Introducing VAMPIRE – Using Kinaesthetic Feedback in Virtual Reality for Automated Driving Experiments

PHILIPP HOCK*, Institute of Psychology and Education, Human Factors, Ulm University, Germany
MARK COLLEY*, Institute of Media Informatics, Ulm University, Germany
ALI ASKARI, Institute of Media Informatics, Ulm University, Germany
TOBIAS WAGNER, Institute of Media Informatics, Ulm University, Germany
MARTIN BAUMANN, Institute of Psychology and Education, Human Factors, Ulm University, Germany
ENRICO RUKZIO, Institute of Media Informatics, Ulm University, Germany

Investigating trust, acceptance, and attitudes towards automated driving is often investigated in simulator experiments. Therefore, behavioral validity is a crucial aspect of automated driving studies. However, static simulators have reduced behavioral validity because of their inherent safe environment. We propose VAMPIRE (VR automated movement platform for immersive realistic experiences), a movement platform designed to increase the sensation of realism in automated driving simulator studies using an automated wheelchair. In this work, we provide a detailed description to build the prototype (including software components and assembly instructions), a proposal for safety precautions, an analysis of possible movement patterns for overtaking scenarios, and practical implications for designers and practitioners. We provide all project-related files as auxiliary materials.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**.

Additional Key Words and Phrases: Automated vehicles; driving simulator; user studies; Immersive technology; on-road simulation.

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1 INTRODUCTION

Driving simulator studies are a useful tool to study driver-vehicle interaction. Due to the inherently safe environment, situations can be evaluated safely, reproducibly, and ethically.

Furthermore, scenes can be generated in the simulator that would not be technically feasible. Currently, automated driving is such an application. It can be realized in the simulator, even if current vehicles do not yet have the appropriate level of technical sophistication, such as a SAE [46] Level 5 automation. Therefore, numerous works have employed either monitor-[18] or Virtual Reality (VR)-based [17, 20] study methodologies to overcome these limitations

gWhile driving simulators in manual driving are often used to measure the driver performance in relation to the driving task (e.g., the average lane deviation [54]), other factors such as trust [20], and acceptance [18] become relevant in

*Both authors contributed equally to the paper

Fig. 1. VAMPIRE is based on an electric wheelchair controllable via software creating kinaesthetic forces in VR through real motion.

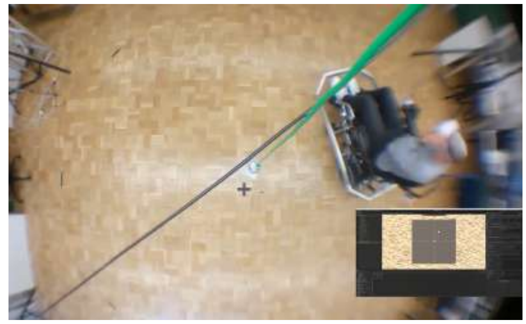


Fig. 2. Top view on the moving *VAMPIRE*.

automated driving. Here, due to the automation, the driver becomes a passenger that can engage in non-driving-related activities such as reading [25]. Thus, besides investigations of driver's performance, simulator studies become more and more of a tool to investigate the passenger's behavior.

However, driving simulators are not the ideal tool as they are particularly suitable for measuring performance and less so for measuring behavior because of their reduced ecological validity. The inherently safe environment of simulators can influence measurements of trust in automation [30]. Although the immersion and presence of simulators can be high, the inherently safe environment can have a negative influence on behavioral validity [58].

Thus, behavioral validity in simulator experiments is an important aspect, and maximizing behavioral validity is an important aspect. Moreover, Salanitri and colleagues could show that the perception of presence influences the propensity to trust [66]. This implies that more immersed participants experience a more realistic feeling of trust. This suggests that increased presence could lead to increased behavioral validity. It can be argued that driving simulator studies investigate driver behavior in automated driving, external validity depends on the presence and immersion of the participant. Kinaesthetic forces through real motion can be used to increase presence in VR [44] and increases ecological validity [19].

Therefore, we introduce *VAMPIRE* (VR automated movement platform for immersive realistic experiences) – a driving simulator specially designed for automated driving studies (see Figure 1). *VAMPIRE* applies real motion by employing a controllable wheelchair while visualizing scenarios using VR. VAMPIRE can be seen as a low-cost supplement to moving-based simulators. Additionally, we propose a novel simulator continuum based on visual and motion fidelity.

Contribution Statement: This work's contributions are: (1) the simulator continuum to place simulators along with their visual and motion fidelity, (2) an implementation and proof of concept of VAMPIRE – a driving simulator specially designed for automated driving studies, (3) software components and assembly instructions to build the system which will be open-sourced, (4) a proposal for safety precautions for user studies, (5) an analysis of possible movement patterns for overtaking scenarios, and (6) practical implications for designers and practitioners.

