VR-OOM: Virtual Reality On-rOad driving siMulation

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ABSTRACT
Researchers and designers of in-vehicle interactions and interfaces currently have to choose between performing evaluation and human factors experiments in laboratory driving simulators or on-road experiments. To enjoy the benefit of customizable course design in controlled experiments with the immediacy and rich sensations of on-road driving, we have developed a new method and tools to enable VR driving simulation in a vehicle as it travels on a road. In this paper, we describe how the cost-effective and flexible implementation of this platform allows for rapid prototyping. A preliminary pilot test ($N = 6$), centered on an autonomous driving scenario, yields promising results, illustrating proof of concept and indicating that a basic implementation of the system can invoke genuine responses from test participants.

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Author Keywords
virtual reality, autonomous vehicles, prototyping, design evaluation

INTRODUCTION
Driving simulators play a critical role in human-centered automotive research applications. They allow researchers to create safe and replicable stimuli, thereby enabling rapid and safe empirical exploration of how people will respond to various road situations and interface designs. A major challenge for driving simulation is replicating the inertial forces and vehicle dynamics that are present in on-road driving—particularly in light of recent psychological studies that point to the importance of inertial and vestibular cues to distance perception and steering (please see [22], for a review). In the age of advanced automation, another emerging difficulty is that in-lab driving simulators lose much of their ability to generate a sense of immersion and presence if the person using the simulator is not actively engaged in driving. Past research finds that perceived danger and immersion are lower and sleepiness is higher in a driving simulator than in a real car [18, 17]. Existing research in automotive UI has pioneered methods for on-road automated driving simulation, using a Wizard-of-Oz driver behind a partition to control the vehicle [6]. That line of research developed tools and methods to anticipate how people will respond to automation to enable testing of prototype mobile device interfaces and assessing of situation awareness in on-road vehicles.

Figure 1. VR-OOM allows participants to experience the physical sensations of the real-world with the controlled virtual environments and events. ***Photo by Arjan Reef.***

In this paper, we introduce a novel in-vehicle driving simulation system which takes advantage of breakthroughs in low-cost virtual reality technology to create experiences that are more immersive than a traditional lab-based driving simulator and that allow for greater flexibility in the test environment than normal on-road driving. This technology enables us to extend on-road driving simulation by injecting virtual objects, interfaces, and environments into the driving context, fusing the physical reality of the car with the simulated scenarios we have created. This VR-OOM: Virtual Reality On-rOad driving siMulation environment, which we call *VR-OOM*, breaks important ground in driving simulation research.

Our contribution of the VR-OOM system and research protocol enables researchers to run on-road studies with controlled events, to simulate autonomous driving in a higher fidelity environment, and to prototype a wide range of human-vehicle

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interactions and interfaces. We provide a detailed description of VR-OOM's system design and setup, as well as an initial validation study of the system. VR-OOM is relatively low-cost, as it uses consumer grade entertainment and gaming hardware within a normal passenger vehicle. We are open-sourcing the software, 3D models and course designs of VR-OOM, in hopes that lowering the barriers to automotive user interface design and experimentation will increase the variety, quantity, quality, and safety of the systems and interactions created.

RELATED WORK

Driving Simulators

Driving simulators span from low-cost driving simulators, like City Car Driving [1] & Grand Theft Auto-based OpenIV [2], to high-fidelity immersion driving simulators, like the National Advanced Driving Simulator at the University of Iowa [13] or Ford's VIRTTEX simulator [4]. An overview of state-of-the-art simulators is offered by [35]. Simulators allow for the study of high-risk scenarios and designs before full product development. Presence is an important criteria for the work that is done in simulator platforms to be ecologically valid [36, 21], but this trades off against cost considerations. High-end driving systems that integrate driving-like motion are expensive, two orders of magnitude beyond low-cost simulators, and yet only create accelerations that are a fraction of those involved in typical driving situations [39].

Virtual Reality (VR) Head-Mounted Displays

Head-mounted displays are an inexpensive, commonly used way for human participants to experience an immersive virtual reality environment [7]. This method can be used in car research by placing a physical steering wheel and foot pedals in front of a participant while they view models of these in the virtual world. Head-mounted displays allow the changing of interface elements like screens and actuators in virtual rather than physical reality, enabling a broader range of experimentation. VR platforms such as the Oculus Rift, HTC Vive, LEAP Motion, and Unity and Unreal game engines are low-cost, available for a few hundred USD/EUR. However, dynamic motion (forces felt on the body) is often absent from research settings using this method. Therefore, this method has similar limitations to a mid-range driving simulator.

Driving Simulation for Design

Driving simulators are traditionally used for human factors testing, training or impairment studies. However, they can also be useful for designing novel interfaces and testing interactions in the car. Early work in automotive gestural interfaces [2] and speech interactions [16, 14, 25, 31], for example, make use of the driving simulator and focus on driving as a primary task that designed interactions should not interfere with.

