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Towards Automotive Augmented Reality

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Zusammenfassung

Die Projektion virtueller Darstellungen in die Realität via Augmented Reality (AR) hat das Potenzial, neuartige Fahrerassistenzsysteme mit sichereren und intuitiveren Nutzerschnittstellen auszustatten. Die Menge an Blicken auf fahrzeuginterne Displays kann reduziert werden und ermöglicht so einen höheren Grad an Aufmerksamkeit auf die fahrrelevanten Geschehnisse in der Umgebung. Beziehungen zwischen Objekten im Umfeld des Fahrzeuges können direkt durch AR visualisiert werden, ohne dass der Nutzer zwischen räumlichen Bezugssystemen wechseln muss. Die vorliegende Dissertation befasst sich mit den Anforderungen die bei der Entwicklung von AR Assistenzsystemen auftreten.

Der herkömmliche Entwicklungsprozess von Fahrerassistenzsystemen in Fahrsimulatoren wird analysiert und mit neu entwickelten Lösungen, teils durch Technologie der AR, unterstützt. Ein statischer Fahrsimulator wird erweitert, um als sogenannte Rapid Prototyping Umgebung für ein breites Spektrum automotiver Systeme zu dienen. Um räumliche Beziehungen im Fahrzeugumfeld zu analysieren, wird ein Subsystem für Kontextanalyse und für Schlussfolgerungen über räumlichen Sensordaten implementiert und in die Rapid Prototyping Umgebung integriert. Zusätzlich ermöglicht eine weitere Komponente mittels eines getrackten Modellautos die Erzeugung realitätsnaher Verkehrsszenarien in virtuellen Umgebungen.

Es werden neue Ansätze für AR Anzeigekonzepte entwickelt und in Nutzerstudien evaluiert. Der Fokus liegt auf ambienter Informationsdarstellung und auf zeitoptimierten Reaktionen von Fahrzeugführern. Eine AR Anzeige für die Darstellung der Bewegungsdynamik des eigenen Fahrzeugs minimiert die Notwendigkeit für Warnungen in letzter Sekunde. Bei zeitkritischen Kollisionswarnungen führt ein AR System die Aufmerksamkeit eines Autofahrers hin zu drohenden Gefahren. Die Evaluierungen der dazu entwickelten Konzepte zeigen unter anderem, dass die Anwendung von AR Reaktionszeiten reduziert und die mentale Arbeitslast nicht zunimmt.

Die Arbeit beschließt mit der Beschreibung eines weiteren Systems, das ermöglicht, AR Präsentationen im realen Umfeld zu erleben. Dieses System legt die Grundlagen, um AR Assistenzsysteme in echte Autos zu portieren, wenn Head-Up Display- und Sensortechnologie die geforderten Bedarfe erfüllen.

Abstract

Projection of virtual presentation schemes into the reality via Augmented Reality (AR) has the potential to equip novel driver assistance systems with more intuitive user interfaces. Information presentation through AR reduces the number of glances towards in-car displays, thus enabling higher degrees of attention towards the environmental events. Spatial relationships between objects in the car's environment can directly be indicated through AR without enforcing the user to switch between different frames of reference. This thesis examines issues which arise when such assistance systems with AR are developed.

The common development process of such assistance systems in driving simulators is analyzed and facilitated with new solutions, which partly incorporate AR technology. A fixed-base driving simulator is extended to serve as a rapid prototyping environment for a broad spectrum of in-car systems. To analyze spatial relationships of the surrounding of the car, a subsystem for context analysis and reasoning on spatial sensor data is implemented and incorporated with the rapid prototyping environment. An additional system enables creation of realistic traffic scenarios in virtual environments using a tracked miniature car.

This thesis also develops new approaches for AR presentation schemes and evaluates them in usability studies. An AR presentation scheme showing the physical behavior of the own car minimizes the need for last second collision warnings. For time-critical collision alerts, an AR system guides the attention of a car driver towards imminent dangers. The evaluations of the concepts indicate, among other things, that the application of AR reduces reaction times and that mental workload is not increased.

The thesis concludes with another system enabling the examination of AR schemes in real environments. The system also enables porting of AR assistance systems to real cars when Heap-Up Display and sensor technology are able to provide the demanded needs.

