Joint Virtual Reality Conference of ICAT - EGVE - EuroVR (2012), pp. 1–8
C. Cruz Neira, K. Kiyokawa, and D. Roberts (Editors)

Redirected Steering for Virtual Self-Motion Control with a Motorized Electric Wheelchair

Abstract

Redirection techniques have shown great potential for enabling users to travel in large-scale virtual environments while their physical movements have been limited to a much smaller laboratory space. Traditional redirection approaches introduce a subliminal discrepancy between real and virtual motions of the user by subtle manipulations, which are thus highly dependent on the user and on the virtual scene. In the worst case, such approaches may result in failure cases that have to be resolved by obvious interventions, e. g., when a user faces a physical obstacle and tries to move forward.

In this paper we introduce a remote steering method for redirection techniques that are used for physical transportation in an immersive virtual environment. We present a redirection controller for turning a legacy wheelchair device into a remote control vehicle. In a psychophysical experiment we analyze the automatic angular motion redirection with our proposed controller with respect to detectability of discrepancies between real and virtual motions. Finally, we discuss this redirection method with its novel affordances for virtual traveling.

Categories and Subject Descriptors (according to ACM CCS): Information Interfaces and Presentation [H.5.1]: Multimedia Information Systems—Artificial, augmented, and virtual realities; Computer Graphics [I.3.7]: Three-Dimensional Graphics and Realism—Virtual reality

1. Introduction

Natural self-motion in immersive virtual environments (VEs) is one of the most fundamental problems in the field of virtual reality (VR) [WCF*05]. While tracking technologies allow users to perform motions in a virtual world that match their movements in a tracked laboratory space, most setups provide such natural interaction only over a range of a few meters [Ins01]. To cover longer distances, users of immersive VEs often have to revert to less natural forms of traveling, such as virtual steering or flying [BKLP04]. Even in the real world, we make use of *walking* as our primary locomotion technique over short distances, but we usually make use of various methods of physical transportation to cover longer distances.

While researchers have proposed different solutions to enable natural walking over large distances in the virtual world while remaining within a relatively small laboratory space in the real world, fewer works have focused on techniques that can provide users of physical transportation devices (e. g., wheelchairs) with the ability to use such devices for natural navigation in immersive VR laboratories [NRI12]. A promising solution for unlimited walking was proposed by Razzaque et al. [RKW01], who showed that users of immersive VEs tend to unknowingly compensate with their body to small inconsistencies in virtual self-motion feeback while walking, which can even be used to guide users on small circles in the physical laboratory space while users think that they are able to walk in all directions in the virtual world. Bruder et al. [BIPS12] have shown that introducing such slight manipulations of the visual feedback to a user's self-motion can also be used to redirect users of physical transportation devices on different paths in the real world than in the VE.

In this paper we introduce a novel approach to redirection with physical traveling devices. We show for a motorized electric wheelchair that it is possible to redirect users onto different paths in the real world and in the VE not by introducing undetectable virtual rotations, but by introducing undetectable physical rotations. We show in a psychophysical experiment that this approach has significant potential for making redirection of transportation devices more applicable in VR laboratories than can be achieved with traditional redirection approaches. Moreover, we provide evidence that detectability of manipulations depends on the speed of self-motions, which has implications for practical implementations of redirection techniques.

The remainder of this paper is structured as follows. Section 2 provides an overview of related work. In Section 3 we present our novel automatic remote redirection approach. In Section 4 we describe a psychophysical experiment that we conducted to determine perceptual detection thresholds for automatic angular motion redirection with our proposed controller on detectability of discrepancies between real and virtual motions. Section 5 concludes the paper and gives an overview of future research.

2. Related Work

Multiple research groups have evaluated the problem of limited physical interaction space, and proposed different hardware [DCC97, SGS*11, BS02, WWB10, IHT06] or software solutions [SBS*12, SBJ*10, NHS04, GNRH05, ECT*08, IRA07]. Simple solutions range from freeze-and-turn resetting techniques introduced by Williams et al. [WNR*07], which are based on freezing the motion tracking whenever a user comes close to leaving the physical interaction space, and instructing the user to turn away from the boundaries, after which the tracking is unfrozen, and the user can continue moving. While such approaches enable unlimited virtual self-motion, transformations introduced by such techniques are overt to users, and may cause breaks in the user's sense of feeling present in the virtual world [SBS*12]. To reduce such problems, Razzaque et al. [RKW01] proposed a different method to reorient users, based on subtle manipulations. Using this approach, the virtual world is slowly rotated around a user while the user is moving, which can be used to make users walk on a different path in the physical world than what they perceive as their self-motion in the virtual world. Razzaque [Raz05] showed that users of immersive virtual environments tend to subconsciously compensate for such virtual rotations, and may even be unable to detect rotations if they are applied with a magnitude that is below human just noticeable differences.

