Development and Evaluation of an alternative VR Interface based on Manual Wheelchairs

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Abstract—**This paper investigates the advantages of having an interface for VR locomotion utilizing a manual wheelchair for non-ambulant and ambulant user groups. In addition, it evaluates if an existing concept for a low-cost wheelchair trainer can be remodeled to be used as an input device for VR locomotion. Literature was primarily used to research existing interfaces for VR locomotion and the advantages of using a wheelchair for VR locomotion for ambulant and non-ambulant users. A rudimentary wheelchair interface was developed and tested with 6 participants to assess feasibility. Developing a wheelchair interface for VR shows clear advantages for non-ambulant users. It makes VR more accessible to this group. Also, ambulant users profit since it allows traversing virtual environments like a wheelchair user would (e.g., for architects exploring their building virtually). Building such an interface is feasible, although improvements to the prototype are required for further use. The feasibility study shows a positive effect on the positive and negative affect scale for all 6 participants. The number of participants is not high enough for further analysis. It concludes that an interface for wheelchair locomotion in VR has clear advantages. Such an interface can be built and is enjoyable, but further engineering and research (e.g., motion sickness with the interface) are required.**

Index Terms—**Virtual Reality(VR), Locomotion, Wheelchair Use**

I. INTRODUCTION

VIRTUAL Reality (VR) describes the general concept of digitally creating a three-dimensional virtual world and immersing a user in it. The user cannot only experience but also interact with this world. Virtual Reality (VR) as an idea made its first appearance starting in 1965 with Sutherland's "The Ultimate Display" [1]. Since then, VR has come a long way. With head-mounted displays (HMDs), new ways to visualize these worlds have been developed. The user can now interact with the virtual environment with a multitude of interfaces (e.g., controllers with joysticks). In addition, a variety of techniques enable the user to navigate these virtual worlds. Tracking the user's position in the real world, teleportation with joysticks or treadmills, to name a few of them. All these changes have been accompanied by a rapid decline in the price of the hardware. All of these lead to a rapid adaption of VR by the general public. For example, the installed base of HMDs in 2019 of 11.6 million is projected to grow to 34.0 million in 2024 [2]. Currently, the main driver for VR is the consumer market [3][4], but adaption in other sectors (e.g., healthcare[5]) is increasing.

Since the development of VR has been driven by a specific sector (i.e., the consumer market), the existing hardware and tools are catered toward the corresponding target user group, young ambulant well-off people. Most companies imagine VR as a medium experienced in a spacious empty room in a standing position to allow free roaming within this space. This focus presents an issue for a multitude of people. For example, some users might not be ambulant or just ambulant in a limited fashion. Imagine an older person with arthritis standing up and walking around for 20 minutes to experience VR. This problem becomes even more pronounced if you consider that VR essentially blindfolds the user. So they will not be able to see where they are stepping or if there is a hindrance within their walking path. Even if there are no body limitations, having ample room you can have for your own is just not available to a lot of people. This last problem led to the development of a multitude of stationary locomotion techniques, which will be explored later on.

These interfaces allowing stationary use are either catered to a standing position, having the issues mentioned before, or do not require any physical engagement. For sedentary users, especially if they

Fig. 1: Symbol image of athletes on a virtual race track.[6]. It shows the initial idea for the use of the wheelchair interface. The interface is based on the Easy-Roller, a wheelchair trainer for wheelchair athletes. The idea was to make the training more immersive.

are not ambulant or wheelchair users [7], such physical engagement would be critical. Therefore, the user group that would likely benefit significantly from VR as a medium, which engages the user not only mentally but also physically, cannot benefit to the full extent from it. In addition, research shows that physical movement provides a better experience in VR than just using abstract interfaces (e.g., joysticks) for locomotion [8], [9],and [10]. Due to this, a seated, stationary interface requiring physical effort would be ideal for the non-ambulant user group. A manual wheelchair is a time-proven and widely used tool for locomotion of non-ambulant people. In the USA alone, there are 6.1 million wheelchair users [11]. Making wheelchair use for VR stationary would provide both an interface that requires physical effort to use and is intuitive. Intuitive because, contrary to, for example, moving a joystick forward, rotating a wheel would also move the wheelchair in reality. Of course, it can also be used by non-ambulant people. A potential use case for non-ambulant people besides the one shown in Figure 1 could be wheelchair training directly after injury. For example, crossing a busy intersection for the first time is a stressful and potentially hazardous experience. With VR, you can train this situation within a safe space without any injury. This could be done directly in the hospital before release or any therapy center without requiring a huge obstacle course. It would also be helpful to ambulant users. For example, state of the art in architecture is to create buildings digitally before they are built. Such a digital model is easy to convert to a VR world. A world that can be explored with a wheelchair could show, for example, the path a wheelchair user needs to take to avoid barriers [12]. This experience could trigger design changes before the building is constructed, changes that might be expensive or not even possible after construction.