Autonomous vehicles bring a new set of concerns to the table, requiring new models for visual display systems, control interfaces, audio alerts and interaction [1, 12]. Many of the experiments for driving simulation involving automation are controlled "transition of control" studies [15, 29]. However, some, such as [33, 32], have taken a more designerly and improvisational approach to sharing or transitioning control with automation. This design- and development-oriented use of driving simulation is also gaining traction for non-automation uses; the Intel Skyline simulator, for example, is focused on making it easy to prototype interactions between the vehicle and brought-in devices such as phones and tablets [3].

[1]http://citycardriving.com
[2]http://openiv.com

On-road Driving Simulation

. For studies and design scenarios where drivers are not always engaged in the driving task, like [30], visually-based simulators become less effective; the level of immersion of a person staring at a tablet in a darkened simulation lab is unlikely to be the same as that of a person engaged in the simulated driving task. Hence, the advent of automation makes on-road simulation more important. The use of the real car and the real road addresses the physical, bodily, environmental and social reality that is the basis of a realistic experience [20]. It increases the transfer, fidelity, immersion and presence of the simulated experience in a way that is difficult to replicate even in high end simulators. As there is less incongruence between the perceived environment and the kinesthetically sensed environment, motion sickness is also less of an issue.

VW researchers pioneered on-road autonomous driving simulation with the Wizard on Wheels protocol, using a specially reconfigured vehicle that featured a hidden second driver in the load compartment who could take over parts of the driving task, varying the degree of automation from manual control to complete automatic control [34]. More recently, Stanford researchers developed a simpler protocol that put a partition between a driving wizard and study participants who were given a fake steering wheel which they could use to "take over" automation [6, 38]. These vehicles are instrumented to capture the study participant as well as the context for each drive [11, 24] since there is an inherent variability to any study that take place on the public roadway. The Stanford platform also permits remote Wizard of Oz interaction between drivers and remote wizards [27].

In-car VR as a Research Platform

CHI researchers have recently investigated the possibility of using VR in the car with head-mounted displays (HMDs). The CarVR system [19] tracks a non-virtual car's motion and renders the corresponding visual perspective of a passenger in the virtual space, which is used to play an arcade-like shooting game. The authors found that moving the game in concert with the car's motion caused less discomfort compared to playing the game while the car was parked. McGill et al. looked more carefully at how correspondence of motion between the visual display using HMDs and the car's motion affected motion sickness [28]. They found that motion sickness would represent an obstacle to use VR in the car in real-world conditions. However, both research projects used smartphone-based VR. Honda's DreamDrive [8], demoed at the 2017 Consumer Electronics Show in Las Vegas in January, suggests that many of the issues with these research systems can be circumvented by using higher-end VR systems with higher visual refresh rate, and by using the car's CAN bus data to more accurately map the virtual world movement to the vehicle's actual movement.

VR-OOM was inspired by military flight simulation. Bachelder et al.'s Fused Reality system [5] enables pilots wearing VR headsets to fly real planes in real skies while experiencing simulated situations. This system is used to help pilots practice take-offs and landings 30,000 feet in the air, where there is no threat of ground collision. It can also be used to simulate mid-air refueling or formation flying without the danger of mid-air collision. Fused Reality provides a higher-fidelity simulation environment than ground-based simulators because the aircraft is real and in motion; only what the pilot sees is virtual [9]. To leverage the benefits of Fused Reality in the in-car VR research space, we created VR-OOM, a novel low-cost virtual reality system that operates in a moving car where the car's physical motion is mapped to the virtual road environment.

IMPLEMENTATION

In VR-OOM, a participant sits in the passenger seat of a car that is driven by a trained driver (the Driving Wizard). The participant wears a VR headset through which she sees herself sitting in the driver's seat of a virtual car. The participant can see a model of her own lower arms and hands in the virtual world. The VR environment is modeled on the actual car chassis so that as the participant reaches out and touches the gaming steering wheel placed in front of her, she sees her virtual hand grab a virtual steering wheel. Over the course of an experimental session along a physical driving course, the vehicle can be "driven manually" by the participant (the Driving Wizard mimics the participant's steering behavior) or "driven autonomously" (the participant experiences traveling in an autonomous car mode while the Driving Wizard is driving). Thus, VR-OOM supports rendering of the virtual environment, tracking of vehicle location and speed, tracking of hands, and steering wheel input.

The participant's visual experience is virtual, but her audio, touch and motion experiences are naturalistic. Audible sources from the physical car (engine and road noise) can be augmented by using headphones and/or the car's audio system. Sensations from touching the steering wheel are from a physical steering wheel rather than tactile gloves. The participant can see her hands in the VR environment, which is modeled on the actual car chassis and steering wheel to support alignment of the feeling of touch with the visual perception of touch. A calibration procedure ensures that the physical objects line up with the virtual objects. Additional props like a game steering wheel complete the illusion of physical presence. The physical car motion also maps directly to what the participant sees in VR. Currently, the motion information is limited to the speed of the car and its orientation in 3D space.

Hardware Components

A system diagram showing the data flow for the VR-OOM hardware and software systems is shown in Figure 2.