2 RELATED WORK

This work builds on previous work on simulator studies with a focus on presence, immersion, simulator sickness, proprioception, and driving simulators in general.

2.1 Presence, Immersion, and Trust

For virtual environments (VE), presence was described as a "sense of being physically present with visual, auditory, or force displays generated by a computer" [69, p. 120]. Weibel and Wissmath [84] define presence as a feeling of being located inside a virtual environment. While there are different categorization approaches, most include the subjective feeling of the person within the VE. Heeter differentiates between personal presence as the feeling of being part of the VE, social presence of other beings in the VE, and environmental presence as "the extent to which the environment itself acknowledges and reacts to the person in the VE" [38, p. 262]. On the other hand, Sheridan states the three determinants of presence are (1) the transcription of real-world information to the virtual domain, (2) controlling the relation of sensors to the environment, and (3) the modification of the physical environment [69]. These aspects seem to characterize a rather objective, sensory experience that would represent the concept of immersion. Due to the link between presence and immersion, it is important to distinguish between these terms.

According to prevailing definitions, immersion, which can be increased by using a VR head-mounted display (HMD) [10], is an objective description of aspects of the VE, while presence is viewed as a subjective sensation of being in and interacting with a VE [6, 68, 72]. Presence can be seen as a psychological response to immersion [39]. Presence is linked to its influence on trust in a vehicle. According to Thielmann and Hilbig [77], trust is based on uncertainty, risk, expectations about another's trustworthiness, and personal vulnerability. In studies with a virtual driving simulator, results indicated that the perception of presence influences the propensity to trust while driving [66]. Furthermore, high presence can lead to higher arousal, which can increase the likelihood of processing information more effectively [64]. Thus, it is assumed that feeling present and highly immersed would result in a more realistic representation of trust in participants, which would increase the external validity of this measure. To achieve this, persuasive strategies based on trust are necessary for successful driving simulator experiments.

2.2 Simulator Sickness and Proprioception

Simulator sickness can cause dizziness, drowsiness, headache, nausea, fatigue, and general malaise [47]. Influencing factors are speed and acceleration [73]. It is a form of motion sickness and is a phenomenon where the absence of motion and presence of visual movement (this is called *vection*) causes the sickness [53], and it is one of the main reasons for simulator sickness [42].

Multiple types of vection exist [55]: *Motion sickness/inverse vection* is the effect when physical movements are perceived but no visible motion. *Contradictory vection* is the effect when vestibular and visual motions are present but they contradict each other. The *magnitude of vection* describes the effect of physical and visual self-motion but they both have a different magnitude.

Moreover, proprioception is another factor adding to the perception of presence in the VE. For example, increased body movement as a method to interact with the virtual surroundings increases the sense of presence [70]. Especially real-life walking compared to walking in place or pointing improved the feeling of presence [71, 80]. Additionally, Hendrix and Barfield [40] found that head-tracking and stereoscopic cues can increase the sense of presence. Creating a convincing VR experience should consequently integrate the real motion of the user. Gemonet et al. [31] showed potentially lower behavioral validity in simulators in risky driving situations when the simulator is lacking vestibular feedback. Yet, it is not fully understood which simulator requirements are needed for different measurements in autonomous driving studies to obtain valid results.

There exist several attempts how to integrate real movements into VE. The widespread used method in driving or flight simulators is a motion-based platform in sync with the VE which integrates vestibular and haptic information into a simulation. These platforms are based on the Gough/Stewart platform [75] and enable lateral, longitudinal, and vertical movements as well as pitch, roll, and yaw rotations, resulting in six degrees of freedom (DOF). For example, the most realistic feeling of moving forward is achieved when a visual acceleration is combined with pitching the platform [5]. However, motion platforms can only operate within a limited space. Thus, washout algorithms smoothly return the simulator back to its original position, unnoticed by the user [37, 59, 83]. Another possible solution would be to redirect motion in VR, resulting in movements that do not correspond to the motion paths that are executed in reality. A person walking in a circle, in reality, could be made believed walking a straight line in VR. Through this technique redirected motion extends the maneuvering space for virtual environments while being in a physically restricted room. Regarding perceptual detection thresholds, redirected driving implemented by participants manually operating an electrical wheelchair [12] is comparable to redirected walking [61, 62] or touch [51, 52]. Especially in slower conditions (0.33 m/s), people are perceiving discrepancies in the driving direction less accurately than in faster ones (0.54 m/s) [29]. For the remote-controlled wheelchair, i.e. redirected steering, the detection threshold was a circular radius of < 5.76 m for driving slowly and 16.52 m when driving fast.

