Figure 1: Game completed through a wheelchair.

Providing Access to VR Through a Wheelchair

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ABSTRACT

Individuals may use their wheelchair to play VR games, explore three-dimensional, visual worlds and take part in virtual social events, even if they do not master the hand- or head- inputs that are common for VR. We present the development of a low-cost, do-it-yourself, wheelchair locomotion-device, which allows navigation in VR. More than 50 people, including 9 wheelchair users, participated in the evaluations of three prototypes and a number of games developed for them. Initially, cybersickness turned out to be a problem, but when we changed to an electric wheelchair instead of a manual and fine-tuned the controls this discomfort was remarkably reduced. We suggest using this device for gaming, training, interaction design, accessibility studies and the operation of robots.

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CCS CONCEPTS

• **Human-centered computing → Virtual reality; Empirical studies in accessibility; Accessibility systems and tools;** *Empirical studies in interaction design;*

KEYWORDS

virtual reality; accessibility; wheelchairs; experience prototyping; assistive technology; cybersickness; game design; human-robot-interaction; gaze interaction

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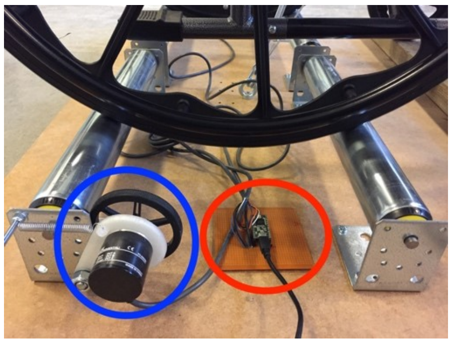

Figure 2: Our first functional prototype with a manual wheelchair. Each driver wheel is lifted by two large rollers, while a small rubber wheel rotates an encoder (blue circle). One micro controller (red circle) collects the data from each of the two encoders.

1 INTRODUCTION

All wheelchairs have one thing in common: wheels. A bridge between the wheels and a VR-model provide new opportunities. For instance, the accessibility of a construction may then be tested by driving in a digital 3D model of it [4]. Individuals may be trained in a simulator before they get introduced to a new type of wheelchair. Finally, driving a wheelchair in VR may give insights to typically-developing people on what it is like to be a wheelchair user, particularly relevant for architects and designers of products, buildings, and surroundings.

Prior work (e.g. [3]) suggests that a wheelchair locomotion-device (hereafter WLD) can be beneficial for driver training, physical exercise, rehabilitation and education. There are no commercially available products yet, but a few platforms have been developed for research purposes (see [7] for an overview). Motion platforms are heavy and expensive due to the motorized jack actuators. Force feedback in the rollers increase the price significantly. Our main research question has been: Does an inexpensive, low-fidelity platform that people can build themselves provide a compelling user experience? Low-cost- and DIY-objectives forced us to exclude the vestibular motion stimulation normally perceived during acceleration, turning, and driving on slopes. Nor did we provide a dynamic haptic feedback that users of manual wheelchairs get when turning the wheels by hand. Do people then get immersed? Do they get cybersick without these sensations? Finally, we wanted to accommodate for a variety of wheelchair models and wheel sizes.

2 METHOD

We went through three iterations. Our first WLD prototype consisted of a manual wheelchair placed on top of 2 × 2 rollers. A rubber wheel, an encoder, along with a micro-controller, picked up the movements separately from each wheels' movements (see Figure 2).

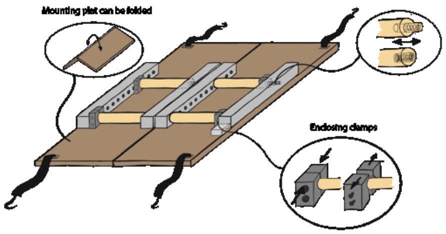

Figure 3: One of our preliminary concepts with call-outs explaining its main features.

