Virtual Wheelchair Accessibility Evaluation Tool for Virtual Environments – Design and Preliminary Tests

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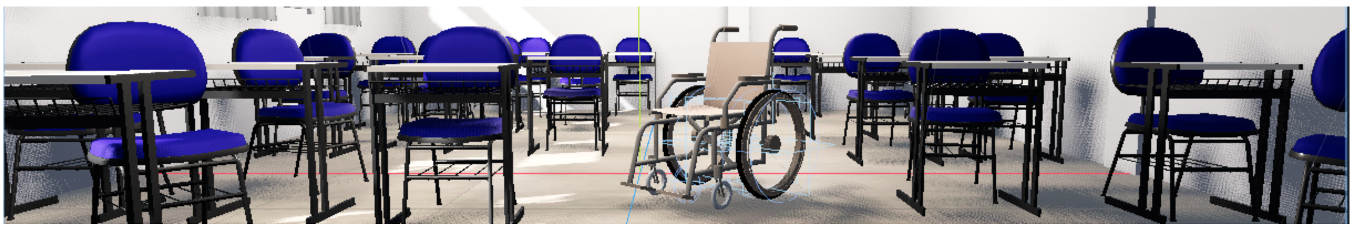

Figure 1: Virtual Classroom and Wheelchair

ABSTRACT

The growing demand for inclusivity towards accessibility in various social settings leads to stricter global standards, which emphasize the importance of having an assessment tool to gauge the virtual environment experience of wheelchair users.

This proposal introduces a virtual reality manual wheelchair simulator able to capture trajectory and time metrics. The objective is to provide designers, architects, and wheelchair users with valuable data for redesign or comparison among virtual environments. The preliminary results of this study indicate promising feasibility in terms of user displacement, although certain aspects of the virtual interface, particularly those related to physics and dynamics calculations, still require improvement. Future work should address those aspects, focus on in-editor modular integration, track check-point system and a questionnaire system.

CCS CONCEPTS

• **Software and its engineering → Software prototyping**.

KEYWORDS

virtual reality, accessibility, simulation, wheelchair

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1 INTRODUCTION

Global standards, trending towards inclusiveness for disabilities, applicable to various public and private settings, are becoming increasingly stringent [18]. In 34 surveyed developed countries, there is a demand for wheelchairs from 10 million people (1% of the population). In 156 developing countries, the number rises to a minimum of 121.8 million people (2% of the population), resulting in a total of at least 131.8 million individuals worldwide requiring wheelchairs. The need for a wheelchair can arise from congenital disabilities, accidents, diseases, or the natural aging process, as it is well-known that elderly individuals often develop mobility disabilities. Therefore, addressing the issues faced by wheelchair users within society means not only addressing a specific group but potentially benefiting everyone. Ensuring accessibility in interior home design is crucial for wheelchair users. By creating an inclusive and barrier-free living environment, wheelchair users can navigate and engage in daily activities with independence, comfort, and safety within their own homes. However, there are several challenges that must be addressed in this context. One primary challenge involves the environment (*e.g.* home, office etc.) layout and spatial design. Narrow hallways, tight doorways, and cramped rooms can restrict wheelchair maneuverability and hinder accessibility. A thoughtful approach, that considers the specific needs and challenges of wheelchair users, is essential for creating an inclusive and accessible environment. Collaboration between wheelchair users and professionals experienced in accessible design, such as architects, interior designers, or occupational therapists, can greatly assist in ensuring the best possible home design solutions.

On another front, significant advancements in Virtual Reality (VR) technology have emerged since 2015, including the introduction of consumer-level VR solutions like the Oculus Rift [11], HTC Vive [16], and PlayStation VR [21]. These devices offer immersive and interactive experiences through head-mounted displays (HMD), precise tracking systems, and responsive motion controllers. The increased affordability and accessibility of these systems have contributed to their widespread adoption, impacting the field of home design.

