the lifter's motion profile to further enhance the flexibility of level design. Figure 3 shows an example as the user takes a transparent elevator to the 40-meter-tall penthouse level in *PrisonEscape*. The user steps into the elevator (Figure 3c) and then sees themselves being transported upwards (Figure 3d) to the rooftop. At the same time in reality, they still are standing on the lifter, but the lifter is actually moving downwards and sending them back to the ground (Figure 3ab). Impossible Staircase achieves this by controlling the lifter to generate an abrupt upwards acceleration in the beginning to match the motion of the virtual elevator while slowly accelerating downwards to the ground. This reverse movement further disconnects the user's spatial perception between the virtual and physical world and allows continuation of climbing no matter which level the user is at in the virtual world. In the end, the user climbs the final stairway to the rooftop to complete *PrisonEscape*.

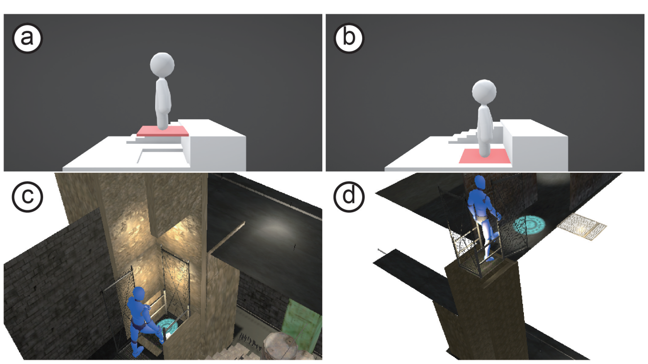

Figure 3: (a)(b) In reality, the user gets reset to the ground by first experiencing an abrupt upwards acceleration from the lifter and then smoothly going down. (c)(d) In the virtual world, the user is taking an upwards transparent elevator to a 40-meter-tall level.

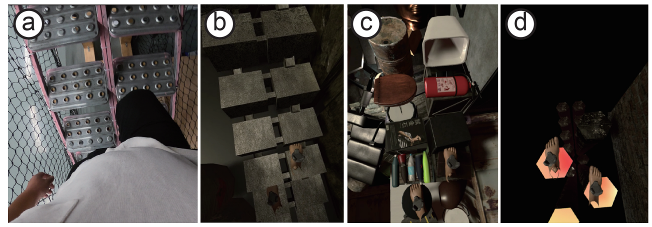

Figure 4: Visualizations of (a) the physical staircase (b) A matching stone staircase (c) A pile of arbitrary objects (d) Rising pillars

In between, the user walks through the same physical stairway (Figure 4a) six times with different virtual representations that fit in six thematic levels. Inspired by Substitutional Reality [24], we explore a range of mismatching visualizations of the physical staircase geometry without significantly affecting real walking experience to help others to design Impossible Staircase experience. We broadly categorize the visualizations into 3 characteristics as shown in Figure 4: (b) skin substitution (e.g., stairs) for maintaining thematic consistency, (c) hash forming (e.g., piling a set of objects) for geometrical variance, (d) animacy (e.g., rising pillars) for interactivity.

Finally, Impossible Staircase borrows the procedural generation method of VRoamer [2] which generates a new level or places a pre-authored level depending on the user's progress in the VR experience.

3 Contributions

The main contribution of this paper is a vertical real walking VR system. We implemented a working system that consists of a one-level scaffold and a lifter to approximate common facilities in buildings: a staircase and an elevator. Our system enables infinite vertical real walking in VR in the target configuration. Our system achieves this by (1) generating reverse and imperceptible motions using the lifter to reset a user's position, (2) delay mechanisms to buy more time to move and reset the lifter, and (3) procedurally generating an infinite number of levels. With the system, we explored and demonstrated interactions with a six-level experience that showcases a wide range of level designs. We also conducted studies to gain more insight into vertical real walking VR and to provide validation of the system. Our preliminary result shows that our system does produce a realistic walking experience in a multi-level tower without producing perceptible incoherence in motion or being informed of the actual one-level structure. Through Impossible Staircase, we envision a future where more existing facilities and space configurations, no matter passive or active, to be used for real walking VR experiences.

4 Related Work

Locomotion is essential for fostering a strong sense of immersion in VR environments. Previous works mostly focus on horizontal locomotion [18], while vertical locomotion was discussed few and far between. We highlight three related bodies of work, real walking VR, locomotion devices, and locomotion techniques in limited space.