VR Headset and Computer

VR-OOM uses a standard consumer VR headset that supports Unity3D, like the OSVR-Headset or the Oculus DK2. The VR-OOM visual system runs on an HP zBook 17 HSTNN-C76C laptop that is connected to the VR Headset sensors and

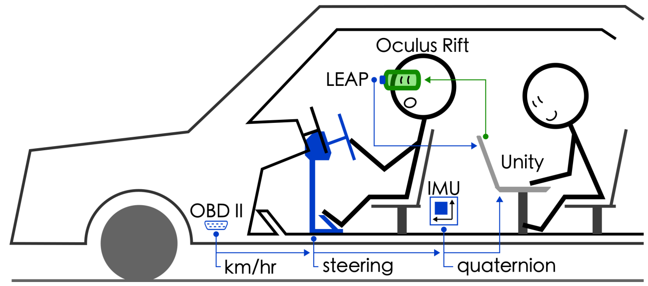

Figure 2. VR-OOM System Diagram (excluding the wizard driver)

a tablet that is used by the wizard driver to view the virtual world.

Inertial Measurement Unit

The Inertial Measurement Unit (IMU) records and processes linear and rotational acceleration. This acceleration information is used to compute, in real-time, the orientation of the vehicle in 3D space. The IMU is augmented with other sensors like magnetometers, temperature sensors and barometers to correct for drift and noise that occur in these types sensors. This data is directly (or after small modifications) used in Unity to map the car's orientation to the virtual car.

In our implementation, an MTi 1-series Development Kit from Xsens is used. It is mounted in the center console between the Driving Wizard and the passenger. This IMU is mounted as close as possible to the center of the car but also as far away as possible from any metal (in order to calibrate the IMU's compass). A small program written in Node.js® forwards the IMU's serial message to a UDP port that is read by the Unity software. We experimented with using a less expensive IMU, but found that a highly accurate signal was necessary to make the VR-OOM system work well.

OBD-II Dongle

The OBD-II (On-board diagnostics) port is a polled serial interface that is typically used for car diagnostics and emissions testing. We use a OBDlink SX EL-220 OBD-II USB serial dongle to connect the VR-OOM laptop computer to the vehicle. The VR-OOM software requests the vehicle speed through this port, which is forwarded by a Node.js® script over a different UDP port to Unity.

LEAP Motion Controller

The LEAP Motion Controller is a sensor device that supports hand and finger motions as input. It is physically mounted to the front of the VR headset to enable the VR-OOM system to track the participant's hands when they are set forward (See Figure:1). The sensor is connected via USB to the VR-OOM computer. The information from the Leap Motion is used to replicate the participant's hand motion directly in VR. The recent release of the Orion SDK significantly improved the tracking performance from head mounted LEAP Motion trackers.

Gaming Wheel

The other input peripheral is a Logitech 920 gaming steering wheel. It is mounted directly in front of the participant, just like the normal steering wheel of the car. The gaming wheel

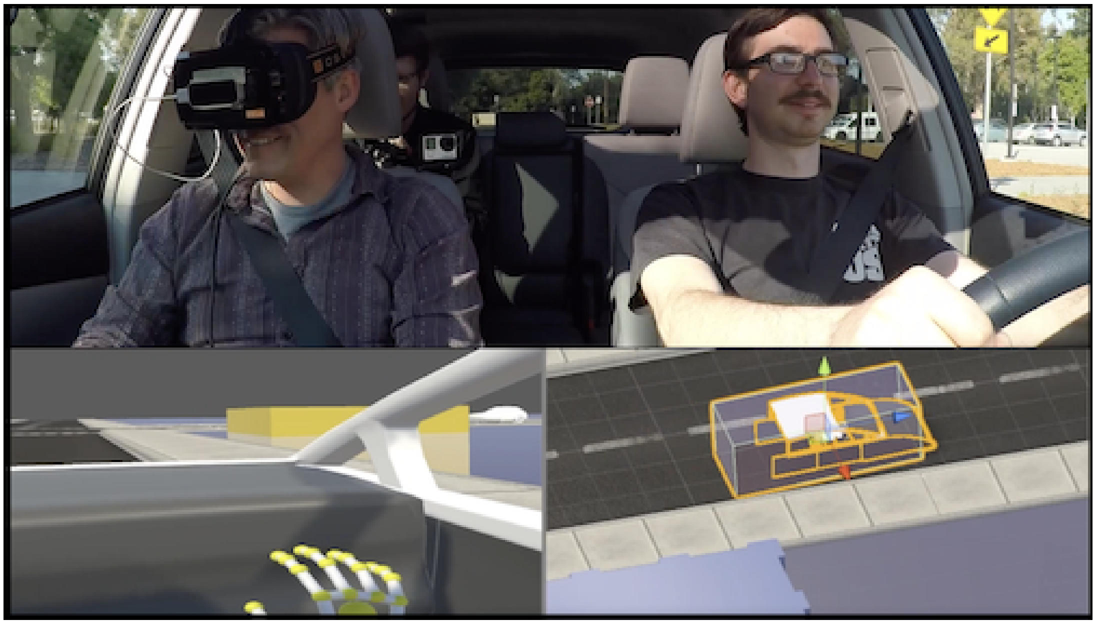

Figure 3. View from inside vehicle with participant on left, Driving Wizard on right, and Interaction Wizard in backseat, *top*. Participant's view with hand in foreground, *left*. Bird's eye view of virtual vehicle in virtual world, *right*.

is connected to the VR-OOM computer, and its motions are directly linked to the visual representation of the steering wheel in the participant's virtual world view. Hence, if the participant turns the wheel in the physical world, they will see the virtual wheel turn.