Steinicke et al. [SBJ*10] evaluated the approach for real walking, and determined detection thresholds up to which magnitude introduced changes may go unnoticed by users if they explicitly focus on manipulations. Bruder et al. [BIPS12] have shown that detection thresholds for wheelchair drivers are similar to those for walking users, but have the potential to be larger, i. e., allowing more undetectable manipulations than for walking. Their results suggest that wheelchair drivers can be redirected onto a circular path with radius of about 8.97m before they can clearly detect manipulations, whereas for walking users a radius of 14.92m may be necessary.

Since many VR laboratories do not have a tracking area of such dimensions, researchers proposed different methods to improve the efficiency of redirection techniques. Peck et al. [PFW09, PFW11] proposed *distractors*, i. e., moving virtual objects in the user's visual field, as a method to expand the range of manipulations that go unnoticed by users. Using a different approach, Bruder et al. [BSWL12] suggested using visual illusions to introduce undetectable changes to self-motions with larger magnitude than would otherwise be undetectable by observers. Suma et al. [SCFW10] suggested yet another technique based on subtle changes to the virtual world which may go unnoticed by observers in certain cases (i. e., based on *change blindness* illusions), and have shown that such changes can be used to reorient users in a physical laboratory space. However, although such techniques can make redirection techniques work with less failure cases in a smaller laboratory space [SBS*12], the possibility for failure cases cannot be eliminated entirely. In this paper, we propose a different redirection approach, not based on influencing the user to reorient, but rather on redirecting the user with an automatic remote controller that has the potential to eliminate such failure cases.

3. Automatic Remote Redirection

3.1. Proxy Steering Controller

In general any electric wheelchair will consist of several generic components. The first is the speed controller, motor drivers, batteries and position controllers which operate together in order to form a feedback loop which controls the wheel velocities. The target velocities are controlled using an input panel which can consist of a directional joystick and optionally buttons to control top speed. Our proxy steering controller works by placing an additional piece of interface hardware between the joystick and the existing wheelchair speed controller. This interface allows us to read the user's joystick inputs and replace them with our own inputs that are then interpreted and acted upon by the speed controller as if the user was steering the wheelchair. The joystick inputs are in two axes: the y axis controls the forward-back motion, and the x axis controls the left-right rotation. A diagram of such a modified system is shown in Figure 1. The specific implementation we used will be discussed in more detail in the following subsection.

Once the hardware has been designed and implemented, software is needed to correctly steer the wheelchair in the absence of human input. To this end we implemented a proportional-integral-derivative (PID) controller which drives the wheelchair along a curved path of specific radius. In our setup we have placed two trackers on the wheelchair. One is mounted on the head-mounted-display and another on the wheelchair itself, as shown in Figure 2. This allows us to separate the head motion of the user from the motion of the wheelchair. The wheelchair motion is used at each timestep by the PID controller to compute the distance traveled, dy, the linear speed, s, and the angular speed, ω_m. Using the target radius, R, and linear speed we then compute the target angular velocity as $\omega_t = -s/R$. The controller then computes a change in the joystick left-right output using the tuned PID parameters (K_p, K_i, K_d). This left-right change is then summed at each step to get the value which is sent to the