The literature provides several examples for wheelchair-based interfaces [13], [14], [15] and simulators and their efficacy [16], [17] , but those were never made available to the public in the course of commercialization or by making it open source. One main reason is that these interfaces are generally over a decade old. At this time, VR was not as developed, with both the performance and price not interesting enough for broader use [18]. This changed with the introduction of commercial hardware and the introduction of powerful game engines to create VR applications easily (i.e., Unity and Unreal Engine).Therefore, the development of a wheelchair-based locomotion interface might be more successful than it has been in the past.

II. METHODS

The interface is built on an existing design of a wheelchair trainer [19] the Easy-Roller. This wheelchair trainer targets wheelchair athletes from low-income countries like Ghana with limited training opportunities. Its design goals are affordability (less than 250 $), ease of manufacturing, and transportable in standard check-in flight luggage (size and less than 50 lbs). Figure 2 depicts the Easy-Roller and its components.

The use of the trainer for VR requires several modifications to the mechanical design. For example, the ride needs to be smoother. Currently, the trainer causes vibrations as if you are going over an uneven surface. This behavior is acceptable outside of VR, but inside it will cause motion sickness, as there will be a dissonance between the visible and perceived surface. In addition, the safety requirements are higher since the user is blindfolded and cannot react in case something happens. For the use as an interface, sensors and processing electronics are added. The software on the electronics sends the wheelchair's wheel rotations digitally to the PC hosting the VR experience. This PC translates the data from the interface into movement in VR. The created interface was evaluated both for validity &

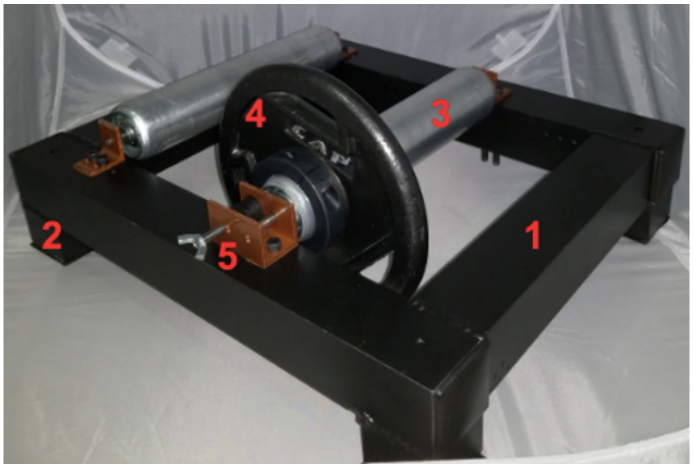

Fig. 2: The EasyRoller with (1) aluminum frame with (2) raised feet, (3) conveyor belt rollers, (4) friction disc brake, and (5) inertial weight [19]. The trainer consists of two such roller systems (i.e., one for each wheel)

Fig. 3: Isometric view of the playground. It is intended to be a fun way to explore various ADA wheelchair design elements.

reliability of the movement and user experience. The validity & reliability were assessed by comparing the behavior of an actual wheelchair to the behavior translated by the interface and PC software. The test consisted of ten repetitions of spinning a single wheel forward and noting down the virtual displacement. For this test, the PC script was changed to get the movement of a single wheel to do movement in a straight line. A marker was placed on the wheel and rotated ten times. Then the same test was repeated with the original PC software to check for rotation. Because of the lack of a dedicated VR experience and resulting issues with simulator sickness [20], the user experience was evaluated via a 2D experience. Six participants were tasked to navigate and explore the digital playground depicted in Figure 3 for eight minutes. The playground was created by the student Brice Bai of the Blended Reality Lab at Yale CCAM.

