User Mobility Simulator for Full-Immersive Multiuser Virtual Reality with Redirected Walking

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ABSTRACT

Full-immersive multiuser Virtual Reality (VR) setups envision supporting seamless mobility of the VR users in the virtual worlds, while simultaneously constraining them inside shared physical spaces through redirected walking. For enabling high data rate and low latency delivery of video content in such setups, the supporting wireless networks will have to utilize highly directional communication links, where these links will ideally have to "track" the mobile VR users for maintaining the Line-of-Sight (LoS) connectivity. The design decisions about the mobility patterns of the VR users in the virtual worlds will thus have a substantial effect on the mobility of these users in the physical environments, and therefore also on performance of the underlying networks. Hence, there is a need for a tool that can provide a mapping between design decisions about the users' mobility in the virtual words, and their effects on the mobility in constrained physical setups. To address this issue, we have developed and in this paper present a simulator for enabling this functionality. Given a set of VR users with their virtual movement trajectories, the outline of the physical deployment environment, and a redirected walking algorithm for avoiding physical collisions, the simulator is able to derive the physical movements of the users. Based on the derived physical movements, the simulator can capture a set of performance metrics characterizing the number of perceivable resets and the distances between such resets for each user. The simulator is also able to indicate the predictability of the physical movement trajectories, which can serve as an indication of the complexity of supporting a given virtual movement pattern by the underlying networks.

CCS CONCEPTS

• **Networks** → **Network simulations**; **Network performance modeling**; **Mobile networks**; **Location based services**.

KEYWORDS

Full-immersive multiuser virtual reality, multimedia wireless networks, mmWave wireless networks, redirected walking, movement trajectory, mobility simulator.

MMSys 21, September 28-October 1, 2021, Istanbul, Turkey

ACM ISBN 978-1-4503-8434-6/21/09…$15.00
https://doi.org/10.1145/3458305.3478451

ACM Reference Format:
Filip Lemic, Jakob Struye, and Jeroen Famaey. 2021. User Mobility Simulator for Full-Immersive Multiuser Virtual Reality with Redirected Walking. In *12th ACM Multimedia Systems Conference (MMSys '21) (MMSys 21), September 28-October 1, 2021, Istanbul, Turkey.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3458305.3478451

1 INTRODUCTION

Virtual Reality (VR) has the potential of revolutionizing the way we perceive the world and interact with others [1]. As such, VR applications find their utility in among others healthcare [2], education [3], and tourism [4]. In order to reach their full potential, VR setups and applications are being rapidly advanced, primarily in the direction of enhancing their immersiveness. In this direction, we are seeing efforts toward enhancing the quality of video content that is being streamed toward the VR users [5]. In addition, research efforts are focused on "cutting the wire" and enabling truly wireless delivery of the video content to the VR users [6]. Finally, one aim of the VR-focused research is to enable multiuser virtual reality setups, in which the users are able to collaborate in way that the action of one user in the virtual world affects the experience of the other, potentially collocated users [7].

Based on the discussion above, it can be imagined that, in the near future, VR systems will be multiuser systems featuring full immersiveness, both in terms of constraint-free mobility for the VR users in the virtual worlds and high quality of the delivered video. To avoid collisions between the collocated users inside constrained physical VR setups, as well as collisions between the users and the boundaries of the physical setups, we envision the usage of redirected walking algorithms [8]. The aim of redirected walking is to enable immersion of the VR users in the virtual worlds (i.e., allowing them to roam freely), while simultaneously and (ideally) imperceivably redirecting them in the physical space.

In the physical world, such setups will be supported by high frequency wireless communication networks, with the primary technological enablers lying in the millimeter Wave (mmWave) (i.e., 30-300 GHz) frequency band [9]. For supporting an always increasing quality of video delivery to the mobile VR users in real-time, the underlying wireless communication will have to be highly directional on both transmit and receive side [10]. The directional communication beams are simultaneously expected to 'track' the users' movements in order to continuously maintain LoS connectivity with each all of them and, therefore, maximize the quality of their video delivery.