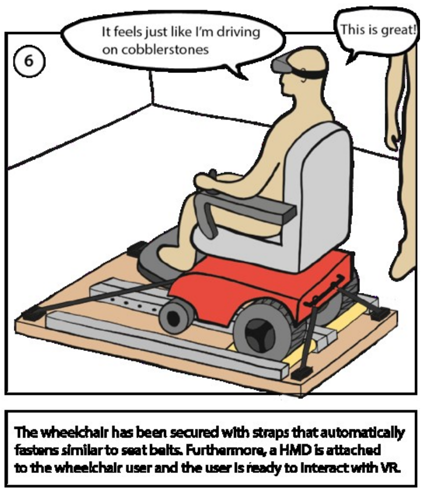

Figure 4: Section from user scenario of set-up, enter and exit.

This prototype was assembled from DIY-components in about 10 hours and costed approx. 250 US$. At first, we created a very simple block world built using Unity 3D and applying a wheelchair model provided by this software. Pushing the blocks around was quite fun, so we kept this pushing-principle and the wheelchair module in our next game: a LEGO city that had stacks of movable bricks spread on the main road [8]. We tested this set-up with 26 typically-developing participants at a VR-exhibition (see next section).

In the second iteration of the prototype, we moved the rollers closer to support the smaller wheels of an electrical wheelchair and built a new game. The game objective was to get through an obstacle course as fast as possible without overthrowing bikes blocking the driving path, while avoiding curbs. This game was tested by 19 typically-developing participants who used our WLD, and 14 typically-developing participants who used a commercial VR-exercise bike [6] (see next section).

To guide the design of our third WLD platform we made 3 fictional personas: (i) Adventurous Allan, who gets his able-bodied friends to set up a mobile WLD when they gather for game playing; (ii) The Family Dad, who builds a WLD in his garage to surprise his son; and (iii) Careful Carina, using the WLD to get familiar with the control functions of her newly acquired wheelchair because she is afraid of knocking everything down with it.

We then observed the use of wheelchairs in a care-home and at a clinic of spinal cord injuries for a week. Both places provided insights into the large variations of wheelchair sizes and types that our design should support (i.e. manual, electric, back-, centre- or front -driven). Also, we got to know some of the individuals, who would later become our test participants. They had very different kinds of challenges, from paralysed legs, but with full hand control and full vision, to severe involuntary body movements combined with paralysed legs and impaired speech.

Our observations were condensed in a list of design challenges, including (i) How to ensure easy entry and exit from the WLD platform? (ii) How to design adjustable rollers? (iii) How to lock rollers into position? (iv) Where to place the encoders? (v) How to secure the wheelchair on the rollers? and (vi) How to make the WLD platform transportable?

We employed the method of morphology [1], which outlines a number of possible solutions to each of the design challenges. Then we created different WLD-concepts by choosing different constellations of sub-solutions. Each concept got their features drawn out (cf. Figure 3) and each of them got a user scenario build around it (cf. Figure 4). Together with our 3 personas, this framed the design discussions on the basis of which we ended up combining features across the preliminary concepts into one final prototype, named “Whee'llConnect”, depicted in Figure 5. In order to halve the weight of the platform parts, we mounted the rollers on two plates held together by clamps. Handles for transportation were drilled out on each of them.

The cost of the components for the third and final iteration is close to 2,000 US$, including a rail system, rollers, an optical encoder, electronics and four belts anchoring the wheelchair. Our version was meant to support a broad variety of wheelchairs. If the design of Whee'llConnect had focused on just one model, the costs could have been 50% lower, because no rail system or sleds would have been necessary.

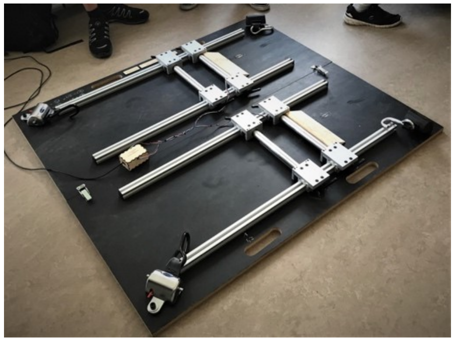

Figure 5: The functional prototype Whee'llConnect ready for user trials.

