

# Short Paper: Redirected Steering for Virtual Self-Motion Control with a Motorized Electric Wheelchair

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## 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

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## 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, many setups provide such natural interaction only over a range of a few meters. To cover longer distances, users of immersive VEs often have to revert to less natural forms of traveling, such as virtual steering or flying. 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].

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 intro-

ducing 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 (e.g. [SGS\*11]) or software solutions (e.g. [ECT\*08]).

Most software solutions require some form of reorientation [PFW10] when the user runs out of available space. However, such techniques are overt to users and may cause breaks in presence [SBS\*12]. Razzaque et al. [RKW01] proposed a method to reorient users by subtly manipulating the position and orientation of the virtual world with respect to that of the user as they move about. 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 this 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.

Redirection has shown to be useful for enabling natural navigation. Peck et al. [PFW11] found that participants had superior performance on tasks requiring spatial awareness when using real walking with reorientation and distractors when compared to walking-in-place or using a joystick. 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 wheelchair that has the potential to eliminate failure cases, and serve as a compliment to walking redirection.

### 3. Automatic Remote Redirection

For these experiments we created an interface device between the wheelchair and the computer running the VR simulation using an Arduino prototyping board. 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. We have implemented in software a PID controller which drives the wheelchair along a curved path in the absence of any user input. The controller uses the wheelchair location as an input parameter so for our experiment we tracked both the wheelchair position and the hmd position, allowing us to separate head movement from chair movement.

## 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 to 51 years, with the average age being 28 years. 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 approximately an hour, and participants were compensated with a \$10 gift card to a national retail chain.

### 4.1.2. Materials

The IVE was presented to the participant through an Nvis Nvisor SX 60 HMD, which has a manufacturer-specified 60° field of view, and a 1280-by-1024 pixel resolution. We attached the cable to the back of the wheelchair seat to relieve its weight from the participant's head and to prevent any positioning feedback from the cable tension. 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 IVE (see Figure 1) 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 experiment using the G3D rendering engine, which ran on an Intel computer with Core i7 processors, 6 GB of RAM and Nvidia Quadro FX 1500 graphics card. We compensated for the pincushion distortion of the HMD (see Figure 1).

The IVE 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 IVE visible and enabling the joystick on the wheelchair. Every trial



Figure 1: A participant's view at the start of a trial.

started at the same point in the IVE. Participants were required to drive down the path in the IVE while pressing forward on the joystick enough that the indicator was yellow.

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 IVE (the participant's steering did not affect the virtual motion) while the wheelchair was 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,  $0.33\text{ m/s}$  or  $0.54\text{ m/s}$ . 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. 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 or become complacent during a block of computer-controlled trials. Although we collected experiment data in all conditions, we observed an implementation error in the 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.

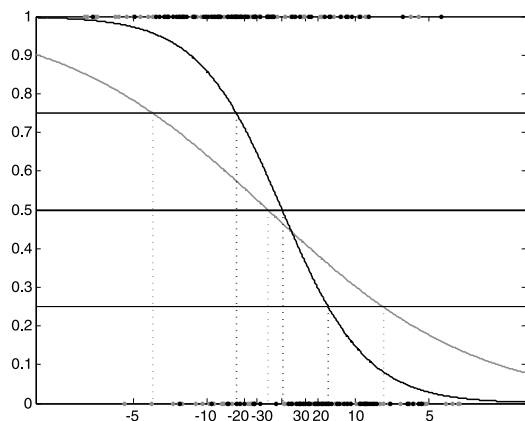
## 4.2. Results

We had to reject one participant for always answering that he was on the right side of the room. Figure 2 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  $f(x) = \frac{1}{1+e^{a-x+b}}$  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  $-57\text{m}$  for the slow trials, and  $595\text{m}$  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  $5.76\text{m}$  for slow movements, and approximately  $16.52\text{m}$  for fast movements with the electric wheelchair.

## 4.3. Discussion

The results plotted in Figure 2 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  $5.76\text{m}$  in case subjects move slowly, whereas for faster movements subjects were able to detect manipulations up to a circular path radius of approximately  $16.52\text{m}$ , 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



**Figure 2:** 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 referring to rightward paths. The y-axis shows the probability of estimating the physical movement path as bent to the left.

judging walking directions if they were walking at a higher velocity. The results shown in Figure 2 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 accel-

eration, 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.

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