View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Repository for Publications and Research Data

ETH zürich Research Collection

Conference Paper

# Real walking in virtual environments for factory planning and evaluation

**Author(s):**
Kunz, Andreas; Zank, Markus; Fjeld, Morten; Nescher, Thomas

**Publication Date:**
2016

**Permanent Link:**
https://doi.org/10.3929/ethz-a-010638252 →

**Originally published in:**
Procedia CIRP 44, http://doi.org/10.1016/j.procir.2016.02.086 →

**Rights / License:**
Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International →

This page was generated automatically upon download from the ETH Zurich Research Collection. For more information please consult the Terms of use.

ETH Library

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 44 (2016) 257 – 262

www.elsevier.com/locate/procedia

6th CIRP Conference on Assembly Technologies and Systems (CATS)

# Real walking in virtual environments for factory planning and evaluation

Andreas Kunz[a,*], Markus Zank[a], Morten Fjeld[b], Thomas Nescher[a]

[a]Innovation Center Virtual Reality, ETH Zurich, Leonhardstrasse 21, 8092 Zurich, Switzerland
[b]t2i Interaction Lab, Chalmers University of Technology, Lindholmen KUGGEN, 41296 Gothenburg, Sweden

* Corresponding author. Tel.: +41-44-6325771; Fax: +41-44-6321125. *E-mail address:* kunz@iwf.mavt.ethz.ch

---

## Abstract

Nowadays, buildings or production facilities are designed using specialized design software and building information modeling tools help to evaluate the resulting virtual mock-up. However, with current, primarily desktop based tools it is hard to evaluate human factors of such a design, for instance spatial constraints for workforces. This paper presents a new tool for factory planning and evaluation based on virtual reality that allows designers, planning experts, and workforces to walk naturally and freely within a virtual factory. Therefore, designs can be checked as if they were real before anything is built.

© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the organizing committee of the 6th CIRP Conference on Assembly Technologies and Systems (CATS)

*Keywords:* Factory planning; production planning; virtual reality; building information model; real walking; redirected walking; redirection techniques; collaborative virtual environments; virtual construction

---

## 1. Introduction

Since years, buildings, production lines, and production facilities are planned and designed using dedicated software, like Computer-Aided Design (CAD), Computer-Aided Architectural Design (CAAD), or Building Information Modeling (BIM). While these systems offer good support for architects and engineers to plan and design installations, they are less suited to address and evaluate human factors in design. Such human factors are for instance the perception of sizes and distances, level of comfort, but also spatial constraints at a workplace, which could be naturally experienced in its dimensions by the possibility of real walking. However, in particular distances and walking times are hard to evaluate with monitor-based systems, and thus also virtual reality (VR) systems are employed. In such systems, the user is immersed in computer-generated environments and can see objects in real size.

However, the perception of sizes and distances is limited by the fact that navigation is still done using mouse and joystick. It was shown by Usoh et al. [1] that such a navigation does not address the natural human perception of real walking. Real walking allows a natural navigation [2] together with better orientation [3] in virtual environments. In general, real walking is superior to other navigation metaphors such as mouse or other gestural walking (e.g. walking-in-place [4] or stepping-in-place) [1]. Virtual environments with real walking capabilities are superior to any other ways of representation because of the following reasons:

- They allow an immersive experience at a very early planning stage without the effort of building a physical mock-up. Thus, it is possible to make multiple iteration steps in the development process without extending the development time and to reduce the costs significantly, see [5].
- Since walking is the most intuitive tool for navigating in virtual environments, also non-experts - which are in most cases the later users of the product - can be integrated in the development process.
- Virtual Reality easily allows the evaluation of human factors in new designs, such as walking distances, space requirements of workers, but also e.g. an early evaluation of human manufacturing and assembly tasks using an MTM method (methods-time measurement).
- Manual operation processes in industry frequently require also walking of a worker, e.g. in a Chaku-Chaku setup [6], where the user is transporting the product or other objects.
- Finally, immersive environments can be used for training purposes prior to the finalization of the real installation.