VR is an effective tool for architects to explore spatial constructions and rapidly create simplified architectural models [20]. During the concept stage of house designing, VR tools provided a voxel-based virtual environment and streamlined block-building functionalities. Usability tests with five professional architects revealed that immersion in VR plays a crucial role in accurately assessing scale, especially when using their bodies as a reference for spatial definition. It is found that VR's immersive experience enhanced architects' spatial understanding and facilitated efficient design iterations.

From an accessibility standpoint, VR has showcased its potential to significantly enhance architects' understanding of the specific needs of wheelchair users [12, 13]. The former achieves this through a design process involving pre-visualization in Blender [10], and VR simulation using Unity [3] on an Oculus Rift HMD. The later employed VR technology along with a wheelchair simulator for a proposed wheelchair-user-assisted design methodology comprising the following stages: adapt the designed object to VR, exploration and report, and design validation. Iterating the stages provides a communication channel through the instructions set by designers and wheelchair user's generated reports, enabling a comprehensive evaluation of the design. A simulator for planning Smart Cities that allows wheelchair users to explore virtual environments and provide feedback on accessibility during the planning phase is developed [22]. Using Unity, a real wheelchair and an HTC Vive HMD, the simulator shows potential to assist architects and interior designers in creating more inclusive and accessible designs by experiencing virtual spaces from a wheelchair user's perspective.

Maneuverability skills are also addressed by using McGill immersive wheelchair simulator [9] together with a haptic feedback roller system [15]. The simulator is first validated and then tested on clinicians and expert wheelchair users for sense of presence, overall experience and ease of use. It is verified that the proposed tactile feedback leads to a stronger presence experience.

Another affordable VR simulator, with the ability to run on regular computers using joystick, monitor, speakers and headset, is developed to provide safe practice environment for young power wheelchair users. It is tested on 6 children, 4 occupational therapists, and 2 wheelchair technicians [19]. Some authors also compare the usability of two display types, monitor and HMD, for VR wheelchair simulation [17]. The latter is rated significantly higher in terms of sense of presence and VR experience but with increased motion sickness symptoms, a well known side effect of the technology. Considering input controls, researchers investigate improvements in a VR power wheelchair simulator comparing driving performance using two solutions, a standard video game analog joystick and a power wheelchair proprietary joystick [8]. It is found that driving performance is not significantly affected by the tested input control type.

Upon reviewing these simulators, it becomes apparent that there is a prevailing trend of using a real wheelchair on a rolling platform as the input method. This choice is directly related to the research area's specific metrics, particularly in the medical field. Joystick support is usually related to cost, reach of the application and parity with power wheelchair controls. The HMD use is justified by the higher level of realism provided, its recent consumer level affordability is mentioned, and the majority of the works suggests its use to be an ongoing trend. Unity, a proprietary well-known industry leader game and application authoring tool, through its free version, is the preferred development system.

Overall, by integrating VR into the design process, virtual environments can be created to provide an accurate representation of space, allowing users to experience it firsthand, make real-time adjustments, provide feedback, and actively participate in the design process. Incorporating accessibility considerations into VR design enables a deeper understanding of the specific challenges faced by wheelchair users. Furthermore, it allows non-wheelchair users to empirically experience the condition, raising awareness and promoting more collaborative and informed decision-making before construction or renovation.

Development of a VR evaluation tool, using consumer-level technology to address wheelchair mobility issues, is this work's main objective. Attention to hardware and software affordability, targeting a low-cost solution, and VR simulator modular independent code are specific objectives. The tool provides a first-person manual wheelchair simulation within imported 3D environment designs and allows for the setting of task tracks as a sequence of location check-points. By experiencing these tracks, objective mobility data such as time, trajectory, rotation, bumps, and failures can be generated. Additionally, subjective data can be collected through in-VR questionnaires on usability and accessibility. This paper introduces the first prototype of the proposed evaluation tool, outlines its design methodology, and presents preliminary test results.