4.1 Real Walking VR

Real walking has been shown as the most natural way to navigate in VR [31]. To enable real walking in VR, many researchers have proposed systems that incorporate surrounding physical environments into virtual experiences so as to prevent users from collisions. Substitutional Reality [24] investigates the acceptable mismatch between virtual elements and their physical proxies to give experience designers creative flexibility without breaking immersion by unexpected tangible feedback. Oasis [27] scans the surrounding physical environment using a Google Project Tango tablet and then uses the full model to procedurally generate a virtual environment where users can walk through. One Reality [22] similarly explores a blended experience ecosystem that incrementally augments a user's experience from the physical to virtual worlds.

Since inside-out tracking becomes a built-in functionality of commercial HMD such as Oculus Quest and HTC Cosmos, researchers have investigated real-time real walking VR that reflects dynamical changes of surrounding physical environments. VRoamer [2] procedurally generates virtual scenes in real-time as users approach various obstacles indoors; pre-authored rooms are placed if there is sufficient space currently in front of the user, and virtual corridors connected to new space are generated otherwise. DreamWalker [33] visually overhauls the physical world in real-time and guides users through walkable paths in outdoor environments. RelityCheck [5] embeds the physical world in the virtual scene by rendering various visual hints to better represents the physical boundary without breaking immersion.

4.2 Locomotion Devices

Researchers have proposed a body of research on walking-based locomotion devices which explore the simulation of walking in VR. The key working principle is to counteract the movement of the user, keeping them in a relatively fixed position. One of the simplest examples is the traditional treadmill [13]. The torus treadmill [9] and Cyberwalk [26] extend the mechanism to support omni-directional walking. String walker [12] uses strings to reposition the user's feet. Virtusphere [16] cancels the user's movement by a human-sized hamster ball.

Researchers also have looked into walking on uneven surfaces. The ground surface simulator [19] is a treadmill equipped with individual height-adjustable elements that simulate bumpy terrains and slopes. The torso force feedback system [7] pulls users walking on a treadmill using an active mechanical link to simulate a slope. Gait Master [11] captures the user on every step and uses motion platforms that position themselves where the user is expected to step next. CirculaFloor [10] builds on the same concept but uses four robot units that maneuver themselves under the user's step with certain elevation. Level-ups [23] make the height-adjusting mechanism wearable, allowing the user to explore uneven terrain in virtual reality freely.

4.3 Locomotion Techniques

In addition to hardware solutions, there are many techniques to achieve locomotion in VR within limited space by trading in realism. The most common locomotion technique in current VR systems is teleportation [1]. Despite causing spatial disorientation and lacking somatosensation, it is affordable, quick and safe. It requires minimal physical space, and does not produce VR sickness, compared with other methods. To incorporate somatosensation, researchers have proposed locomotion based on proxy gestures that require the user to perform gestures to move inside the virtual world. The most common gesture is walking-in-place [25], where the user performs stepping gesture on the spot. Adopting navigation control with a joystick or a controller to fly through a virtual world is the least favorite as it produces sickness.

Recent research on locomotion techniques revolve around exploiting human perception to even further approximate real walking when the given physical space is smaller than the virtual scene. Redirected Walking [21] imperceptibly maneuvers users on a path that is different from what they experience in the virtual world to ensure that they do not collide with the boundaries of space. A previous study has shown that redirection requires a large empty space to make the redirection imperceptible [28]. Unlimited Corridor [15] similarly maneuvers users along a straight path in a virtual experience while in reality they are guided by a circular corridor to reduce the required space for imperceptible redirection. On the other hand, impossible spaces [30] employ a self-overlapping structure that exploits human spatial perception to extend the available virtual spaces for users to walk through multiple virtual rooms that share the same physical space. Scenograph [14] procedurally splits a virtual scene into smaller virtual scenes to be adapted to a smaller physical space for users to walk in.

4.4 Summary

In summary, our work extends real walking VR to vertical space by incorporating a common physical structure, a staircase, into a substitutional reality. Unlike previous locomotion devices that require practice to maintain balance and perceptible physical adoption, our system borrows the concept of redirection and impossible spaces together with our fine-tuned lifter control to achieve a realistic and unlimited walking experience in the vertical direction.

5 Implementation

As illustrated in Figure 5, our system consists of (1) a one-level scaffold, (2) a Unity-based VIVE VR system, (3) a lifter and its control system. In our system, we tracked the user's feet and the lifter's position using VIVE trackers and used a VIVE Pro HMD with a wireless module. For safety concerns, we hung safety nets on both sides of the staircase and installed fences and a door on the lifter as shown in Figure 1c.