Real walking becomes problematic when the virtual environment is larger than the physical space, e.g. for complete shop floors. To overcome this problem, mechanical locomotion devices such as e.g. the Torus Treadmill [7] or the omnidirectional treadmill [8] were developed. These locomotion de-

2212-8271 © 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the organizing committee of the 6th CIRP Conference on Assembly Technologies and Systems (CATS)
doi:10.1016/j.procir.2016.02.086

vices allow walking over large distances in the virtual environment, but keep the user in a small space within the real world. However, such devices are costly, allow only a single-user experience, and still do not provide a fully realistic sensation.

Thus, recent research is based on so-called Redirected Walking [9], which "compresses" large virtual environments into a smaller physical room by applying a subtle redirection to the user. These systems allow real walking without any additional mechanical interfaces and thus offer the highest possible immersion. Since this approach becomes increasingly mature, the goal is now to apply it to real industrial use cases, such as training or emergency scenarios, in which the perception of distances plays an important rule. This system allows natural and free walking inside a virtual factory even when the physical room, where a user is actually located, is smaller than the virtual factory. This spatial compression is based on redirected walking, a technique that allows free walking in large virtual environments without using locomotion hardware like treadmills. Since even large virtual environments could be experienced by redirected walking in a limited physical space, redirected walking should be applied now for factory planning and optimization of factories. However, this imposes the reserach question which redirection algorithms could be applied for this application case and how the controller needs to be modified to exclude non-suitable redirection techniques.

Therefore, the paper's main contribution is to apply this new system to factory planning and evaluation, based on VR that allows designers, planning experts, and other work-forces to walk naturally and freely within a virtual factory. The paper shows the first application of redirected walking to a real problem in production industries. Real walking and experiencing the virtual environment from an egocentric perspective is in particular important for evaluating the user behavior e.g. for MTM, which currently can not cope with real walking. This paper shows how redirected walking can be optimized for free walking in virtual factories. The resulting system allows improving and checking models very early in the design process – before anything is built – and thus avoids costly redesigns at a later stage.

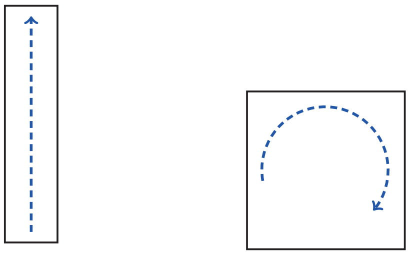
The paper first introduces the field of Redirected Walking (RDW). After showing a typical system for unlimited walking in virtual environments, it describes which RDW algorithms can be used for an application in factory planning and evaluation. The remainder of the paper describes the currently available interaction capabilites of the system. Finally, the paper concludes with an outlook on future work.

## 2. Background

### 2.1. Redirected walking

Technically, enabling a user to really walk inside arbitrary virtual environments – including virtual factories – is best realized by letting the user walk in a physical/real room. A tracking system can be used to track the user's viewpoint in real time and render the virtual environment from that perspective. Typcially, the rendered scene is shown to the user using a head mounted display (HMD). The HMD blocks the user's sight on the real room and just lets him see the virtual environment.

However, this approach has the disadvantage that the size of the real room (or the tracked space) limits the size of the virtual environment that can be walked through. In order to avoid costly or unnatural mechanical locomotion interfaces and still be able to walk freely in arbitrary virtual environments, Razzaque et al. [9] proposed RDW. This is a method that uses a set of techniques to guide a user on a different path in the real room than what he is walking in the virtual environment. Primarily, RDW manipulates the visual output presented on the HMD. For instance, by slowly rotating the virtual environment about he user while he is walking along a straight path. If this rotation is below the human threshold for sensing orientation or movement with non-visual cues, the user will not notice the rotation and walk on an arc in the real room. I.e. the user gets redirected. The fundamental psychological foundation for RDW is that vision generally dominates other modalities (e.g. proprioceptive senses) of perception [10,11].