2 METHODOLOGY

The methodology involves a sequential approach in which the key initial components are the selection of VR hardware and authoring software. Subsequently, a VR development workflow is constructed on this foundation, incorporating additional software for creating and manipulating assets. This workflow undergoes testing to create a basic first-person VR application that simulates human movements, assesses hardware and software performance, explores different outputs, experiment with real and virtual environments, and identifies any potential limitations. The subsequent phase involves modeling the manual wheelchair object and its mechanical aspects, establishes virtual world physics and dynamics, and ensures their seamless integration. In the final stage, the first-person VR experience, wheelchair system, and physics solution are combined, with a focus on the virtual user interface. The resulting system is tested aiming to evaluate its functionality and usability.

2.1 VR hardware and authoring software

The minimum requirement for VR hardware primarily consists of a HMD that can provide stereoscopic vision, stereo sound, and tracking capabilities for position and orientation. Additionally, two hand controllers with tracking capability, haptic feedback and grip buttons are required. The Meta Quest 2 [2], besides the above criteria, offers additional features that align with the objectives. These features include a self-sufficient operating system, low requirements for development workstations, affordability, widespread availability, and extensive support from authoring software.

The selection of the Godot Engine [14]as the authoring software is due to its lightweight, open-source and cross-platform characteristics. Its object-oriented nature promotes modular coding, allowing for a structured approach to development. Additionally, the software offers the ability to utilize and customize its own native work interface, enabling the simulator to seamlessly integrate with it, by taking advantage of the built-in I/O features, front and backends. Another noteworthy aspect is its support for openXR and webXR standards [1, 4], ensuring compatibility not only with existing HMDs but also with potential future devices.

2.2 VR development workflow

VR is mainly a multimedia experience, and software to capture, generate and modify assets are needed. These assets encompass 3D objects, 2D images, video clips, sounds, and music. Any software capable of addressing these aspects and communicating with others through a compatible format may be employed.

Blender [10]is a 3D modeling open-source tool and it is inline with the nature of Godot. A deeper integration between both is ongoing, favoring it above other available solutions. It is also capable of 2D asset generation, video editing, format conversion, 2D and 3D animation.

Gimp [23]is an open-source image manipulation tool that can be used to generate and process 2D images for a plethora of goals ranging from texture, normal and bump maps, conceptual designs, sketches and illustrations, including a degree of vector path support. Its nature is on par with the other tools making it a suitable candidate to cover this area.

Audacity is the choice of open source cross-platform sound and music record and processing tool and finally, VLC is the choice for extra multimedia visualization and conversion [5, 24]. Development workflow may start with any of these programs and evolve in a circular crossed fashion culminating on the final output from Godot.

2.3 Workflow test run

The workflow is tested resulting in a first person VR application where the user can move around a square platform (10 m × 10 m). The ambient is modeled on Blender and used photographs manipulated on Gimp as texture maps seen in Fig. 2.

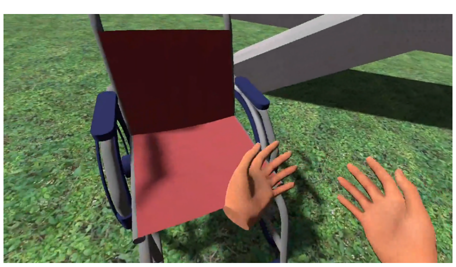

Figure 2: First Person VR Application Test

Godot XR Tools [6], a set of openXR based scripts made towards easy of use VR development, is employed to generate the virtual hands and its functionalities in accordance with the controllers. Keyboard and mouse controls are also added. Audacity is used to process captured ambient sounds. The application is compiled for native run on the Quest 2, PC desktop linked to the Quest 2 and internet webXR usage.

Results suggest that the webXR output has the potential to be a wider reach solution. The ability to run on any web browser connected computer, VR hardware or not, provides this reach with the expense of lower visual and processing capabilities as well as additional cost to host the website. The desktop output can deliver the highest level of visuals and processing power as it scales according to the desktop configuration, portability is compromised and overall cost rises as higher-end desktops may not be generally affordable. The native Quest 2 output is the more portable easy-to-use solution and stands between the other two when it comes to visuals and processing power but needs to be distributed under the manufacturer's digital ecosystem. Overall, the developer has a good range of options to deliver the final product and can choose one or more outputs depending on the project's nature.

