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On-road Virtual Reality Driving Simulator

Human Media Interaction - Master thesis

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Abstract

For autonomous vehicles to become market ready it is important to better understand how drivers and passengers will interact with this new technology. This includes the interface design and how the vehicle's motion is perceived by the passengers. We propose a new method to evaluate this interaction, which combines the use of simulators and on-road methods.

Through virtual reality, participants can experience what it is like to drive in an autonomous vehicle. They are seated on the passenger of a regular vehicle, which is operated by the experimenter. Throughout the experiment, participants perceive a simulated traffic scenario through a virtual reality headset. Additionally, they can indicate steering motions through a steering wheel in front of them.

This new method allows for a rapid prototyping approach in autonomous vehicle design in a highly immersive virtual environment. The integration of virtual reality in a real car allows for a realistic and immersive experience while being cost-effective.

A preliminary validation study yielded promising results and showed that the proof of concept implementation of the system can immerse the participants in a virtual driving scenario. The realism of the system was convincing enough to evoke reflexive behaviors in some test participants in response to the environment. Thus, the results from this study were promising however, further research needs to be done to fully validate this method.

Chapter 1

Introduction

The emerging technology of Autonomous Vehicles (AVs) pose new questions on how people interact with AVs and react to their interfaces, behaviors and motion. Existing methods to address these issues use simulators and on-road methods. However, simulators are often expensive (above 50K$ [10]) and on-road studies are very limited in the type of traffic scenarios that can be encountered.

Therefore, in this document we present VR-in-Car a simulation and on-road hybrid method that addresses the aforementioned issues. It integrates off-the-shelf Virtual Reality (VR) technology into a moving vehicle. VR-in-Car allows participant to experience what it is like to drive in an AV. This method is comparatively low-cost, offers inertial vestibular cues and dynamic traffic environments. The main contributions of this work are the development, a proof-of-concept implementation and evaluation of this new method.

The next section describes the different areas of related work on vehicle and simulator research. In section 3, this new method is discussed and compared to the related work. Section 4 describes the technical implementation details. Section 5 through 6 discuss the application of this method in a study. The results are described and discussed in section 7 and 8 respectively. Sections 9 and 10 layout future work and prospective applications.

Figure 1.1: VR-in-Car allows participants to experience the physical sensations of real-world motion while being visually in a virtual environment.

Chapter 2

Related Work

VR-in-Car is a research tool that is particularly cost-effective in creating immersive traffic experiences from the drivers' and passengers' point of view. In the following section we will look at existing work in the field of drivers-AV interaction research to evaluate this new method against prior work.

2.1 Driving Simulators

Driving simulators are a commonly used method to evaluate interface design and human behavior in simulated traffic situations.

In advanced driving simulators, a participants enters a mobile car chassis which contains screens or projectors instead of the actual windshields to create a visual virtual environment. Many types of driving simulators exist. They can primarily be differentiated by the level of immersion they can create. Generally, it follows that the more sensory inputs a simulator can synthesize for, the higher the immersive potential of a simulator. Immersiveness is important to provoke genuine responses in the participants[15].

Simulator research always has to negotiate between cost and the required immersion for any given research question. For instance if the focus is on reflexive behavior, a high fidelity simulator is required to provoke the required response [9, 23].

Simulators range in complexity from basic on screen simulators like City Car Driving or OpenIV[1] to very advanced facilities that also include the capabilities to create a felt sense of inertial motion. Examples of these high-end simulators are the NADS simulator at the University of Iowa [12] and Fords advanced VIRTTEX simulator[2]. However, these expensive and elaborate set-ups, are still only able to produce a fraction of the actual

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

motion one feels driving in the real world[10, 8]. More information on the importance of motion cuing can be found in Appendix: C.

VR-in-Car is set-up and run in a real car therefore, the motion felt by the participant is very realistic. At the same time, this method is much cheaper to set-up. The cost to equip a regular car with VR-in-Car is, at the time of writing about 5000 to 7000 euros. These costs may become even less when the used equipment will be more readily available. This is significantly less than even the simplest motion base simulator that start at about 50k€. Is the acquisition or renting of a research vehicle required, the costs are about the same as a simple motion base simulator[9].

2.2 On-road driving experiments

In on-road driving experiments, participants enter a mobile vehicle, that is often an instrumented regular car, which is driven through the the real world. This differs from on-road observational studies such as [11, 17] which observe without interacting with the drivers themselves. Past theoretical work that has analyzed the value of conducting research with users in naturalistic environments, have claimed that the benefits include that people have awareness of the physics, their own bodies, the environment, and their interaction[14].

Traditionally, on-road driving experiments or on-road tests have participants drive in a normal vehicle rather then an autonomous vehicle[18]. Given that researchers do not often have access to autonomous vehicles, this work uses a Wizard of Oz approach to create the illusion that the normal vehicle used in the experiment is autonomous. Prior work that has used this technique to create the illusion in two of three ways by hiding the driver [4, 24] or by controlling the vehicle by a hidden wire system [22]. Similarly, other studies have used a similar approach to investigate the interaction between pedestrians and AVS [21].

For general interaction and behavior related questions, on-road and simulator methods are a common choice. Each method also extends into different specialized areas to answer specific research questions. These specific versions are not covered here as they do not differ significantly from the already introduced methods. The new research platform combines some of the advantages of these existing methods in an affordable way, enabling more research on passenger-AV interaction and on questions that up until now have been difficult to answer.

Chapter 3

VR-in-Car as a research platform

VR-in-Car aims to combine the benefits of driving simulators and on-road experiments described above. In this hybrid approach, participants wear a head mounted virtual reality headset as the simulator component, while they are riding a regular vehicle that is simulated to be autonomous as the on-road component.

The following components are in line with driving simulator methodology - the environment that is perceived by the participants is simulated. Fake control surfaces and hand tracking complete the illusion of sitting in an autonomous vehicle. The following components are in line with the on-road experiments - the motion of the real vehicle is used to create the felt motion for the participant and an easy and cost-effective way to set-up the scenario for the tests.

The idea of this approach is based on work done by NASA on pilot training. Bachelder used similar fused reality to train helicopter aircrews [3] and work at the NASA Armstrong Flight Research Center[1] used fused reality to train pilots air refueling and landing sequences at a safe height.

Using virtual reality in the car is also in the automotive space not an entirely new idea. Hock et al. and McGill et al. demonstrated the use of VR in the car for entertainment purposes and to alleviate motion sickness [13, 19].

3.1 Advantages of VR-In-Car

Simulator research is based on the primes that participants need to suspend their disbelief while being in the virtual environment. Similar to watching a movie, the participant is expected to accept the virtual environment as their current new reality. It is highly likely that the more believable the illusion is, the more natural the participants' responses to

[1] https://www.nasa.gov/centers/armstrong/features/fused_reality.html

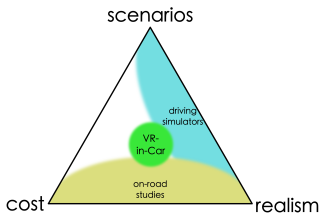

Figure 3.1: Methodological advantages of using VR-in-Car as a research tool kit.

the actions in the virtual environment will be. VR-in-Car meets the requirements for this type of simulator research on driving and interface design by creating an immersive experience for the participants by synthesizing or augmenting their sensory perception. The participants' experience can be broken down into the different sensory inputs this technology produces or uses:

Visual - Synthesized The view of the participant is completely computer generated.