3 SIMULATOR CONTINUUM

3.1 Diving Simulators

User studies investigating manual or automated driving were conducted in different types of driving simulators, ranging from low-cost to high-cost [11, 56], and differ in visual and motion fidelity [87].
Visual fidelity is referred to the level of reality in representing the environment. This includes the representation of the outside world and the vehicle interior. Current driving simulators use one or more 2D screens [15, 56], or a VR HMD [19, 44, 45] to display the driving environment. A combination of 2D screens and a real vehicle compartment, either by using a vehicle model [79] or a real vehicle [1, 4, 15], is often used by high-cost simulators to increase the participants' feeling of sitting in a real vehicle.
Motion fidelity refers to the level of realistic motion cues induced by the driving simulator. Regarding driving simulators, motion fidelity can be subdivided into fixed-base simulators with [9, 24] and without motion cues [28, 45], and moving-base simulators with different degrees of freedom (DoF) of the motion platforms [15, 19, 56].

3.1.1 *Low-cost Driving Simulators.*

Simulators such as the *SwiVR-Car-Seat* proposed by Colley et al. [19] represent longitudinal and lateral vehicle dynamics with a 1-DoF rotation. This is implemented based on the findings of Rietzler et al. [63] that angular impulses of the chair are sufficient to represent vehicle acceleration or deceleration. Rietzler et al. showed that the substitution of the movement axis is possible if the visual perception is prominent over the vestibular perception. For *SwiVR-Car-Seat*, vehicle dynamics in curves were matched also to the chair's rotation. Therefore, simultaneous motion feedback of both longitudinal and lateral vehicle dynamics with this system is not possible. To increase the DoFs, more movement axes are required similar to motion-based simulators on the consumer market that include 3 and more DoFs. There are mostly used in the context of gaming for driving and flight simulations. For example, the *YawVR* [48] motion simulator induces motion feedback via the 3-DoF rotations yaw, pitch, and roll. Users sit in a swiveling shell that induces motion feedback by wearing a VR HMD that visualizes the environment. As the motions are induced over the shell placed in a base, the motion range is limited.

With increasing progress in computer graphics, high visual fidelity can be achieved by using VR HMD and high-performance graphic cards that visualize the driving environment. However, it has been shown that participants conducting driving simulations in simulators without motion cuing have an increased risk of experiencing motion sickness due to the sensory conflict of visual and vestibular systems [42]. Hock et al. [44] and McGill et al. [55] showed that mapping vehicle movements from a real car to visual information in a VR environment, so that visual sensory information is consistent with vestibular information, decreases simulator sickness. Apart from that use case, it enables the building of low-cost prototypes of fully AVs to study interactions in such vehicles [49, 86]. This method is based on the *Wizard-of-Oz* technique, where an automated system is simulated by a human experimenter, the wizard [35]. In the context of human-vehicle-interaction, the approach is implemented by using a real car on real roads driven by an experimenter, unseen by participants either because they wear a VR HMD [33, 86] or the experimenter is hidden behind visual protection [3, 82]. Therefore, high motion and visual fidelity are achieved with a low-cost prototype when using the *Wizard-of-Oz* technique in a real car. However, this technique needs a lot of space due to real-world driving and, therefore, it is hardly suitable for conduction in a controlled environment.

3.1.2 High-cost Driving Simulators. High-cost simulators address the limited movement range with motion platforms based on a 6-DoF parallel manipulator called hexapod or Stewart platform [76], that is implemented using linear actuators providing translational and rotational movement along the x, y, and z-axis [8]. High-fidelity simulators such as the *NADS* [15] include up to 13-DoF with a large motion range by using a hexapod motion platform mounted on a turntable that is attached to a platform that moves on a 2-dimensional rail system. This allows accurate real-world motion feedback in driving scenarios [11]. These examples of high-cost driving simulators show that high visual and motion fidelity could be achieved. However, the physical space and costs of research institutes are limited and this concludes the need for low-cost driving simulators.

In previous research, electric wheelchairs were used with VR HMDs to offer a safe environment to train wheelchair driving [81], testing new control interfaces [41], or investigating passengers' behavior during autonomous navigation scenarios [88]. Similar to the driving simulators of section 3, wheelchair simulators are available in different motion fidelities. Hernandez-Ossa et al. [41] implemented a fixed-base wheelchair simulator, whereas Vailland et al. [81] prevent simulator sickness by providing an implementation of a 3-DoF moving-base wheelchair simulator. To achieve high motion fidelity, Yoshitake et al. [88] conducted their autonomous navigation scenarios outdoors to have enough space to map virtual movements to real wheelchair movements. None of such wheelchair simulators were used to simulate the driving of a fully AV although the induced motion forces are similar to a real driving vehicle.