Infrastructure

There are a few infrastructure-related components necessary to create a VR-capable car interior.

Power Power is supplied primarily to the gaming steering wheel from the research vehicle's 12V outlet and through a DC/AC converter. The VR-OOM laptop runs on its internal battery. For longer participant experiments, the laptop requires an external power source.

Networking Networking between the different system components needs to be fast and reliable. In our current setup, a basic Wi-Fi router, powered by the car's 12V power, hosts a standard 2.4GHz-802.11n wireless network that the VR-OOM laptop and the Driving Wizard tablet connect to.

Car All modern production vehicles (since 1996) have an OBD-II port that can be used to gain speed information from the car. In some cases, the OBD-II connector can be replaced with a CAN Bus port that could supply more information in addition to the vehicle speed. This includes internal accelerometer data and vehicle steering angle. This information could be used to more accurately map the vehicles motion in the virtual environment.

While conceivably the system could be run in any size car, it's most practical to use a four-door sedan or larger. The vehicle is set up as follows: (1) Back seat - A researcher with a laptop running the VR software connected to the gaming steering wheel and IMU; (2) Driver side - A driver and a tablet next to the steering wheel displaying the virtual environment and an IMU in an open space near the gear shift; (3) Passenger side - the participant and a gaming steering wheel.

Over the course of this system's development, we have deployed VR-OOM in a Prius V, a right-hand drive Jeep Wrangler, and an Audi A6. We have found that the system worked well in all these vehicles, although it was most advantageous to set up in the Prius V because the CAN Bus provides more data that standard OBD-II.

Software Components

The core of the VR-OOM software system is scripted in C# and runs in Unity. It is responsible for combining the sensor input streams, updating the virtual scene based on that information and rendering the scene to the participant's headset.

There are three main software components that simulate the environment and use the sensor data to create virtual experience of driving in an autonomous Vehicle.

Car Object

The virtual car object hosts scripts and mesh information that are used to create a convincing car interior. The orientation and speed information of this object is controlled by the orientation and speed forwarded from the sensors over the UDP buses. The car's speed received every 20 *Hz* and is a 16-bit integer with *km/h* accuracy. The IMU delivers four quaternion values as 32-bit floats at a rate of 100 *Hz*.

LMHeadMountedRig

`LMHeadMountedRig` is a standard asset provided by the LEAP Motion plug-in. It hosts the VR-Camera for the headset and scripts to correctly render the participants tracked hands in the virtual view. The hand position is also used to calibrate the head position which is fixed to the car object. This allows the VR-Camera to rotate freely while moving along with the car.

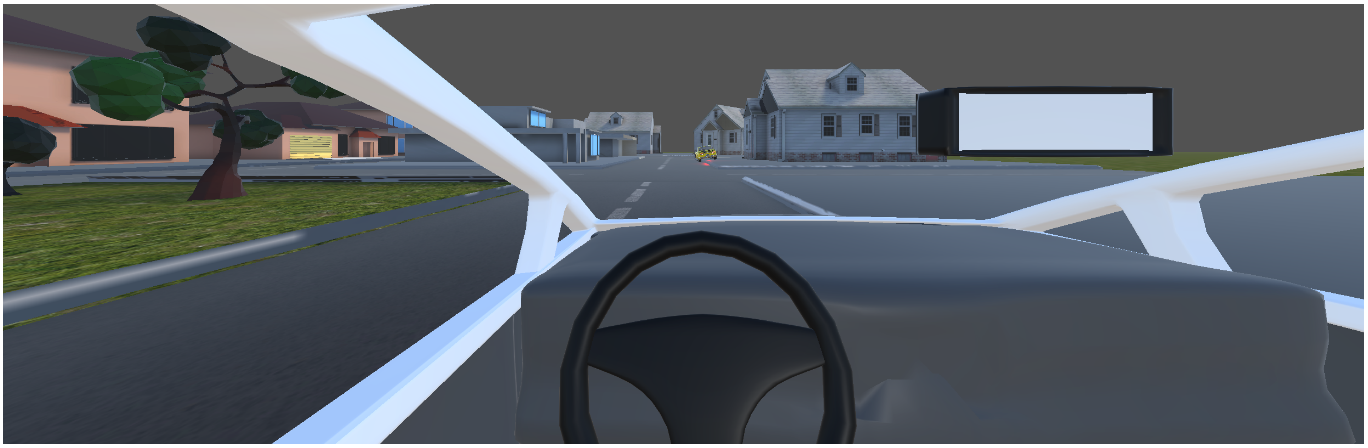

Figure 4. Participant view at the start of the experiment (excluding the tracked hands).

This is very similar to what is happening in the real world. A relative positional tracking solution for within the car would be a better solution. However, no currently existing consumer hardware could handle the moving reference frame. This issue is addressed in our discussion.

