Towards the Inclusion of Wheelchair Users in Smart City Planning through Virtual Reality Simulation

Timo Götzelmann[1]
[1] Department of Computer Science
Nuremberg Institute of Technology
D-90489 Nuremberg, Germany
Timo.Goetzelmann@ohm-university.eu

Julian Kreimeier[1,2]
[2] Department of Smart City Engineering
Nuremberg Institute of Technology
D-90489 Nuremberg, Germany
Julian.Kreimeier@ohm-university.eu

ABSTRACT

The planning of Smart Cities is a complex task. In particular, accessibility rules based on legal regulations but also on empirical values must be observed. However, it is difficult to determine in advance the exact needs of people with disabilities for concrete planning. Previous approaches mainly aimed at existing urban environments. Ideally, citizens should be directly involved in the planning process of buildings and urban environments. For existing urban environments, crowdsourcing approaches exist to obtain suggestions for improvement from citizens. We present a novel approach for the direct integration of wheelchair users in the urban environments to be planned (participatory urban development) in virtual reality. We present an easy-to-reproduce simulator that allows wheelchair users to directly explore the planned buildings and urban environments in a virtual, spatial environment. This means that these 3D models can be commented already in the planning phase and provide valuable information about accessibility.

CCS CONCEPTS

• **Social and professional topics → User characteristics→ People with disabilities** • Human-centered computing → Human computer interaction (HCI) → Interaction paradigms → Virtual reality • **Human-centered computing → Interaction design → Interaction design process and methods → Participatory design**

KEYWORDS

Smart city planning; wheelchair simulator; virtual reality; ambient intelligence; participation; participatory urban development.

PETRA '20, June 30–July 03, 2020, Corfu, Greece

ACM ISBN 978-1-4503-7773-7/20/06…$15.00
https://doi.org/10.1145/3389189.3398008

ACM Reference format:

Timo Götzelmann and Julian Kreimeier. 2020. Towards the Inclusion of Wheelchair Users in Smart City Planning through Virtual Reality Simulation. In *PETRA'20: PErvasive Technologies Related to Assistive Environments, June 30–July 3, 2020, New York, NY. ACM, New York, NY, USA, 7 pages.*
https://doi.org/10.1145/3389189.3398008

1 INTRODUCTION

Currently, a large part of the population lives in cities and this trend is steadily rising. It is expected that by 2050 more than two-thirds of the world's population will live in urban areas [37]. Ongoing urbanization requires complex planning processes to make urban growth sustainable. A growing trend is the creation of or the conversion into *Smart Cities* - a term for which there are many definitions. One of the most common characteristics, however, is the social inclusion of the various urban residents [1]. Particular attention should be paid to the inclusion of special groups of people such as wheelchair users, visually impaired people and elderly people. According to the WHO, there are currently about 70 million wheelchair users [39]. However, a major criticism of smart cities is that inclusion has often been neglected.

A key role for the well-being and acceptance of citizens is active involvement in the design of smart cities. In the sense of participatory design, besides experts also citizens should also be involved in the planning process of urban transformation. Of course, this includes people with disabilities when buildings and urban environments are planned. This means, instead of selecting citizens for planning, that interested people can choose for themselves whether and in which planning they want to participate.

There are already participatory approaches that assess the accessibility of existing buildings and urban areas. However, these are used in conjunction with abstract maps and do not deal with future planning. This paper presents an approach to enable wheelchair users to experience future urban and building plans in virtual reality, to annotate them in the 3D model and to make them available to urban planners.

2 RELATED WORK

The use of equipment to transform wheelchairs into tools for training, planning and analyses is not a new phenomenon.

Wheelchair Ergometers

So-called *wheelchair ergometers* have been used since decades for the training of wheelchair users and product design. Studies in this area focus on the one hand on measuring the physiological parameters of wheelchair users, on the other hand they aim at optimizing the technical parameters of wheelchairs. Using computer-controlled wheelchair ergometers, parameters such as inertia, rolling and air resistance can be evaluated [24]. There are numerous papers on how to optimize such ergometers and their measuring accuracy and realism (e.g., [4]). Initially, the focus was on optimizing the technical parameters in an artificial environment. Nowadays, however, ergometers are used in an environment that is immersive for wheelchair users (e.g., [33]).