(a) Virtual environment (b) Real room

Fig. 1. Working principle of redirected walking. The dashed blue line indicates a user's path. The user believes that he is following the straight path in the VE (a). However, because the VE is continuously and imperceptibly rotated clockwise about the user, he actually walks on an arc in the real room (b).

This working principle is illustrated in Fig. 1. Here, the user walks along a straight corridor in the virtual environment. As the scene is slowly rotated clockwise around he user, he actually follows a circular path in the real room. I.e. visual dominance over proprioceptive senses causes the user to compensate his real walking path without noticing. This example also shows how RDW can be used to explore a virtual environment that is longer than the longest straight line fitting into the real room.

### 2.2. Redirection techniques and control

Different redirection techniques were proposed so far. For instance, the redirection technique that is used in Fig. 1 is referred to as curvature gain because it makes users walking on a curved path in the real room, while walking on a straight line in the virtual environment. For these sorts of redirection techniques it is important to know the gains. The gain is essentially the strength parameter of a redirection technique and given as the maximum applicable redirection without the user noticing the manipulation. Common redirection methods are:

- Curvature gain: rotation that can be added when a user is walking on a straight line, see [9,12,13].
- Rotation gain: scaling of the user's rotational movements like head turns or full body turns, see [9,12].
- Translation gain: scaling of the user's translational movement. I.e. the user's speed in the virtual environment is increased or decreased, see [12,14].
- Architectural illusions and change blindness: tricking the user's spatial memory or perception by using specialized

virtual environments or modifications thereof. E.g. with self-overlapping geometries, see [15,16].

- Reset techniques: sometimes using the above redirection techniques is not sufficient to make sure that a user is kept within the boundaries of the real room. In this case reset techniques are applied. They essentially stop a user and instruct him to perform some activity so that he can be reoriented or repositioned, see [17–19]. Resets are not imperceptible in contrast to the above redirection techniques.

This list only gives a brief and incomplete overview. For a complete summary see Suma et al. [20] who proposed a taxonomy of redirection techniques. The taxonomy distinguishes between subtle and overt redirection techniques, continuous and discrete techniques, and techniques which reorient or reposition a user. However, not all of them are applicable for industrial applications or factory planning. Hence, this paper shows how and which redirection techniques are suitable. Architectural illusions for example would behave like teleporting portals. Since this would result in wrong time measures for bridging a distance by walking, they cannot be used here.

Besides using natural walking for navigation, there are also various metaphors that allow traveling over large distances without walking. Such metaphors could be based on classic navigation using interaction devices [21], use some sort of teleportation metaphor [22], or travel metaphors built right into the environment like escalators for going upstairs.

Redirection techniques are not sufficient to allow for free walking in large virtual environments. A so-called steering algorithm or RDW controller is needed to decide which redirection technique can be applied and with what parameters. For instance, in Fig. 1 an RDW controller has to determine that a curvature gain must be applied to redirect the user clockwise in the real room. So-called steer-to-target RDW controllers are simple heuristic controllers that continuously redirect a user towards a fixed point in the real room or on an orbit, see [23,24]. These controllers are limited to a subset of redirection techniques. In contrast, planning RDW controllers as in [19,25] use path prediction and a model of the virtual environment to determine the optimal redirection. Furthermore, these controllers are capable of combining several redirection techniques.

### 2.3. VR for factory planning

Buildings, factories, or complete production facilities are planned and designed digitally nowadays. A multitude of commercial CAD and CAAD software is available for that purpose. To further augment the models with context information, BIM software and standards, e.g. [26], are used. In other words, factory planning is already done “virtually”but still lacks immersion. Immersive VR means that the user/planning expert is fully integrated in the virtual factory (and feels physically present in it). Wiendahl et al. [27] have shown that immersive VR is an important tool for co-operative factory planning, especially when the viewpoint of different planning expert gets visualized. For instance, a logistics expert might want to explore and evaluate a factory model but is not a CAD expert himself. Immersive VR and RDW allows him to get into the model in the most natural way possible.