Preface

In 2002, I had the lucky opportunity to participate in a project on the subject of Augmented Reality. I wrote my diploma thesis in the context of this project in Augmented Reality. Since then, I have been fascinated by the subject: a technology offering great potential, but also a multitude of research problems.

Starting my doctorate program I had to face even more interesting problems. Investigating the applicability of Augmented Reality for car driver assistance required me to incorporate the human into my research. Now, not only technical problems had to be solved, but also problems of human understanding. I had to accept that this huge amount of problems could not be investigated in a real car, so I had to make a step back. I developed an environment that enables experience and testing of automotive Augmented Reality systems for car diver assistance. After four years I am pleased to report my experiences which open the way for the step into real cars.

I like to thank the BMW Forschung & Technik GmbH, especially Mr. Bengler and Mr. Fenk, for funding of research and for valuable and enlightening discussions.

I have been fortunate to receive the support of many people in completing this dissertation. Thank you, Gudrun, for your advices and the vision on the field of Augmented Reality, and your support for my work. Thank you, Martin Wagner, Asa MacWilliams, Christian Sandor, Verena Broy, Martin Bauer, Daniel Pustka, Rudi Lindl, Leonhard Walchshäsl, Florian Echtler, Manuel Huber, Simon Nestler, Björn Schwerdtfeger, Michael Schlegel, and Patrick Maier, for much hard work in our group and in the communities. Thank you, TUMMIC project partners, with whom I had the chance to get insight into many other research areas. Thank you, Michael Schlegel, Jan-Gregor Fischer, Dimitri Alexeev, Anton Kostov, Laura Thompson, Uli Koch, Troels Frimor, Darya Popiv, Marek Orschewski, Leslie Klein, Michail Yordanov, Stefan Machleidt and many more, for helping make my projects and research a reality. Thank you, Christian Lange, for productive collaborations. Thank you, Patricia Badi Ulmer, Philipp Rubner, Claudia Quade, Anne-Katrin Pfeifer, Manuel Tönnis, Stefan Beyer, Manuel Huber, Bernhard Zaun, Verena Broy, Marina Plavšić, Stefan Machleidt, and Peter Keitler for feedback on my dissertation.

Special thanks to my parents making this possible in every way and for keeping my feet on the ground. Thank you, Anne and Iris, for enduring me all this time while writing this thesis. Thank you, Patricia, for unlimited patience and confidence.

And finally, to you, the reader: thank you for the time you are investing to read this dissertation – I hope it proves worthwhile! Please notice, there is a fully hyperlinked electronic version of the document in PDF.

For questions or feedback, please do not hesitate to contact me at marcus@toennis.de.

Overview

Time	Activity				Reported in
	Computer Science		Ergonomics	Human Factors	
	Augmented Reality	Software Engineering			
Ongoing	Fundamentals		Fundamentals	Fundamentals	Sec.2
Ongoing	Related Work				Sec.4
May 2004 - Oct 2004	AR Concept Development		AR Concept Development	AR Concept Development	Sec. 3.1, 3.3; Sec. 3.2; Sec. 3.4
May 2004 - Oct 2004		Analysis Driving Simulator			Sec. 5.1
May 2004 - Oct 2004		Architecture Rapid Prototyping Environment			Sec. 5.2
Oct 2004 - Dec 2004		Refactoring initial Driving Simulator			Sec. 5.3.1
Oct 2005 - May 2005	Spatial Context Analysis				Sec. 6.2ff
Oct 2005 - Feb 2006			First Set of User Studies		Sec. 5.3.1.7, 8.3
Feb 2006 - May 2006		Refactoring Step 2 of Driving Simulator			Sec. 5.3.2
Feb 2006 - Feb 2007	Creation of Spatial Context				Sec. 6.1
May 2006 - Jul 2006			Second Set of User Studies		Sec. 5.3.2.1, 7, 8.4
Jul 2006 - Mar 2007		Refactoring to New Driving Simulator			Sec. 5.3.3
Oct 2006 - Oct 2007	AR Visualization System				Chap. 9
Mar 2007 - Today			User Studies with new Simulator		Sec. 5.3.3.3

Contents

List of Figures

List of Tables

1 Introduction

Augmented Reality as resource for car driver assistance and approaches to investigate dependent concepts