3.2 Introducing the Simulator Continuum

In order to provide an overview of low- and high-cost driving simulators described above, we placed them on a *Simulator Continuum* (see Figure 3) based to the classification of Yeo et al. [87]. We provide a more granular approach to distinguishing simulators. For instance, we distinguish between *fixed-base* and *moving-base* simulators. Within the *fixed-base* simulators, there is the possibility to add motion cues (e.g., wind [20] or shaking via loudspeaker). Therefore, we separate the *fixed-base* simulators (called *No Motion* by Yeo et al. [87]) into *no motion* and *motion cues.* The no motion × 2D screen is highlighted red as an indication that this, while used frequently, is considered to be the least immersive and should be avoided. The motion cues are also highlighted in orange as the cues increase immersion but no real kinaesthetic feedback or their effects can be simulated. While Yeo et al. [87] distinguish *Motion Platform* and *Real Vehicle*,

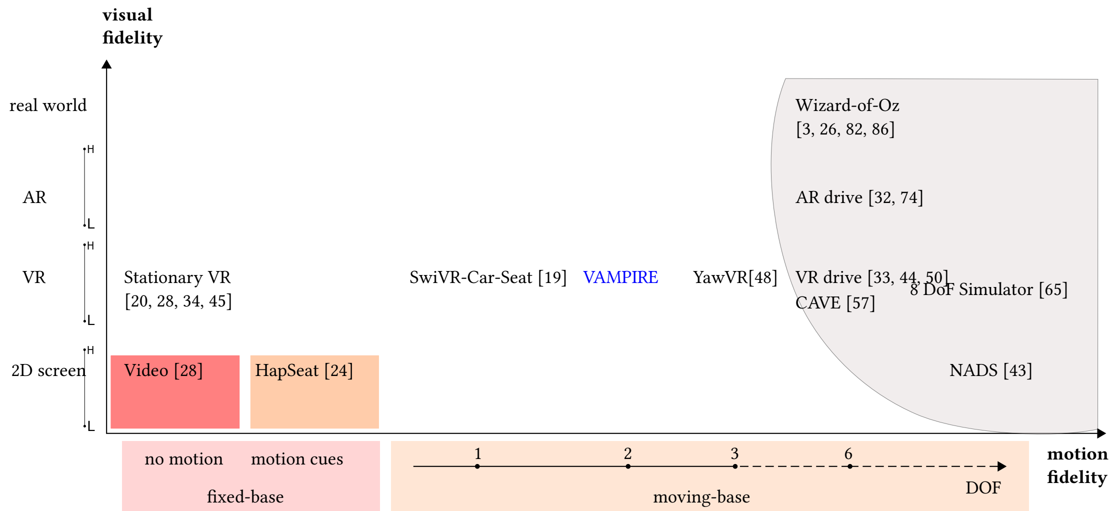


Fig. 3. Driving simulators placed on a *Simulator Continuum* spanned between visual and motion fidelity.

we argue that the more important distinguishing factor is the Degree of Freedom (DoF) the simulator provides. This is because a motion simulator can also include a real vehicle on a moving platform. The *Simulator Continuum* shows that some work has already provided simulators with DoFs or that real vehicles are used, however, we highlighted these in grey to indicate that these are costly and therefore, less accessible. Regarding the visual fidelity, Yeo et al. [87] claimed to be able to enable real-world fidelity by employing 360° video footage. However, we argue that this should be seen in the category of VR as an intermediary device (the HMD) is necessary. To account for the different visual fidelities available in each of the categories, therefore, we further divide the categories of visual fidelity on a continuum from Low (L) to High (H). While our classification inside the *Simulator Continuum* is not exhaustive, it becomes clear that some combinations are not used or are even not useful at all. For example, a *fixed-base* real-world simulator is feasible but not desirable as the visual effects of driving could not be induced. Future work should define which further combinations are **possible**, **useful**, and **desirable**.

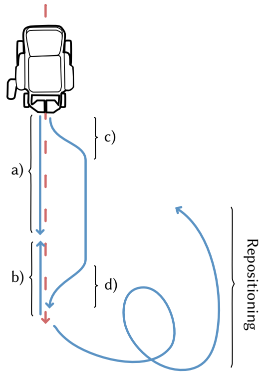
Our approach *VAMPIRE* is located in the middle of the continuum on both axes as we want to leverage the advantages of a low-cost moving-base simulator with sufficient visual fidelity.

4 CONCEPT AND IMPLEMENTATION

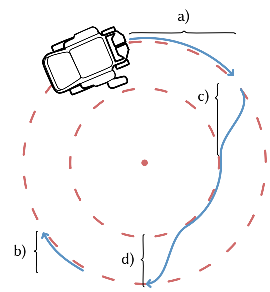
We present *VAMPIRE* in-depth and describe the most important concept aspects and the hard- and software configuration.

4.1 Towards Valid Motion Simulation

VAMPIRE increased behavioral validity in simulator experiments by increasing the immersion and presence using the real motion of the vehicle combined with VR (see Figure 1). For this, an electric wheelchair was modified to enable software-controlled wheels. The movements of the simulated drive are mapped the real movements of the wheelchair. For motion mapping, several approaches are possible (which can also be combined):



(a) The linear mapping. Acceleration and deceleration forces are executed by moving forward and backward.