Mujber et al. [28] summarized the state of VR for manufacturing process simulation and its advantages. They determined that fully immersive VR is highly useful for planning and designing in industry. However, the costs of such an immersive VR system were very high and thus the systems could not be applied to real business processes. The VR system presented in this paper based on RDW (and recent consumer level HMDs), reduces these costs significantly.

## 3. Virtual reality system for real walking

### 3.1. Hardware

Inaccurate tracking, low refresh/update rate, high latency, jitter, etc. can quickly cause simulator sickness and render the VR system useless. Hence, it is crucial that the tracking system has a low latency (ideally below 10 ms), high update rate (ideally at least 100 Hz) and high precision (less than 5 mm RMS and 2 degrees RMS (random mean square)). Absolute accuracy is less important as the user will not notice that anyway. Similarly, the HMD should have a low latency, high refresh rate and a low persistence screen. Finally, the notebook should be equipped with a high performance graphics card to reduce the rendering delay and increase the rendering quality.

(a)

(b)

Fig. 2. VR system composed of a HMD, tracking system, backpack, and a notebook. (a) A user walking through a virtual factory. (b) Standing user using a gamepad for interacting with the virtual environment.

The fully wearable VR system for really walking in virtual environments is shown in Fig. 2. The system is composed of an Oculus [1] DK2 HMD (960x1080 resolution per eye) and a back-

---

[1] https://www.oculus.com/

pack to carry a notebook. In order to track the user's viewpoint in the real room, an Intersense IS-1200 6 degrees-of-freedom tracking system [29] (180 Hz update rate, 6 ms latency) is attached to the HMD. The notebook processes the tracking data from the tracking device and renders the scene. Furthermore, it powers all hardware components. Hence, the whole VR system is wireless allowing the user to walk freely in the real room. The size of the used tracking space is about 12 m by 6 m.

### 3.2. *Software*

The software of the VR system processes tracking data, runs an RDW controller, applies redirection, and forwards this data to a rendering engine. For this paper, the Unity3D [2] game engine is used. Fig. 3 shows the resulting data flow. As for the hardware it is crucial that the data processing pipeline adds very little latency to the whole system. In the current configuration, the latency of the whole software between the tracking system and the rendering engine is around 1 ms. The latency of the rendering engine heavily depends on the scene complexity.

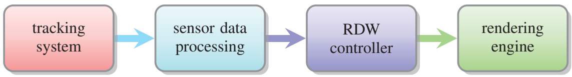


Fig. 3. Data flow for the VR system.

## 4. Redirected walking for walking in virtual factories

In Section 2.2 different redirection techniques were introduced. While these techniques have all been used and studied before, not all of them are applicable to factory planning and evaluation. In fact, depending on the application, certain redirection techniques might not be desired. For instance, architectural illusions introduce changes (permanent and non-permanent) to the virtual environment and some trick the user's spatial cognition about the structure of the virtual environment. For factory planning and evaluation this is not desired. The virtual factory should be experienced like the real factory without changes in the design just for the purpose of redirection.

A related problem arises when translation gains are used. I.e. the user moves faster (or slower) in the virtual factory than in the real room. While this could be useful to quickly traverse a large area, it reduces (or increases) the real time it takes to walk from a location A to another location B. Hence, for training applications or for MTM where exact measurements are required, translational gains cannot be used.

Curvature gains and rotation gains are the most generic redirection techniques and typically do not influence the time for traveling in the virtual factory. In some cases rotation gains might be undesired however. E.g when a more or less stationary user is training at a virtual assembly station and often has to turn around for fetching parts. This would cause redirections forcing the user to make more physical turns. Thus, time measurement for performance analysis of a design would be inaccurate. In general however redirections from rotation gains will have very little effect on time measurements.