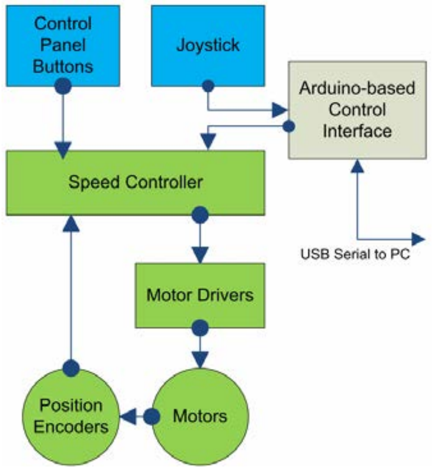


Figure 1: *A generic electric wheelchair will consist of a speed controller, motor drivers, batteries, motors, and position encoders which form the speed control loop. The target wheel speeds are specified via a joystick and potentially other input buttons on a control panel. Our modification is to place a hardware interface between the joystick and speed controller which allows us to monitor the user's joystick inputs and, if needed, substitute them with our own during the redirection.*

wheelchair interface controller. A diagram showing the PID control variables during a specific trial is shown in Figure 3(a) and the resulting path is shown in Figure 3(b).

3.2. Proof of Concept Implementation

For our specific implementation we are using a Hoveround MPV5 wheelchair and an Arduino prototyping board to serve as the hardware interface. The Hoveround wheelchair joystick has balanced voltages for each axis. What this means is there is a reference voltage signal (between 0v and 5v), a positive voltage signal (between 0v and 2.5v), and a negative voltage signal (between 0v and -2.5v) for each axis which gives a total of six values which we need to read from the joystick. The Arduino supplies 5v to power the joystick independently of the wheelchair, and reads the six input voltages using its six analog to digital input pins. Six output signals are then created using one of the Arduino's PWM (Pulse Width Modulation) outputs connected to a low-pass filter (as shown in Figure 4) for each signal. The low-pass filter is used to smooth the square-wave PWM output to keep the wheelchair speed controller from rejecting it. The input and output voltage values are sent over a bidirectional serial USB connection to the host PC which is running the PID controller and VR simulation.

The input and output signals, as well as supply voltage for the joystick, are carried over Cat5 cables between the wheelchair and the Arduino. These cables also can be disconnected which allows the wheelchair to return to a stock configuration just by the use of a patch cable. The Arduino is placed into a protective plastic box and mounted beneath the seat of the wheelchair. Initially the Arduino received power over USB which worked well during the development of the firmware. However, when we switched to using a 32 foot USB cable for the experiment the Arduino could no longer reliably get 5 volts input, which the wheelchair speed controller would reject. To fix this we added a battery pack to the bottom of the Arduino which ensures a reliable source of 5 volts. The Arduino build and installation are shown in Figures 5 and 6.

Figure 2: *Here is shown the dual tracker setup used to differentiate the subject's head motion from the motion of the wheelchair. The wheelchair and head motion is used for rendering the virtual scene, and the wheelchair position is used in the PID steering controller.*

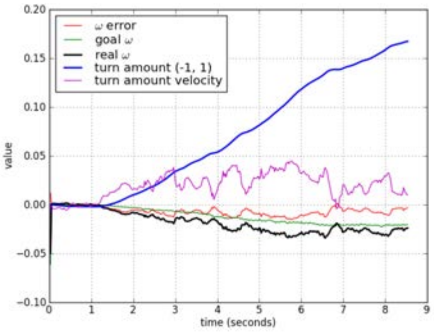
4. Psychophysical Experiment

4.1. Experiment Design

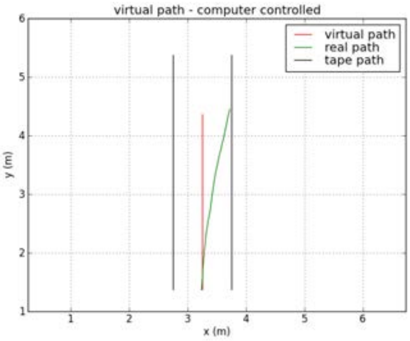
We evaluated computer-controlled redirected driving in an experiment with 10 participants. Participants experienced redirected driving at two speeds and randomized curvatures. Participants responded in a *two-alternative forced-choice* (2AFC) task to identify the direction of the curvature.

4.1.1. Participants

Eight males and two females participated in the study. They were recruited from the department of computer science and the authors' acquaintances. Participants ages ranged from 18 years to 51 years, with the average age being 28 years.