Information Density

A car driver is exposed to a wide variety of information from the in-car environment and from the outside. Automotive environments accommodate enough space to integrate all possible communication and information channels to the outer world and society. The modern environment for car drivers already supports many channels, for instance, free-hand mobile phones. In-car systems moreover provide information ranging from comfort and entertainment functionality over car-related status data to navigation and guidance information. All these systems require the driver for supervision or attention, and some increase a driver's cognitive load. At the outside of the car, the surrounding traffic with its increasing density requires a driver to invest a further amount of his mental workload to supervise the traffic flow. Not only in cities, but also on rural roads and high speed environments, such as highways, live traffic reaches higher levels of density every day and the amount of discernible input increases. A car driver must pay attention at any point in time to react to any sudden event.

Car Driving

When steering a car, safety issues arise immediately. Size and weight of each single car represent variables critical to life when not correctly under control. Accidents in fact can occur due to weather conditions and technical malfunctions, but many are caused by driver mistakes [68]. In more detail, mistakes in driving behavior occur through absent-mindedness, wrong prioritization of concurrent events or by ignoring an important event in the outside traffic flow. The reason for a driver to react on unimportant information or neglect important input again may lie in a too high load of information.

Condensed Perception

Approaches to reduce mental input and perception time for car drivers use several directions. The two main categories manage the outside and the in-car environment. Environmental placement of driver related information like signs or advertisements can be controlled and can enforce that such information does not to have a too high impact onto the human senses. Still certain coincidences between environmental settings and upcoming traffic can have unpredictable effects on the mental workload of a driver. Restrictions in the in-car environment try to reduce the personal information density of a driver. This approach is possible for in-car systems whose information is unnecessary for driving. However, limiting personal needs through restricted access to communication systems does not necessarily coincide with personal preferences. Car drivers do not want to be restricted in their access to their various devices. In fact, car drivers expect a hedonic automotive environment that is joyful to use. Thus restricting approaches should only be applied when inevitable.

Safety

To preserve and strengthen safety of car drivers and other participants in traffic, the personal space of a car driver and his perception must be managed. It becomes necessary to organize and control the information flow towards the user. The quantity of distractive user interfaces and of those requiring the driver to redirect his attention must be reduced or at least the effects of mental absence must get reduced. For instance, to reduce blind times of traffic surveillance, important information can get relocated to a location where it can be perceived faster. Such approaches to enhance performance indirectly support safety aspects. Approaches focusing on safety directly can incorporate new kinds of warning systems such as distance control to a leading car. Here again, the user interface must improve driving performance. The positive effect has to outperform all negative dependencies of the system that itself again provides new input to the driver and thus increases information density.

User Interfaces

Design principles for new and innovative user interfaces have to follow a user-centered approach. Guidelines for information presentation must enforce safety in such time-critical environments. The guidelines must not require long attention and perception times to gather the meaning of the presented information. Existing interfaces of in-car systems have to be reconsidered with new and upcoming technologies. To cope with increasing information density and critical safety issues, user-centered interfaces must:

- Enhance situational awareness
- Reduce traffic blind times
- Combine associated/related information/events
- Minimize distraction
- Enrich information density by maintaining the overview
- Prioritize information
- Highlight relevant input for the user

1.1 Motivation

Augmented Reality

Augmented Reality (AR) extends the three-dimensional world by superimposing computer-generated virtual objects into the environment of the user. Three-dimensional virtual objects can be integrated into the real world. Additive information furthermore no longer requires stationary displays as carrier, but can move into the world. Spatially embedded virtual objects can contain and transfer information about associated real objects, places or events. The paradigm of AR [5] integrates such virtual objects, admits interaction.

Spatial Relationships

Driving a car is a task that is strongly related to spatial relationships. In live traffic many objects, the own car and many other cars or vehicles are driving through the streets. Distances between all participating objects and their headings change continuously at high rates in dependence on the behavior of all drivers and the street scenery. The rapid changes in the spatial relationships require continuous supervision from each car driver to achieve a safe driving.

Driving Performance

Especially Advanced Driver Assistance Systems (ADAS, herein after referred to as ADAS system) aim at improving driving performance by monitoring the surrounding of the car.