Acoustic - naturalistic In the proof of concept implementation the acoustic experience was not augmented. So that only natural audio sources were present, e.g. engine - and road noise. Later versions of VR-in-Car could play additional sounds that are emitted from virtual objects through the car speakers or open-headphones to augment the already existing sounds.

Tactile - augmented The participants' hands are tracked and are visible in the VR environment. The interior of the virtual vehicle is closely modeled after the physical car. That also means that the steering wheel shape and position are similar. A calibration procedure ensures that the physical objects line up with the virtual objects.

Motion - naturalistic The physical car motion maps directly to virtual vehicle the participant sits in and sees in VR. The motion is hence limited to the driving abilities of the wizard.

The complete experience can be seen in Figure: 4.2 and Figure:4.5

VR-in-Car has three main advantages as compared to existing methodologies. First, in comparison to driving simulators it is a low-cost method to acquire and operate. Second, in comparison with on-road tests without a VR headset this method can be used to evaluate almost all traffic scenarios from normal city driving to critical highway situations. Third, the motion felt and the visual environment displayed are very immersive and close to advanced driving simulators or on-road studies. VR-in-Car aims to allow for an optimal trade-off between cost, realism and testable scenarios types as shown in Figure: 3.1.

3.2 Development Challenges

The main challenge in developing VR-in-Car was to use off-the-shelf VR display and sensor technology to create an implementation that can reliably be used to test human participants. This underlying concept made repeatability and ease-of-use a key factor in developing the technical components for this method.

The core functionality of the system is tracking the participant and the experiment car accurately and in a synchronized way to consistently mirror their behaviors in the virtual environment. How these design and implementation objectives were achieved is described in the following implementation sections

Chapter 4

VR-in-Car System Design

The VR system is made up of several different components that work together to create an immersive experience for the participant. The explanation is split into three parts: input, core and output. The input consists of mostly sensor technology that is used to measure actions in the real-world. The core keeps track of these changes in the virtual environment to then render out appropriate changes through the outputs like e.g. screens or Head Mounted Display (HMD) to the participants. The schematic layout of the related hardware components are depicted in Figure: 4.1.

4.1 Inputs

There are a few different input streams into the core that all contribute different pieces of information that are used to mirror the car's and the participant's behavior in the virtual environment. The car is tracked using internal and external sensors. The participants head motion and hands are tracked with off-the-shelf VR technology.

4.1.1 Car orientation tracking

An Inertial Measurement Unit (IMU) was used to track the orientation of the vehicle. Many different IMU types are available with different cost-benefit trade-offs. Picking the right sensor is crucial in making the system work. In this section we describe the integration and choice of IMUs for this implementation.

An IMU is commonly a combination of different Micro Electro Mechanical Systems sensors that are used to determine orientation of the device in three-dimensional (3D) space. Most IMUs that are available on the market use a type of sensor fusion like a Kalman filter to merge Accelerometer, Gyroscope and Magnetometer data into a quaternion orientation vector.

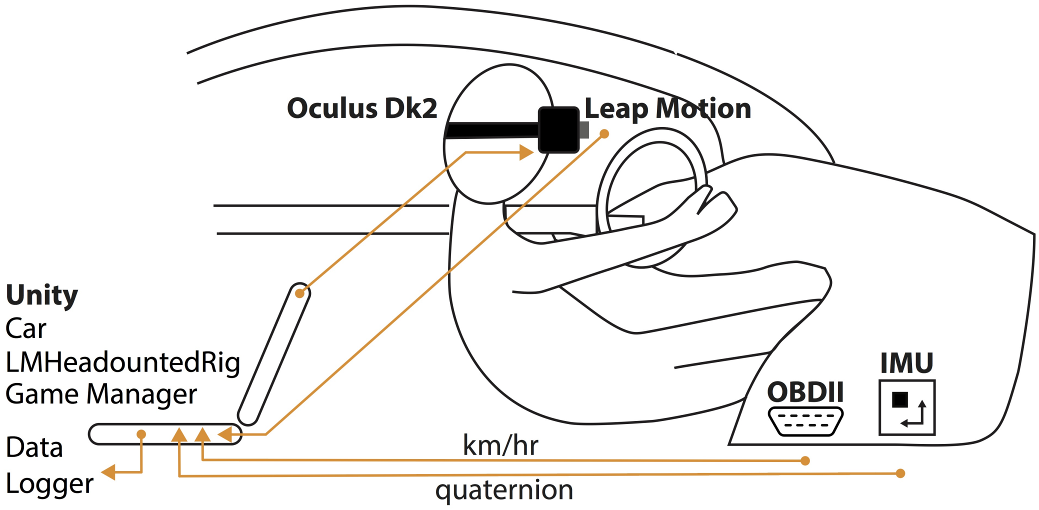

Figure 4.1: Sensor and Hardware diagram showing the placement and organization of the different hardware components. Credit: Dr. Wendy Ju

A variety of different IMUs exist all with different sensors and fusion algorithms. For the proof of concept implementation we ended up using an Mti-1 from Xsens. The evaluation process to pick this particular IMU is laid out in Appendix: C.1.

The IMU is mounted in the center console between the driver and the participant as close as possible to the center of rotation of the car but also as far away as possible from any metal. The quaternion vector send by the IMU can directly be used in the core to link the physical car's orientation to the orientation of the virtual car.

Marker Tracking and Drift Correction

An IMU is also used to track the orientation of the head of the participant. However, since IMUs are imperfect sensors, the orientation vectors of the head and the car will slowly drift apart. In other words, after some time the rendered view of the participant's HMD might look out of the virtual car window even though the participant is sitting straight (i.e. looking forward) in the car. This mismatch between the virtual representation and the real situation can induce severe visual-vestibular conflicts that can lead to simulator sickness, since the motion of the actual car no longer aligns with the motion of the virtual car. Several different approaches were implemented and evaluated to detect and correct for this relative drift of the sensor systems.

The first approach used ARToolkit's [1] marker tracking to track the head rotation relative to the car's orientation. The tracked rotation would then be used to compare and correct against the drifting IMU rotation. However, the light sensitivity of the camera and an unstable tracking algorithm caused this approach to not reliably correct for the drift.

[1] https://artoolkit.org/

Other algorithms and approaches, such as comparing the acceleration vectors between the car and the headset or LED tracking were explored. None, however, could deliver the necessary frame rate and accuracy to reliably correct for the IMU drift. For the proof of concept implementation this problem was circumvented by recalibrating the orientation vectors between the different conditions of one experiment.

4.1.2 OBD II and CAN-Bus

Another piece of important information to mirror is the car's motion is its speed. This information stream needs to be frequent, reliable and accurate. In general, serial buses in the car offer this type of information. The On Board Diagnostics Port II (OBDII) and CAN-Bus offer this information. In the proof of concept implementation the OBDD II port was used. Details on the CAN-Bus implementation can be found in Appendix: D.

The OBDII or On-board diagnostics port is a polled serial interface that is typically used for car diagnostics and emissions testing. The vehicle speed is one of the parameters that can be requested through this port. Its refresh rate and accuracy is lower as compared to the CAN-Bus. OBDII has an average data through-put of about 14.4KB/s and the speed value uses integers with KM/h accuracy.