From here, it is intuitive that the design decisions made for the virtual worlds the VR users are immersed in will have an effect on the performance of the supporting wireless networks. For example, by increasing the complexity of the VR user's mobility in the virtual world, the number of rerouting decisions and hard (i.e., perceivable) resets made by the redirected walking will increase as well [11]. This will in turn result in less predictable movements in the physical worlds, which will cause the degradation in beam-tracking performance. Similarly, the design decisions from the physical worlds, for example the physical size of the VR setup, will affect the user experience in the virtual worlds. In other words, as the physical sizes of the VR environment are reduced, the number of rerouting decisions and hard resets made by the redirected walking will increase, in turn degrading the experience of the VR users.

Based on these observations, we see a clear need for a simulation tool that is able to provide a mapping between the VR users' mobility in the unconstrained virtual worlds and their consequent mobility in constrained physical VR setups. The main aim of this paper is to present such a simulator. The idea behind the simulator is to provide the mapping between the VR users' mobility in the virtual world as a function of the utilized redirected walking algorithm, number of collocated VR users, and physical sizes of the VR setup. Given the predefined users' mobility in the virtual world and the boundaries of the physical VR environment, the simulator is able to output the number of hard resets each user will experience, as well as a metric characterizing the predictability of users' movements in the physical space, which in turn can be used to evaluate the "tracking" performance of the supporting wireless networks.

2 RELATED WORK

In this section, we provide a short overview of the related efforts along two main dimensions. First, we outline efforts proposing high frequency wireless networks (primarily mmWave) as enablers of multiuser full-immersive VR applications. Second, we overview the existing simulators with similar functionalities, as well as position our work against those efforts.

2.1 Wireless Network for Supporting Multiuser Full-immersive VR Applications

mmWave networking is often considered as an enabler of truly wireless VR, as lower frequencies cannot meet the VR requirements [9, 12]. Signal propagation in mmWave frequencies inherently features high path loss and attenuation, hence the transmitter and the HMD must both focus their energy towards each other in a process called beamforming. In the MoVR solution, HMD's built-in location and orientation tracking is used to steer transmit and receive beams directly at peers. Zhong et al. [13] present a programmable mmWave wireless solution using Commercial Off-The Shelf (COTS) hardware and investigate rendering-based optimizations. [14, 15] follow by further investigating such optimizations. For prerecorded VR content, frames can be sent over mmWave in a proactive fashion using predicted near-future viewing directions [16, 17]. Pose information-assisted networks leverage location and orientation measurements from on-device sensor in HMDs for beam and AP selection, focused on spatial sharing between clients [18]. Moreover, CoVRage forms flexibly shaped receive beams for uninterrupted connectivity during predicted rapid head movements [19]. In addition, OScan utilizes UV-based location coordinates [20] for fast 3D beam steering toward HMDs.

We believe the above efforts indicate that mmWave is a suitable candidate for supporting multiuser full-immersive VR applications. Moreover, the outlined efforts suggest there will be a need for beam-tracking in VR-supporting mmWave networks, indicating among other things the need for simulation of the VR users' physical mobility. Finally, the above approaches rely on the tracking of the LoS beam between the AP and HMD, as it is expected that only infrequently the LoS between the communicating devices will be broken. This is because of the fact that the APs are usually envisioned to be mounted on ceilings in physical VR setups, while the HMDs are expected to be worn on the heads of the VR users [19]. Nonetheless, the two main approaches for dealing with blockages in mmWave frequencies are to utilize Device to Device (D2D) relaying and Non-Line-of-Sight (NLoS) reflections [21]. NLoS beam-tracking and D2D relaying can still be optimized by utilizing the mobility patterns of the VR users, with some examples being [22, 23], suggesting that simulating the VR users' physical mobility will also be needed in such scenarios and further motivating our work.