Postivive Affect and Negative Affect Schedule (PANAS) [21] was used to assess positive and negative affect as transient states. The scale was used in the present experiment to evaluate the feeling of the participants "right now" (before the experience and after the experience). The PANAS is widely used in many fields of psychology, and we used the version with 20 items that describe different positive and negative affects (e.g., active, proud, irritable, afraid) and asked participants to rate how much they were currently experiencing that affective state on a scale of 1 (not at all) to 5 (extremely). Since the sample size of 6 is relatively small, no sophisticated statistical analysis was done, except for mean, median, and standard deviation. In addition the participants are verbally asked for feedback on how it felt using the wheelchair in regards of mechanical properties.

III. Implementation

As described in methods, the initial design of the Easy-Roller had to be modified to make it more stable and the right smoother. This was achieved by putting the rollers on a frame made with 1x1 inch aluminum profiles, as it is shown in Figure 4. On each side, one axle is connected to a belt drive transmitting the wheel rotation to a rotatory encoder (Yumo E6B2-CWZ3E). On the other axle, flywheels can be added to increase inertia. The drums/rollers were machined to guarantee a smooth right. Their diameter of 125 mm is significantly larger than before to reduce rolling resistance. The overall dimensions are shown in Figure 5. Since the diameter is still significantly smaller than the ones used for testing drag resistance (e.g.,[22]), rolling resistance will be higher than using a wheelchair on a flat hard surface like concrete. The theoretical rolling resistance wasn't calculated. Increasing the rolling resistance further would reduce manufacturability, drive up the cost, and most importantly, be a safety hazard. Since the drums are placed below the wheels, any drum size increase lifts the wheelchair further from the ground. An increased

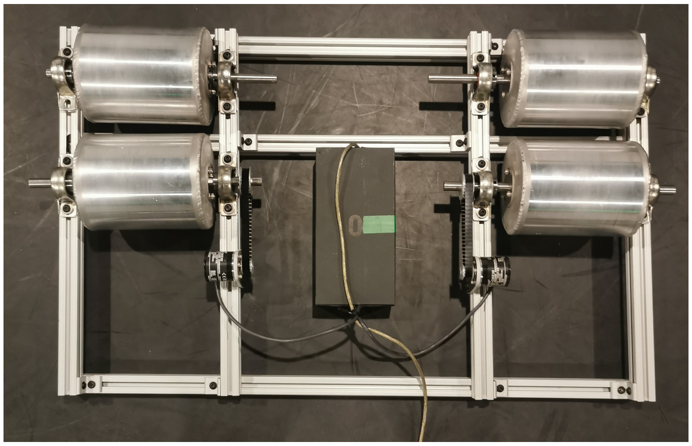

Fig. 4: Wheelchair interface with aluminum frame, roller pairs, rotary encoders, and electronics in a protective box. The longer axles allow the addition of inertial flywheels. In use the wheelchair's main wheels rest between the two aluminum drums. In this version the front wheels are placed on wooden boxes.

diameter makes it harder to put the wheelchair on the interface and increases any potential harm from falling off. Therefore, it was decided that 125 mm is the ideal drum diameter, even though it will lead to higher rolling resistance. In a further iteration of the wheelchair interface, it would make sense to include motor support. This motor support would also allow the simulation of different surfaces and slopes (i.e., going up would be more challenging than going down). This system is not included in the prototype.

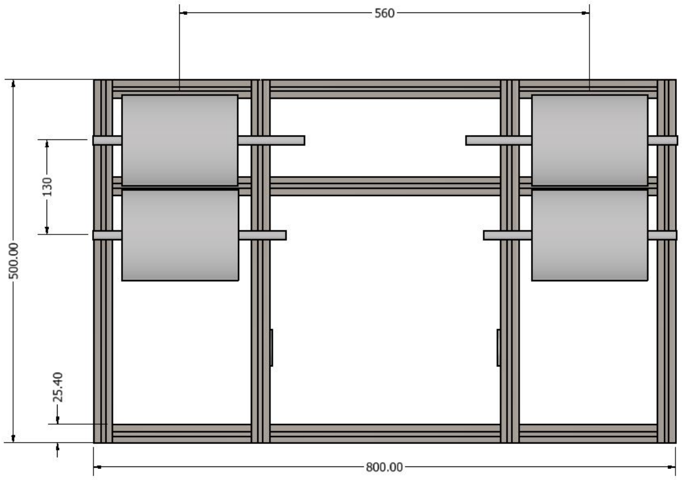

Fig. 5: General dimensions of the wheelchair interface. The diameter of the rollers are 125 mm.