4.1.3 User input

To further enhance the virtual experience, the user interface interaction consists of two parts.The first one being the *LEAP Motion*, which tracks the hands of the participant. This enables the system to render the hands of the participants in real-time in the virtual environment, and hence, it significantly supports creating the illusion of the virtual environment.

The second interactive component is a gaming steering wheel (Logitech G920). It is connected to the main computer. Its rotation is logged over time and is directly linked to the visual representation of the virtual steering wheel. The virtual steering wheel is depicted in Figure: 4.2 while its physical counterpart can be seen on the bottom right corner of Figure:1.1.

It is important to note is that in this proof of concept implementation, the participant was sitting physically on the passenger side while virtually sitting on the driver side.

Both input methods are also used to calibrate the view position of the participant in the virtual environment as the real world positions relative to the car are known.

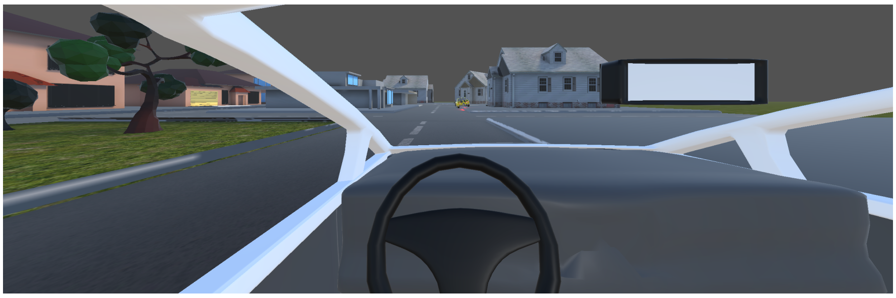

Figure 4.2: Visual appearance of the Virtual Environment.

4.2 Virtual Environment Core

The virtual environment is design and organized in Unity3d, a freely accessible game engine[2]. It combines the various data streams and mirrors the vehicle and participant in the virtual environment. Dedicated virtual reality add-ons are used to render this environment back to the participant. The different game elements are scripted in C#. The most important elements to enable the core functionality are:

UDP Bus manages two to three different threads. These threads receive receives the sensor information like speed and orientation over different UDP ports and makes them available as global variables to other game objects.

Car uses the orientation and speed information available from the **UDP Bus** object, to mirror the real cars motion and position. Additionally, it has a secondary camera, which renders a forward facing view to a texture that is compressed and sends out over UDP to the tablet application. This is used as the view for the wizard driver.

LMHeadMountedRig manages the main position of the VR-camera and is the reference point for the LEAP Motion tracked hands. This object keeps a relative position to the **Car** object and can freely rotate based on the HMDs IMU. This relative position is determined during the calibration process as described above.

GameManager keeps track of which environments and experiment conditions are loaded in. Furthermore, it manages a data logger (running in a separate thread) which samples in-game variables, such as the car's speed and orientation, and sends them out over a UDP port to an external logging program.

The performance of the complete system was not extensively profiled. The only profiling measure was the resulting frame-rate with the most performance hungry task being the wizard view camera streaming. Overall, around 60 frames per second was achieved, which is enough to create an immersive VR experience.

[2]https://unity3d.com

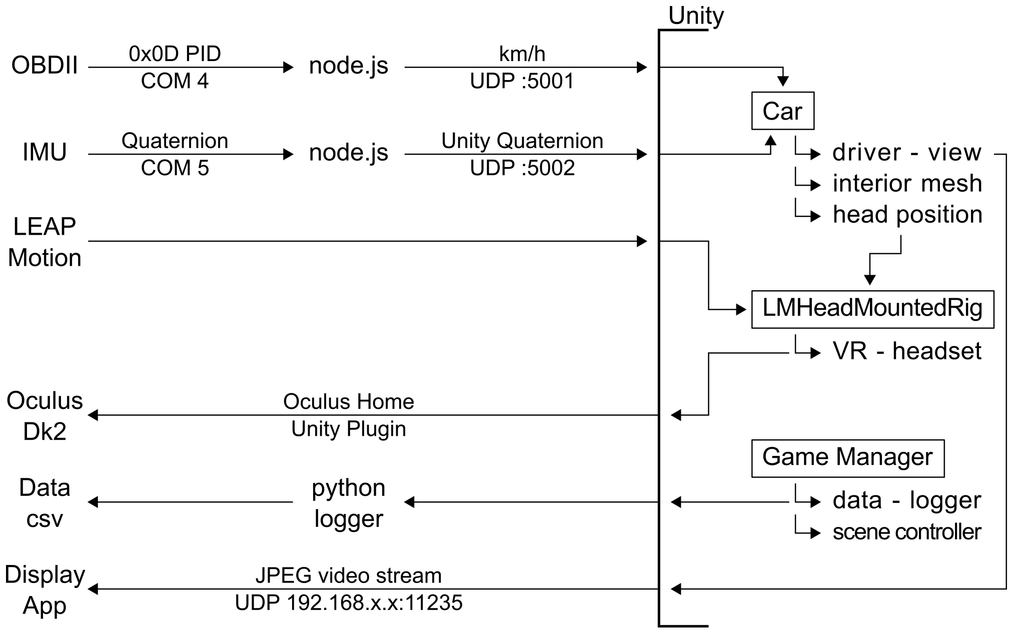

Figure 4.3: Software diagram showing what kind of information flows where.

4.3 Outputs

The main output of the system contains is the rendered virtual environment that is presented to the participant through the HMD. Two different implementations where realized. In the first implementation we used a combination of SteamVR and the OSVR headset. The second implementation used the OculusHome Unity plug-in and the Oculus DK2 as the VR headset.[3] An essential limitation in the implementation was the lack of any absolute tracking or on-the-fly recalibration. This issue is discussed in more detail in the future work section.

The other visual stream that was produced and streamed out of virtual environment was a forward facing camera. The program used JPEG compression to reduce the size and sends them over a UDP-port. This image stream was received by a tablet[4] that displayed the images. This tablet was mounted in sight of the experimenter driving the car. Due to performance limitations this system ran at a lower frame rate.

[3]These implementation details are likely not going to help a lot in a replication study as this technology, the hardware and associated SDKs are quickly changing and being updated frequently. A discussion about this aspect can be found in the conclusion.

[4]Galaxy Tab A

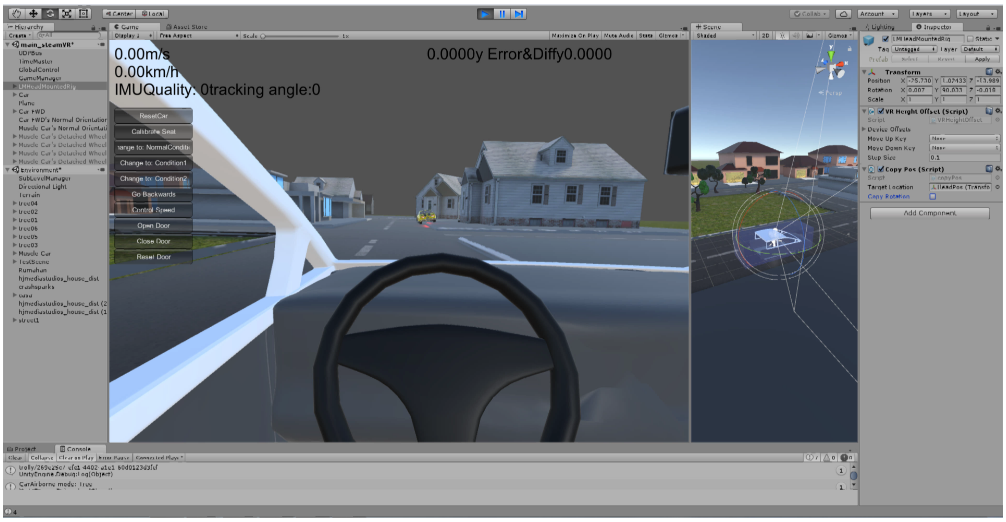

Figure 4.4: On the left side is the screen showing the perspective of the participant. on the right side a birds eye view on the scene. This is the experiment Wizard.