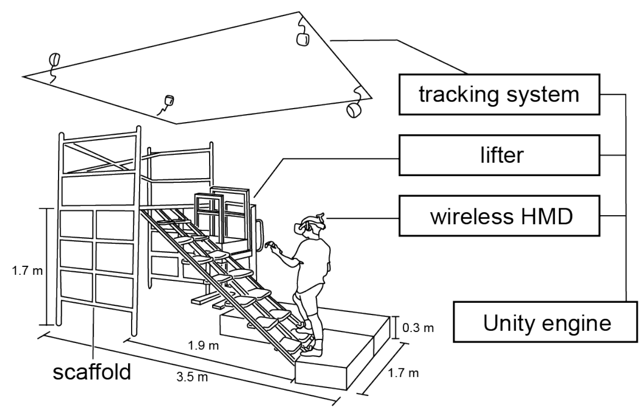

Figure 5: System overview

Figure 6a shows the electric-powered hydraulic lifter in our system. The electrical motor in the lifter pumps oil into the hydraulic cylinder to raise the lifter at a constant speed while using the weight of the platform to squeeze oil out from the cylinder to lower the lifter. To control the descending motion of the lifter, we assembled a control unit as shown in Figure 6b to control the hydraulic valve of the lifter as shown in Figure 6c. We used a MG996R 360 servo motor to rotate the valve as shown in Figure 6c so as to throttle the releasing speed of oil from the hydraulic cylinder. We used a NodeMCU board to receive commands from the software system and to drive the servo motor.

The geometries and positions of the scaffold, the staircase, and the lifter are recorded by manually constructing the 1-1 model and placing a VIVE tracker as shown in Figure 7a for calibration. Each virtual level is designed or generated based on the calibrated result (Figure 7b).

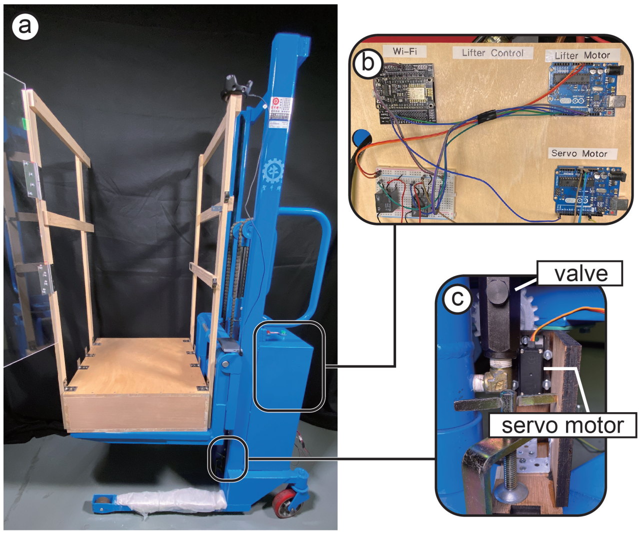

Figure 6: (a) The lifter is controlled by (b) the control unit which drives (c) the servo motor to control descending of the lifter by opening or closing the valve.

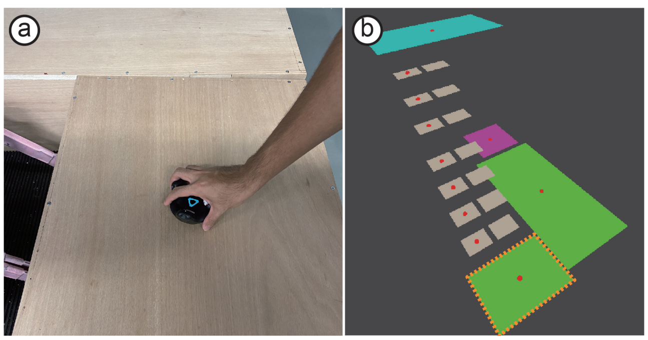

Figure 7: (a) We placed a tracker at different parts of the tracked area to (b) calibrate the physical geometry in our VR system.

5.1 Vertical Illusions

We achieved two vertical illusions: *still* (Figure 2) and *reverse* (Figure 3) to allow more flexible experience design.

The *still* illusion is implemented as shown in Figure 8. After the user walks from the first floor to the overlapping second floor (Figure 8a), they are stopped by a delay mechanism. While they are waiting, the surrounding scene follows the movement of the descending lifter so that they do not visually perceive motion (Figure 8b to c). They walk forward after the lifter arrives at the ground, and a new level appears once they leave the lifter (Figure 8d).

We elaborate how we implemented the *reverse* illusion with Figure 3c. The surrounding of the virtual elevator starts to move downward at the moment when the lifter starts descending. The surrounding of the virtual elevator is descending faster than the lifter actually does. This makes the user visually perceive staying in an ascending elevator in VR. In *PrisonEscape*, the user elevates 40 meters in VR (Figure 3 c to d) whereas the user descends 1.4 meters in real world (Figure 3 a to b).