Wheelchair Integration into Virtual Environments

Also, the development of wheelchair interfaces for applications with virtual environments has been pursued for many years. Harrison et al. introduced a sophisticated simulator for evaluating wheelchair access [18] including breaking mechanism. This approach was finally used for user studies, which, among other things, revealed the problem of simulator sickness when using wheelchair simulators with head-mounted displays (HMD) [17]. Other researchers focused on developing a low-cost wheelchair access for virtual environments for manual [35] and motorized [15] wheelchairs. *Panadero et al.* investigated the emotional experiences of people who are confronted with everyday situations for wheelchair users using a wheelchair simulator [27]. *Alshaer et al.* investigated the immersion and presence factors of wheelchair simulators in VR regarding display type, field of view (FOV) and an avatar's visualization [2]. The results suggest that using a third person perspective with avatar can be beneficial to presence. The FOV should also be adjustable.

Other research groups were dedicated to the simulation of a wheelchair in a virtual environment, which can be controlled by a brain-computer interface and investigated the possibility of navigation via this interface [12]. Others undertook these studies on a real wheelchair, which was additionally equipped with a 3D visual interface [20].

Wheelchair Simulator for Training Purposes

Another use of wheelchairs in connection with virtual environments are training applications. Simulators were developed early on to train the use of an automatic wheelchair (e.g., [25]). These simulators were also used to investigate how, depending on the degree of disability, the user's tasks could be transferred to the wheelchair. How to safely introduce inexperienced users to the operation of a wheelchair, to learn its maneuverability and to find their way in complex environments was analyzed in this study [16]. A system for safe training of crossing a busy road was presented by *Becker et al.* [3]. Different views of the virtual training environment were evaluated in their user study. *Crichlow et al.* [7] presented a concept of a wheelchair simulator for rehabilitation purposes using hydraulic motion platform including force feedback.

Wheelchair Simulator in Buildings and Urban Environments

There are early papers that describe the idea to use wheelchair simulators for evaluating the accessibility of buildings [18]. This also addresses the idea that an architect together with a handicapped person can use visualizations to create a joint, accessible design of architecture [19]. *Stredney et al.* [36] aimed at the same aspect and assessed the user proficiency of wheelchair users for new buildings. *Palmon et al.* presented an interactive visualization of spatial environments which should allow the planning, design and evaluation of home and work settings for people with physical disabilities [26].

Church and Marston introduced a general, theoretical model for measuring accessibility for people with a disability [5]. They introduced several metrics to assess buildings and urban areas, however, without the use of virtual reality.

Smart City Planning and Accessibility

Ferrari et al. investigated portals for urban transport and how to optimize the routing of disabled people [9]. Major limitations were the current conditions of the public transport network. The public transport network is primarily designed for people without disabilities. Using the example of wheelchair users, they were able to show that, purely due to the framework conditions of the existing transport network, they took about twice as long to reach their destination.

There are numerous works pointing out that wheelchair users have severe problems with barriers navigating their wheelchairs outside in winter [32], they can make less use of medical assistance [10] or literally feel disabled [8] because buildings and places are planned or designed for (and by) people without disabilities. This often results in frustration [28] and less community participation [32,38].

Participative Accessibility Planning Approaches

There are numerous papers on crowdsourcing for urban accessibility. A highly popular approach is the website *Wheelmap* [23], which is based on *OpenStreetMap* (*OSM*). *OpenStreetMap* itself is an easily accessible platform where ordinary citizens can contribute to a detailed global map. This map, produced by volunteers, is sometimes available faster and in some places more detailed than commercially available maps. *Wheelmap* is based on this platform and provides users with a low-threshold interface to map wheelchair-related features. A simple traffic light system allows individual locations, shops and facilities to be evaluated for wheelchair accessibility.

Another approach [22] was to invite a large number of wheelchair users to fill in questionnaires, in which they could list accessibility issues in their environment that they were familiar with. Only about 25% of the people asked took part in this voluntary action. The data was then merged with a geographic information system (*GIS*) to form a common database. The information system *MAGNUS* was developed to serve as a tool for urban planners to evaluate the accessibility of existing urban environments.

An approach based on smartphones is described in the paper of *Rashid et al.* [31]. GPS can be used to record positions that have accessibility problems. For this purpose photos can be stored and a short list of questions can be answered. There are other approaches that also store audio data in a geo-referenced manner to provide clues for the accessibility [13].