GameManager

The last essential component is the `GameManager`. This object hosts the logger script that streams any log messages such as state changes and variables over a UDP port to an external Python logger that organizes the variables by time code and creates one consistent CSV file from each experiment run.

The other component controlled by the `GameManager` is the Interaction Wizard's interface. This interface allows the Interaction Wizard to control different aspects of the virtual scene. For example, the Interaction Wizard can "remotely" open and close doors of parked cars in the virtual environment or load different scenes and components. The loading of different scenes is designed to create an uninterrupted experience for the participant. In the example implementation, the car, as well as the environment, stay the same in the scene. All other additional actors and components for the different conditions are only loaded when needed.

Generating the Virtual World View

The main camera is rendered directly to the VR-headset. Two different implementations were realized. In the first implementation, we used a combination of SteamVR and the OSVR headset. In the second implementation, we used the OculusHome Unity plug-in and the Oculus DK2 as the VR headset.

An essential issue in the implementation was the lack of any absolute tracking or on-the-fly recalibration to deal with the inherent sensor drift of the IMUs. This issue is discussed in more detail in the discussion section.

Generating the Wizard View

To allow the Driving Wizard to control the research vehicle so that its movements correspond to in-world roads and turns, a separate forward facing view of the virtual environment is rendered and streamed out to an Android tablet. This tablet is mounted in sight of the Driving Wizard. The proof of concept implementation used a low frame rate stream of JPEG images transmitted via Wi-Fi over UDP to the tablet.

REPLICATION SETUP CONSIDERATIONS

Designing a study with VR-OOM involves determining the driving location, training the driver, creating the study protocol, designing the virtual world and handling the generated data. We discuss each step below.

Physical Setting and Virtual World

For on-road driving tests, it is best to find a neighborhood road to drive on and to replicate that road in the virtual environment. For other scenarios, it is better to find a large open field that can be used as a testing area for any arbitrary set of roads in the virtual world.

We believe the ideal driving location is an open paved field environment [7] because it allows maximum design freedom for the virtual world to be tested. Such an open field has fewer road users, fewer objects and fewer road regulations than a residential road.

However, open fields are difficult to locate. For our experiments, we have made use of empty parking lots during hours when few people are around. To run studies in a parking lot, the virtual world must be designed to match the constraints of the physical setting. It is best to use information from map data to match the virtual environment to the constrains of the physical world. Figure 5 shows how this was done for the validation study.

Video Recording

In addition to the data logged from VR-OOM system events, we also capture two video streams. One from the physical and one from the virtual world. A physical camera records a 360° view of the participant's surroundings inside the car. The other video stream captures the Interaction Wizard's laptop, which features a bird's eye view of the virtual VR-OOM environment and the participant's point of view (see the bottom half of Figure3).

Driving Wizard Instructions and Training

We believe Driving Wizard training is critical to the success of VR-OOM. This training should encompass:

- gaining familiarity with the research vehicle and Wizard Interface;
- practice drives of the various scenarios on the physical course;
- pilot tests with pseudo participants to ensure the Driving Wizard knows how to stop the car if necessary;
- driving training to ensure the inertial movement of the vehicle is as smooth and slow as would be expected from an autonomous system.

This combination of considerations helps to ensure that the study setup is safe, believable and does not make the participant sick.

Preventing Motion Sickness

Because people can be susceptible to motion discomfort and motion sickness in cars and virtual reality environments in general, care needs to be taken to combat motion sickness. Some pragmatic procedures in virtual reality experiments, such as ensuring a high refresh rate on the VR system, and screening participants for epilepsy or simulator sickness, can be helpful. Also, the study protocol should include planning for what to do if a study participant should feel unwell.

Participants can become disoriented and experience nausea if the participant is not facing forward in the virtual world since their virtual world would be indicating sideways motion while they are physically experiencing forward motion. Thus, the calibration phase of the tracker is particularly important.

VALIDATION STUDY

To validate VR-OOM as a research platform, we conducted a pilot study with participants to prove the system functionality and the practicability of the research protocol; aside from our reflections and experience, we were interested in participants' qualitative impressions of the experience.

Participants

A total of six university staff and students (4 male, 2 female) participated in our pilot. Participants were recruited to elicit a range of backgrounds, including two Bachelor students, two Master students, one staff and one post-doc. Participant ages ranged from early 20s to late 40s. Participants were recruited from a university campus in the Netherlands.

Experimental Procedure

Following the signing of informed consent forms, participants follow the Interaction Researcher to the VR-OOM car. The participant, Wizard Driver and Interaction researcher then drive to the start of the physical course. Participants sit in the front passenger seat. The Driving Wizard sits in the driver's seat. Participants are told that the Driving Wizard will be controlling the vehicle and that they will be wearing a VR headset which simulates an autonomous vehicle passenger experience (see Figure 4 for the participant view of the virtual driving simulation environment).