2.2 Simulating User Mobility in Multiuser Full-immersive VR

The need for simulating the physical mobility of VR users has been recognized in the research community. Specifically, Hodgson *et al.* [24] present WeaVR, a self-contained and wearable immersive virtual environment simulation system. This portable VR rendering system was used to demonstrate the applicability of keeping the VR users in a constrained physical space, while being immersed in an unconstrained virtual world. The proposed system utilized the redirected walking for this purpose, with a limitation that the simulation/experimentation with redirected walking has to be done jointly with the rest of the hardware and software system. The most similar to our work is the Redirected Walking Toolkit presented in [25]. Similar to WeaVR, the Redirected Walking Toolkit is a proprietary tool that has to be used as a Unity3D package, resulting in relatively high complexity of its utilization. In our work, we reduce this complexity to a stand-alone simulator that can be run on personal computer with Python 3.7 being the only requirement. In addition, the Redirected Walking Toolkit is currently unable to capture the performance metrics for providing insights to the developers of the supporting wireless infrastructures. In contrast, in our simulator we currently support near-future physical trajectory prediction for this purpose. Moreover, the GitHub repository and project website of the Redirected Walking Toolkit have been inactive for several years, presumably making the projects obsolete.

3 EXPERIMENTATION CAPABILITIES

The designers of VR applications have a substantial degree of freedom in defining the mobility patterns of the VR users. However, the decisions made for the users' mobility in the virtual world affect the complexity of supporting such applications from the perspective of wireless communication. In addition, an increasing number of collocated VR users in a constrained physical space will cause the redirected walking to re-steer the users more often, which will in turn cause more hard resets and affect the quality of their experience. Similar observations can be made for the physical spaces, where their sizes and shapes will inevitably have an effect on the

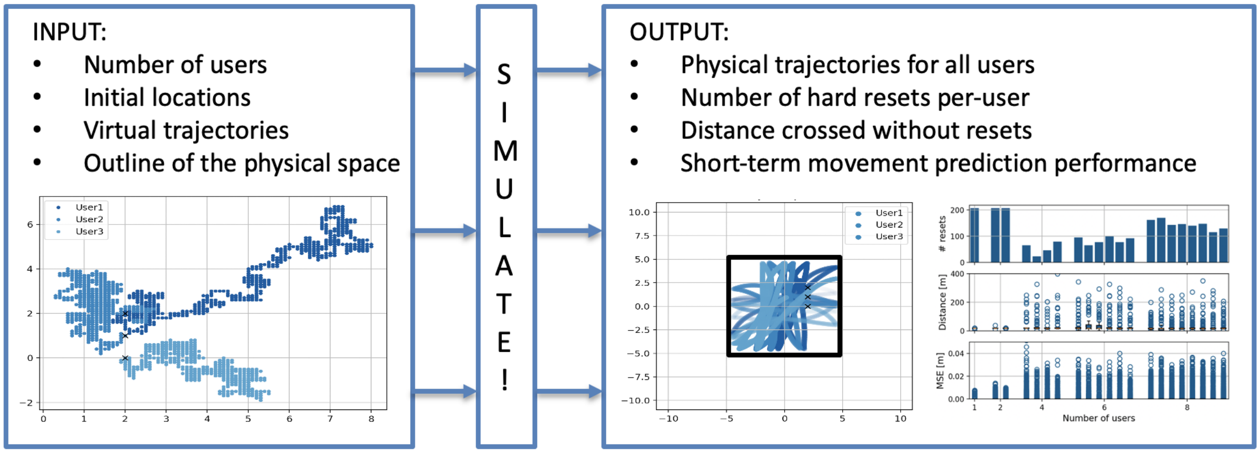

Figure 1: Overview of the experimentation capabilities

number of perceivable resets made for the VR users, again having a negative effect on their experience.