(b) Circular mapping. Virtual rotations are mapped by increasing and decreasing the radius.

Fig. 4. Different motion paths implemented in VAMPIRE.

- The simulated movements are matched exactly to the real movements (e.g., [44]). Such a mapping requires a real vehicle which is undesirable due to cost and reproducibility concerns.
- The simulated movements could also be multiplied by a factor, such that speed, velocity, and rotations are similar, but the real movements are toned down (e.g., speed and acceleration) or amplified (e.g., rotation). Bruder et al. [12] used amplification of rotations to enable high mobility while constraining space requirements.
- Another approach is to match the forces perceived by the participant without matching actual movements (e.g., [19, 36]). Therefore, when the simulated vehicle drives at a constant speed (without accelerating or turning), no real movement is necessary. A disadvantage could be that if there are no real movements, users might notice the lack of vibrations, thus, breaking immersion and presence. To prevent users from noticing that the system is at a standstill, a uniform constant movement (for example, by a circular motion) could solve this problem.

We tested two approaches for the VAMPIRE platform: A linear motion and a circular approach. For various driving-related simulations to be possible, four movement patterns are crucial: a) *acceleration*, b) *deceleration*, c) *reeving*, and d) *shearing*. For the linear approach, the wheelchair executes acceleration and deceleration while striving for an idle position and a standstill when no forces are applied. For rotational forces, forward and backward movements could also be combined with slight turns. After acceleration, the wheelchair could slowly roll out such that users would not notice a standstill. In the simulation, the vehicle would drive at a constant speed. Deceleration could be implemented by driving backward (see Figure 4a).

For the circular approach, the wheelchair always drives a circular path, even if the virtual car drives in straight lines. Even though the real movement diverges from virtual ones, the participant does not necessarily notice this [12]. Acceleration and deceleration are mapped by an equal action of the wheelchair, but the real speed and acceleration are weaker than the simulated movements. Curves would result in increasing and decreasing the radius of the circular path. This approach is shown in Figure 4b.

4.2 Hardware

For *VAMPIRE*, we used the Eltego wheelchair by Bischoff & Bischoff [7] which uses the *PG Drive VSI* controller by Curtiss-Wright [85]. It can reach a top speed of 6 km/h and can carry up to 120 kg.

VAMPIRE interposes between joystick and controller and feeds joystick signals using custom hardware and software, thus, the implementation can be translated to any wheelchair using the *PG Drive VSI* controller.

The modified system uses an Arduino Uno Wifi and a custom-made circuit shield to emulate these voltages. As shown in Figure 7 a), the joystick is forwarded to the circuit. The ribbon cable contains all outgoing connections of the joystick and the return connections to the motor control board. By toggling the switch shown in Figure 7 c), the source is switched between either the analog joystick or the emulated joystick. During the emulated mode, the AD-converters on the shield emulate the required voltages which were prompted to the Arduino over the network.

As mentioned, the required voltages for the neutral position differ depending on different factors such as load, road surfaces, battery load, and probably other currently unknown factors. Therefore, apart from the boundary values, no clear mapping of emulated joystick voltage value and steering angle can be implemented. To overcome this, we iteratively adapted to the conditions in the given environment.

To also enable joystick control, the board was additionally equipped with a switch (see Figure 7 c) to switch between emulated joystick and real joystick commands.

When changing between forward and backward directions, the pre-installed front wheels tend to flip which resulted in a noticeable wiggle. It can also interfere with the planned trajectory which brings the chair slightly off course. Thus, we changed the front wheels to omni-directional wheels [60] (see Figure 5). A downside of these wheels is that the dampening was decreased due to the lack of a proper suspension.

Fig. 5. Omni-directional wheels were used to avoid noticeable wiggle of the pre-installed wheels when changing directions.

4.3 Software

The Arduino board receives signals over WiFi and sends them directly to the joystick as voltage outputs. To ensure that packet loss will not result in uncontrolled movements of the chair, the protocol to send input commands was idempotent and stateless. This means receiving packages are control signals over a very short time period. Not receiving any data would result in a stillstand. Any higher functions, such as a circular movement, were outsourced to an application sending control inputs. For example, the circular movement was implemented in Unity using a PID controller. A Meta Quest controller was attached to the wheelchair base to identify the position in the room (see Figure 7 top right).

The package itself, which is currently available at [1], can be imported using the *Unity Package Manager*. The package contains several scripts and prefabs which enable developers to communicate with the wheelchair. Note that this communication is tailored to the specific firmware deployed to the Arduino [2]. Every change to the Arduino firmware needs to correspond to changes on this package.