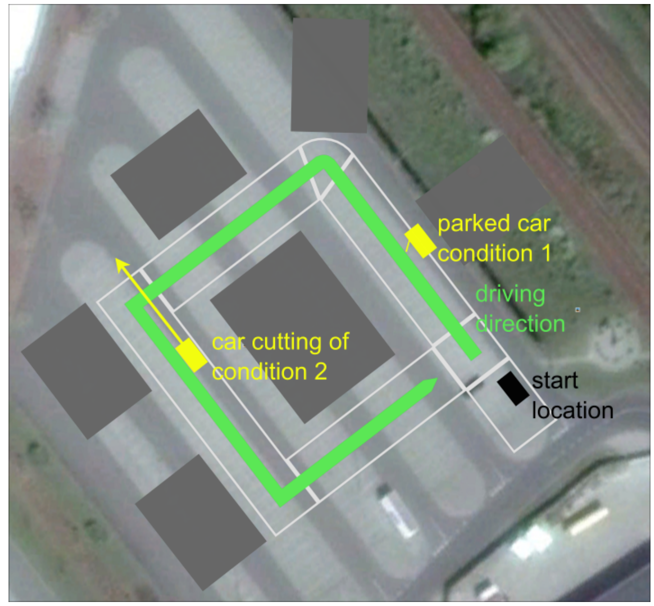

Figure 5. The virtual route overlaid on a satellite map. The black box is the starting location, conditions one and two are marked by the yellow cars and the white outline is the shape of the road. The gray boxes indicated the approximate locations of buildings in the virtual scene.

The researcher then explains that in the virtual world, the autonomous vehicle is not able to detect all traffic events; they are cautioned to take over control whenever they feel unsafe. The researcher explains that the purpose of the study is to see how people behave when the vehicle fails to detect events. The proof-of-concept study had two events that would not be detected by this autonomous Vehicle. These are a parked car opening the driver door and another car cutting in front of the participants car.

After calibrating the VR system, the Driving Wizard drives a pre-determined rectangular course consisting of four road segments that corresponded to driving around a virtual block in a generic-looking suburban neighborhood environment (see Figure 5).

The test features three drives around a building. In the first drive (normal condition), nothing particular happens. In the second drive ("car door open" condition 1), a car door opens in the path of the car. In the third and final drive ("car cutoff" condition 2), a passing vehicle cuts off the participant's car from the left side, on the side the participant is sitting in the virtual car.

After all three conditions are done, we perform semi-structured interviews to understand the participants' experiences. Sessions last approximately 20 minutes in total. The verbal comments of the participants during the drives were audio-taped and transcribed. In the case of two participants, the audiofiles were missing because the recording equipment ran out of power.

Analysis

To synthesize the results of the validation study, we reviewed the transcripts of the interviews and picked out salient themes. Themes also stemmed from the Interaction Wizard's observations of participant behavior and the Wizard debriefing that occurred after each session. We focused on identifying issues that affect the user's experience or methodological validity in the on-road virtual reality driving simulation, as well as logistical issues that would affect the practicability of running studies with this setup.

DISCUSSION

In this section, we report the most interesting observations and reflect on the VR-OOM system and what we learned about its viability as a research platform for autonomous driving simulation.

User Experience

At the start of each session, participants sounded surprised and curious about their experience. Participants would turn the steering wheel to see what happened in the virtual world and voiced surprise on noticing that the hands visible were "their own." The sensation of moving through a virtual world while knowing and feeling that the real car they were in was driving on a real road evoked exclamations of surprise and bewilderment. Shortly after, participants would start paying more attention to the events that were happening in the VR environment.

While each participant was informed of the driver's role, participants behaved as if they were in an actual autonomous vehicle. Five out of the six participants grabbed or held the steering wheel when a critical situation occurred or they where unhappy with how the car was driving. One Dutch male participant of 20 years of age mentioned: "*The second car really that just came from the left by surprise. That was really a reflex to grab the steering wheel*." Only one participant spoke to the Driving Wizard during the experiment, indicating explicit awareness of the driver.

There were noticeably different approaches toward intervening. Four of six participants steered the car often, even when there were no critical events. They did this to stay further from the middle of the road or other preferred driving. Two participants hardly ever intervened, only when absolutely necessary, because of a critical event. We could not explain this from participants' characteristics. There are probably different types of autonomous car drivers that could be identified in the future to inform personalized autonomous car driving styles.

Congruence between Physical and Virtual world

Participants frequently commented on feeling the motion of the car in congruence with what they were seeing in VR. A 20 year old male French participant commented on the sensation of turns: "*It felt like the car really turned, it really turns like in real life and virtual reality.*" In relation to the added sensory experience of driving, the same participant mentioned: "*It was really interesting to feel the real road, which feels real in the VR world where everything is fake.*" He had therefore noticed the feeling of the road surface while being driven.

Our test was conducted in a parking lot with slightly raised parking spots. While it was possible to drive diagonally over the parking lot, the slight up and down motion was noticeable. Participants reported that they were positively surprised to see this motion from the car in the virtual environment. Participants were confused, however, because there was nothing visible in the virtual world to account for the motion sensation caused by these humps. This phenomenon did not break the illusion of the virtual world but did seem to cause face validity issues with the simulation. Therefore, road texture is an aspect that needs to be carefully matched in the design of the virtual test environment.