The imperceptible motion in the two illusions is achieved by controlling the motion of the descending lifter. We throttle the descending speed by controlling the spinning duration of the servo motor. Since the servo motor as shown in Figure 6c spins at a

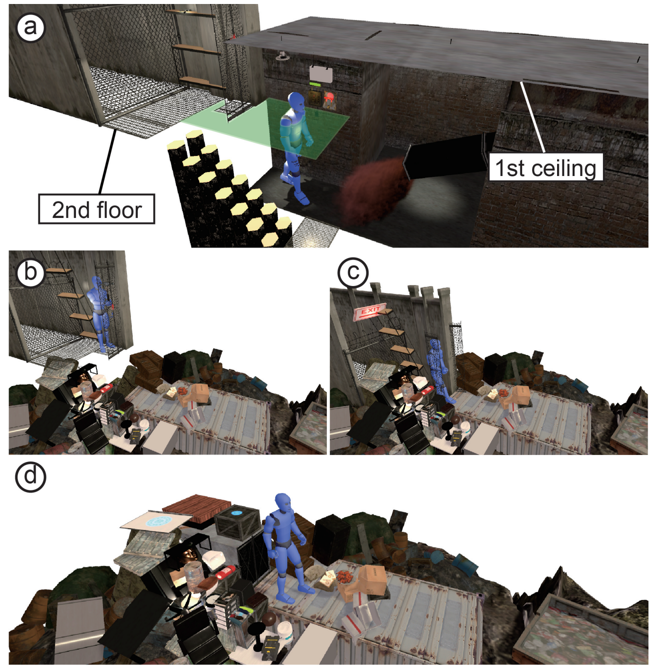

Figure 8: (a) The user walks and climbs through the two overlapping rooms. (b)(c) When they enter the lifter and start to descend, the surrounding scene follows the movement of the user so that they do not perceive descending. (d) The next level appears after they leave the lifter.

constant speed, the longer it spins, the valve opens/closes the hydraulic more, causing the lifter to descend faster/slower. The valve is initially closed to stop the lifter.

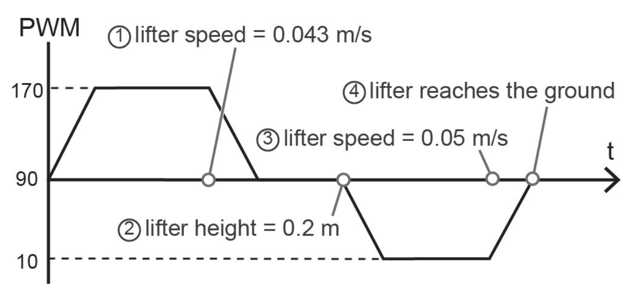

Figure 9: The control scheme of the servo motor

The perceptible vertical acceleration is 0.07 m/s^2 [17]. To maintain imperceptible motion while shortening the descending time, we empirically tested four control schemes and chose the most imperceptible one from a pilot study. The chosen control scheme has four phases as shown in Figure 9. (1) Once a user stands on the lifter, the motor gradually opens the valve (Pulse width modulation (PWM) value 10 = full-speed counterclockwise, 90 = stop, 170 = full-speed clockwise) until the speed of the lifter reaches 0.043 m/s and stops. (2) The motor starts closing the valve when the lifter is less than 20 cm above the ground. (3) The motor stops when the lifter reaches 0.005 m/s. (4) The lifter continues descending slowly until reaching the ground. The height of the lifter is sampled every 20 milliseconds using the VIVE tracker mounted on the lifter. The speed of the lifter is calculated by differentiating the maximum displacement in a fixed time window (0.5 second).

To achieve the *reverse* illusion, we were inspired by VisuaLift-Studio [4] and controlled the lifter to ascend for two seconds using default control to simulate the initial motion of a real ascending elevator. Afterwards, the lifter moved following the aforementioned control scheme to achieve the imperceptible motion.

As a side note, to enlarge a room vertically while preserving the realism of climbing, we incorporated impossible spaces [29] to place two vertically overlapping enlarged rooms as shown in Figure 8a; when the user passes through the corridor, the second floor then appears.

5.2 Procedural Generation

To achieve endless real walking, we implemented a story-based procedurally generated experience inspired by VRoamer [2]. In this experience, a user continuously climbs upward in a bizarre tunnel. They either defeat monsters or upgrade the weapon in each level. Once monsters are beaten, they find a treasure in the next level. The complete state diagram is shown in Figure 10. Whenever a task is finished, the state falls back to idle. The state machine determines what type of the task occurring at the next level. After the next task is decided, the registered prefabs corresponding to the task are spawned randomly in the next level.