An overview of the experimentation capabilities is given in Figure 1. Given that the number of collocated VR users and their mobility patterns, as well as the physical sizes and shapes of VR setups will be different for distinct VR applications, there is a need for a straightforward tool for mapping between the mobility of VR users in the virtual worlds and the corresponding mobility in a particular physical space. Such a mapping is envisioned to enable rapid assessment of the benefits of selecting a given virtual trajectory, which is envisioned to be used by the VR application designers. The benefits are envisioned to be assessed on the macroscale in terms of the number of hard resets experienced by each user, as well as on the microscale through short term prediction of physical trajectories of the users. The observations made on the macroscale are envisioned to give insights on the quality of the users' experience, while the microscale observations indicate the complexity of supporting the envisioned application by the wireless infrastructures, i.e., by maximizing the accuracy of such prediction the network performance (i.e., beam-tracking) will be maximized.

4 SIMULATOR OVERVIEW

4.1 Design Requirements

Along the above discussion, we envision three main design requirements for the proposed simulator for simulating user mobility in multiuser virtual reality with redirected walking. First, it is clear that the movement trajectories in the virtual worlds will be rather complex, consisting of a variety of movements that are complex to replicate in a simulator in a long time-frame. Thus, we envision such trajectories to be separated into smaller and more manageable chunks. This would imply that in the testing, there will be a number of partial virtual trajectories to be assessed, indicating that a *rapid assessment* will be needed. Thus, the first design requirement is to support simulations in the "reasonable" time-frame, so that the designers can use the simulator for testing of a variety of smaller hypotheses. Second, we envision the simulator to be used for providing rapid insights to the designers of VR applications, as well as to the designers of the supporting wireless networking architectures. Given the disparate expertise of the targeted audience, we see it as a design requirement to provide *a tool that can be used ubiquitously* and in a straightforward way, without the need for specialized domain knowledge. Finally, we expect the redirected walking algorithms to be further advanced in the future. In addition, given the heterogeneous targeted audience, we expect the interest in differing aspects of the performance of the simulated systems. For these reasons, we aim at designing a modular simulator in which several aspects of the simulation, for example the utilized redirected walking algorithm or the derived performance metrics, to be *fully modular, easy replaceable, and extensible.* In summary, our aim is to provide a highly modular tool that can carry out rapid simulations and be used by people with different expertises.

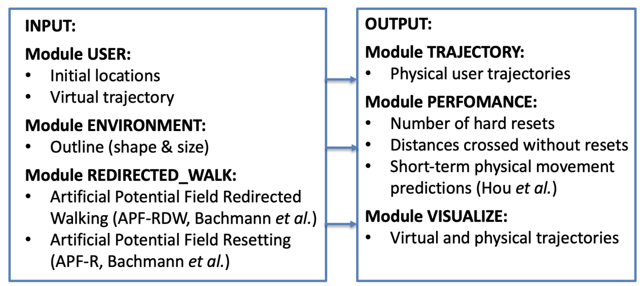

Figure 2: High-level design and implementation

4.2 Design and Implementation

A high-level overview of the simulator design and implementation is given in Figure 2. The experimenter is envisioned to provide as an input three main sets of parameters, as shown in the figure. First, the experimenter is expected to input the outline of the physical environment in which the multiuser full-immersive VR system is to be deployed. In the current implementation, the experimenter can define the boundaries of the physical environment as a (geometric) polygon. The VR users are expected to be roaming inside of the boundaries of the defined physical environment. Each user in the defined environment is specified with its virtual trajectory, which in turn is specified as a set of virtual coordinates the user is expected to navigate through as a simulation run progresses. More precisely, through the parameter *Number of points per trajectory* the experimenter is able to specify the frequency of provisioning $[1/s]$ of virtual coordinates to the VR user through redirected walking. Moreover, the experimenter is able to specify the duration of a simulation run, which, together with the previously discussed frequency of provisioning, can be used to define the total number of virtual and physical coordinates to be visited by each VR user during one simulation run.