One participant, in particular, would lift up the headset from time to time to re-connect with the actual physical surroundings. This break from illusion suggests low immersiveness and it may be that higher quality graphics or a virtual environment that more closely resembles the real world environment would help the participants to stay immersed.

However, the fact that participants behaved as if in an autonomous car suggests a high level of immersiveness. Accordingly, no participant reported acute or severe motion sickness. This could be an artifact of the characteristics of the participants selected, but it may suggest that the congruity of the physically and visually experienced motion has a positive effect of reducing nausea. One male Dutch participant in his mid 20's who mentioned beforehand that he only had basic experience in VR stated: "*I am not dizzy or nauseated but maybe if I do it for a long time. I had it the first time when I was popping in and out of the car, that was not pleasant.*" The 'popping in and out of the car' mentioned was an experience during calibration while the car was not in motion. The system would reposition the view of the participants relative to their hands holding the steering wheel. In some cases, this calibration looked like the environment and the car shifting around the participant. While this experience induced motion sickness, the experience of driving through the environment did not.

Interestingly, four participants later reported slight discomfort about one hour after the experiment was over. It is unclear why there would be such a delayed onset of slight discomfort. We believe further manipulation of the driving environment and the study protocol might help to understand and combat this phenomenon. It needs to be addressed particularly if longer duration studies are to be supported.

Sound

In the test implementation, the sound of the physical surroundings was not incorporated, altered, or augmented. Outside noises did not seem to impact the participant's experience. There were other cars driving in the parking lot (predominantly a slow-moving driving-school vehicle), but this was not observed to affect the acoustic perception of the participant. However, the use of open headphones and the corresponding implementation in Unity could allow designers to create sounds that increase the believability of virtual world events. In addition, designing a soundscape for the experiment prevents unexpected and potentially distracting sound sources (e.g. approaching trucks or trains) from affecting the experience.

Criticisms

Critique of the system mainly concerned the quality of the graphics in the VR rendering. At least three participants commented on this. It is very likely that the user experience of VR-OOM can be enhanced by providing a high fidelity graphical rendering. However, we were able to get natural responses to traffic events from participants with the current low fidelity graphics (see Fig. 4). Therefore, to asses responses, the graphics quality may not be essential. Fortunately, it is relatively simple to improve upon this aspect of VR-OOM. It involves the digital design of a consistent and complete environment filled with assets like houses, cars, people, benches, trees, and other objects. Additionally, aspects such as light rendering in the virtual world could be improved by fine-tuning the build in Unity.

Technical improvements

Other critiques concerned technical components of the platform. One participant mentioned "*I am missing the pedals. After the last round, the driver was parking very close to the other car and I noticed I was pressing my foot down. Just to brake. Reflex of pressing my foot down.*" People who drive regularly may have the inclination to press the foot pedals or switch on a light. The current study focused on participants' tendency to grab the steering wheel. From this comment it seems likely that other reflexive behaviors can be similarly investigated.

In the current implementation of the system, the VR-Camera is fixed, relative to the car after the calibration but the rotation is decoupled between the headset and the car. This means that the car and the headset determine their orientation independent of each other. The noise in the sensors being used to determine orientation cause both components to slowly drift apart over time. This is why it was necessary to recalibrate the participants viewing orientation after every condition in the proof of concept implementation.

This issue could be circumvented by either using higher quality IMUs or by implementing a tracking solution that can determine the VR-headset position and rotation relative to the car. Consumer grade room tracking solutions cannot operate in a moving reference frame, which is why the system needs to either extend open source solutions like OSVR[3] or use other tracking methods like marker tracking. The addition of positional tracking would also allow the participant to move their head around more freely in the car interior.

Latency is another aspect that affects the quality of a VR experience. If the latency between head-motion and displayed image becomes too great (> 75 ms [37]), the participant perception and motor control will be affected, influencing how naturally they can act in the virtual environment. It is unclear how the delay between the tracked car motion affects well-being and immersion. The frame rate of the VR operating system also affects latency. While 90 frames per second (fps) are typically recommended for VR [10], this project ran at about 60 fps. This was due to the computational overhead of the Wizard View. Future implementations will need to address this. Either though native plug-ins for video capture and better timing within the frame[4] or simply by using more powerful computing hardware.

[3] Open Source Virtual Reality http://www.osvr.org/

Participants' qualitative experiences and the experimenter observations indicate the applicability of a low-cost Fused Reality car simulator such as VR-OOM to assess people's genuine responses to driving situations. This first pilot study also offered directions for technical improvements to increase the immersiveness and practicability of the system. Moreover, this proof of concept validation offers insights for the application of VR-OOM for the on-road testing and development of autonomous vehicles.

Experimenters Perspective

From the experimenter's perspective, VR-OOM allows for rapid development of user testing. However, there are a few important considerations that should be taken into account by experimenters:

The communication between the experimenter and wizard driver is a key factor in streamlining the experiment process. In the proof of concept implementation, short instructions from the experimenter were relayed to the wizard driver by hand signals and sometimes voice. Voice should be avoided in as these instructions will be overheard by the participant. A clear set of hand signals could help improve the communication and streamline the process of running experiment. Clearer and coordinated instructions will also give the wizard driver a better understanding of what to do.