Especially when the real room is small, the subtle redirection techniques above will not be sufficient to always keep the user within the boundaries of the real room. In these cases, resets are required. A reset stops a user when he comes too close to the boundary and asks him to make a full turn about himself (as in [19]). During this full turn a rotation gain is applied that redirects him. Of course resets disturb the user and take time to perform. However, for time measurements or performance evaluations their effect can simply be subtracted from the measurements because resets have a well defined start and end.

An overview of the applicability of different redirection techniques is given in Fig. 4. In contrast to the taxonomy in [20], for factory planning important criteria are: if a technique is altering the scene/model, if it distorts real time measurements and for resets how disturbing and how fast they can be performed.

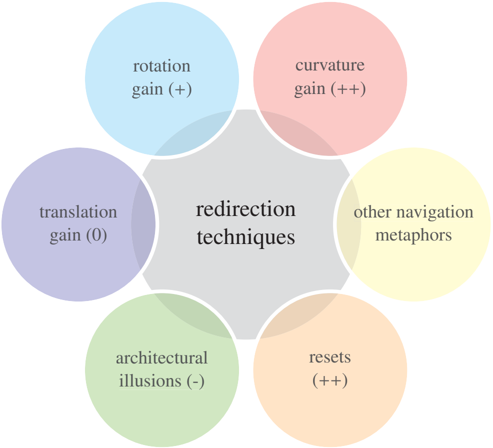


Fig. 4. Applicability of redirection techniques to factory planning. (++) or (+) mean highly or well applicable, (0) means applicability depends on task, (-) not applicable. 'Other navigation metaphors' are presented in Section 5.

## 5. Navigation methods in virtual factories

For virtual factory walk-throughs – e.g. in contrast to private houses – often large distances have to be covered. Factories or production facilities often reach lengths of several hundreds of meters or more. Hence, pure walking is not feasible for quickly checking out a few "hot spots" in the model or for a virtual planning discussions in the virtual factory. Hence, alternative metaphors for navigation can be combined with RDW.

### 5.1. *Gradual translation*

Gradual translations can be realized with objects that transport a user in the virtual environment – like escalators. Because RDW does not (easily) allow climbing virtual stairs, stairs can simply be replaced with escalators.

### 5.2. *Flying*

The most well known navigation metaphors for desktop systems are mouse, joystick, or keyboard based flying techniques. Here the user uses manual interaction to move the viewpoint

---

[2] http://unity3d.com/

through the virtual environment. However, for immersive VR strong visual acceleration or movement combined with no real physical acceleration or movement is a cause of simulator sickness. In order to reduce the effect of simulator sickness the user should be equipped at least with a moving frame of reference. E.g. in order to fly through a scene a user should be forced to use a "flying carpet" or a virtual car. During the movement the user can then still move naturally on the carpet and look around while maneuvering the carpet with a joystick for instance.

### 5.3. Teleporting

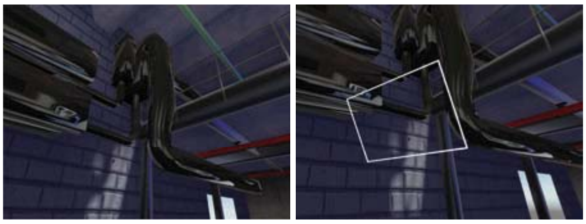
Very useful metaphors for quickly moving from one discrete location to another are teleporting methods. E.g. a "beaming" metaphors fades the virtual scene to black, places the user at a new location in the virtual factory and fades back to the virtual scene. Instead of beaming portals can be used. When a user manually selects his destination in portal mode, a portal appears. As soon as he walks through the portal he is teleported to the new location. Teleporting has the advantage that there is now risk of causing simulator sickness. Teleporting can be combined with redirection by placing the portal dynamically at a clever location, see e.g. [30].