A redirected walking algorithm is then used to map the users' movements in the virtual world to the corresponding movements in the physical deployment environment. In the current version of the simulator, we utilize the redirected walking algorithms from Bachmann *et al.* [8], while the ones to be added in the near future primarily include *Steer-to-Multiple-Targets* and *Steer-to-Multiple-Targets-and-Center* from [26]. Bachmann *et al.* [8] propose the Artificial Potential Field Redirected Walking (APF-RDW) algorithm for imperceivable redirected walking in multiuser full-immersive VR applications, and the Artificial Potential Field Reseting (APF-R) algorithm to re-orient the VR user towards the safest available area in case there is a need for hard resets.

APF-RDW is based on determining the steering direction of a VR user by considering its relation with other users, walls, and obstacles in the deployment environment. Specifically, for each wall, obstacle, or other user APF-RDW generates a force vector that is directed away from that obstacle and has a length inversely proportional to its distance from the user. APF-RDW then determines the steering direction (i.e., pointing toward open space) by summing the individual force vectors. Similarly, APF-R aims at reorienting the user towards the least crowded area during resets by summing the individual force vectors from other users and obstacles. More details on the operation of the algorithms can be found in [8].

The output of one simulation run is a set of physical movement trajectories from all defined VR users in the deployment environment. Based on the derived physical trajectories, in the current implementation we capture a set of macroscale performance metrics, characterized by the number of hard resets and average distances between resets for each VR user. In addition, we capture a microscale performance metric characterizing the predictability of the physical movement trajectory for each VR user. For characterizing the predictability of physical movements, the simulator currently supports the approach presented in [17]. Specifically, the simulator aims at predicting the near future locations of the VR users by utilizing an Encoder-Decoder Long Short-Term Memory (LSTM) model which can learn general body motion, given the previous sequence of motions. The performance metric characterizing the predictability of the physical movement is then calculated as the Mean Squared Error (MSE) between the true and predicted sets of future locations. The prediction horizon is a tunable parameter, as well as the number of historical locations on the physical trajectory used for making predictions in a given horizon. This was done for enhancing the flexibility of experimentation, given that the beam-widths of the supporting wireless infrastructures are expected to vary due to the difference in the utilized hardware. Thus, the horizon for predicting near-future physical locations of the VR users will inevitably be application-dependent.

Table 1: Simulation parameters

Parameter	Value
Number of points per trajectory	10 [1/sec]
Duration of simulation	3600 [sec]
Redirected walking	
Exponential falloff due to other users	1.4
Arc radius or redirected walking	7.5 [m]
Maximum rotational rate	15 [°]
Velocity threshold	0.1 [m/s]

The simulator was implemented[1] in Python 3.7. Python 3.7 has been selected due to its ubiquitous utilization across different expertises. In other words, given that the simulator is envisioned to be used by both VR application and supporting wireless network designers, we believe Python-based implementation will enable a rapid and straightforward experimentation regardless of experimenter's technical background, in contrast to more complex domain-related tools such as ns-3 in wireless networking-based simulations or tools like Unreal [27] or Unity [28] in the VR context.

We argue that the presented system implicitly addresses the design requirement of modularity. In particular, our simulator allows for straightforward modifications of any input parameters, including novel redirected walking algorithms. In addition, due to its modular design, the simulator provides a simple way of modifying or adding new performance metrics, as well as their visualization. By utilizing a well-established programming language such a Python,the presented simulator can find its utility for experimenters with varying expertises, addressing the corresponding design requirement. In the following section, we will demonstrate that the presented design addresses the final design requirement targeting rapid simulations and derivations of insights.

5 PERFORMANCE DEMONSTRATION

In this section, we demonstrate the capabilities of the simulator, as well as establish the duration of each simulation run to indicate that the presented tool can be utilized for deriving rapid performance insights. The simulation parameters are given in Table 1, with more details about the redirected walking-related ones provided in [8].