(a) PID variables



(b) result path

Figure 3: *This figure shows the variables of the PID controller as they vary over the course of a specific trial, and the motion path produced by the controller. The turn amount variable is the value sent to the hardware interface which is the integrated value of "turn amount velocity" output by the PID controller at each timestep.*

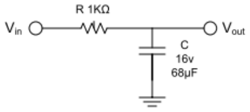
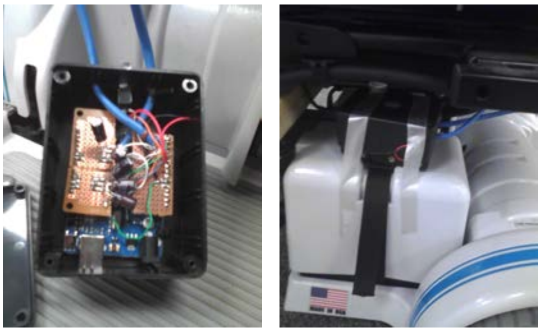


Figure 4: *The specific low-pass filter used on each PWM output channel of the Arduino. Without this the wheelchair speed controller will reject the square-wave PWM signals and enter a fail-safe mode where it will not move.*

(a) finished interface (b) added batteries



(c) internals (d) under-seat installation

Figure 5: *The Arduino control interface developed. These figures show the protective plastic box and Cat5 interface cables of the finished interface, the internals of the low-pass filters, the battery pack which gives a reliable 5 volts (via the Arduino's onboard regulator) and the installation of the interface under the wheelchair seat.*

Figure 6: *A front view of the interface installation. Notice the blue Cat5 wires which carry the input and output signals and the red connections that allow the Arduino to be completely disconnected from the wheelchair.*

All participants had normal or corrected to normal vision, and none reported any problems with stereo vision or balance disorders. Six participants reported having much experience with 3D games, although only two were regular players. Seven participants had experience with HMD virtual environments, including three participants who are authors on this paper. The experiment lasted an hour to an hour and 15 minutes, and participants were compensated with a $10 gift card to a national retail chain.

4.1.2. Materials

Participants sat in the wheelchair described in Section 3.2. The virtual environment was presented to the participant through an Nvis Nvisor SX 60 head-mounted display (HMD), which has a manufacturer-specified 60-degree field of view, and a 1280 pixels by 1024 pixels resolution. We attached the cable to the back of the wheelchair seat to relieve its weight from the participant's head. This also prevented the participant from getting positioning feedback from the tension on the cable. Tracking of the participant's head and the wheelchair was provided by a Hiball 3100 optical ceiling tracker. A veil of two layers of black felt was attached to the HMD to prevent participants from seeing any part of the environment beyond their own torso. Brownian noise was also played through the HMD headphones to mask auditory positioning cues.

The virtual environment (see Figure 7) was modeled from our laboratory using Google Sketchup. A realistic appearance was achieved by using photographs of the lab interior as texture maps. We implemented the virtual environment and experiment using the G3D rendering engine, which ran on an Intel computer with Core i7 processors, 6 GB of main memory and Nvidia Quadro FX 1500 graphics card. We compensated for the pincushion distortion of the HMD (see Figure 7).

The virtual environment included a path on the ground marked with two strips of tape and a circular indicator centered at 80% eye height on the door at the end of the path. The indicator showed the participant's speed through color. Green meant "go faster", red meant "slow down", and yellow corresponded to the correct speed. The color of the indicator was tied to the participant's forward joystick input. Since we were keeping the speed of the wheelchair at a set value, the indicator was there to encourage the participant to keep the joystick pushed forward and give the illusion that they controlled the speed.

4.1.3. Methods

Participants began by signing a consent form and filling out the Kennedy-Lane simulator sickness questionnaire (SSQ) [KLBL93] and a demographics questionnaire. Participants read printed instructions for the experiment.

Participants performed 72 trials in four blocks of 18. While the participant saw text on the screen instructing him or her to wait, an experimenter used a joystick to position the wheelchair at one end of the room. The experimenter then pressed a button to begin the trial, making the virtual environment visible and enabling the joystick on the wheelchair. Every trial started at the same point in the virtual environment. Participants were required to drive down the path in the virtual environment while pressing forward on the joystick enough that the indicator was yellow.