## 6. Factory planning and interaction

Immersive VR for factory or production planning is useful when it comes to demonstrating, evaluating, and checking designs or for training purposes. The design itself is done with CAD software and not within the virtual environment. However, as real walking in virtual factories brings the people into the design, it becomes part of the design process. In that process an important feature is the capability to annotate areas of interest and mark errors while walking through a virtual factory. As the current system does not track a user's hands, a gamepad/joystick like device is used for interaction, see Fig. 2(b). An example scene of a virtual factory is shown in Fig. 5.

Fig. 5. Screen-shot of an example scene from a virtual factory showing a shop floor with manufacturing machines. Tubes and cable channels are also visible.

In the current system, a user can annotate an area of interest or a feature by taking a "screen-shot" of his field of view. This tool allows recording the user's position, orientation, an audio message, a description tag, and his full field of view. An extension to this method allows the user to place a virtual photo frame to more accurately "photograph" a critical area for later discussion or revisiting, see Fig. 6 for more details. Since the coordinates are stored other users can easily be "sent" to the same location at a later time.



(a) (b)

Fig. 6. Screen-shot of a the user's view on a problematic area in the virtual factory. (a) The user can store his current view (full field of view) like a screenshot and/or his current location and orientation. (b) The user manually selects picture mode to place a 3D photo frame in his current field of view. He can then move freely (frame stays put) to zoom before recording the final screenshot including his current location and orientation.

In summary, the proposed system has the following characteristics:

- Combination of production planning and MTM, which results in a reuse of existing data.
- Optimization of a manufacturing layout under various aspects such as geometry, or workers' movements (MTM), while always working on the same data set.
- Enhancement of the existing MTM by new capabilities such as walking.
- Perception of distances and sizes by the integration of human locomotion as interaction modality with the virtual environment.
- Automatic capturing of a worker's walking trajectories together with the corresponding temporal information.
- Reuse of data from MTM and production planning for other tasks such training and education.

## 7. Conclusion and future work

This paper showed an immersive VR system that allows real walking in virtual environments. The system consists of the mentioned hardware together with the visualization software, redirection algorithms and the controller for selecting suitable redirection techniques depending on the current position of the user in the real and virtual environment. With this system designers, planning experts, and work-forces can walk naturally and freely within a virtual factory before anything is built. By using RDW, users are able to walk freely through virtual factories even if they are physically located in a much smaller room. A guideline for how to tailor RDW to different factory planning situations was shown. Furthermore, other navigation methods were presented that allow users to travel over large distances in the virtual factory when walking does not make sense. Finally, a few methods were shown how users can record or annotate features in the virtual factory for later discussion or later visits.

Future work will also focus on a comparison between the traditional and the VR-enhanced MTM regarding the overall performance time and the accuracy of the results.

At its current stage, the VR system does not allow showing a virtual representation of the user's body in the virtual environment. Especially the user's arms and hands are missing. In future, manual or bimanual interaction metaphors would greatly improve the possibilities to interact with the virtual environment in an intuitive and natural way. For instance, this would make it very easy to place or align a photo frame in the virtual factory for recording a snapshot. Or for navigating, a user could drive a virtual car through the virtual factory and steer with a virtual steering wheel.

Another relevant extension is multiuser support. I.e. multiple users could visit the same virtual factory and walk through it together. This requires an avatar based representation of each user so that they can see each other. Most interestingly however, both (or more) users could be using the same tracking space/real room at the same time. RDW controllers can not only make sure that users do not collide with real room walls but also make sure that two walking users do not collide with each other. Because in this setup two users might be physically close to each other but virtually far apart and vice versa.

Finally, a recently built addition to the VR system allows a local audience to see what the VR user is seeing on the HMD. This works by filtering the tracking data accordingly and rendering a smoothed second view of the virtual environment for being displayed on a large screen.

## References

[1] Usoh, M., Arthur, K., Whitton, M.C., Bastos, R., Steed, A., Slater, M., et al. Walking > walking-in-place > flying, in virtual environments. In: SIGGRAPH '99: Proceedings of the 26th annual conference on Computer graphics and interactive techniques. ACM. ISBN 0-201-48560-5; 1999, p. 359–364. doi:10.1145/311535.311589.