When talking about volunteers, the question also arises as to how trustworthy the data collected is, or whether it is comparable with professionally collected data. There are also some studies that evaluate this. With regard to *OSM* data, the difference in quality compared to ordnance survey datasets was already quite small in 2009 [14]. In the meantime, the level of detail of *OSM* has increased considerably. *Prandi et al.* [29] showed with their work that crowdsourced data can be treated as a reliable data source that can be used for urban accessibility applications. They describe a system *mPass* to collect accessibility information from citizens based on a map through crowdsourcing [30] and propose to store the information together with the geolocation in a database. *Zambonelli* [40] recognizes the benefits of crowd-sourcing in the context of smart cities. In addition to ubiquitous technology (ambient intelligence), computationally intensive problems in particular should be outsourced to volunteers. This includes accessibility issues.

While the described crowdsourcing approaches were based on abstract maps or focused on the improvement of existing urban environments, the aim of this paper is to present an approach that allows the participation of wheelchair users already in the planning process.

3 APPROACH

In this section we first introduce the requirements for a wheelchair simulator, then describe the integrated 3D models and finally our interaction concept. In this process a wheelchair expert (and user) kindly supported with his advice.

3.1 Technical Requirements

Nowadays, digital twins of new buildings are usually created for the purpose of planning construction and maintenance work. Apart from polished rendering images, these 3D information should be also made 'drivable' and therefore accessible for wheelchair users. Similarly, urban places are most often visualized either on complex 2D drawings (e.g., see Fig. 1) or in highly polished 3D renderings of planning experts. These information could and should also be made accessible to wheelchair users in terms of a VR simulation.

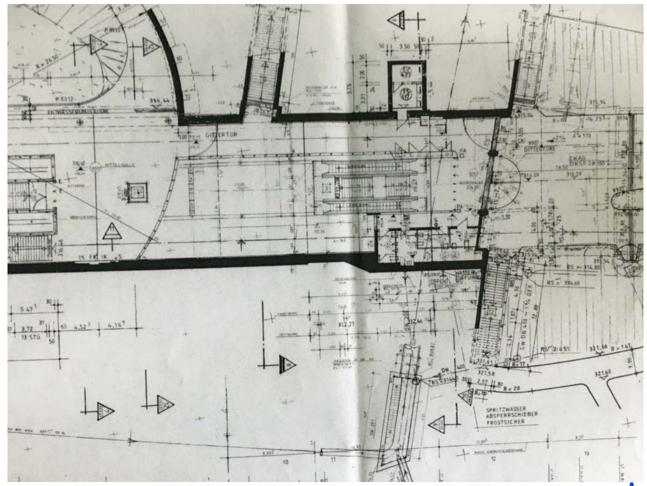

Figure 1: Detailed and complex drawings are the current standard of planning indoor and outdoor spaces and only usable for experts. This excludes both normal and special users, such as wheelchair and other impaired users.

To ensure maximum dissemination of this promising approach, the interface should be as inexpensive and simple as possible. Also, the VR locomotion should be implemented as realistically as possible with regard to rotation and translation using both rear wheels of the wheelchair to minimize the training period and maximize the realism. In this context the interface should also allow the users to use their own wheelchair with as few modifications as possible.

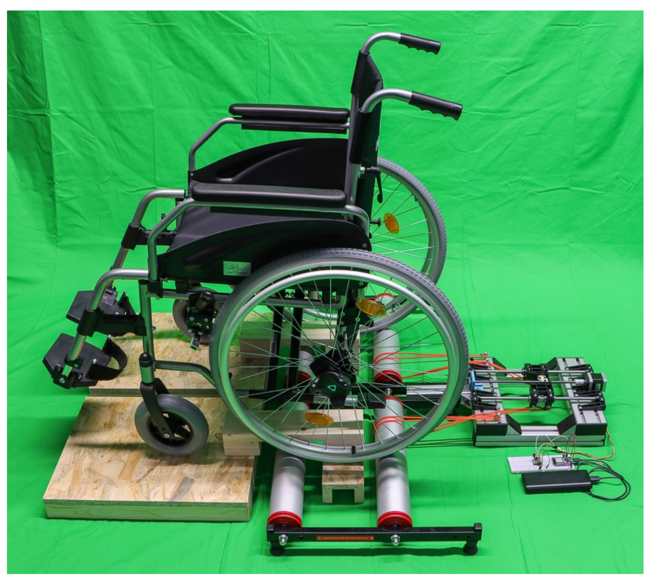

Figure 2: Overall view of our prototype in front of a green screen. Underneath the wheelchair one can see the platforms and the rollers as well as the brake mechanism.