4.4 Data Collection

The data collection for this project involved several different parts. The values from the sensors as well as other information from the virtual environment were logged out of the game engine. Besides that we recorded 360° video and audio of the participants and the experimenter's laptop screen with in-game audio and the laptops microphone. The recorded laptop screen showed the view of the participant as well as a wizard interface for controlling the scene and the conditions.

The internal unity data was streamed over UDP to a Python program that combined different messages into one timestamped data log. Variables were logged with the speed of the frame rate and all share a common time code. Additionally, specific events were logged independent of the frame rate e.g. on button presses or certain interaction moments.

For the pilot experiments, we selected 25 different values to be logged. Most of these were position and rotation information from the different actors in the scene. Additionally, interaction information from the wizard and the gaming steering wheel from the participant were collected. An excerpt from the data recording can be found in Table A.1 in the Appendix A.

Each of these variables was logged at frame rate level between 14 to 60 times per second. The different data streams of video and data recordings included the start time and date in their filenames through which they can be associated with the corresponding participant data.

4.5 Testing set-up and support hardware

The rendering laptop, VR headset, sensors and interaction technologies were supported by a few infrastructure components that enable the system to run. The fact that the complete system needed to operate in a car complicated some of these issues[5].

Power was supplied to the gaming steering wheel through a DC/AC converter that was fed by the car's engine with 12V. Re-implementations of this study should include a 12V battery and a strong enough power converter so that the laptop can also be charged during an experiment.

Networking The different components needed to communicate through a fast and reliable network connection. A basic Wi-Fi router that was directly powered out of the cars power grid operated a local Wi-Fi. In this implementation, the laptop and the wizard's drivers tablet used this connection to stream the wizard's driver view. The hosted network was a standard 2.4GHz-802.11n Wi-Fi network.

Environment The area for the experiment needed to be carefully picked. A flat open space without obstacles is preferable (for more open research scenarios). For instance a black lake, airport runway or a flat paved parking lot. The proof of concept of the system was tested on an empty parking lot. A different option is to remodel an existing scenery and use the VR-in-Car strictly in that environment. This could be a suburban environment or a part of a highway. The parking lot used in the proof of concept implementation was not an ideal location as humps in the space meant that the surface was not perfectly flat. This surface feature was not matched in the virtual environment.

In general, the physical environment should be matched to the virtual environment and the requirements of the experiment. For more information on course selection please see Appendix E.

Car The vehicle itself did not need to fulfill any specific technical requirements. All normal production cars now-days have an OBD2 available that is used to send the speed information from the car. The other basic requirement was the availability of a 12V connector to supply the power system. The actual energy consumption should be calculated on beforehand to make sure not to stretch the car's energy provisioning would be stretched too much.

The system was deployed on three different cars: a Prius V, a right hand drive Jeep and an Audi A6. The implementation on the Prius worked particularly well due to the CAN-Bus access.

[5] Video explaining how the setup worked at the University of Twente. https://youtu.be/ZlXmFxDz17A

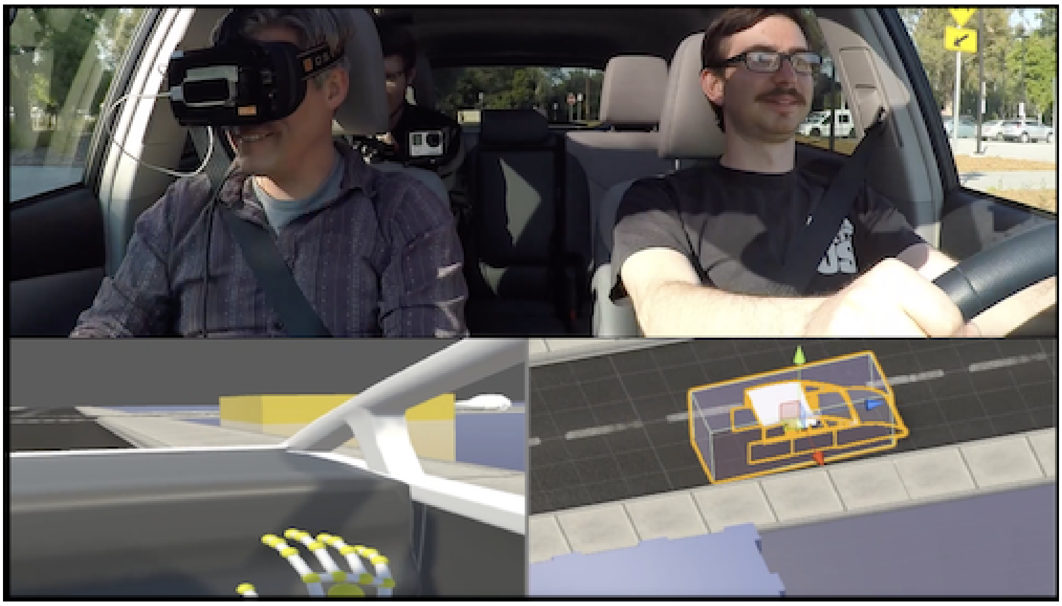

Figure 4.5: The top half of the picture shows the driver on the right, participant on the left, and experimenter in the back of the car. On the bottom left one can see the image the participant sees, on the bottom right a birds eye view as seen from the experimenter.

Chapter 5

Setup and Protocol Considerations

The operational context of this method is similar to running on-road experiments. Three aspects need to be prepared. First, physical course needs to be selected, second the vehicle with VR-in-Car needs to be prepared and Third experimenter driver needs to be trained.

One additional important requirement is the approval of the internal review board or ethics board as this research does human subject testing. The protocol for the proof of concept study was approved by the ethics board at the University of Twente.

5.1 Vehicles, Wizards and Participants

The setup of the experiment in the car was straight-forward. Conceivably this setup can be run in any sized car that can hold five people. However, it is strongly advisable to use a four-door car to assure easy access for experimenter.

During the experiment three people(+ equipment like cameras, laptops and tablets) were in the car. First, the experiment wizard sat in the back with the laptop running the VR-in-Car system. The experiment wizard needed to also monitor the experience and well-being of the participant. Second, the experiment driver who sat in the car's driver seat with a tablet showing the virtual environment. This screen was placed where normally a navigation screen would be placed. The last person is the participant who is sat in the passenger front seat wearing an HMD and with a gaming steel mounted in front of them.

5.2 Driver Instructions/Training

The wizard driver needs to be trained for reasons of safety and to create a convincing, immersive and consistent driving experience for the participants.