Figure 7: *A participant's view at the start of a trial.*

When the participant pushed forward on the joystick, one of two controller modes was activated: computer-controlled or human-controlled. In the computer-controlled trials the participant drove on a straight path in the virtual environment (the participant's steering did not affect the virtual motion) while the wheelchair was physically moved on a curved path in the real environment. In the human-controlled trials, the participant's view of the virtual world was rotated as they moved forward, and the participant had to steer the wheelchair to stay on a straight path. The participant's steering also controlled the physical wheelchair. Participants completed equal numbers of computer-controlled and human-controlled trials. The wheelchair also moved at one of two possible maximum speeds, 0.33 m/s or 0.54 m/s. The speed was limited by clamping the joystick input to a maximum value.

For each mode and speed combination, participants saw each of six curvatures three times. The curvatures corresponded to following circular paths of these radii: 10 meters to the left, 20 meters to the left, 30 meters to the left, 30 meters to the right, 20 meters to the right, and 10 meters to the right. The fast and slow trials were grouped into two blocks, and half of the participants saw the fast trials first, while the other half saw the slow trials first. Within those blocks the mode-curvature combinations were presented in randomized order. We preferred to randomize the mode condition, be-cause we felt that participants would become complacent during a block of computer-controlled trials. By interleaving the trials so that the participant could not anticipate the controller mode, we felt that the participant would be more attentive to the task of driving and would be less likely to use a different strategy for detecting the curvature. Although we collected experiment data in all conditions, we observed an inaccuracy in the experiment logs of the human-controlled trials, and decided to exclude those conditions from further evaluation.

After the wheelchair had traveled 3 meters it stopped, and instructions on the screen asked the participant on what side of the *real* room, right or left, did he or she end up. The participant indicated the answer by pushing on the joystick.

After the participant answered the question, the display showed instructions asking them to wait while the experimenter moved the wheelchair into position for the next trial. After every 18 trials the participant was required to take a five-minute break. We wanted to prevent fatigue, and we were concerned that if the breaks were optional, then participants might choose not to take them.

After completing 72 trials, participants then completed another SSQ and a short questionnaire about the experiment and were paid their gift card.

4.2. Results

We had to reject one participant for always answering that he was on the right side of the room. Figure 8 shows the pooled results for the tested curvature radii on the x-axis, with negative values referring to physical paths bent to the left, and positive values referring to physical paths bent to the right. The y-axis shows the probability for estimating the physical path as bent to the left while moving straight in the VE. We represented the discrimination performance via a sigmoid psychometric function of the form $f(x) = \frac{1}{1+e^{a\cdot x+b}}$ with fitted real numbers a and b. The gray psychometric function shows the results for the slow trials, and the black function for the fast trials.

The curvature radii at which subjects answered that they were redirected towards the left side of the room in 50% of the trials is taken as the *point of subjective equality* (PSE), at which subjects judge the virtual motion to match the physical movement. From the psychometric functions we determined PSEs at a radius of -57m for the slow trials, and 595m for the fast trials, i. e., the responses indicate that subjects on average judged straight movements in the real world as straight. As the radii decrease or increase from the PSE the ability of subjects to detect the difference between physical and virtual motion increases. A practically applicable range of manipulations is given by the smaller (i. e., conservative) detection threshold of 75% correct judgments, i. e., the middle between the 50% chance level and 100% certainty of subjects that they have been manipulated, which we determined from the psychometric functions as radii larger or equal to approximately 5.76m for slow movements, and approximately 16.52m for fast movements with the electric wheelchair.

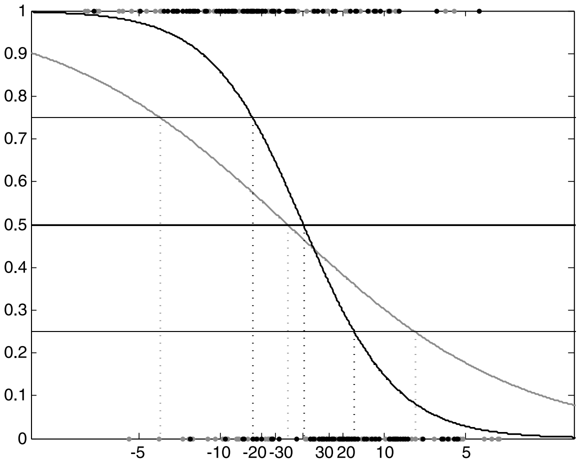


Figure 8: *Pooled results of curvatures for the fast trials (black function) and slow trials (gray function). The x-axis shows the circular path radii in the real world, with negative gains referring to paths bent to the left, and positive gains to rightward paths. The y-axis shows the probability of estimating the physical movement path as bent to the left.*