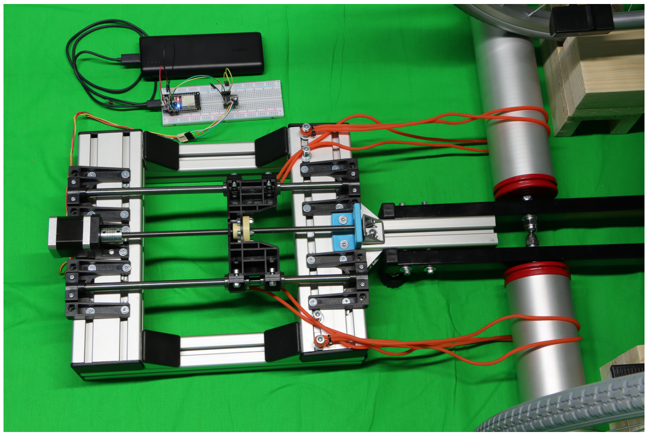

Figure 3: Our proposed wireless brake mechanism in detail. A power bank driven ESP-32 microcontroller controls a stepper motor with a spindle mechanism attached. Similar to a brake tester, the rolling resistance can thus be gradually adjusted.

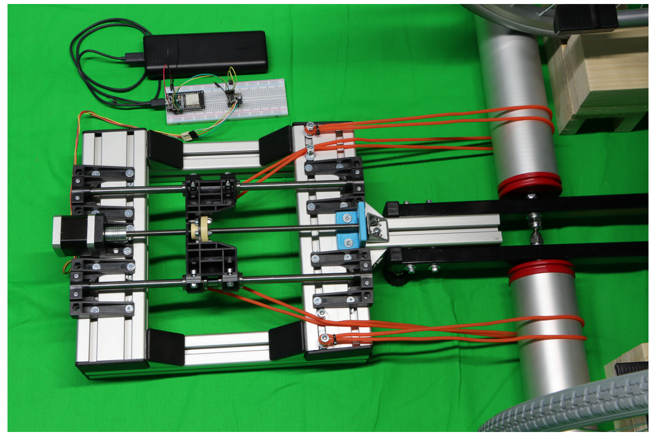

Figure 4: When the belts' tension over the rollers is increased, the rolling resistance is also increased. This simulates the increased effort which is required when driving on an incline.

Unlike for walking people, even lower gradients can be exhausting for wheelchair users. Additionally, for wheelchair users, higher curbs can present insurmountable obstacles. Such terrain characteristics should be implemented as realistically as possible by applying a mechanical brake to the main wheels.

Generally, driving in VR should feel as realistic as possible, i.e., the physics simulation should be as accurate as possible in terms of mass, inertia and effort. Besides accelerating and steering the wheelchair, braking should also be implemented. For example on descending sections, the VR wheelchair could accelerate increasingly due to the physics engine. But we consciously decided not to communicate this by actuating the wheelchair wheels, as this would have entailed a not negligible risk of injury. On contrary, the virtual wheels should be breakable by gripping the real wheel handles.

Finally, the virtual environment should be interactive, e.g., the user should be able to open virtual doors or trigger virtual pedestrian traffic lights. This interactivity should be further increased for documentation and planning purposes by capturing low-threshold, location-related comments from users, such as "this passage here is too narrow" or "this ramp is too steep and too long".

To meet these requirements, we developed the interface presented in the following. We decided on a prototype wheelchair stand (see Fig. 2), so that the users can use their own wheelchair as intuitively as possible and do not physically move from one place to another. To ensure that the wheelchair is horizontal, the front wheels are placed on a wooden platform. The rear wheels are placed on rotating rollers, which can be mechanically braked by the friction of an attached belt (see Fig. 3). The tension and thus friction of the belt is adjustable by a stepper motor with spindle mechanics (see Fig. 4). The rotation of each wheel is captured by a VR tracker. These were fixed to the axle of each wheel with a Velcro strap. Accordingly, the physics calculation of the VR engine converted the wheels' rotation to the actual movement of the user in the virtual environment.

3.2 Integration of 3D-Models

We mapped both a real urban space and a model of a building into VR using the *Unity* engine, both were visualized by a *HTC Vive* wireless head mounted display. Both virtual environments are drivable using the previously introduced wheelchair stand. Our models are geo-referenced in order to be able to put them into a real context. So, one can use the models with existing urban structures. In this subsection we will conceptually explain both data integration approaches and detailed information on the user interface implementation will be presented in the following section.