The spatial relationships between tracked objects are evaluated and upcoming critical events are computed. If enough time is left for the driver to react, ADAS systems warn the driver about the occurrence of the critical situation. Other ADAS systems automate certain tasks fully or in part.

Supportive Information

Not only ADAS systems deal with spatial relationships. Also In-Vehicle Information Systems (IVIS) provide supportive information that deal with spatial dependencies. IVIS systems tend to enhance comfort and personal needs of the driver. An example for a spatially dependent IVIS system is a navigation system.

Secondary Displays

What many in-vehicle systems, whether ADAS or IVIS systems, have in common is, that often secondary in-car displays are used to transfer the information. These displays require the driver to look from the street scenery onto the information on the display. The benefit brought in through the systems often suffers due to the cost of the time needed to perform the glance. In this time period, supervision of traffic is not possible. In addition, a driver's mental load increases, because the information must get detected, interpreted and transcribed to the outside environment.

Implicit Information

With the AR paradigm, information has the potential to be presented at the place where the cause for the need of information presentation is located. Thus, the number of glances to in-car displays can be reduced. The combination of objects or places and their inherent information allows for condensed information and thus for enhanced perception. The presentation of information changes and uses new, implicit presentation schemes that require less mental load for interpretation. Especially information related to the spatial relationships in the environment of the car have the capability to be transferred to AR. AR thus has the potential to become a notion for the incorporation of driver and safety related information into the automotive domain.

New Metaphors

Traditional approaches of information presentation now have the potential to be extended with new schemes for presentation. Information hitherto presented through two-dimensional schemes on in-car displays now can make use of three-dimensional spatially registered presentation. The AR paradigm enables the transcription of new metaphors for information presentation.

Studying Effects

For AR in automotive environments, engineering of presentation devices as well as detailed studies on the effectiveness of selected presentation schemes must be conducted. Only when AR metaphors show a true benefit for increased safety car industry will consider taking them into their production lines. To sufficiently test AR schemes, suitable presentation devices are necessary. Insufficient presentation capabilities of devices could falsify the results of user studies conducted on the presentation schemes. The main question of this thesis can be summarized in the question *Does AR prove useful for use in automotive environments?* First steps toward answering this question investigate the effects of AR: among other things, user studies have to measure improvements in driving performance and reduction of mental workload without generating additional distraction. Mental workload not only means, that a driver can capture spatially embedded information more effectively, but also that the driver does not focus his eye contact onto that scheme and thus becomes distracted. The situational awareness of the driver must be maintained or better, increased.

1.2 Hypothesis

The work conducted in the context of this thesis is based on the following hypothesis:

> Augmented Reality applied in Advanced Driver Assistance Systems is expected to
>
> - reduce response time to spatial information, whether time-critical or informative.
> - improve driving performance because less cognitive work is required to interpret spatial relationships.

1.3 Delimitation

Wide Research Field

The implicit issues of AR for automotive assistance span a wide field for research. To investigate questions pertaining the applicability of AR in automotive environments in primary and effects of AR for time-critical applications in secondary, certain delimitation is necessary to generate timely accurate results. Investigation of all issues related to AR would immediately incorporate other fields of research and extend work exponentially. Dependent and base-level systems integrate applied sensor systems to provide the data necessary for registration of AR schemes to real objects.

Full System

To have a holistic AR system in a car, a rich sensor system for the outside environment must be combined with a suitable presentation system for the driver. Both subsystems need applied solutions to meet the constraints of the area of application. To the end, the resulting system would require a real car and real life setup to be demonstrable and testable. Therefore legal reasons would have full impact and technical justifications were necessary, which in common take several months to allow a modified car to get on the road.

Dependencies

A full system capable of AR content requires knowledge about environmental spatial context of a car and a adequate presentation technology. A spatial context is a model of relevant spatial data containing location and movement information about all objects in the own cars near environment. Spatial context either is generated through separate sensors placed in the car, the environment, or is generated through fusion of several sensor systems. Such spatial knowledge is necessary for AR applications to deduce parameters as position and orientation of presentation schemes. The spatially aligned presentation of AR then requires in-car tracking to determine the driver's position. Through the exact position of the driver, the technical parts of the presentation system can display the AR content on a screen position correctly aligned to the head position of the driver. Thus the AR scheme appears to be located at the exact outside position. Fig. 1.1 shows all these dependencies in a graph diagram.