4.3. Discussion

The results plotted in Figure 8 show an impact of the wheelchair speed on responses. The results show that the subjects were less accurate at detecting manipulations of physical driving directions when they were driving slowly compared to the trials with the faster driving speed. The data suggests that the detection threshold may be reached at a circular path radius of less than 5.76m in case subjects move slowly, whereas for faster movements subjects were able to detect manipulations up to a circular path radius of approximately 16.52m, which indicates a surprisingly strong effect of movement speed on direction estimates. Effects of movement velocity on redirection techniques have first been observed by Neth et al. [NSE*11] in an experiment on redirected walking, in which subjects were significantly better at judging walking directions if they were walking at a higher velocity. The results shown in Figure 8 are interesting, since they suggest that this observation also holds when driving a wheelchair, and, moreover, that it seems not to be caused by the fact that traditional redirection techniques require users to adapt to visual rotations. Since subjects in the present experiment were passively reoriented without the requirement to actively compensate for virtual rotations, the increased discrimination performance in the experiments may be related to less ambiguous proprioceptive and vestibular physical self-motion cues during redirection.

The detection thresholds for the trials with fast movements are in line with results for redirected walking in previous experiments. Bruder et al. [BIPS12] observed a radius of 14.92m as detection threshold, whereas Steinicke et al. [SBJ*10] observed a radius of 22.03m for walking subjects. The differences in the results may be caused by the different redirection techniques, i. e., walking versus driving, and different visual stimuli used in the experiments. The detection thresholds for the trials with slow movements indicate that passive redirection as used in the present experiment can result in less observable manipulations than using traditional redirection techniques when driving a wheelchair, for which an experiment with similar motion speed has suggested a detection thresholds of 8.97m [BIPS12].

5. Conclusion

This study and previous redirection studies have focused on curvature as the parameter under investigation. This was appropriate when those studies assumed a steady walking speed. However, this study shows that speed affects participants' sensitivity to curvature. This is not surprising, since greater acceleration along a curve leads to greater angular acceleration and centripetal force, and participants do not sense the curvature directly, but they do sense linear acceleration, angular acceleration, and centripetal force. Future studies of redirected driving should focus on finding acceptable ranges for these parameters, which could then be used in designing a full redirected driving application.

References

[BIPS12] BRUDER G., INTERRANTE V., PHILLIPS L., STEINICKE F.: Redirecting walking and driving for natural navigation in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics (TVCG) 18*, 4 (2012), 538–545. 1, 2, 7

[BKLP04] BOWMAN D., KRUIJFF E., LAVIOLA J., POUPYREV I.: *3D User Interfaces: Theory and Practice*. Addison-Wesley, 2004. 1

[BS02] BOUGUILA L., SATO M.: Virtual locomotion system for large-scale virtual environment. In *Proceedings of Virtual Reality (VR)* (2002), IEEE, pp. 291–292. 2

[BSWL12] BRUDER G., STEINICKE F., WIELAND P., LAPPE M.: Tuning self-motion perception in virtual reality with visual illusions. *IEEE Transactions on Visualization and Computer Graphics (TVCG) 18*, 7 (2012), 1068–1078. 2

[DCC97] DARKEN R. P., COCKAYNE W. R., CARMEIN D.: The omni-directional treadmill: a locomotion device for virtual worlds. In *Proceedings of the Symposium on User Interface Software and Technology (UIST)* (1997), pp. 213–221. 2

[ECT*08] ENGEL D., CURIO C., TCHEANG L., MOHLER B., BÜLTHOFF H. H.: A psychophysically calibrated controller for navigating through large environments in a limited free-walking space. In *Proceedings of the Symposium on Virtual Reality Software and Technology (VRST)* (2008), ACM Press, pp. 157–164. 2

[GNRH05] GROENDA H., NOWAK F., RÖSSLER P., HANEBECK U. D.: Telepresence techniques for controlling avatar motion in first person games. In *Proceedings of the International Conference on Intelligent Technologies for Interactive Entertainment (INTETAIN)* (2005), pp. 44–53. 2

[IHT06] IWATA H., HIROAKI Y., TOMIOKA H.: Powered shoes. *SIGGRAPH Emerging Technologies*, 28 (2006). 2