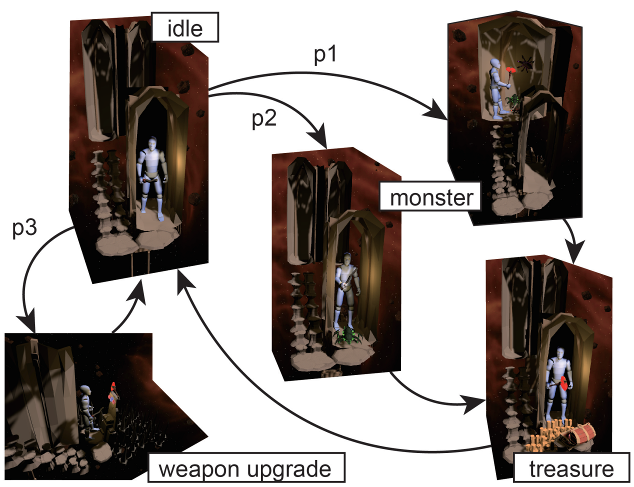

Figure 10: Each level is procedurally generated according to this state machine. The state machine decides the story happening in the next level. Pre-authored objects for each story type are spawned randomly.

5.3 Delay Mechanisms

Interactions and events in VR are used to prevent users from entering forbidden zones and to buy more time for the system to move and reset the lifter. Figure 11 shows a sequence of forbidden zones.

The first two sequences show that the user cannot walk backward when they are leaving the lifter and that both sides of the lifter cannot be entered as the lifter is rising. Figure 12 shows an example of events occurring in the first two sequences. The lights are turned off when a user enters the corridor. They have to pull the lever and wait until the lights recover as indicated by the progress bar (Figure 12b). In reality, the lifter is rising without being noticed.

Lastly, they cannot leave the descending lifter. Figure 13a shows a user is breaking the chain on the fence door blocking their way, and meanwhile, the lifter is descending to the ground. At the moment when the lifter reaches the ground, the chain is broken, and the fence door opens (Figure 13b).

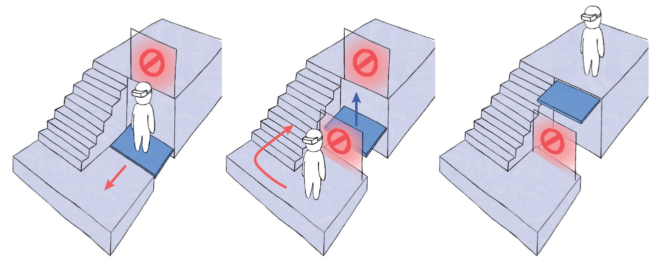

Figure 11: Interactions and animations are designed as delay mechanisms to stop a user from entering dangerous areas, such as going backwards when the lifter is on the ground, entering the ascending lifter and leaving the descending lifter.

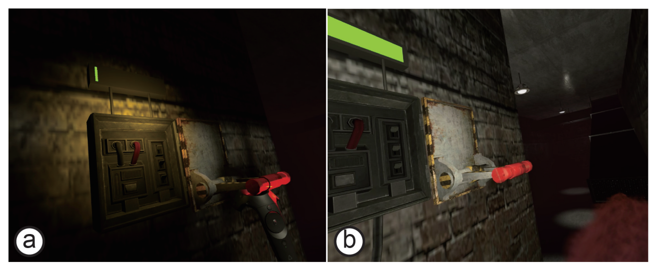

Figure 12: (a) A user pulls a lever down to recover lights while the lifter is rising. (b) The lights get recovered as shown by the progress bar indicating the lifter reaches the top.

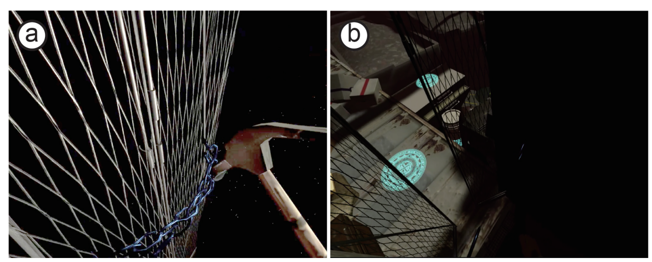

Figure 13: (a) As the lifter descends, a user is breaking the chain. (b) The chain is broken, and they are able to walk forward once the lifter reaches the ground.

6 Preliminary Study

We conducted a preliminary study to validate the functionality of Impossible Staircase and to gain insights from the participants. Our focus is understanding vertical real walking rather than being compared with other locomotion devices. We tested our in-lab set-up and had one experimenter monitoring behind the screen displaying what a participant was seeing and giving hints and warnings. Besides, we had a safety crew guarding the user's safety.