Safety is the primary concern when running these experiments. To that end, the driver was trained to be able to momentarily evaluate their actions in VR before focusing back on the road. Additionally, t training was also important so that the wizard driver could act consistently as the autonomous system of the vehicle. This also included consistent acceleration and steering behavior. The tasks for the experiment driver can be broken down into the following three prioritized steps:

1. Check the path of the vehicle in the real world.
2. If the participant grabs and turns the steering - copy that motion.
3. Follow the virtual environment. This can be to follow a street, a car in front or to mimic a specific driving style.

The path of the vehicle in the virtual environment was prepared as part of the experiment procedure and discussed with the driver before practicing that path several trial runs. After the training, the driver was familiar with the path, conditions and occurrences that could happen in the virtual environment, so that he or she could focus on the road during the experiment.

5.3 Motion Sickness

As discussed in the related work section, motion sickness is a serious issue for simulator studies. There are a few things that can and need to be done to ensure a successful study execution and participant well-being.

Participants should be screened and excluded from the study should they have epilepsy and/or are prone to simulator sickness in VR or simulators. Additionally, the experiment protocols should include clear instructions on what to do in case a participant gets motion sick or starts to feel generally unwell.

During the experiment, the experimenter needed to assure that the frame rate of the VR environment was high enough and that the calibration between participant and car was still good. Recalibration can help combat this issue. In the validation study, the participants orientation and position was recalibrated in between the different experiment conditions.

Dealing with motion sickness, driver training and test preparation are key practical aspects to successfully use VR-in-Car as a research method. In the following section, we will examen how these procedures and the technical implementation were applied in a proof of concept validation study.

Chapter 6

Validation Study

The novelty of the VR-in-Car approach requires that it gets validated to assure that it can be used to produce meaningful data and results.

The full evaluation and validation of a new research method requires several different studies that evaluate the different important aspects of this new method. In a first step, the validation study evaluated whether or not the desired experience of driving in an autonomous vehicle could be elicited with this approach. The results are based on the qualitative experience of participants that used VR-in-Car. The

This study is only a first initial step towards validating this new method. Future evaluation may include pilot experiments or comparative studies where the same situation is tested with this method and other related methods e.g. a static driving simulator.

6.1 Participants

Six students and staff(4 male, 2 female), selected through convince sampling. (Age range from 20s to 40s) from the University of Twente participated in the pilot evaluation study.

All participants were screened to assure that they were not prone to epileptic seizure and indicated to not have had previous motion sickness experiences in virtual environments. In general, participants did not have much experience with VR. All participant where tested individually.

6.2 Virtual Course Scenario

The virtual environment consisted of a simple suburban environment, with houses, trees and a car parked on the side. A bird's eye view of the complete scene can be seen Figure 6.1.

Figure 6.1: Image showing a bird's eye view of the complete virtual environment. The participant's car starts on the bottom left side arm and drives around the center building three times.

In all experiments, the vehicle started the bottom right road of the virtual environment, as indicated in black in Figure 6.2. All experiments also had the car follow the same path, circling around the house in the center (see Figure 6.1) as indicated in green in Figure 6.2. Each run consisted of three drives. After one circle i.e. one condition the car would back up into the starting position for recalibration.

Normal condition The car drove around the block with no other entity in the virtual environment interacting with the participant or car.

Open Door condition The car drove around the block and encountered a second car that was parked on the side of the road. The driver side door of the parked car opened in the way of the participant's autonomous vehicle right before it would pass by.

Cutoff condition During the drive around the block the participants car would be cut off by a second car that quickly drove past. Sometimes, if no action was taken by the participant it would hit the participant's car. This encounter happened at the second turn the participant's car would take.

The different conditions are marked in Figure 6.2 green for the normal condition and yellow for the remaining two conditions. The participant were told the focus of the study was on testing autonomous car behaviors to create a convincing story for their participation and for motivating the different conditions. The participants' reactions and behaviors towards the autonomous vehicle are, in this study, not further investigated. However, the design and structure of this study could be used as a starting point when using VR-in-Car to address these aspects.

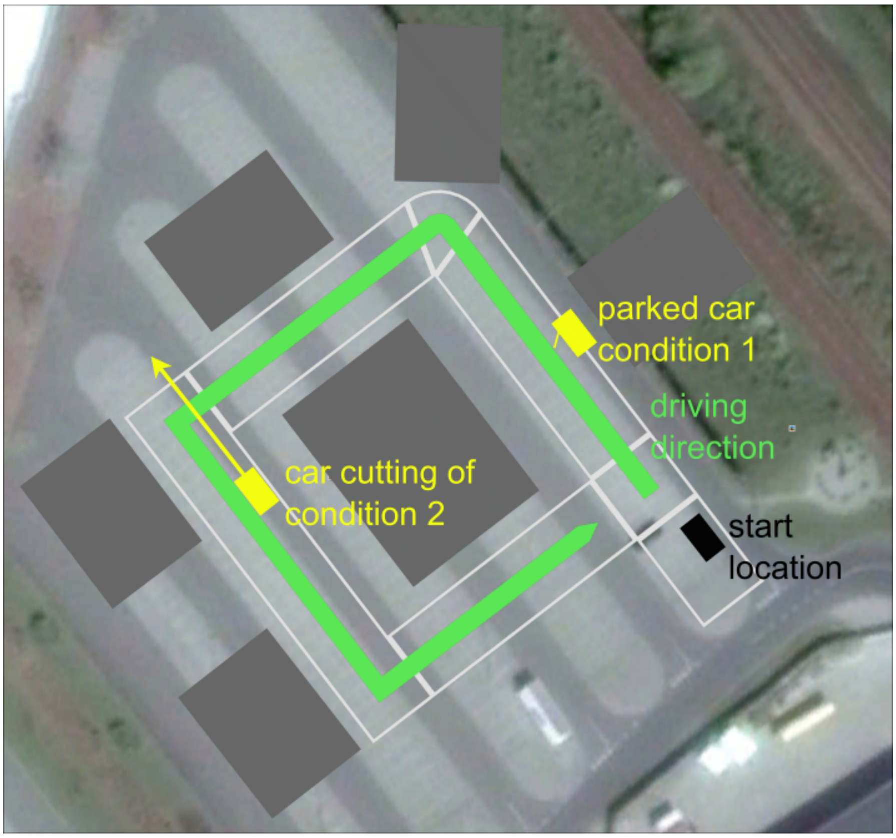

Figure 6.2: The virtual course overlaid on satellite map obtained from Google Maps. The black box is the starting location, conditions one and two are marked by the yellow cars and the white outline is the shape of the road. The gray boxes indicated the approximate locations of buildings in the virtual scene.

6.3 Physical Course

The virtual course spanned a space of 45 by 26 meters, the physical space that was used was 74 by 41 meters large. The padding between the virtual and physical space was necessary as a safety margin and to leave enough room to avoid obstacles. The parking lot was selected after surveying for different open spaces on Google maps in and around the University campus. In the end, the choice fell on the parking lot in front of the local ice rink[1].

All experiments where run in the month of August in which the ice rink was still closed. The only other traffic that appeared sometimes during the test were driving schools that practice driving. They did not, however, disrupt the experiments.

[1] WGS84 location: 52°14'25"N 6°49'56"E

6.4 Experiment Procedure

The experiment started with the experimenter introducing the experiment task with a written text (see Appendix B.2) to the potential participant. If the participant understood the information and fall within the screening parameters she or he would be instructed to read and mark the consent form.