Outdoor

The static model of the real urban space was built using the popular modeling tool *Sketchup* with photorealistic textures and dynamic content like other road users was animated using a *VISSIM* traffic simulation, see Fig. 5. This approach has already been proven with a pedestrian simulation in this context [21] and was enhanced with interactive sounds (e.g., engine sounds, talking pedestrians, ringing cyclist).

Indoor

For the indoor simulation (see Fig. 6) we used the digital *Building Information Modeling (BIM)* data from of an actual building under construction. These planning was done by civil engineers previously and was imported to our VR simulation. Thus, this content is particularly suitable for a graphically appealing and realistic simulation.

3.3 Interaction Concept

In addition to the implementation of wheelchair locomotion (as previously described in our wheelchair stand), the type and extent of interaction in virtual environments represent a significant added value for wheelchair users. With our approach, the users hold a

Figure 5: Example of outdoor application: Users can explore and examine planned digital urban spaces with their own wheelchair (photomontage of actual rendering).

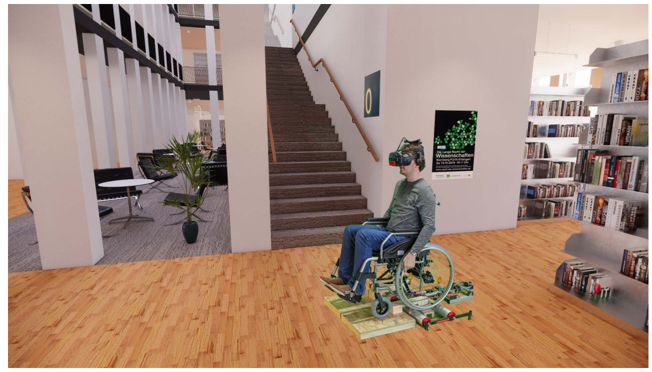

Figure 6: Example of indoor application: Users can explore and examine planned digital building models with their own wheelchair (photomontage of actual rendering).

VR controller (*HTC Vive*) on their lap and use it when standing in front of a door or at a traffic light. With the corresponding hand movement, the door will open or the traffic light trigger.

Also, the annotation of the 3D model can be directly linked to location-based comments. For this purpose, the user can mark a location in the model during interactive exploration. When using the controller as a pointing device, an annotation at this specific location can be captured. We decided to use voice recording in this context, as this type of annotation seems to be low-threshold and relatively easy to access as well as more effective compared to text input or screenshots.

4 IMPLEMENTATION

Our proposed implementation was supported by the advice of a wheelchair expert and in the following we will present individual aspects.

4.1 Sensing Platform

To prevent the user from actually driving in the real space, the wheelchair stood on a platform like structure as shown in Fig. 2. Corresponding to a 'walk-in-place' approach, one could 'drive-in-place' while wearing a HMD (*HTC Vive*) at the same time. To convert the individual rotation of both wheels as realistically as possible to a corresponding locomotion in VR, we captured their rotation using *VR trackers* which were attached to each wheel's axis using *GoVark* Velcro Straps. In the next step, the integrated physics engine of *Unity* calculates the corresponding forces and movements (translation and rotation). Thus, the user can intuitively control translation and rotation along the floor: Turning on the spot, driving forwards or backwards or even taking curves like real driving.

However, this also means not only driving on a straight surface: When going up an incline, for example, one has to exert much more force and downhill, on the contrary, one even needs to brake. Such sloped sections in building or urban spaces (e.g., ramps or underpasses) can be exhausting to wheelchair users and should be simulated as realistically as possible. So we integrated a variable breaking mechanism for simulating steepness. This mechanical brake ensures that the wheels (respectively, the *RockBros* rollers below) can only be turned with more force input. To be more precise, a stepper motor (*Wantai 42BYGHW811*) tensions a belt over the rollers via a spindle mechanism making them gradually harder to turn. The motor is controlled by an ESP32 microcontroller, which in turn is triggered wirelessly from the VR simulation using *Bluetooth*. This mechanism also allows it to immediately stop at obstacles, for example curbs.

The brake (to delay virtual movement) was technically implemented by using the two handholds for the wheelchair wheels as capacitive touch sensors. These are sensed by the microcontroller [41], which could be even used to determine the strength of the user's grip [34].

The wheelchair user can drive up onto the platform and the rollers from the front using simple wooden ramps; to drive down, the rollers are braked firmly so that the rear wheels have a propulsion effect again.