6.1 Task & Procedure

The task was to walk through *PrisonEscape*. The experimenter brought a blindfolded participant in our lab at a time (Figure 14a). The experimenter equipped trackers on the participant's feet (Figure 14b), briefly explained the task and assisted them in putting on the HMD. The participant was then guided to the starting point. Positions and rotations of their head and feet and timestamps when entering and leaving each step of the staircase for each foot were recorded. After completing the task, they filled out two questionnaires. One questionnaire had questions selected from The Game Experience Questionnaire [8] with 7 points Likert Scale (1: strongly disagree, 7: strongly agree) and assessed their perception of the structure they walked on, the realism of taking virtual elevator experience, and whether different visualizations of the real staircase affected their confidence while stepping on the staircase through an in-depth interview. The other questionnaire assessed whether they perceived they were sent back to the ground by the lifter. The whole experiment took about 60 minutes.

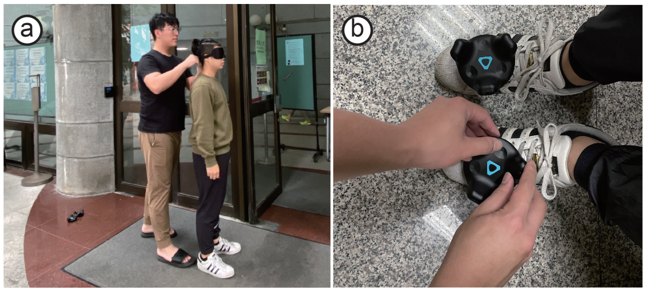

Figure 14: (a) The participant was blindfolded before the study to ensure he did not see the exact structure of the building. (b) Before the study, we tied trackers on his feet.

6.2 Participants

We recruited eight participants (three females, ages 21–24, M = 22.5, SD = 1) from our institute, one out of the eight participants had frequent VR experience before, the other participants reported limited or no experience. None of the participants have seen the experimenting area. No authors or people familiar with the project participated. They were rewarded with ten dollars per person.

6.3 Results

All the participants did not perceive they were sent back to the ground by the lifter and two of the participants guessed they were moved down by some kind of device but could not tell it occurred at which part of the experience. Other participants guessed they were circling a rectangular area and kept walking upward. Seven out of eight participants felt taking a rising elevator in VR realistic (Figure 3bc).

The mean score of the experience being fun was 5.75/7 (SD = 0.97). P1 said, "It feels like I was playing a real version of NS-SHAFT." P4 said, "It feels realistic, just like I kept walking upward." P6 said, "It's very realistic because I kept walking up on foot." Some participants felt nervous with a mean of 4.875/7 (SD = 1.45). P1 and P3 said, "I was worried about stumbling." P2 said, "The safety net was not rendered, but I could touch it." P3 said, "Worry decreased my balance while walking in VR. Walking on the staircase decreased my balance more. When I climbed up, the feet should bend, but they did not bend in VR. The mismatch of the shape of my feet also decreased my balance." P5 said, "I was nervous when I climbed on levitating objects." Most of the participants were curious about how we achieved Impossible Staircase with a score of 6.375/7 (SD = 1.11).

We ran one-way ANOVA by comparing four different staircase visualizations in our experience. We found no significant performance difference (F-ratio: 1.88247, p-value: .1635) between four staircase visualizations in *PrisonEscape* as shown in Figure 15.

7 Limitations

From our study, while Impossible Staircase enables users to walk and experience in an unlimited vertical virtual space given a limited physical playing area. However, several limitations are brought by the current system.

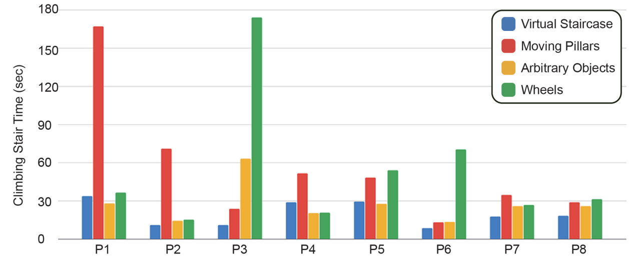

Figure 15: Staircase climbing time for each participant in each level

7.1 Level Design

As mentioned in the Implementation section, some interactions have to be incorporated as delay mechanisms. When a user enters a new level or is inside the lifter, they have to complete a task or wait due to an event. This requires a designer to come up with at least one interaction at a level and in the lifter. In addition, our current procedural generation algorithm supports only one storyline. Although it fits our need of the current prototype that does not support moving backward, more sophisticated generation algorithms may allow more flexible and general level design.