The outlines of the physical environments are defined as squares with sizes of 5, 7.5, 10, and 12.5 m, as depicted in Figures 3, 4, 5, and 6, respectively. We carry out the simulations considering different numbers of users, specifically 1, 2, 4, and 8 of them coexisting in the physical environments. In the virtual world, the users are assumed to be moving freely, which has been modeled by defining their virtual movement trajectories as random walks, which is the model often utilized in the context of pedestrian mobility for wireless networking experimentation [29, 30].

As visible in the figures, the number of hard resets yielded by the redirected walking is highly dependent on the physical sizes of the deployment environment. For example, in a two-user system the number of hard resets per user equals roughly 700 for the rather small physical environment with the size of 5 m during one hour of the VR users' continuous walking in the simulated time, as visible in Figure 3. The number of such resets is reduced to respectively

[1]Available at: https://bitbucket.org/filip_lemic/pm4vr/src/master/

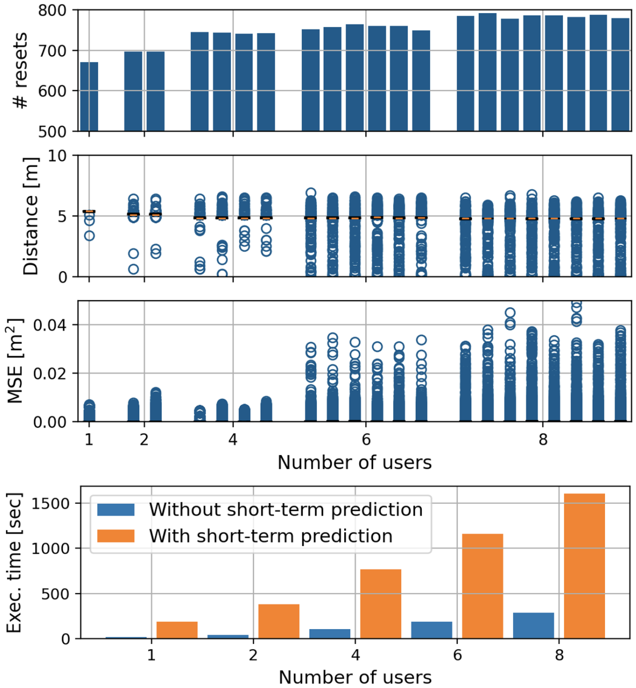

Figure 3: Performance and simulation times (5x5m^2)

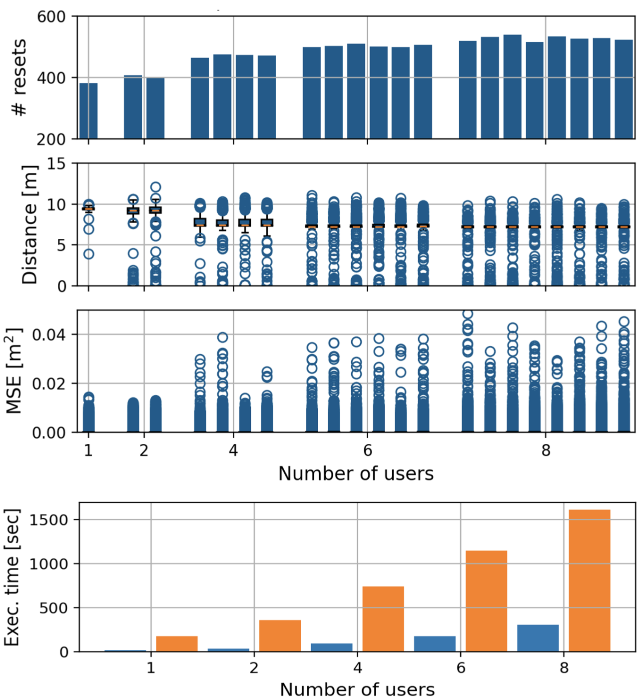

Figure 4: Performance and simulation times (7.5x7.5m^2)

400, 300, and 250 per hour as the environment sizes are increased to 7.5, 10, and 12.5 m. Moreover, the number of hard resets increases with the increase in the number of coexisting users. For example, for the environment with size of 5 m the number of resets per user is increased from roughly 650 to almost 800 as the number of users increases from 1 to 8.