4.2 Integration as Controller into Interactive Environment

Similar to the pedestrian simulation in [21], the virtual urban environment in *Unity* reacts to the user, for example cars honk and cyclists ring in the risk of a collision.

In addition, prototypically implemented Smart City aspects like location-based information, ambient sensing or planning intelligence can be integrated into this VR environment with simple effort. In such a virtual environment, even extensive variations such as architectural conditions and environmental functions can be varied at the touch of a button. Meanwhile, wheelchair users can explore the respective environment or function and provide planners with rare and valuable feedback on accessibility. But as reported by [17], simulator sickness has been shown as an issue for few participants. In their study an adjustable field of view (FOV) had a positive effect on this issue.

Therefore we integrated a customizable setting of the FOV, so that users can adapt this value to their personal requirements.

4.3 3D Model City Planning Software

In our prototype we use several programs as data sources for the virtual environments in *Unity*. For the simulation of a real urban space, we used *Sketchup* to design a static 3D model, while *VISSIM* was used to populate this environment with dynamic traffic like moving cars, bicycles or trams.

The *BIM* model of the building was developed in *Revit* and the data were as well used as virtual environment. In this context, further parameters such as structural features, location-related information or other smart city functional components can be tested effectively and interactively in the *Unity* VR simulation. Other programs can certainly be named and used here, but we had good first experiences with this combination.

5 CONCLUSION

Together with the input of a wheelchair expert, we built an easy to recreate yet effective interface that allows wheelchair users to be involved in the planning process of Smart Cities. Similar to a 'walk-in-place' approach for walking people, users can use their own wheelchair and a VR HMD to explore and examine virtual models of urban places or building. Meanwhile, planners can vary parameters (e.g., in terms of construction and/or function) in order to obtain rare and valuable feedback on accessibility from actual wheelchair users.

Our work is a promising step towards a long-term inclusive participation in the planning process of smart cities and urban spaces. This work unveils the potential of virtual reality in this context and should motivate further research in this young field.

6 FUTURE WORK

As a next step we plan to comprehensively evaluate the proposed interface together with wheelchair users, for example, regarding the determination of pushrim forces and moments [6] to improve the realism of the wheelchair controller. Also, the measurement and modelling of the turning, rolling and obstacle resistance [11] will be focused on. Additionally, the breaking mechanism will be adjusted to steepness parameters together with wheelchair users' input.

Future work could also verify the increase in presence when using a third person view using an avatar [2] and should quantify the added value of such VR wheelchair exploration in the context of a real planning task.