[Ins01] INSKO B.: *Passive Haptics Significantly Enhances Virtual Environments*. PhD thesis, University of North Carolina at Chapel Hill, 2001. 1

[IRA07] INTERRANTE V., RIES B., ANDERSON L.: Seven league boots: a new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *Proceedings of the Symposium on 3D User Interfaces (3DUI)* (2007), IEEE Press, pp. 167–170. 2

[KLBL93] KENNEDY R. S., LANE N. E., BERBAUM K. S., LILIENTHAL M. G.: Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology 3*, 3 (1993), 203–220. 5

[NHS04] NITZSCHE N., HANEBECK U., SCHMIDT G.: Motion compression for telepresent walking in large target environments. *Presence 13*, 1 (2004), 44–60. 2

[NRI12] NYBAKKE A., RAMAKRISHNAN R., INTERRANTE V.: From virtual to actual mobility: Assessing the benefits of active locomotion through an immersive virtual environment using a motorized wheelchair. In *Proceedings of the Symposium on 3D User Interfaces (3DUI)* (2012), IEEE Press, pp. 27–30. 1

[NSE*11] NETH C. T., SOUMAN J. L., ENGEL D., KLOOS U., BÜLTHOFF H. H., MOHLER B. J.: Velocity-dependent dynamic curvature gain for redirected walking. In *Proceedings of Virtual Reality (VR)* (2011), IEEE Press, pp. 1–8. 6

[PFW09] 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 (TVCG) 15*, 3 (2009), 383–394. 2

[PFW11] PECK T. C., FUCHS H., WHITTON M. C.: An evaluation of navigational ability comparing redirected free exploration with distractors to walking-in-place and joystick locomotion interfaces. In *Proceedings of Virtual Reality (VR)* (2011), IEEE Press, pp. 56–62. 2

[Raz05] RAZZAQUE S.: *Redirected Walking*. PhD thesis, University of North Carolina at Chapel Hill, 2005. 2

[RKW01] RAZZAQUE S., KOHN Z., WHITTON M. C.: Redirected walking. In *Proceedings of Eurographics (EG)* (2001), ACM Press, pp. 289–294. 1, 2

[SBJ*10] STEINICKE F., BRUDER G., JERALD J., FENZ H., LAPPE M.: Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics (TVCG) 16*, 1 (2010), 17–27. 2, 7

[SBS*12] SUMA E. A., BRUDER G., STEINICKE F., KRUM D. M., BOLAS M.: A taxonomy for deploying redirection techniques in immersive virtual environments. In *Proceedings of Virtual Reality* (2012), IEEE Press, pp. 43–46. 2

[SCFW10] SUMA E., CLARK S., FINKELSTEIN S., WARTELL Z.: Exploiting change blindness to expand walkable space in a virtual environment. In *Proceedings of Virtual Reality (VR)* (2010), IEEE Press, pp. 305–306. 2

[SGS*11] SOUMAN J. L., GIORDANO P. R., SCHWAIGER M., FRISSEN I., THÜMMEL T., ULBRICH H., DE LUCA A., BÜLTHOFF H. H., ERNST M. O.: Cyberwalk: Enabling unconstrained omnidirectional walking through virtual environments.

ACM Transactions on Applied Perception (TAP) 8 (2011), 1–24. 2

[WCF*05] WHITTON M. C., COHN J., FEASEL P., ZIMMONS S., RAZZAQUE S., POULTON B., UND F. BROOKS B. M.: Comparing VE locomotion interfaces. In *Proceedings of Virtual Reality (VR)* (2005), IEEE Press, pp. 123–130. 1

[WNR*07] WILLIAMS B., NARASIMHAM G., RUMP B., MCNAMARA T. P., CARR T. H., RIESER J., BODENHEIMER B.: Exploring large virtual environments with an HMD when physical space is limited. In *Proceedings of the Symposium on Applied Perception in Graphics and Visualization (APGV)* (2007), ACM Press, pp. 41–48. 2

[WWB10] WENDT J. D., WHITTON M. C., BROOKS, JR. F. P.: GUD WIP: Gait-understanding-driven walking-in-place. In *Proceedings of Virtual Reality* (2010), IEEE Press, pp. 51–58. 2