A second test is conducted, utilizing a classroom model that includes only the boundaries, scaled to match a real environment. The classroom's dimensions fall within the 10 m × 10 m Quest 2 free movement limitation. By aligning the starting position and orientation in the simulator with the real room, the results demonstrate that the user can freely walk around the space, with both the real and virtual boundaries matching their expected positions accurately.

2.4 VR manual wheelchair simulator

The next step involves modelling a manual wheelchair in scale, the Graham-Field Traveler L4 model [7] is preferred as it is a popular affordable unit. The object is composed of a body, two large wheels and two small wheels, it is then assembled mechanically inside Godot considering each part connection and its freedom of motion. A ground plane is created, physics and dynamics are adjusted to address a scale of reality comprising a minimum computed size of 1 mm, weight ranges from 1 to 90 kg and forces that can produce a maximum 10 km/h speed. The wheelchair motion is dealt by Godot's physics engine and by the algorithms we develop ourselves, particularly the wheel's angular acceleration, wheelchair system's inertia and traction.

2.5 User interface

An experienced manual wheelchair user operates it intuitively, when in motion his focus is on the path or the goal, spatial and muscle memory provide assurance when driving neglecting the need to look at one's hands. This is a challenge to port to VR for the hardware is incapable to provide equal real experience. A solution using the haptic feedback available on each controller is presented. When the grip analog button is pushed to the full and the virtual hand is in connection with the wheel, its angular speed determines the strength of the vibration. The goal is to provide a sensory feedback that is on par with the visual motion.

2.6 Functionality and usability test run

A test run using the beta wheelchair simulator in a standard fully modelled classroom, as seen on Fig. 3, with six laboratory students is assembled.

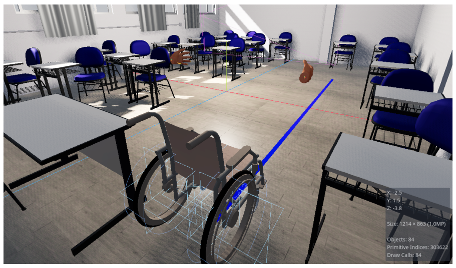

Figure 3: Virtual Modelled Environment

The test comprises two tasks, the first, to operate a real manual wheelchair over a 5 m straight line where users are asked to drive the wheelchair towards its end, perform an 180° turn and ride back as close as they can to the line, completing a 10 m trajectory as seen on Fig. 4. The second task repeats the action but with the virtual wheelchair, as shown on Fig. 5.

Figure 4: First Task (Real)

Figure 5: Second Task (Virtual)

Subjects are selected based on having no prior experience driving a real wheelchair, mild frequency of 3D video game usage and no or minimum prior experience with VR equipments. The first task is video recorded and tracked using Blender, producing spatial data. The second task has the simulator generating the same data.

3 RESULTS

Real and virtual trajectory paths can be seen on Fig. 6 and Fig. 7, while the raw data, including trajectory length, task time and average speed can be seen on Table 1.

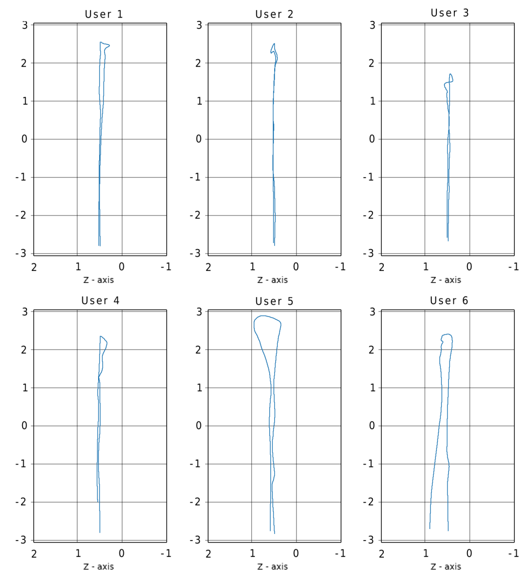

Figure 6: Real Wheelchair Trajectory (distance in meters)