REFERENCES

1. Vito Albino, Umberto Berardi, and Rosa Maria Dangelico. 2015. Smart Cities: Definitions, Dimensions, Performance, and Initiatives. *Journal of Urban Technology* 22, 1: 3–21. https://doi.org/10.1080/10630732.2014.942092
2. Abdulaziz Alshaer, Holger Regenbrecht, and David O'Hare. 2017. Immersion factors affecting perception and behaviour in a virtual reality power wheelchair simulator. *Applied Ergonomics* 58: 1–12. https://doi.org/10.1016/j.apergo.2016.05.003
3. Marvin Becker, Maike Ihmig, Florian Borsum, and Clara Terbeck. Wheelchair Traffic Assistant - Ein Konzept für mehr Sicherheit durch Usability. 5.
4. Félix Chénier, Pascal Bigras, and Rachid Aissaoui. 2014. A New Wheelchair Ergometer Designed as an Admittance-Controlled Haptic Robot. *IEEE/ASME Transactions on Mechatronics* 19, 1: 321–328. https://doi.org/10.1109/TMECH.2012.2235079
5. Richard L. Church and James R. Marston. 2003. Measuring Accessibility for People with a Disability. *Geographical Analysis* 35, 1: 83–96. https://doi.org/10.1111/j.1538-4632.2003.tb01102.x
6. Rory A. Cooper, Rick N. Robertson, David P. VanSickle, Michael L. Boninger, and Sean D. Shimada. 1997. Methods for determining three-dimensional wheelchair pushrim forces and moments: a technical note. *J Rehabil Res Dev* 34, 2: 162–70.
7. L R Crichlow, G R Fernie, J L Campos, and P R Grant. 2011. A Full Motion Manual Wheelchair Simulator for Rehabilitation Research. In *Proceedings of the 2011 RESNA/ICTA Conference on Advancing Rehabilitation Technologies for an Aging Society*, 1–4.
8. Rosemary D F Bromley, David L Matthews, and Colin J Thomas. 2007. City centre accessibility for wheelchair users: The consumer perspective and the planning implications. *Cities* 24, 3: 229–241. https://doi.org/10.1016/j.cities.2007.01.009
9. Laura Ferrari, Michele Berlingerio, Francesco Calabrese, and Jon Reades. 2014. Improving the accessibility of urban transportation networks for people with disabilities. *Transportation Research Part C: Emerging Technologies* 45: 27–40. https://doi.org/10.1016/j.trc.2013.10.005
10. J. Fiske, S. Gelbier, and R. M. Watson. 1990. Barriers to dental care in an elderly population resident in an inner city area. *Journal of Dentistry* 18, 5: 236–242. https://doi.org/10.1016/0300-5712(90)90020-F
11. T.G. Frank and E.W. Abel. 1989. Measurement of the turning, rolling and obstacle resistance of wheelchair castor wheels. *Journal of Biomedical Engineering* 11, 6: 462–466. https://doi.org/10.1016/0141-5425(89)90040-X
12. G. G. Gentiletti, J. G. Gebhart, R. C. Acevedo, O. Yáñez-Suárez, and V. Medina-Bañuelos. 2009. Command of a simulated wheelchair on a virtual environment using a brain-computer interface. *IRBM* 30, 5: 218–225. https://doi.org/10.1016/j.irbm.2009.10.006
13. Cole Gleason, Alexander J. Fiannaca, Melanie Kneisel, Edward Cutrell, and Meredith Ringel Morris. 2018. FootNotes: Geo-referenced Audio Annotations for Nonvisual Exploration. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 3: 1–24. https://doi.org/10.1145/3264919
14. Mordechai Haklay. 2010. How Good is Volunteered Geographical Information? A Comparative Study of OpenStreetMap and Ordnance Survey Datasets. *Environment and Planning B: Planning and Design* 37, 4: 682–703. https://doi.org/10.1068/b35097
15. John Paulin Hansen, Astrid Kofod Trudslev, Sara Amdi Harild, Alexandre Alapetite, and Katsumi Minakata. 2019. Providing Access to VR Through a Wheelchair. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems - CHI EA '19*, 1–8. https://doi.org/10.1145/3290607.3299048
16. A. Harrison, G. Derwent, A. Enticknap, F. D. Rose, and E. A. Attree. 2002. The role of virtual reality technology in the assessment and training of inexperienced powered wheelchair users. *Disability and Rehabilitation* 24, 11–12: 599–606. https://doi.org/10.1080/09638280110111360
17. C. S. Harrison, P. M. Grant, and B. A. Conway. 2010. Enhancement of a Virtual Reality Wheelchair Simulator to Include Qualitative and Quantitative Performance Metrics. *Assistive Technology* 22, 1: 20–31. https://doi.org/10.1080/10400430903520223
18. C S Harrison, P M Dall, P M Grant, M H Granat, T W Maver, and B A Conway. 2000. Development of a wheelchair virtual reality platform for use in evaluating wheelchair access. *Virtual Reality*: 9.
19. J Edward Swan Ii, Don Stredney, Wayne Carlson, and Beth Blostein. 1994. The Determination of Wheelchair User Proficiency And Environmental Accessibility Through Virtual Simulation. 9.
20. I Iturrate, J Antelis, A Kubler, and J Minguez. Non-Invasive Brain-Actuated Wheelchair Based on a P300 Neurophysiological Protocol and Automated Navigation. 14.
21. Julian Kreimeier, Daniela Ullmann, Harald Kipke, and Timo Götzelmann. 2020. Initial Evaluation of Different Types of Virtual Reality Locomotion Towards a Pedestrian Simulator for Urban and Transportation Planning. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (CHI EA '20), LBW068:1–LBW068:6. https://doi.org/10.1145/3334480.3382958
22. Hugh Matthews, Linda Beale, Phil Picton, and David Briggs. 2003. Modelling Access with GIS in Urban Systems (MAGUS): capturing the experiences of wheelchair users. *Area* 35, 1: 34–45. https://doi.org/10.1111/1475-4762.00108
23. Amin Mobasheri, Jonas Deister, and Holger Dieterich. 2017. Wheelmap: the wheelchair accessibility crowdsourcing platform. *Open Geospatial Data, Software and Standards* 2, 1: 27. https://doi.org/10.1186/s40965-017-0040-5
24. Ret al Niesing, F. Eijskoot, Ries Kranse, A. H. Den Ouden, J. Storm, H. E. J. Veeger, L. H. V. Van der Woude, and C. J. Snijders. 1990. Computer-controlled wheelchair ergometer. *Medical and biological engineering and computing* 28, 4: 329–338.