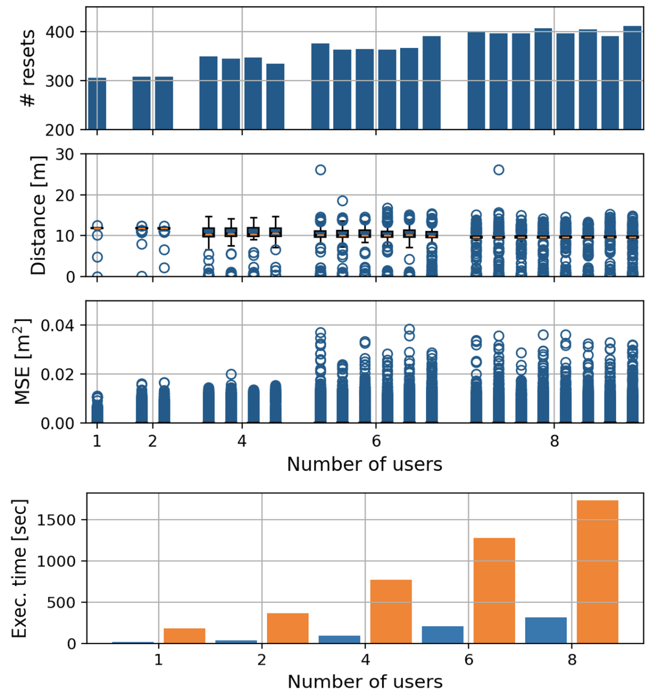

Figure 5: Performance and simulation times (10x10m^2)

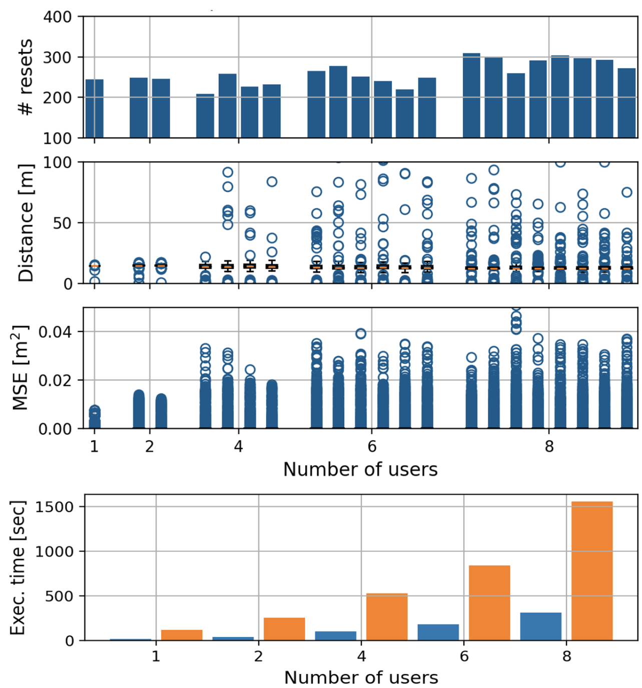

Figure 6: Performance and simulation times (12.5x12.5m^2)

The average distance that a user can roam in the physical space without hard resets is also affected by the number of users, as well as by the physical sizes of the environment. In particular, for smaller environments the distances that can be traversed without hard resets are generally smaller than the ones observed for the larger ones, as shown in the figure. As the number of users increases, the variability in the traversed distances without resets increases as well. This is expected, as an increase in the number of users increases the number of force vectors used for redirected walking, causing more complex mobility patterns with higher variabilities in traversed distances without hard resets.