The rotary encoders are connected to an Arduino Mega. Each line (i.e., A/B/Z) of the encoder is connected to an interrupt to detect the ticks of the encoder. Each rotation of the encoder totals to 1024 ticks. With a transmission ratio between the wheelchair wheel and the encoder of 9.85, one rotation of a wheel causes around 10 000 ticks, leading to a theoretical maximum accuracy of about ±0.2 mm.The ticks are summed up and sent every 10 ms to the PC via a wired connection, as shown in Figure 6.

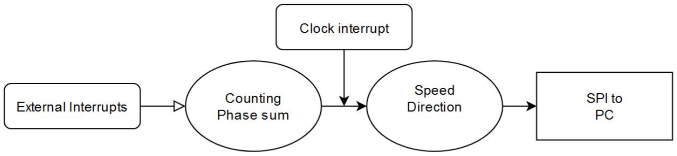

Fig. 6: The general process of the software on the micro-controller. The microcontroller sums up the inputs and the phase shift. On every clock interrupt the angular speed and the direction is calculated and send to the computer.

The PC software receives the movement data and translates it to motion via a numeric approach. First, the rotation is calculated, then the translation. Since a frame/update rate of around 90 frames per second is used, the error is minimal compared to an analytical approach. In the case, the frame rate drops, the error would become more pronounced. Still, it is improbable that the user would perceive any discrepancy from the movement they would expect. For the evaluation test, a wheelchair is placed on the interface, fixated, and a 2D screen is put in front, as shown in Figure 7.

IV. EVALUATION RESULTS

The validity and reliability test yielded the results shown in Table I. The average translational movement of 1.91 meters deviates 0.01 meters from the nominal value of 1.92 meters or 0.5%. The reliability is ±0.02 meters or ±1 %. The average rotational movement of 185.8° deviates 4.1° from the nominal rotation of 189.9°.

Six participants explored the playground on the interface, seeing the changes on a 2D screen. Each of them did the pre- and post-PANAS. The results are listed in Table II and visualized in Figure 8. The median and mean improved (negative affect went down, positive affect went up) after the experience compared to the pre-test results. The results

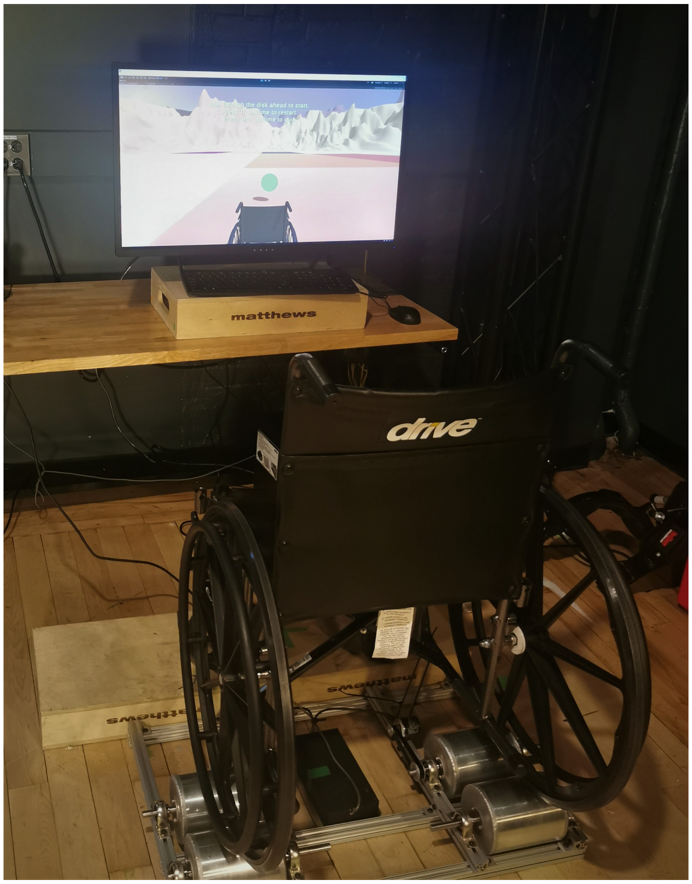

Fig. 7: The wheelchair is in front of a 2D screen and stands on the interface. The user's wheel propulsion is translated into movement in the playground from Figure 3. The user is in the experience for eight minutes.