[2] Ruddle, R.A., Lessels, S.. The benefits of using a walking interface to navigate virtual environments. ACM Transactions on Computer-Human Interaction 2009;16(1):1–18. doi:10.1145/1502800.1502805.

[3] Ruddle, R.A., Volkova, E., Bülthoff, H.H.. Walking improves your cognitive map in environments that are large-scale and large in extent. ACM Transactions on Computer-Human Interaction 2011;18(2):10:1–10:20. doi:10.1145/1970378.1970384.

[4] Templeman, J.N., Denbrook, P.S., Sibert, L.E.. Virtual locomotion: Walking in place through virtual environments. Presence: Teleoperators and Virtual Environments 1999;8(6):598–617. doi:10.1162/105474699566512.

[5] Dunston, P., Arns, L., Mcglothlin, J., Lasker, G., Kushner, A.. An immersive virtual reality mock-up for design review of hospital patient rooms. In: Wang, X., Tsai, J.H., editors. Collaborative Design in Virtual Environments; vol. 48 of *Intelligent Systems, Control and Automation: Science and Engineering*. Springer Netherlands. ISBN 978-94-007-0604-0; 2011, p. 167–176.

[6] Wornack, J.P., Jones, D.T., Roos, D.. The machine that changed the world: The story of lean production - Toyota's secret weapon in the global car wars that is now revolutionizing world industry. Simon and Schuster; 2007. doi:10.1002/hfm.4530040310.

[7] Iwata, H.. The torus treadmill: Realizing locomotion in VEs. Computer Graphics and Applications 1999;19(6):30–35. doi:10.1109/38.799737.

[8] Darken, R.P., Cockayne, W.R., Carmein, D.. The omni-directional treadmill: a locomotion device for virtual worlds. In: Proceedings of the 10th annual ACM symposium on User interface software and technology. ACM. ISBN 0-89791-881-9; 1997, p. 213–221. doi:10.1145/263407.263550.

[9] Razzaque, S., Kohn, Z., Whitton, M.C.. Redirected walking. In: Proceedings of Eurographics. 2001, p. 289–294.

[10] Posner, M., Nissen, M., Klein, R.. Visual dominance: an information-processing account of its origins and significance. Psychological Review 1976;83(2):157.

[11] Berthoz, A.. The brain's sense of movement. Harvard University Press; 2000.

[12] Steinicke, F., Bruder, G., Jerald, J., Frenz, H., Lappe, M.. Estimation of detection thresholds for redirected walking techniques. IEEE Transactions on Visualization and Computer Graphics 2010;16(1):17–27. doi:10.1109/TVCG.2009.62.

[13] Neth, C., Souman, J., Engel, D., Kloos, U., Bülthoff, H., Mohler, B.. Velocity-dependent dynamic curvature gain for redirected walking. IEEE Transactions on Visualization and Computer Graphics 2012;18(7):1041–1052. doi:10.1109/TVCG.2011.275.

[14] Williams, B., Narasimham, G., McNamara, T.P., Carr, T.H., Rieser, J.J., Bodenheimer, B.. Updating orientation in large virtual environments using scaled translational gain. In: Proceedings of the 3rd symposium on Applied perception in graphics and visualization. ACM. ISBN 1-59593-429-4; 2006, p. 21–28. doi:10.1145/1140491.1140495.

[15] Suma, E., Clark, S., Krum, D., Finkelstein, S., Bolas, M., Warte, Z.. Leveraging change blindness for redirection in virtual environments. In: Proceedings of the IEEE Conference on Virtual Reality. IEEE; 2011, p. 159–166. doi:10.1109/VR.2011.5759455.

[16] Suma, E., Lipps, Z., Finkelstein, S., Krum, D., Bolas, M.. Impossible spaces: Maximizing natural walking in virtual environments with self-overlapping architecture. IEEE Transactions on Visualization and Computer Graphics 2012;18(4):555–564. doi:10.1109/TVCG.2012.47.