7.2 Hardware

The lifter of our system has a constant upward-lifting speed, which cannot create the illusion of infinitely walking down nor the sense of descending in VR while ascending in reality. The dimension of the platform where users can stand is 64 by 60 centimeters which limits ranges of interactions. Each step of the scaffolding staircase is small compared with the real size of each step of a staircase in a building. The current set-up only has one staircase, the repeated walking path may let users feel mundane as reported by the participants of our preliminary study. Besides, users' waiting time in the lifter has a lower bound due to perceptible thresholds of speed and acceleration, which means we cannot achieve non-stop climbing. The lifter generates noise when ascending. Our current solution was to use noise cancelling headphones. An alternative solution could be using acoustic foams to insulate the pump in the lifter.

7.3 Safety

In our preliminary study, we found that rendering walls or objects in an empty space, especially the edge of the playing area may put some confident users in danger. We observed the tendency of confidently leaning on a virtual wall or gaining the confidence of penetrating virtual walls without haptic feedback. This increases the possibility of falling. The current system requires manual labors being safety guards, and they may be interrupting during the experience. More responsive visual warnings and more rigid and automated safety devices may enhance the safety and immersion of the system.

8 Conclusion

We have presented Impossible Staircase, a VR system that allows infinite vertical real walking using a one-level scaffold and a lifter. We have focused on implementing an in-lab working system and exploring possible interactions for infinite real walking VR in the vertical direction. We also have described our system implementation in detail and provided system validations and limitations. While our preliminary result was positive, we also found several issues to be solved in order to deploy Impossible Staircase in an arbitrary building. In the future, we will look into incorporating redirected walking into our system to allow a more flexible experience design.

Acknowledgments

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References

[1] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey. Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, pp. 205–216, 2016.

[2] L.-P. Cheng, E. Ofek, C. Holz, and A. D. Wilson. Vroamer: Generating on-the-fly vr experiences while walking inside large, unknown real-world building environments. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 359–366. IEEE, 2019.

[3] L.-P. Cheng, T. Roumen, H. Rantzsch, S. Köhler, P. Schmidt, R. Kovacs, J. Jasper, J. Kemper, and P. Baudisch. Turkdeck: Physical virtual reality based on people. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, p. 417–426. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2807442.2807463

[4] T. Hachisu, M. Koge, and H. Kajimoto. Visualiftstudio: Using an elevator as a motion platform by modulating perceived direction with a visual illusion. 2018.

[5] J. Hartmann, C. Holz, E. Ofek, and A. D. Wilson. RealityCheck: Blending virtual environments with situated physical reality. In *Conference on Human Factors in Computing Systems - Proceedings*, pp. 1–12, 2019. doi: 10.1145/3290605.3300577

[6] O. Hayashi, K. Fujita, K. Takashima, R. W. Lindernan, and Y. Kitarnura. Redirected jumping: Imperceptibly manipulating jump motions in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 386–394. IEEE, 2019.

[7] J. M. Hollerbach, R. Mills, D. Tristano, R. R. Christensen, W. B. Thompson, and Y. Xu. Torso force feedback realistically simulates slope on treadmill-style locomotion interfaces. *The International Journal of Robotics Research*, 20(12):939–952, 2001.

[8] W. IJsselsteijn, Y. de Kort, and K. Poels. *The Game Experience Questionnaire*. Technische Universiteit Eindhoven, 2013.

[9] H. Iwata. Torus Treadmill: Realizing locomotion in VEs. *IEEE Computer Graphics and Applications*, 19(6):30–35, 1999. doi: 10.1109/38.799737

[10] H. Iwata, H. Yano, H. Fukushima, and H. Noma. Circulafloor [locomotion interface]. *IEEE Computer Graphics and Applications*, 25(1):64–67, 2005.

[11] H. Iwata, H. Yano, and F. Nakaizumi. Gait master: A versatile locomotion interface for uneven virtual terrain. In *Proceedings IEEE Virtual Reality 2001*, pp. 131–137. IEEE, 2001.

[12] H. Iwata, H. Yano, and M. Tomiyoshi. String walker. In *ACM SIGGRAPH 2007 Emerging Technologies*, SIGGRAPH '07, p. 20–es. Association for Computing Machinery, New York, NY, USA, 2007. doi: 10.1145/1278280.1278301

[13] L. Kassler, J. Feasel, M. D. Lewek, F. P. Brooks, and M. C. Whitton. Matching actual treadmill walking speed and visually perceived walking speed in a projection virtual environment. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, APGV '10, p. 161. Association for Computing Machinery, New York, NY, USA, 2010. doi: 10.1145/1836248.1836283

[14] S. Marwecki and P. Baudisch. Scenograph: Fitting Real-Walking VR Experiences into Various Tracking Volumes. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pp. 511–520. ACM, New York, NY, USA, 2018. doi: 10.1145/3242587.3242648

[15] K. Matsumoto, Y. Ban, T. Narumi, Y. Yanase, T. Tanikawa, and M. Hirose. Unlimited corridor: redirected walking techniques using visuo haptic interaction. In *ACM SIGGRAPH 2016 Emerging Technologies*, pp. 1–2. 2016.