TABLE I: Results of the experimental measurement of the validity and reliability of the translation of the wheelchair movement. The results display the effect of a single wheel rotation (i.e., test results were devided by ten). The translational movement is accurate since it was used to calibrate the coefficients. The rotation deviates more, but is still close enough, do be unlikely to be perceived by the user. The reliability for both types of movements is adequate. The rotational component will get significantly worse with reduced frame rate. The test has been conducted at 90 fps.

	Nominal	Measured Average	Standard Deviation
Translational / m	1.92	1.91	0.02
Rotational / °	189.9	185.8	1.5

TABLE II: PANAS before and after the users navigated the playground on the interface.

	Meausre	Median	Mean	SD
Pre-PANAS	Positive Affect	36	29.2	9.5
	Negative Affect	14	12.0	2.35
Post PANAS	Positive Affect	39	32.0	9.14
	Negative Affect	13	11.4	1.95

show that the experience was perceived positively by the participants. Due to the low number of participants more sophisticated analysis was not done. Regarding mechanical properties, participants reported high rolling resistance and low inertia. Maneuverability is regarded as good. Similar results have been reported by the test athletes for the Easy-Roller project [19]. The high rolling resistance and low inertia was of close to no issue for the athletes intend on training, for casual use this poses an issue and needs to be addressed in a further prototype iteration. For this version of the interface it feels like going over a thick carpet.

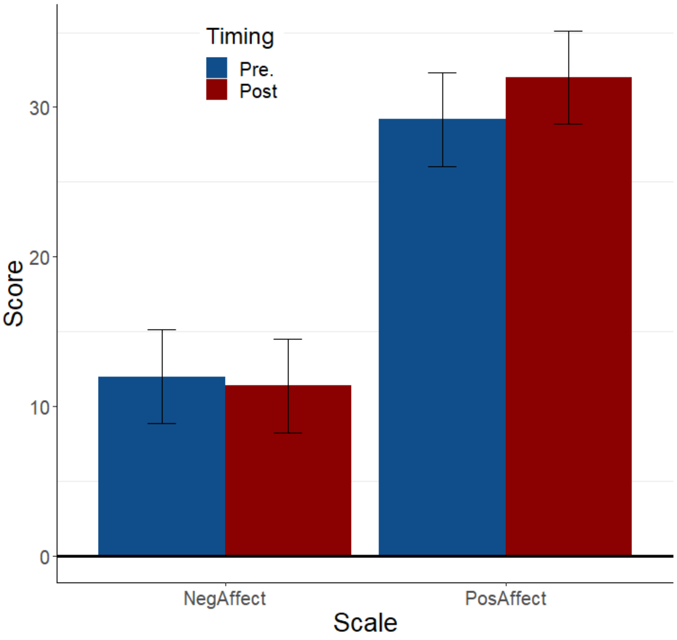

Fig. 8: Change in PANAS before and after navigating the playground on the interface.

V. CONCLUSION

This paper demonstrates the general need and value a VR interface for manual wheelchairs might bring. In addition, a simple prototype interface was built. This interface provides the means to translate wheelchair movement in VR via rotary encoders. The translation is accurate and reliable enough for VR use. The minor deviations are unlikely to be perceived by users. Compared to actual wheelchair use, the interface has a higher rolling resistance and close to no inertia. This cannot be solved by purely mechanical considerations and will lead to a new iteration of the interface with motor assist. This assist would also allow more sophisticated feedback to the user (e.g., slopes, simulated inertia). A small study with six participants shows a positive impact of the interface on positive and negative affect. This paper proves the feasibility of such an interface and makes a case for continued work. The prototype can already be used for simple tasks like exploring a VR environment. Further work is required to make the interface sophisticated enough for mainstream use.

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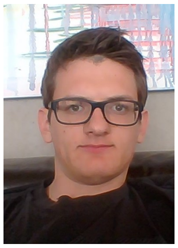

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