After the participant read the information sheet, and gave consent to partake in the experiment, he or she would be introduced to the experiment driver. Then participant, wizard and experiment driver entered the vehicle and drove to the starting point of the course.

At the starting point, the gaming steering wheel was installed in front of the participant. After that, the HMD is handed to the participant, who was instructed to strap it to their head. At this point, the experimenter started following the protocol to set up and run the experiment as laid out in Appendix B.1.

Prior to the experiment, a calibration phase was run, which required the participant to look forward and to put their hands on the steering wheel. This calibration took 10 seconds during which the participant should move as little as possible.

The participant was given some time to get acclimated to their new visual environment, which is a standard procedure for this type of head mounted VR research. This step was also necessary to let the participant feel comfortable. Typically, a car is an environment which requires attention and oversight. In this experiment, it was important to make sure that the participant felt comfortable enough to fully focus on the virtual driving experience.

After the acclimatisation phase, the task instructions were read out-loud to the participant. Then the actual experiment starts. The experiment driver drove around the trained course across the parking lot. This course lead the virtual car around the center virtual house three times, each condition once as described in Section 6.2.

Once all conditions were completed the participant was asked to remove the HMD followed by a short pause to let them adjust to the real environment.

The experiment concluded with a semi-structure interview (steps 14-22 in Appendix B.1), which was audio and video recorded. On the drive back to the pick-up location the participant had the chance to ask and discuss any questions they might have about the experiment.

This experiment was approved by the Ethics board from EWI on the 24th of August 2017.

The total duration of the experiment was approximately 30 minutes for each participant.

6.5 Analysis

The analysis of this study was based on the responses to the semi-structured interview at the end of the experiment. The transcribed responses were compared to find common themes, strong and weak points, as well as comments regarding the quality of the experience.

The analysis focused especially on the motion experience and potential motion sickness. Of particular interest was also if the participants were able to suspend their disbelief and trust, and if they acted like they were in an autonomous vehicle.

This open type of semi-structure interview was important in order to identify potentially hidden issues or inconsistencies that could threaten the integrity of the experience or methodology.

Two out of the six responses were lost due to power failure in the recording equipment. These responses could not be included.

Chapter 7

Results

The results of the validation study are based on the post test interviews with the participants. While not generalizable, they can still give an indication on how well the system performed in creating the illusion of driving in an autonomous vehicle.

The results showed that most (5 out of 6) participants had an easy time suspending their disbelief, to accept the VR environment as their new surrounding and that none of them felt sick or unwell during the experience. Furthermore, the successful completion of the validation study indicates that this method can be safe and usable.

7.1 Motion Mirroring and Orientation

The motion matching or mirroring is the essential part of this new methodology to enable the simulated but immersive experience for the participant. The mirrored motion needs to function well enough to add to the immersive experience to reduce the induced (simulator) motion sickness.

The motion perception of the participant was therefore directly addressed in the post-test interview. The results showed that none of the participants felt motion sick during or right after the experiment. One participant mentioned that

> "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."
> Mid 20s, Master student, male

This popping in and out of the car the participant mentioned happened during the calibration phase were the view point of the participant was moving relative to its hands. This typically should not happen and will not happen if the procedure is correctly followed.

Generally, the matched motion between the physical and virtual car was perceived well by the participants and functioned sufficiently well to not induce motion sickness.

That said, most participants (5 out of 6) reported feeling unwell about one hour after the experiment. Why that happened is not particularly clear and will be addressed in the discussion section.

For most participants, the motion mirroring was initially a strange or new experience when the experiment driver started driving. However, this new experience was accepted relatively quickly to a point where only one participant mentioned the motion of the vehicle during the experiment.

During the interview participants were specifically asked how they perceived the motion of the vehicle. The answers to this question were very different between participants. Some commented directly on the motion of the vehicle in virtual reality:

> "It felt like the car really turned, it really turns like in real life and virtual reality." Mid 20s, Bachelor student, male

Some other responses addressed the driving behavior of the virtual autonomous vehicle.

> "Smooth a bit reckless at points. Yea but other then that, it was ok." Early 20s, Bachelor student, female

And while the motion of the virtual vehicle matched the motion of the physical car the surface shape of the physical and virtual world were not exactly the same. Since the parking spots that are slightly elevated on this testing ground and this was not translated to the virtual surface. This inconsistency was noticed by some participants.

> "I liked the physical motion. It wasn't as in sync as it should be I guess. I was quite impressed that the bumping of the car was also translated to my simulation." Mid 20s, Master student, male

While this participant negatively noticed this disconnect between physical and virtual world some other did not seem to notice.

> "It was really interesting to feel the real road, which feels real in the VR world where everything is fake." Mid 20s, Bachelor student, male

Another important aspect is disorientation that one participant felt during the experiment. the participant felt disoriented after each condition to the extent that he had to shortly remove the VR headset. He explained that lifting the headset was necessary for him to regain a sense of orientation in the physical world. This indicates that the participant was not fully immersed in the environment.

7.2 User Experience

After strapping on the HMD, participants had a few moments to get used to the virtual environment. Most participants were surprised by their tracked hands, which was reflected in extensive observation and turning of their hands. For many, the next logical step was to grab the virtual steering wheel that was right in front of them. This was a useful procedure on two levels. First, the hands needed to be on the steering wheel for the calibration and secondly, because it gave the participant a direct way to interact with the virtual world, helping them to accept this new environment.

When the car started driving most participants were initially surprised about the motion of the virtual car, but all participants quickly accepted this matched motion. Directly after the initial surprise, they started to focus on events and objects that were present in the virtual environment.

Even though all participants had been informed that the wizard driver would be driving the car still most of them (five out of six) grabbed the steering wheel to intervene at some point during the experiment. Three of them steered only at specific sections when it was necessary whereas the other two participants steered almost constantly.

In some cases, the design condition indeed elicited the reflexive reactions as intended by the condition from the participant. In reaction to the second condition a participant reported that:

> "The second car really that just came from the left by surprise. That was really a reflex to grab the steering wheel." Mid 20s, Master student, male

Two out of the six participants reacted to either of the scenarios by steering away or by mentioning it to the experimenter. However, this behavior was not recalled during any of the other interviews.

7.3 Sound

Sound was in this implementation a naturalistic modality. The main sound came from the engine and car itself. While as mentioned above other cars, especially driving schools, were present, they did not come close enough or were loud enough to be registered inside the car. Participants did not explicitly comment on the sound.

7.4 Feedback

Participants were encouraged during the post-test interview to elaborate on aspects of the experience that they did not like or appreciate. All participants had different comments about what they did not like. Besides the aforementioned disorientation and VR headset quality two critical comments focused on aspects of the VR-in-Car system.

One participant mentioned that:

> "I am missing the pedals. After the last round [the experiment driver] was parking very close to the other car and I noticed I was pressing my foot down. Just to break. Reflex of pressing my foot down." Mid 20s, Master student, male

The interactions that the participants referenced happened all in the virtual environment. This shows a level of immersion but also at the same time demonstrating a limit of the current proof of concept implementation.

Another participant mention the environment and specifically the weather in the virtual environment.

> "The environment was not necessarily pleasant to go through, in." Early 20s, Bachelor student, female

She repeated this point at the last open question of the interview. She advised to:

> "Put up sunny weather next time its really dark and it changes the mood."