[17] Williams, B., Narasimham, G., Rump, B., McNamara, T.P., Carr, T.H., Rieser, J., et al. Exploring large virtual environments with an HMD when physical space is limited. In: Proceedings of the 4th symposium on Applied perception in graphics and visualization. ACM. ISBN 978-1-59593-670-7; 2007, p. 41–48. doi:10.1145/1272582.1272590.

[18] Peck, T.C., Fuchs, H., Whitton, M.C.. Evaluation of reorientation techniques and distractors for walking in large virtual environments. IEEE Transactions on Visualization and Computer Graphics 2009;15(3):383–394. doi:10.1109/TVCG.2008.191.

[19] Nescher, T., Huang, Y.Y., Kunz, A.. Planning redirection techniques for optimal free walking experience using model predictive control. In: Symposium on 3D User Interfaces. IEEE; 2014, p. 111–118. doi:10.1109/3DUI.2014.6798851.

[20] Suma, E., Bruder, G., Steinicke, F., Krum, D., Bolas, M.. A taxonomy for deploying redirection techniques in immersive virtual environments. In: Virtual Reality Short Papers and Posters. IEEE; 2012, p. 43–46. doi:10.1109/VR.2012.6180877.

[21] Cirio, G., Vangorp, P., Chapoulie, E., Marchal, M., Lecuyer, A., Drettakis, G.. Walking in a cube: Novel metaphors for safely navigating large virtual environments in restricted real workspaces. IEEE Transactions on Visualization and Computer Graphics 2012;18(4):546–554. doi:10.1109/TVCG.2012.60.

[22] Bruder, G., Steinicke, F., Hinrichs, K.H.. Arch-explore: A natural user interface for immersive architectural walkthroughs. In: Symposium on 3D User Interfaces. IEEE. ISBN 978-1-4244-3965-2; 2009, p. 75–82. doi:10.1109/3DUI.2009.4811208.

[23] Razzaque, S.. Redirected walking. Ph.D. thesis; The University of North Carolina at Chapel Hill; 2005.

[24] Hodgson, E., Bachmann, E.. Comparing four approaches to generalized redirected walking: Simulation and live user data. IEEE Transactions on Visualization and Computer Graphics 2013;19(4):634–643. doi:10.1109/TVCG.2013.28.

[25] Zmuda, M., Wonser, J., Bachmann, E., Hodgson, E.. Optimizing constrained-environment redirected walking instructions using search techniques. IEEE Transactions on Visualization and Computer Graphics 2013;19(11):1872–1884. doi:10.1109/TVCG.2013.88.

[26] Cerovsek, T.. A review and outlook for a building information model (BIM): A multi-standpoint framework for technological development. Advanced Engineering Informatics 2011;25(2):224–244. doi:10.1016/j.aei.2010.06.003; information mining and retrieval in design.

[27] Wiendahl, H.P., Harms, T., Fiebig, C.. Virtual factory design–a new tool for a co-operative planning approach. International Journal of Computer Integrated Manufacturing 2003;16(7-8):535–540. doi:10.1080/0951192031000115868.

[28] Mujber, T., Szecsi, T., Hashmi, M.. Virtual reality applications in manufacturing process simulation. Journal of Materials Processing Technology 2004;155156:1834–1838. doi:10.1016/j.jmatprotec.2004.04.401; proceedings of the International Conference on Advances in Materials and Processing Technologies: Part 2.

[29] Foxlin, E., Naimark, L.. Vis-tracker: A wearable vision-inertial self-tracker. In: Proceedings of the IEEE Conference on Virtual Reality. IEEE. ISBN 0-7695-1882-6; 2003, p. 199–206.

[30] Freitag, S., Rausch, D., Kuhlen, T.. Reorientation in virtual environments using interactive portals. In: Symposium on 3D User Interfaces. IEEE; 2014, p. 119–122. doi:10.1109/3DUI.2014.6798852.