[1] https://gitlab-mi.informatik.uni-ulm.de/projektseemerollin/vrealchair_unitypackage, accessed February 07, 2022
[2] https://gitlab-mi.informatik.uni-ulm.de/projektseemerollin/WheelchairConnection, accessed February 07, 2022

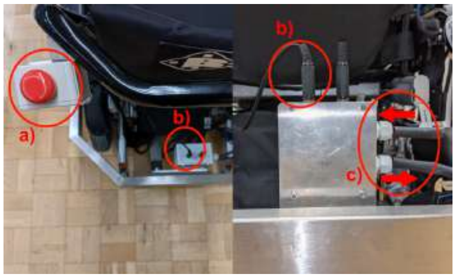


Fig. 6. Emergency shutoff components. Up to two different switches can be connected to Relay-Box (b). The relay interrupts the current flow (c) from the battery (incoming) to the motor (outgoing). An emergency button (a) is already connected.

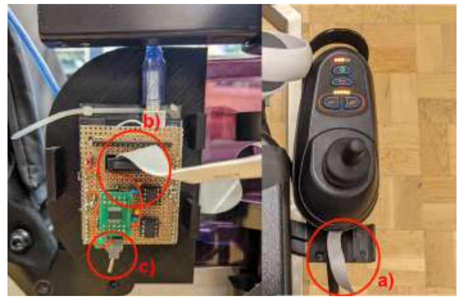


Fig. 7. Connections between the Arduino Uno Wifi and the Joystick. A ribbon cable connects the Joystick (a) and the custom-made Arduino shield (b), routing the joystick input data into the Arduino. The switch (c) toggles the motor control signal between the joystick and the remotely generated input data.

We introduce the core features of this package. For deeper insights, please refer to the technical documentation in the supplementary material.

WheelchairRemoteConnection Prefab: The package contains a prefab named *WheelchairRemoteConnection*. This prefab is used to establish the connection and functions as an API for other classes, which can utilize it to send commands and, therefore, control the wheelchair. The *Wheelchair Remote Connector* script should be used to enter the necessary connection information such as IP address and port number. Probably the most important method of this script for developers is the `SendCommand(Byte[] command)` method. The method requires an Arduino Firmware compatible command as a Byte Array. This method is used to transmit these commands to the wheelchair. The script takes care of the remaining actions needed such as timing the transmission.

ControlCommands: To overcome the need for the developer to create the Byte Arrays needed for specific commands, the class *ControlCommands* offers methods that return the Byte Arrays for desired commands. These include commands such as `Move(Vector2 direction, float speed)`, `Forward(float speed)`, `Left(float speed)` and others.

Attachment Scripts: To control the wheelchair in a specific way, attachment scripts can be applied to the *WheelchairRemoteConnection* object. Some useful scripts are included in the package. One of these scripts, for example, is called *ManualDriving*. It sends commands to the wheelchair depending on the defined movement input from the *Unity Input Manager*. As a result, one can move the wheelchair remotely by utilizing a gamepad or the arrow keys by using this script. Other scripts, such as *AnalogDriving*, serve the purpose of debugging and experimenting.
A specifically useful script is the *PidCircleDrivingBehaviour*. It utilizes the *PIDController* script to achieve a stable circle driving behaviour of the wheelchair. From a technical viewpoint, it should be mentioned that the usage of this script requires rebuilding the room scales and including the desired middle point, and updating the current position of the wheelchair. The parameters of the PID controller need to be tuned for specific usage, e.g., circle radius, and speed.

Incorporation into Other Driving-Related Packages: VAMPIRE allows the creation of additional movement patterns. This allows easy integration to high-level traffic simulations. We combined the *Simple Traffic System* (STS) [78] which is a waypoint-based traffic system, with *VAMPIRE*. Via the waypoints, triggers can be set for executing movement patterns. Therefore, the visualization was done via STS and *VAMPIRE* can focus on the actual movement.

4.4 Safety Concept

The safety of users/participants has the highest priority, especially as occupants in a VR scenario can not see upcoming obstacles and, therefore, prepare for a possible collision, which could lead to more serious injuries.

Therefore, besides the existing seat belt, we equipped the wheelchair with the following additional security features.
Steel frame: We surrounded the wheelchair with a custom-made, 4cm thick steel frame. This way, the limbs of the occupant are protected in case of any collision. Furthermore, the wheelchair is also protected in case of collisions during the development phase, as forces are applied to the frame instead of the wheels, the joystick panel, or other sensitive outreaching parts.
Emergency shut-off system: The power supply can be interrupted by a relay. The signal lines of the relay can be attached to different security systems. Currently, an emergency shut-off buzzer (see Figure 6 a)) and a distance limiter (not visible in Figure 6) are attached. The buzzer is triggered manually, the distance limiter triggers when the cap is pulled off. The cap is attached with a rope and will be pulled off when the wheelchair exceeds the limit of the rope.

With the seat belt, the low driving speeds of this wheelchair, and the continuous supervision of at least one other person (i.e., the experimenter), we consider this system to be safe enough for human occupants (i.e., participants).