Both comments pointed towards the rendering, visual quality and specifically lighting conditions of the virtual environment and how she did not feel particularly comfortable being in that environment.

However, in general, the participants reported an engaged experience. Especially the key factor of motion mirroring was positively noted and clearly helped some participant to suspend disbelief and act and respond as if they were in an autonomous vehicle.

Chapter 8

Discussion

The results as they have been described above are based on the subjective impressions from the participants reported during the post-test interviews. In the following sections we will discuss these findings and put them into context of this method and future work.

8.1 Participant Experience

From the interviews several limitation, or points of improvement of the system became apparent.

8.1.1 Graphical Fidelity

The most common topic that came up was the graphical fidelity of the simulation. Three out of six participants mentioned this as an important point. The fidelity of the graphics was indeed in this context somewhat limited as can be seen in Figure 6.1. Most of the houses are more or less flat shaded boxes with not a lot of detail.

This is an issue that can easily be improved through different strategies. One approach could be to improve the overall lighting of the scene. Recently added features to Unity are baked lighting, ambient occlusion and dynamic lights. These techniques can add a lot of visual realism to a scene by making objects blend together into one visual representation.

A different approach could be to remodel the houses and roads in one consistent style. In the proof of concept implementation the models are based on a variety of different styles from realistic architectural to cartoon-like houses. A consistent model catalog would help to create a believable environment, even if it is not photorealistic.

8.1.2 Motion Sickness

An important issue that arose after the experiment was the delayed onset of motion sickens for five out of six participants. The participants were asked about their well-being during the interview but no participant reported feeling unwell or motion sick at that time. However, most participants reported a slight sense of motion sickness about one hour after the experiment was over.

This delayed onset of the motion sickness is a phenomenon that cannot yet be explained based on the data that was gathered during this test. This point needs to be further investigated before this method can be used for longer form studies. A first simple way to investigate this issue would be by consistently monitoring the participant after an experiment with VR-in-Car is complete.

8.2 Technical Improvements

A simple improvement would be the addition of control paddles (accelerator, clutch and break). In the version that was tested during the user test only the steering wheel was available as a control surface. However, at least one participant noted the missing paddle as he tried to stop the car at one point during the experiment.

The IMU drift issue as discussed in section 4.1.1 needs to be addressed with a more robust solution. Different technologies for marker tracking and other approaches need to be evaluated to allow for longer form studies that don't allow for frequent recalibration. An ideal solution would be to fuse the different inertial measurements in the tracking algorithm for the headset. The OpenSourceVR (OSVR) platform would be suitable for such a modification as the code is available.

In general, performance improvements would be desirable to create a more fluid environment and to rule out lower frame rates as a cause for simulator sickness. in the current implementation the most time consuming task in each frame is the compressing and sending the separate camera view for the experiment driver. This process can be optimized by synchronizing these tasks with the rest that ism happening on the GPU. This has been demonstrated how such an optimization can work in Unity[1]. In general however, a higher performance laptop and separate logging computer would also improve the performance.

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

Chapter 9

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 work on this method. While the aforementioned technical improvements focus more on extending the participants experience the main focus of future work should lie on validating this new method.

Further validation is an essential next step to establish VR-in-Car as a research method. Especially, the comparison to existing simulators and simulator research is an important step in establishing VR-in-Car as a research method. Further development should also look at the data logging stream, integration of higher quality sensors, and a streamlined data evaluation. Additionally, it would be worthwhile to develop a quantitative measures for simulation quality, e.g. through measuring the orientation drift of the car over time.

Chapter 10

Prospective Applications

VR-in-Car presents a new method to investigate human responses to AV related behaviors and designs in a realistic and immersive way. The combination of immersion and low-cost implementation enables this AV of research in a more diverse setting than previously possible. In the following section, the different new application areas are explored that can be addressed with this new evaluation methodology.

10.1 Autonomous Vehicle Design

In traditional car design, the car interfaces for e.g. media and environmental-controls have been as simplistic and clear. Buttons with clear functions are optimized for cost reduction and clarity in the interface. AVs bring a new dimension to the design consideration as these interfaces suddenly also become an important contact point for the communication between the autonomous technology and the passenger. This means that the evaluation of these interfaces becomes more context dependent and shifts from clarity and safety to entertainment and trust building.

The VR-in-Car method allows for rapid prototyping and evaluation of different interface designs in safe as well as critical traffic environments. These new types of interfaces need to be usable to understandable in any traffic sitation.

10.2 Human Behavior in Autonomous Vehicles

Once drivers are asked to relinquish control to the autonomous technology these need to have a minimum level of trust in the system to drive the car safely through the traffic environment.VR-in-Car can be used to develop trust building tasks and behavioral patterns for the AVs. One simple but important example behavior question would be:

How soon before a turn should the AV switch-on the indicators?

These interactions between the passenger, the AV, and other traffic participants can easily be evaluated in this new proposed method.

10.3 Inertial Motion as signaling for AVs

The felt inertial motion of a vehicle is an important sensory cue that can have great influence on how safe a passenger feels. Additionally, the inertial motion of an AV could be used to e.g. signal its intent. Accurate and flexible motion cuing is an essential part of VR-in-Car. Trained wizard drivers can use different driving styles to induce the felt sense of different control parameters in the AV.

10.4 Handover scenarios

Partially autonomous vehicles are likely going to be introduced before fully autonomous vehicles become available. These cars are capable to operate autonomously in only a certain type of traffic environments e.g. highways. The use of these vehicles implies the occurrence of handover scenarios. In these scenarios, drivers need to relinquish and after the end of the autonomous period regain control of the vehicle. These types scenarios are often critical, especially if they happen unplanned. This new method can be used to evaluate how drivers respond in a handover scenario.

10.5 Design or entertainment and secondary activities

Secondary tasks like entertainment or work are expected to happen more frequently and become the main occupation during the ride in an autonomous vehicle. The interface design on how these tasks could be incorporated is another design aspect for which VR-in-Car can be used as a prototyping and evaluation method. Especially, video games and video screen can easily be implemented in the virtual car environment and tested with users directly.

Chapter 11

Conclusion

New requirements to rapidly develop and evaluate AVs interface designs, and advances in VR have lead to the proposition, implementation and validation of a new method for in car research. VR-in-Car utilizes modern VR toolkits to create an immersive environment in which behaviors of AVs in different traffic scenarios can be tested with human participants.

It combines established on-road and simulator methodologies to create, for the participant the illusion of driving in an AV while in realty the car is driving by an experimenter. The multi-modal experience includes among others visual, acoustic, tactile and vestibular motion cues.

The validation study of the proof of concept implementation produced promising results and points towards aspects that need to be improved to create a fully functioning and reliable evaluation tool. Future work should address the graphical fidelity and the sensors' drift.