Figure 6: Image of the high, gray curb in the LEGO city, which the users were asked to pass–to experience a real-life situation of a wheelchair user.

A fixed installation, for instance in a gym, may just be bolted to the floor, which would then exclude the plate. We applied four relatively expensive seatbelts certified for use in cars, because a worst-case scenario is a heavy-duty wheelchair driving at top-speed when one of the rollers accidentally gets blocked, for instance by wires from the headset. If a manual wheelchair is used, instead of an electric wheelchair, the seatbelts may be substituted with a less costly way of tightening. All in all, we estimate the cheapest version may be built for approximately 300 US$; see https://github.com/GazeIT-DTU/Low_cost_wheelchair_simulator for a specification of components, encoder software and game software.

When Whee'llConnect had been built, we brought it to the care-home and the clinic for evaluation. In the next section we will present the findings from these visits and tests of the other two prototypes described above.

3 FINDINGS

The first user test was conducted with a manual wheelchair at a VR-exhibition. The participants were encouraged to move around freely in a LEGO city and to try pushing the LEGO bricks. They were also asked to drive through a corner in the city which required passing over high a curb (see Figure 6). The software would in fact not allow the wheelchair to pass the curb, so they got stuck in front of the sidewalk. After the trial, which took 3 to 5 minutes, we asked how they would describe their wheelchair experience. Participants found it intuitive to navigate the wheelchair in the VR world, commenting, for instance: *"... much like I would expect it to be when driving a wheelchair"* and *"It really felt like you were driving a wheelchair"*. It even seemed to have an emotional impact on some: *"It made me more empathetic to the plight of the motor impaired";* and *"Frustrating not to be able to drive on the sidewalks"*.

The motion feedback was ineffectual to several: *"Did not feel like I was forward propelling, maybe some inner balance thing was telling me something that the VR couldn't overcome"*; *"The simulator miss the ability to wheel freely. It stops as soon as I let go"* and *"It was difficult because the wheelchair moved very slowly"*. Most disturbingly, the graphics was lagging when turning: *"When I turned the wheelchair, the field of view turned very fast"* and *"Disturbing with the frame rate flicker when moving the head quickly"*.

The visual problems during fast turns had a strong impact on some participants, in fact 7 of them reported being dizzy or motion sick: *"It was more fun than Disneyland and I wish I could do it longer. But I got really car sick, like I am going to puke if I continue"* and *"This was uncomfortable. It might be because of the wheelchair turns really fast or because the picture lags when I turn my head"*. The main findings we got from this first trial were (i) people had an immersive experience of driving in a wheelchair (ii); some people got uncomfortable due to fast turns and lagging graphics; (iii) the manual wheelchair was slow and hard to drive; (iv) some peopled noticed that the vestibular

Figure 7: (A) Participant on bicycle locomotion device with VR headset; (B) Participant on wheelchair locomotion device with VR headset; (C) Parking-mode, showing the panning view of the real scene with keyboard tool activated; keyboard- and driving-mode buttons are located in the lower part of the field of view. All but- tons can be activated with gaze and head input.

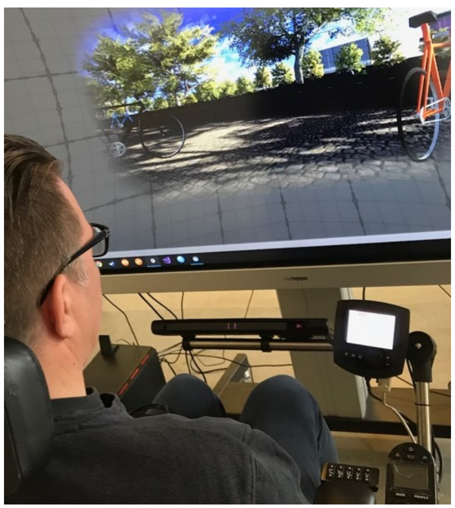

Figure 8: Gaze-driving a wheelchair while looking at a large monitor. A remote gaze- tracker is mounted on the wheelchair in front of the user.

feedback was missing. Consequently, we got a more powerful computer, we built a new game with less complex models, and fine-tuned the encoders motion response. Finally, we changed from a manual to an electric wheelchair because this requires no effort to drive and people will not expect it to keep wheeling when the motor stops.