Focus of Work

An applicable delimitation can be drawn between human factors and sensor systems. The red diamond shape outlines the focus of this thesis: the main focus is given through the motivating question of the applicability of AR in automotive environments. To explore such concepts, a suitable development and test environment is required. In subsequence, presentation concepts are developed and investigated in user studies. To generate solutions for

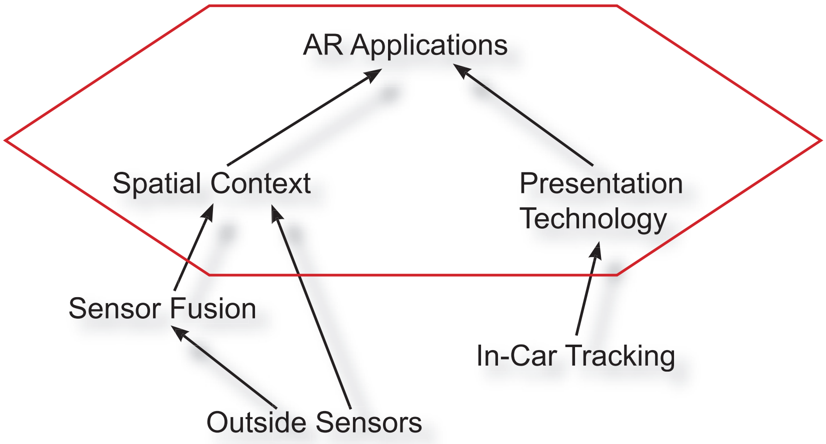


Figure 1.1: Delimitation of research focus outlined in red diamond shape

these questions it is also necessary to focus on the next underlying issues: *Spatial Context* and *Presentation Technology*. The subsequent research issues aim towards sensor systems, and have been spared out. Sensor data will either be simulated or gathered through acceptable workarounds (e.g. Wizard of Oz-concepts). Thus the three arrows partly lap into the area of main interest, indicating that such data is generated by simulation.

1.4 Interdisciplinary Scope

Beyond Computer Science

Despite the delimitation of the scope several disciplines are covered or at least touched by the remaining focus. This section illustrates the influence of all the different disciplines and identifies how related work and other system approaches can be applied to facilitate automotive assisting AR. The main disciplines cover ergonomics, human factors and computer science, optics is touched. The actual impact of the covered disciplines is illustrated, and findings and systems that are of interest for application in context of the work at hand are investigated briefly.

Ergonomics Ergonomics is one of the central elements with strong influence on the context of this work. Ergonomics investigates the triangle between system developers, the realization with available technology and the end user. Formalized concepts defining quality of service and efficiency of work are defined in its context [35]. *System ergonomics* puts the human and the systems in a control circuit, where both are coupled by interfaces for information perception and transcription. Perception interfaces use the human senses, but a user's information transcription does not use all possible organs. Extremities still are the main channel for system input, but speech input and even glance input systems are under development, extending possibilities of multi-modal interaction. A major focus of ergonomics lies in usability of systems. Guidelines for design and interaction thus are a major topic of system ergonomics. *Usability studies* [30] therefore are covered in the context of ergonomics.

Human Factors Closely coupled to ergonomics are human factors. While ergonomics is also called human factors engineering, its focus lies on the application of scientific information concerning objects, systems and environment for human use. Human factors focus on understanding the properties of human capabilities. They often are seen as the vice versa approach to ergonomics which starts investigation through the application. *Mental models* of task execution in control circuits and *effects of distraction* are topics of concern for human factors. Cognitive generation of spatial models for navigation and orientation tasks [63] thus belong to the area of human factors. Spatial dependencies also affect social dependencies which have influence of communication structures. Information presentation concepts thus must incorporate such interaction models [18]. Also of major importance is *human glance behavior* [71, 171] because car driving strongly relates to the visual sense. Assisting systems must keep cumulated glance duration low.

Optics Glance duration is strongly influenced by *display technology*. AR systems are not only required to place information at the correct visual location, but also in the correct focal distance. Only then glance duration can be minimized. Transformations of optical elements [151] enable realization of such displays, but also generate certain constrains.