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Appendix A

Data Collection Snippet

Table A.1: Example data excerpt from one of the user validation studies. Showing the time stamp and rotation and position of the participant VR camera.

time	CenterEye Anchor-xPos	CenterEye Anchor-yPos	CenterEye Anchor-zPos	CenterEye Anchor-Qx	CenterEye Anchor-Qy	CenterEye Anchor-Qz	CenterEye Anchor-Qw	UDPBus -CANSpeed
33.1060	-0.08095084	-0.0205598	-0.02973895	-0.1169599	0.5007497	-0.02769995	-0.8572064	0.6905600
33.2354	-0.08055592	-0.02031492	-0.02936840	-0.1155024	0.4986092	-0.02695162	-0.8586743	0.6905600
33.37512	-0.08027087	-0.02009382	-0.02921532	-0.1150438	0.4967721	-0.02627926	-0.8598207	0.6905600
33.49089	-0.07904724	-0.02037172	-0.02846303	-0.1168476	0.4847208	-0.02362210	-0.866506	0.690560
33.61824	-0.07701690	-0.02003012	-0.02618088	-0.1158988	0.4672449	-0.02218239	-0.8762177	0.8632000
33.73357	-0.07449994	-0.02008322	-0.02546967	-0.1213208	0.4322064	-0.02299458	-0.8932805	0.8632
33.87788	-0.06687431	-0.02030293	-0.02021930	-0.1224712	0.3277334	-0.0342998	-0.9361704	0.8632
34.01057	-0.0425495	-0.02247774	-0.00582948	-0.127713	0.08062697	-0.01535903	-0.9884091	0.8632000
34.11627	-0.01841046	-0.02243997	0.003451466	-0.1199094	-0.07128521	-0.01002450	-0.9901715	0.8632000
34.24910	0.01168845	-0.02192903	0.01192851	-0.113892	-0.09755548	0.004145067	-0.988683	0.8632
34.37261	0.01581646	-0.0204647	0.01330119	-0.09379995	-0.068815983	0.000719485	-0.9932096	0.8632

Appendix B

Experiment Documents

B.1 Procedure

The introduction:

1. They put on the VR-Headset
2. Let them see their hands and look around.
3. "Ok, Please look straight forward now and put your hands on the steering wheel. We need about 10 seconds to calibrate your position so please hold still!"
4. "Ok good!, Now can you shorty describe what you are seeing, where you are?"
5. ...the participants describe their experience...
6. "The autonomous car is now going to drive you around the block, just so you know it might fail in some cases so you maybe have to correct the cars path."
7. Drive the first round (Normal)
8. When stopping. Good Now we need to quickly re calibrate and reset so Just close your eyes for a moment.
9. Drive the second round (Condition1)
10. When stopping. Good Now we need to quickly re calibrate and reset so Just close your eyes for a moment.
11. Drive the third round (Condition2)
12. "Now we are done! so you can take the VR-Headset of."
13. –short break– to let the participant arrive back in Reality

14. Can you explain in your own words (shortly) what you experienced.
15. Did you notice a car rushing by or crashing into you?
16. Did you see a car door opening from a parked car?
17. How did you experience the motion of the car?
18. What did you like about the experience?
19. what did you not like about the experience?
20. How nauseated do you feel right now?
21. Do you feel unwell in any other way (related to the experience?)
22. Is there any thing you'd like to add, let us or mention?
23. ——End of experiment—-
24. Thank your time and while we are driving back is there something you would like to know from us?

B.2 Participant recruiting text

Hello, I am looking for participants for my research project. It focuses on Autonomous Vehicles and how passengers and Autonomous Vehicles will interact in traffic in possible future scenarios. The experiment will take between 30 to 45 minutes.

If Yes then:

There are three requirements:

1. Do you have a drivers license?

2. Have you been in a traffic incident that still affects your capabilities to operate a vehicle normally in a normal traffic environment?

3. Have you used/been in Virtual Reality before and if so did you ever feel unwell using it, specifically nausea or epilepsy?

3a. If this does not apply did you show any of these symptoms when playing a video game?

Appendix C

Motion cuing

Motion cuing tries to address the visual-vestibular conflicts that can occur if the visuals i.e. what the person is seeing does not align with the motion information received by their vestibular system. For head mounted Virtual Reality application the head motion has to be well measured and applied to the rendering so that it does not cause this conflict[1].In complex driving simulators this is done through the motion base, that moves the participant and possible the car in which their are situated. Tuning the control of a simulators motion platforms has been the focus of much prior work [16, 10, 5, 7, 6]. And has also been identified as crucial to invoke more genuine driver responses[20].

C.1 IMU evaluation and testing

For this project several different types were used to improve the performance for the system. There are various performance measure among which IMUs can be evaluated there are primarily two that are important for this project.

First, the refresh rate. Typically one would want to update the orientation of a tracked object at about 1kHz refresh rate. However, in this example 100Hz appeared to be a high enough refresh rate for an accurate tracking of the vehicle. This is likely due to the fact that the vehicle does not typically make fast orientation changes that would go unnoticed in a 100Hz sampling rate.

Second, the yaw drift. Yaw is the rotational axis that is normal relative to the ground plane and with that a reversed gravity vector. The fact that it coincides with the gravity vectors makes it particularly difficult to track as there is no good reference for it. Roll and pitch can both be referenced against the gravity vector. This means that the yaw rotational axis is purely integrated based on relative measurements and not referenced over time in most lower end IMUs. Some IMUs attempt to reference yaw based on earth magnetic field, however these sensors are often not accurate enough to do that reliably especially when deployed inside of a vehicle made out of metal.

Five different IMUs where experimented with two of them stood out and performed well enough to track the cars orientation reliably. These IMUs were the BNO055 from Bosh and the MTi-1 from XSens. For future projects and implementation we would strongly advice to get better quality orientation tracking systems like the MTi-300 form XSens. They feater active yaw stabilization to further reduce or eliminate the yaw drift. The IMUs that did not perform well enough to map the motion where the LSM9DS1[1], the Razor IMU M0[2] and the UM7-LT[3].

[1]https://www.sparkfun.com/products/13284
[2]https://www.sparkfun.com/products/14001
[3]https://www.pololu.com/product/2763

Appendix D

CAN-Bus implementation

The CAN bus, which is only accessible for some cars, is a car internal data network where important operation information is shared between different components of the car. E.g. the Anti-Lock Breaking System(ABS) often use the individual wheel speed and other information through the CAN-bus to determine if ABS needs to be engaged. CAN bus is a low-level protocol its data rate can be as high as 1Mbit/s. The accuracy depends on the car manufacturer in the example implementation with a PriusV the speed was reported in 10m/h steps. Therefore, the CAN-bus should always be used if it is accessible. This implementation was used in the Prius V setup at Stanford University.

Appendix E

Course Selection

The underlying goal of the system is to enable the participant to feel the real motion during a drive with this VR in car system. This, however, implies that there is a physical space necessary emulate these motions.

Depended on the scenario that is to be tested two options are available. The first option is to re-create a the physical test environment like e.g. a highway entrance or suburban environment in the virtual environment. The behavior of the virtual car can then follow the physical car. This approach works best for primarily secondary or tertiary tasks evaluation of the driver/passenger, meaning for non-driving related interface and behavior questions.

The second option is to execute the study on an open, empty and paved area. These can be found in big parking lots close to stadiums, concert halls or other event locations. These parking spaces are often deserted during the day. Other options would be a designated research area like General Motors black lake facility or a disused runway. This option gives the most freedom regarding the scenario and the repeatability since these space are typically empty hence the wizard driver is free to steer the vehicle more freely without having to worry about other drivers or obstacles. The main limitation for running experiments in e.g. a parking-lot is the physical size and obstacles like light poles. The virtual world and the path vehicle need to be adapted to this limitation. In most cases it is best to measure out the boundary conditions of the parking lot, then to design the experiment with in that information and to finally test and readjust the design to match to any limitations.