5 PERCEPTION AND MOTION PATH ANALYSIS

To evaluate the concepts of *linear* and *circular* motion paths (see Section 4), we conducted a hands-on experience evaluation with three developers.

5.1 Procedure

The evaluation took place in a laboratory with a square space of about 5 x 5 m. This allowed for a circular radius of 2 m and a maximum acceleration/deceleration path of 4 m. We recommend additional buffer space of 1 m, and room for an operator/safety-operator. A minimum space requirement of 6 m x 8 m is therefore required. The virtual scene was a straight road with and without different obstacles. During the evaluation, it was known which motion path was used prior to the trial. The evaluation was exploratory and did not follow a strict schedule. The evaluation took approximately 60 min.

5.2 Scenario

We implemented an overtaking scenario using the game engine *Unity3D* to show the feasibility of our system. The wheelchair was *accelerating* and *decelerating* on a circular path with a radius of 2m. Due to restricted space in our lab, we did not implement the motion mapping for the patterns *reeving* and *shearing* necessary for overtaking. The inner circle, which the wheelchair would have had to drive on after a lane change of the virtual vehicle, would have been too narrow with a radius of 1m and, therefore, the occurring centripetal force was no longer impalpable for the passenger. However, the lane-changing of the virtual vehicle while overtaking a leading vehicle was designed to be smooth and, therefore, a motion cue was not needed for this virtual movement. Using the wireless VR HMD *Oculus Quest 2*, the virtual visuals including the environment, other vehicles, and the rural road shown in Figure 8 were streamed via Wi-Fi to the HMD to ensure high-quality graphics. The controller of the HMD was used to determine the position of the wheelchair in the room. It was mounted to the wheelchair armrest to calculate a counter-rotation which was added to the virtual camera's rotation to counteract the influence of the wheelchair's rotation. Vibrations resulting from driving affect the controller mounted to the armrest and the camera correction. Thus, we used a 1€

filter ($f = 120Hz, f_{cmin} = 0.001, \beta = 0.01, f_{dcutoff} = 1.0$) [14]. However, we could not remove the vibrations completely. Therefore, the shaking of the camera could increase simulator sickness.

Fig. 8. Participants ego view while sitting in VAMPIRE and driving the overtaking scenario with a fully AV.

5.3 Measurements

We investigated the motion paths in terms of perceived safety in VR, perceived safety in reality, and perceptibility of lateral acceleration in curves. We also evaluated the linear and circular approach in terms of perceived immersion and safety. The distinction between perceived safety in VR and in reality was made because we assumed that perceived safety in VR might differ from or be influenced by the perceived safety of the system. If sitting in the wheelchair and driving around is perceived to be unsafe, this could affect the perceived safety in the simulation. Here, the manipulation would not be due to elements in VR but the implementation in reality and could lead to incorrect interpretations of results. Finally, we evaluated whether the approach is feasible in the available space of a common laboratory. For this, we evaluated different radii. We found that for our case, the radius was mostly limited by the available space, thus, we employed the maximum radius of 2m. We did not employ standardized questionnaires but opted for a qualitative approach and discussions among the developers.

5.4 Results

Linear Motion: In the linear motion approach, acceleration followed by constant velocity is translated to a forward movement that blends over slowing down until a standstill. During this process after accelerating, we noticed that it requires more space and time than initially assumed to slow the wheelchair down without noticing it. The re-positioning process afterward is also noticeable even when driving slowly. Occurring vibration further amplifies this sensation. This implies that the linear motion approach is time-consuming and requires a large surface area to navigate. This limits the driving scenario design.

Circular Motion: We expected that the curvature of the real motion path would be perceived, but in our observations, we were not able to confirm this assumption. The curvature of the circle (2m radius) while driving a straight line in VR could not be perceived. Furthermore, the constant vibration and mild air stream were a more intense experience than the linear motion approach. The circular movement additionally created some sort of consistency compared to driving the linear approach where the system accelerates towards a solid wall in reality. When accelerating towards a wall, the estimation of when the chair would hit the wall was different from reality and in some cases created trust issues and anxiety while driving along a straight and empty road in VR. In contrast, the circular motion does not have an implicit collision course with a real-world object which leads to more trust in the wheelchair. In general, the circular motion path was preferred over the linear path.

6 DISCUSSION

We presented a *Simulator Continuum* based on motion and visual fidelity. Additionally, we presented *VAMPIRE*, a novel driving simulator leveraging a motorized wheelchair. In the following, we discuss practical implications and layout research questions that this novel simulator helps address. We also critically assess the limitations of our work.

6.1 Use Case Visions

We expect that employing the *VAMPIRE* will allow for numerous interesting applications and to answer pressing research questions, which we outline as follows.