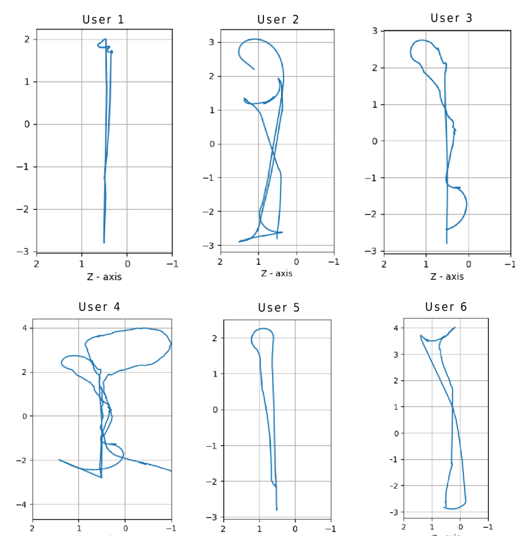

Figure 7: Virtual Wheelchair Trajectory (distance in meters)

Users naturally deviate from the 10 m path length proposed, both on real and virtual experiences, and an index of deviation can

User	Real Wheelchair			Virtual Wheelchair		
	Length [m]	Time [s]	Average Speed [m/s]	Length [m]	Time [s]	Average Speed [m/s]
1	10.30	20	0.51	10.15	37.59	0.27
2	10.07	29	0.34	21.97	137.31	0.16
3	8.25	27	0.30	12	70.58	0.17
4	9.03	32	0.28	41.68	277.86	0.15
5	11.45	32	0.35	10.57	105.7	0.1
6	10.07	24	0.41	17.09	63.29	0.27

Table 1: Raw Spatial Data

User	Real Wheelchair	Virtual Wheelchair
1	0.029	0.014
2	0.006	0.544
3	0.212	0.166
4	0.107	0.760
5	0.126	0.053
6	0.006	0.414

Table 2: Deviation Index

be seen on Table 2. The index is generated by scaling the 10 m proposed path based on the length an user achieves, it is shifted and flipped to yield a value within the range of [0, 1] according to the following formula: $index = ((10/length) - 1) * -1$.

Indexes close to 0 indicate a performance closer to the proposed 10 m path. It is expected that each user generates similar real and virtual wheelchair indexes.

4 DISCUSSION

Godot is currently past a significant rewrite with version 4.0 released early 2023. As an ever-evolving project, it is important to be aware of its known issues and to use version control during development. Nevertheless, it proves to be a reliable choice, providing alternative solutions to address the challenges faced.

One key strengths of Godot, other than lightweight, cost-free and open-source nature, is its capacity for in-editor interface configuration. Allowing the simulator to function as a self-contained module within Godot while leveraging its various tools and I/O capabilities. This is beneficial for users who may wish to customize the code according to their specific needs. Additionally, this approach ensures seamless execution, the output is generated directly from the authoring tool, eliminating the need for specific outputs, adherence to software ecosystems or distribution environments.

The virtual classroom accurately replicates the real counterpart in terms of simulation and metric generation, enabling the assessment of virtualized real locations. Aligning the virtual and real spaces is currently a challenging task. However, it is important to note that this procedure is only necessary to validate the simulation and is not needed for the final use.

When comparing the user's performance in real-world situations to virtual ones, a significant divergence is evident after the 180° turn, resulting in a subsequent loss of control. Among the participants, users 1, 5, and 6 manage to regain control at the expense of time. Users 2, 3, and 4 encounter considerable difficulties in restoring control, with the latter even surpassing the test boundaries and user 2 reporting mild motion sickness, discomfort and headache.

Physics and dynamics system, the more challenging element on this simulation, is providing the required functionality least the interface affecting the simulation on narrow angle rotations needs adjusting, precisely our own algorithms. The interface and haptic feedback prove valuable to the overall experience and can be more in-depth developed, possibly adding more channels of vibrations other than traction response.

Future steps on this research involves generating the basic Godot in-editor simulator interface and modular integration, implementing user's weight data, track point creation and questionnaire systems.

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