It also worth emphasizing that the number of hard resets experienced by the VR users is rather high from the practical deployment perspective, as shown in Figures 3, 4, 5, and 6. Consequently, the distances that the VR users can traverse without perceivable redirections is low for the selected simulation parameters. This is due to the fact that the VR users' virtual movement trajectories are generated in a fully random fashion, resulting in poor performance of the redirected walking algorithms. This is because these algorithms are grounded in extrapolating near future virtual paths, which cannot be accurately done for random movements in the virtual world. In addition, random walk can be considered as the "worst case" in the sense that the user is constantly in motion, while, depending on the application, a real person might stand still for a significant portion of the playtime. More realistic virtual movement trajectories, as well as re-dimensioning of the physical environments, can be considered for reducing the number and frequency of hard resets.

In terms of near-future physical trajectory prediction, it is interesting to observe in Figures 3, 4, 5, and 6 that the environment sizes do not play a significant role in the prediction performance. This is because the prediction is based solely on the historical points on the physical trajectories of the VR users, and does not depend on environmental characteristics. Nonetheless, the accuracy of the short-term physical movement prediction highly depends on the number of VR users. For example, in the smallest considered environment the MSE of the prediction is increased from less than 0.01 m^2 to more than 0.04 m^2 as the number of users increases from 1 to 8, as visible in Figure 3. Note that in the derivation of the results, we have utilized 9 historical movement points for predicting one future step, corresponding to the prediction horizon of 100 ms.

In terms of the duration of simulation, we distinguish two scenarios based on the utilization of the near-future trajectory prediction or the lack thereof, as shown in the figures. This is because these durations are substantially longer when the near-future prediction is enabled, given that this prediction utilizes machine learning that consumes a substantial amount of computational resources. Given that the experimenter might be interested solely in the macroscale metrics, we see it beneficial to also establish the durations of simulations for this scenario. Note that the durations have been captured on a MacBook Pro laptop (2,3 GHz Intel Core i5).

As visible in Figures 3, 4, 5, and 6, the environment sizes do not play an important role in the durations of simulations, as the durations do not increase with the increase in environment sizes. This is because the simulation utilizes the calculation of force vectors in the mapping between virtual and physical trajectories of the VR users, and the increase in the environment size only changes the amplitudes of these vectors, not their number and consequently nor the number of computations. Adversely, an increase in the number of simulated VR users substantially increases the duration of simulations, exactly because the number of necessary computations increases with the introduction of each new VR user. Nonetheless, as visible in the figures, even the simulations with large numbers of users can be executed on a personal computer in a matter of minutes, e.g., 25 min for simulating 8 users during the virtual time of 1 hour. We see these durations as suitable for rapid hypotheses testing, which is the main purpose of the provided simulator.

6 CONCLUSION

We have presented a tool for simulating user physical mobility in multiuser full-immersive Virtual Reality (VR) applications with redirected walking. The simulator is written in Python 3.7, features a modular design, and can be used to rapidly derive complex insights even on a personal computer. The simulator is primarily envisioned to be used by the designers of VR applications and the supporting networking infrastructures. Its envisaged purpose is to enable rapid assessments of various design hypotheses in the virtual world and their effects on the physical mobility of the users. Potential additional usage possibilities include comparative benchmarking of redirected walking algorithms and utilizing the simulator as a physical mobility module in network simulators such as ns-3. Future efforts will include further enhancements of the simulator, primarily in the direction of introducing additional mobility patterns and implementing novel redirected walking algorithms, as well as new approaches for near-future physical trajectory prediction. Moreover, we will aim at evaluating the level of realism of the simulator through experimentation with realistic VR traces. Finally, we envision an integration of the simulator with ns-3 in the form of a physical mobility model for experimentation with wireless networks for supporting multiuser full-immersive VR applications.

ACKNOWLEDGMENTS

The author Filip Lemic was supported by the EU Marie Curie Individual Fellowship project Scalable Localization-enabled In-body Terahertz Nanonetwork (SCaLeITN, nr. 893760). This work also received support from the Research Foundation - Flanders (FWO, nr. 1SB0719N) and University of Antwerp's Research Fund.

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