Manual Driving: We envision that the *VAMPIRE* could also be used to simulate manual driving. Here, an interesting starting point for implementation would be to map the available space to redirect the input by the manual driver. This would be an interesting adaptation of the *Redirected Walking* paradigm [13]. There are already applications for low-speed and application-controlled VR applications and Bruder et al. state that "many of the controllers developed for redirected walking can be directly applied for manipulating a user's movements when steering a vehicle" [13, p. 540]. This would enable the replication of prior studies to (in-)validate their findings.

Automated Driving: In the area of automated driving, currently, there are various attempts to understand future interactions and necessary visualizations [17, 18, 20, 23, 67]. However, these lack external validity due to their usage of static VR or monitors. Therefore, *VAMPIRE* enables for a more externally valid evaluation of these research questions. This can also include scenarios with multiple vehicles. Additionally, as *VAMPIRE* enables controlling a vehicle and bodyworks could be attached to the wheelchair, external communication of automated vehicles (e.g., see [2, 16, 21, 22, 27]) could be evaluated in a semi-realistic way.

6.2 Perceived Safety towards Automated Driving vs. the Simulator

One use case for *VAMPIRE* is to induce a more realistic driving performance to induce appropriate levels of trust and perceived safety in automated driving [20]. We believed that the real movement improves the simulator in this area significantly. However, during the internal trials and the final evaluation, we became aware that the simulator induces two different trust and perceived safety levels: (1) towards the simulator and (2) towards the simulated automated vehicle. We believe that this difference should be more prominent in simulator evaluations. We also must stress that this is a limitation of *VAMPIRE* because it implies a lowered external validity.

6.3 Practical Implications

Immersion: While we present the first findings of a small sample regarding the immersion of using *VAMPIRE*, the perception may differ between participants in terms of immersion and abstraction. We anticipate that some participants may try to locate themselves in reality and anticipate collisions with real objects, while others are fully immersed in VR. This will negatively influence immersion and, thus, external validity. Therefore, the experimenter using the *VAMPIRE* should reduce location cues and make sure that the VR headset is properly adjusted.

Assessing the Simulator vs. the Simulation: When using *VAMPIRE*, the experimenter should consider the influence of the apparatus on perception. The experimenter should distinguish between the perception of the system and the perception of the simulation via subjective feedback. We propose to ask participants to state their agreement to the following statements regarding perceived fear of events in the **virtual** world ("I was afraid of colliding with an obstacle or other road users in the driving situation.", "I was afraid of being in an accident in the virtual world in the driving situation."), perceived fear of events in the **real** world ("I was afraid of driving into a wall in the room", "I was afraid to crash in the real world with the driving simulator."), perceived physical risk during simulator use ("I had the feeling of being exposed to a physical risk."), perceived confidence towards the driving simulator ("I trust the driving simulator in this situation.", "The situation was risky.", "The driving simulator has made an unsafe decision in this situation.", "The driving simulator responded appropriately.").

Perceived Risk Mitigation: We assume that establishing a safe perception of reality is a good starting point. A false impression of unsafety, in reality, should not carry over into VR and, for example, confound the perceived safety of the automation. This can be done by assuring participants that colliding with real objects is not possible and is backed up by several safety mechanisms. Control questions regarding perceived safety in VR and reality can further explain behavior. We propose using the circular motion path because it avoids being on a direct collision course with a wall. Moreover, we propose to instruct and demonstrate the path to participants so that they can see and anticipate the non-collision motion path.

Settings: We found that adjustments to *VAMPIRE* depended on the ground condition. For example, depending on different forms of laminate, the perceived motion could be changed. Therefore, a calibration phase is necessary. This is also true for the used acceleration and deceleration forces, as these are perceived very sensitively [19, 63].

6.4 Limitations

The main limitation is that *VAMPIRE* was currently only evaluated qualitatively with three developers. Therefore, these first findings have to be validated with a larger and especially a more diverse sample. Therefore, our findings should be considered as first impressions and as a starting point for future research that evaluates the research platform.

7 CONCLUSION

In this paper, we propose a *Simulator Continuum* with motion and visual fidelity as factors. We also present a novel moving simulator environment called *VAMPIRE* to investigate behavior in automated driving studies using an electric wheelchair. This work serves as a first building block to further investigate the platform itself in further studies and, based on this, to be able to conduct behavioral analysis studies in (automated) driving. We investigated two movement types to map real and virtual movements: The linear motion path and the circular motion path. The linear path translates occurring lateral and longitudinal forces from reality to VR by accelerating, decelerating, and rotating from an idle position. Constant motion is not mapped by this approach. In the circular motion path, the wheelchair drives constantly in a circle (when the car is moving). Acceleration and deceleration are mapped by an appropriate acceleration and deceleration. Lateral forces are mapped by increasing and decreasing the radius. In a preliminary investigation, we found that the circular motion path outperforms the linear path and creates a greater immersion. We also provide a safety concept that minimizes injuries and accidents when conducting user studies. Finally, we propose practical implications that help to conduct future research.

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