Generally, streamlining the experiment process can always be done by using checklists and by automating some of the interactions directly in Unity. In the proof of concept implementation, the trial runs prior to the experiments were essential in understanding which parts needed experimenter control (e.g., condition-level loading) and which parts were better to automate (e.g., opening the parked car's door).

An important area for future system improvement is the wizard driver's perspective into the virtual world. The proof of concept implementation utilizes a small tablet with a fixed view in the virtual world. This was good enough to drive the car along the virtual road and to react to the predefined and trained scenarios (conditions 1 and 2). In principle, VR-OOM can also support improvised scenarios to respond to unplanned events or impromptu actions in the moment. For these more dynamic scenarios, the wizard driver needs a better view into the virtual world, either through a bigger tablet or a different virtual perspective.

PROSPECTIVE APPLICATIONS FOR VR-OOM

It is our intent that VR-OOM be a flexible set up to enable a wide variety of on-road testing and development of autonomous vehicle interactions. Here we discuss potential applications made possible by the VR-OOM system.

[4] https://medium.com/google-developers/real-time-image-capture-in-unity-458de1364a4c

Autonomous vehicle design

VR-OOM supports testing exploratory design concepts in graphical user interfaces, sound interfaces and motion interfaces for autonomous vehicles. Graphical user interface displays, such as heads-up displays or audiovisual hand-over alerts, can be prototyped in virtual reality and implemented at specific moments during a course (as with a car simulator). Sounds are an essential part of user experience and can be explored by overlaying system sounds over natural car noise. Algorithms for car motion design that have different acceleration and curvature characteristics can be tested to determine which are most suitable for a given culture or passenger personality. Graphical, sound and motion interfaces for the automobile can be tested by the system in the context of a real driving environment. This can lead to better sound design that accounts for engine and ambient noise, as well as better motion design that accounts for real driving motions.

Human behavior in autonomous vehicles

VR-OOM can also be used to look at the design of car behavior for specific scenarios in an autonomous vehicle. Car behavior during scenarios such as accelerating to pass a yellow light or finding a parking location could be tested to assess human behavior and determine which of several car behaviors is best received. VR-OOM might also be able to identify design guidelines for comfortable versus uncomfortable car behaviors. For example, by looking at whether people grab the steering wheel during a simulation.

Inertial motion as signaling for autonomous vehicles

Based on the tight linkage between the physical car motion and the virtual car motion, VR-OOM can also be used to explore the use of inertial motion as signaling for autonomous vehicles. The underlying idea here is to first explore the already available motion design space for autonomous vehicles before considering augmenting technologies such as screens or audio that would signal the vehicle's intent to its passengers. Small variations in the car's path might also be used to convey the car's intended course, personality or driving mood to riders.

Testing of critical and dangerous scenarios

Many on-road scenarios that are critical or dangerous often require split-second decisions and are reflexive in nature [23]. In general, virtual reality can be used as a research tool to asses this type of behavioral response [26]. VR-OOM extends this functionality to on-road in-car scenarios. Given an appropriate test area, VR-OOM could be used to test anything from traffic dense urban environments to highway sudden-takeover scenarios. When designing car behavior during critical scenarios, car designers may want to take into account whether and how people grab the steering wheel or press the brake. While these scenarios might require additional safety features like support wheels on the experiment vehicle, the core system as described in this paper would not change.

Design for entertainment and secondary activities

Virtual reality offers a great opportunity to study in-car virtual reality entertainment, prototype new possibilities and test limitations. With VR-OOM this design evaluation can move directly into a vehicle, which may be a growing site for entertainment given television and mobile phone use in vehicles. The rise of autonomous vehicles has also prompted discussion about how passengers may use their available leisure time while these cars are in autonomous mode.

FUTURE WORK

In addition to the improvements derived from the participants' responses, there are a few technical and methodological developments that will be the focus of future VR-OOM development. On the technical side, we will look at data logging, integration of higher quality sensors, and streamlining data evaluation. On the methodological front, further validation is an essential to establishing VR-OOM as a research method. An important step for that will be benchmarking VR-OOM to existing simulators and simulator research. Additionally, it would be worthwhile to develop quantitative measures for simulation quality, e.g., through measuring the orientation drift of the car over time.

CONCLUSION

VR-OOM is the first on-road VR driving simulator. The driving simulation environment features the controlled events and scenarios of traditional driving simulators with the physical sensations, immediacy and presence of actual driving. Our initial validation tests indicate that it can serve functionally as a driving simulation environment for autonomous driving scenarios to test driver situation awareness and intervention. Further validation studies are ongoing to ensure that this novel driving simulator can help bridge the gap between safe testing of human response and effective prediction of human performance.

By using the system description and protocol described in this paper, researchers can have access to a highly immersive driving simulation environment for relatively low cost and effort. We hope this broadens the pool of people who will design future interactions and interfaces for automobiles, and encourage broader empirical testing to understand human response in the road ahead.

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The work described here is open-source and will be made available on GitHub at the time of publication on `https://github.com/DavidGoedicke/VR-OOM`.

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