25. H Niniss and A Nadif. 2000. Simulation of the behaviour of a powered wheelchair using virtual reality. *Virtual Reality*: 6.
26. O Palmon, R Oxman, M Shahar, and P L Weiss. 2004. Virtual environments as an aid to the design and evaluation of home and work settings for people with physical disabilities. *Virtual Reality*: 6.
27. Carmen Fernández Panadero, Carlos Delgado Kloos, and David Morán Núñez. PhyMEL-WS: Physically Experiencing the Virtual World. Insights into Mixed Reality and Flow State on Board a Wheelchair Simulator. 20.
28. Linda L. Pierce. 1998. Barriers to Access: Frustrations of People Who Use a Wheelchair for Full-Time Mobility. *Rehabilitation Nursing* 23, 3: 120–125. https://doi.org/10.1002/j.2048-7940.1998.tb01763.x
29. Catia Prandi, Silvia Mirri, Stefano Ferretti, and Paola Salomoni. 2017. On the Need of Trustworthy Sensing and Crowdsourcing for Urban Accessibility in Smart City. *ACM Transactions on Internet Technology* 18, 1: 1–21. https://doi.org/10.1145/3133327
30. Catia Prandi, Paola Salomoni, and Silvia Mirri. 2014. mPASS: Integrating people sensing and crowdsourcing to map urban accessibility. In *2014 IEEE 11th Consumer Communications and Networking Conference (CCNC)*, 591–595. https://doi.org/10.1109/CCNC.2014.6940491
31. Omer Rashid, Amanda Dunabr, Sara Fisher, and Jo Rutherford. 2010. Users Helping Users: User Generated Content to Assist Wheelchair Users in an Urban Environment. In *2010 Ninth International Conference on Mobile Business and 2010 Ninth Global Mobility Roundtable (ICMB-GMR)*, 213–219. https://doi.org/10.1109/ICMB-GMR.2010.73
32. Jacquie D. Ripat, Cara L. Brown, and Karen D. Ethans. 2015. Barriers to Wheelchair Use in the Winter. *Archives of Physical Medicine and Rehabilitation* 96, 6: 1117–1122. https://doi.org/10.1016/j.apmr.2015.01.020
33. Zohreh Salimi and Martin Ferguson-Pell. 2018. Development of Three Versions of a Wheelchair Ergometer for Curvilinear Manual Wheelchair Propulsion Using Virtual Reality. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 26, 6: 1215–1222. https://doi.org/10.1109/TNSRE.2018.2835509
34. Munehiko Sato, Ivan Poupyrev, and Chris Harrison. 2012. Touché: enhancing touch interaction on humans, screens, liquids, and everyday objects. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI ’12*, 483. https://doi.org/10.1145/2207676.2207743
35. Lars Yndal Sørensen and John Paulin Hansen. 2017. A low-cost virtual reality wheelchair simulator. In *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments - PETRA ’17*, 242–243. https://doi.org/10.1145/3056540.3064963
36. Don Stredney, Roni Yagel, Wayne Carlson, Torsten Möller, Po-Wen Shih, and Mark Fontana. 1997. Assessing user proficiency through virtual simulations. 1–3.
37. United Nations Department of Economic and Social Affairs. 2018. 68% of the world population projected to live in urban areas by 2050, says UN. *UN DESA | United Nations Department of Economic and Social Affairs*. Retrieved March 12, 2020 from https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html
38. Dana Wilson-Kovacs, Michelle K. Ryan, S. Alexander Haslam, and Anna Rabinovich. 2008. ‘Just because you can get a wheelchair in the building doesn’t necessarily mean that you can still participate’: barriers to the career advancement of disabled professionals. *Disability & Society* 23, 7: 705–717. https://doi.org/10.1080/09687590802469198
39. World Health Organization. WHO | Wheelchair publications – an overview. *WHO*. Retrieved March 12, 2020 from http://www.who.int/phi/implementation/assistive_technology/wheelchair-publications/en/
40. Franco Zambonelli. 2011. Pervasive urban crowdsourcing: Visions and challenges. In *2011 IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops)*, 578–583. https://doi.org/10.1109/PERCOMW.2011.5766956
41. Arduino Playground - CapacitiveSensor. Retrieved March 31, 2020 from https://playground.arduino.cc/Main/CapacitiveSensor/