The game designed for our next round of user test was inspired by comments we have got from wheelchair users that they hate bikes parked all over the sidewalks and that high curbs are dead ends. To address this, we built an obstacle course of bikes and curbs. The bikes could be tossed away if gazed at for a second - which affected the time-score - or the user was allowed to run over the bikes, with a penalty score. Before entering the game section, the user had a chance to practice at a virtual parking lot in front of the course. When in park-mode, the user could explore how the course environment looked in reality via 360-degree images and were able to activate a keyboard tool to send messages, c.f. Figure 7(c)).

We conducted an experiment with this set-up, presented in Minakata et al. [6]. The purpose of the experiment was to test an interface wheelchair control of a telerobot that we are currently developing [2]. It supports field-of-view panning, mode selections and keyboard typing by head- and gaze-interaction. We tested it on 19 participants using a WLD, and by 14 participants using a VR exercise bike. The WLD was faster and more manoeuvrable than the bike. This was unexpected, since all participants were familiar with exercise bikes but none had used a wheelchair. There were no differences in the subjective rating of challenge, comfort, and fun between the WLD- and the bike-group, but none of the people in the WLD-group reported any symptoms of cybersickness, while two participants in the bike group got uncomfortable; one of them had to quit immediately. Several participants noted that the vibrations from the wheelchair driving on the rollers contributed to the realism of the experience, commenting, for instance: *"Very realistic, the wheelchair vibrated." and "It was fun, I enjoyed the fourth dimension of vibration."*

We also used this obstacle game to test a commercial product, "GazeDriver", in front of a large monitor. Driving a wheelchair with gaze commands can be difficult and potentially dangerous [9], so it makes sense to let people try it first in VR. This particular product uses an external, remote gaze-tracker as a steering device for the wheelchair, so we could not wear a head-mounted display while testing it. With a large monitor set-up the tests worked well and driving felt much like real gaze-driving (see Figure 8).

To explore a futuristic concept of gaze-responsive environments, we simulated a pair of AR glasses that would display an eye-icon when driving close to a gaze-responsive object. Looking at these objects and nodding turns it on and off [5]. A ramp in our game simulation could be lowered down by connecting to it with gaze and confirming the action with a nod, c.f. Figure 9. Bikes blocking the sidewalks could be thrown into the air. The gaze-and-nod principle worked well and several people started laughing when they figured out how to get rid of a bike–especially because it exploded when hitting the ground, c.f. Figure 10.

Figure 9: Gazing at the ramp and nodding makes it go down. The monitor behind the user shows what he sees in the head-mounted display.

Figure 10: A bike explodes when it hits the ground after having been thrown away with a head nod.

The final iteration, Whee'llConnect, was evaluated by six wheelchairs users at the care-home. None of them had ever had the opportunity to play a computer game before. Four of the six wheelchair users made use of the HMD. None of the six wheelchair users reported any kind of discomfort during the trials, in fact they were highly concentrated while driving and expressed overwhelming joy (see Figure 1). We observed them combining a set of symbols on their communication board to talk about the system: the head-mounted display was designated "television-on-eyes". We also observed that although the wheel dimensions of the wheelchairs differed in size, the distance between the rollers did not vary much. Most of the wheelchairs fitted to an approximate distance of 10-12 cm between the rudder axis.

Three wheelchair users and two medical professionals tested Whee'llConnect at the Clinic of Spinal Cord Injuries. Two of them used a manual wheelchair, whereas the third used a front-wheel driven electrical wheelchair. One of the manual wheelchair users felt a little dizzy with the HMD, but not enough that she wanted to take the HMD off and continue with a monitor instead.