[16] E. Medina, R. Fruland, and S. Weghorst. Virtusphere: Walking in a Human Size VR "Hamster Ball". *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 52(27):2102–2106, 2008. doi: 10.1177/154193120805202704

[17] A. Nesti, M. Barnett-Cowan, P. R. MacNeilage, and H. H. Bülthoff. Human sensitivity to vertical self-motion. *Experimental Brain Research*, 232(1):303–314, Jan 2014. doi: 10.1007/s00221-013-3741-8

[18] N. C. Nilsson, S. Serafin, F. Steinicke, and R. Nordahl. Natural walking in virtual reality: A review. 16(2):1–22, 2018. doi: 10.1145/3180658

[19] H. Noma, T. Sugihara, and T. Miyasato. Development of ground surface simulator for tel-e-merge system. In *Proceedings IEEE Virtual Reality 2000 (Cat. No. 00CB37048)*, pp. 217–224. IEEE, 2000.

[20] L. S. PENROSE and R. PENROSE. Impossible objects: A special type of visual illusion. *British Journal of Psychology*, 49(1):31–33, 1958. doi: 10.1111/j.2044-8295.1958.tb00634.x

[21] S. Razzaque, Z. Kohn, and M. C. Whitton. *Redirected walking*. Citeseer, 2005.

[22] J. S. Roo and M. Hachet. One reality: Augmenting how the physical world is experienced by combining multiple mixed reality modalities. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, pp. 787–795, 2017.

[23] D. Schmidt, R. Kovacs, V. Mehta, U. Umapathi, S. Köhler, L.-P. Cheng, and P. Baudisch. Level-ups: Motorized stilts that simulate stair steps in virtual reality. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pp. 2157–2160, 2015.

[24] A. L. Simeone, E. Velloso, and H. Gellersen. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pp. 3307–3316. ACM, New York, NY, USA, 2015. doi: 10.1145/2702123.2702389

[25] M. Slater, A. Steed, and M. Usoh. The Virtual Treadmill: A Naturalistic Metaphor for Navigation in Immersive Virtual Environments. In M. Göbel, ed., *Virtual Environments '95*, pp. 135–148. Springer Vienna, Vienna, 1995.

[26] J. L. Souman, P. R. Giordano, M. Schwaiger, I. Frissen, T. Thümmel, H. Ulbrich, A. D. Luca, H. H. Bülthoff, and M. O. Ernst. Cyberwalk: Enabling unconstrained omnidirectional walking through virtual environments. *ACM Trans. Appl. Percept.*, 8(4), Dec. 2008. doi: 10.1145/2043603.2043607

[27] M. Sra, S. Garrido-Jurado, and P. Maes. Oasis: Procedurally Generated Social Virtual Spaces from 3D Scanned Real Spaces. *IEEE Transactions on Visualization and Computer Graphics*, 24(12):3174–3187, 2018. doi: 10.1109/TVCG.2017.2762691

[28] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of Detection Thresholds for Redirected Walking Techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):17–27, 2010. doi: 10.1109/TVCG.2009.62

[29] E. A. Suma, Z. Lipps, S. Finkelstein, D. M. Krum, and M. Bolas. Impossible spaces: Maximizing natural walking in virtual environments with self-overlapping architecture. *IEEE Transactions on Visualization and Computer Graphics*, 18(4):555–564, 2012.

[30] E. A. Suma, Z. Lipps, S. Finkelstein, D. M. Krum, and M. Bolas. Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture. *IEEE Transactions on Visualization and Computer Graphics*, 18(4):555–564, apr 2012. doi: 10.1109/TVCG.2012.47

[31] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks Jr. Walking >Walking-in-place >Flying, in Virtual Environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '99, pp. 359–364. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 1999. doi: 10.1145/311535.311589

[32] Z. Wang, K. Bauernfeind, and T. Sugar. Omni-directional treadmill system. In *11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings.*, pp. 367–373. IEEE, 2003.

[33] J. Yang, C. Holz, E. Ofek, and A. D. Wilson. Dreamwalker: Substituting real-world walking experiences with a virtual reality. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pp. 1093–1107, 2019.