The pace of the demo game was too slow for a manual wheelchair and it acquired a lot of effort to finish the game. We realised, that if Whee'llConnect should be compatible with manual wheelchairs, we should be able to adjust the rollers rotational factor within the game itself and not just from an initial setting. The clinic professionals saw a potential in Whee'llConnect for the purpose of driver training, for instance if the wheelchair users could get the opportunity of driving around in a well- known environment recreated in VR. Furthermore, the wheelchair users mentioned that it would be a great tool for cardio exercises and strengthening of the arms.

4 DISCUSSION

A low-cost, wheelchair locomotion-device could mean a lot to people who have never been able to play computer games. A couple of our participants from the care-home liked watching others play so much that they participated in an IT group every week, but they had always wondered how it would be to play a game themselves. With a WLD they got a chance to do so.

The WLD has been useful in our research because it allows us to try out alternative interaction concepts in VR before we build them. The game engine is a powerful tool for prototyping that makes it possible to build virtual worlds and games with a reasonable effort. The total time spent on developing the games presented in this paper amounts to approximately two months for a skilled Unity developer, not including time to build the graphical models, though, because they already existed. The flexibility of the software tool used made it possible for us to modify interfaces and combine interaction methods (i.e. head, gaze and wheelchair) in novel ways. The development of the WLD was easy because we only applied DIY-components. We spend quite some time, however, in figuring out how they should be combined to meet the needs that we observed in our field test. This process included several prototypes and took place over 2 years. Still, our solution is not final. For instance, the size of it should be reduced to fit into smaller living rooms. The price should also be further reduced by large quantity manufacturing. If it becomes a requirement for future building projects to conduct accessibility test involving wheelchair users driving in 3D project models this might kick-start a demand.

Figure 11: Controlling a telerobot with the wheelchair. The camera on top of the robot transmits a full, immersive, 360- degree view to the operator who drives it with the wheelchair joystick.

Also, game designers should start thinking about an API that would allow a LWD to be used for their games. A wheelchair module is already available in the game engine we used. We observed that none of the existing computer games that we tested could be used with our WLD, so a bit of effort in making a wrapper for them may be required. We found a need for our system to include a selection mechanism (i.e. trigger), because many wheelchair users do have a 0/1 switch that can be activated, for instance, with the head. In addition to providing access to popular games, our users would like to get into Google Earth VR to travel around the world and explore locations that they would never be able to go to in real life. An application like Google Earth VR would also be motivating for physical exercises, allowing, for instance, to drive miles in a manual wheelchair through interesting areas.

We observed that typically-developing people also enjoyed the wheelchair driving experience, especially when we used an electric wheelchair that made realistic vibrations. The feeling of rolling would partly compensate for the missing vestibular motion stimulation. Also, when seated they did not have to struggle with wires being twisted around their body, which often spoils the illusion of immersion when moving around in VR worlds with a wired headset.

An HMD is not an option for all the users and use-cases. Some people have glasses that do not fit into the HMDs and some users get uncomfortable wearing them. However, just driving the wheelchair in front of a monitor can be sufficient in many cases. Particularly in social settings with other people, for example, when playing games together, the monitor might be the best option because it leaves the real room open for social interactions. When introducing a LWD for people who have never tried to play a computer game before or never experienced VR, we would recommend to start with the monitor and then progress into VR. Using a game engine that supports both view-forms would be a requirement for this, of course.

Eventually, we overcame the initial challenges with people becoming cybersick. However, this is still a risk that should be considered, especially when introducing a WLD to people with impaired speech. We asked our test persons very frequently if they were feeling well while playing and stopped right away if they expressed any signs of discomfort.

5 CONCLUSION & FUTURE WORK

The low-cost WLD that we have designed is a viable way for people in wheelchairs to explore VR. The combination of a WLD and a flexible game engine provides the option to make fast prototypes of designs and interaction principles. While cybersickness remains a risk to be considered, we were able to reduce it considerably by implementing our redesigns. Future work will focus on using WLDs to provide people in wheelchairs the possibility to control robots remotely. Hopefully, this will make it possible for them to become active members of a workforce, for example, working in a warehouse, operating floor-cleaning machines or driving camera dollies. In particular, LWD-operation of telerobots seems promising, because this will make it possible to take part in events that would otherwise be inaccessible (see Figure 11).

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