Computer Science Computer science, as the area in which this work has been conducted, offers some major notions for investigation of the combination between AR and driver assistance systems. Yet, environments for design and experience of automotive applications did not aim at the investigation of AR. Pure driving simulator environments provide responsive virtual environments, but AR systems require more complex interactivity between the 3D virtual instances and the assistance systems under design. *Software engineering* strategies provide principles and tools for such complex systems. Iterative exploration and discussion of different concepts can be facilitated by dynamic exchange of components [107]. Structured software development also overcomes issues of later porting to other sensor systems in real car setups. Further investigation of the research area of *3D user interfaces* [31] provides another view onto the coalescence of cars and computer systems. When the outer world becomes enriched by superimposed virtual information, developers for car driver assistance systems will face issues for interactivity. The area of *Augmented Reality* finally is not only the desired area of application of driver assistance systems, but also can facilitate concept development processes. Investigation of available spaces for presentation and examination of presentation schemes are difficult as long as no appropriate presentation technology exists. Concepts as the *window into the world* [55] have the potential to enable early experience while capable displays are developed. Such concepts can support collaborative discussion, which would not be possible with visual systems that are personalized to the driver.

1.5 Approach

Chronological Approach

To explore the applicability of AR for car drivers, several steps and experiences were necessary. First, the development process of ADAS systems in combination with AR had to be facilitated so that efficient development and testing is possible. Second, ADAS systems required a strong fundament, based on systems managing the spatial relationships in the environment of the car. Specialized tools, such as driving simulators, had to provide such functionality in simulated environments. Sets of tools and development environments finally enabled investigation of the central hypothesis. This section gives an overview of the chronological steps, I performed in my work.

Novel Schemes

Research towards application of AR in automotive environments started with a two year research project towards creating and evaluating novel visualization and interaction schemes for car drivers. The project, called *TUMMIC* (Thoroughly User-centered Man-Machine-Interaction in Cars) was conducted with BMW[1] and an interdisciplinary research team from three universities covering the fields of computer science, ergonomics, electrical engineering, phonetics and psychology. Here the main focus relied in detection and determination of issues concerning the task of driving. Factors as accident counts and driver requirements were collected, investigated and implemented through applied AR schemes.

Sphere of Vision

To allow structured classification and task independent visualization schemes, relevant presentation areas for AR have been examined and classified to different groups. The groups have been collected under the paradigm of the *Sphere of Vision*. This model describes a virtual sphere around the driver of a car. The sphere is not visible to the user; it rather states the whole area where AR presentation schemes can be placed when no extra constraints apply. Depending on the relation of the task to the subsequent presentation scheme, the sphere changes its radius. For personal information, the sphere has a small radius, surrounding the driver's head in short distance. For information related to larger distances, it can also contain the car and thus can present information at the outside. Extra constraints to the presentation area apply, for instance, through occlusion of areas of the sphere and the nature of the task. Navigation tasks, for instance, require large focal distances, thus the sphere of vision gets large. The roof and the pillars of the car then restrict the area of the sphere that remains visible. Thus, the area applicable for AR content is reduced. The *Sphere of Vision* initially served as a model for the examination of possible application spaces for AR. Further extension of the examination models mainly incorporate the work of Benford et al [18] who investigated interaction and communication principles for groups of people. The combination of the models served as a foundation for the subsequent development of a general concept for AR in car driver assistance systems.

Spatial Knowledge

While working on a model for a classification of presentation schemes, the issue to generate spatial knowledge from sensor data has been investigated in parallel. Based on the assumption that each local environment as well as each mobile unit will be equipped with sensors, a software framework for dynamic ad-hoc networks between stationary and mobile units has been developed. The distributed framework applies the features of dynamic ad-hoc interconnections as published by MacWilliams [107] for the DWARF framework. This framework not only collects spatial data but also deduces spatial knowledge. Based on ontologies as investigated by Davies et al [46] towards application in semantic webs, context models are aggregated and kept ready for use in AR systems that require spatial information, such as the time to collision with an obstacle.

Evaluation Environment

Further steps towards applicability of AR for car drivers lead to the setup of evaluation environments. A fixed-base driving simulator has been extended to meet the requirements for the integration of AR schemes. In cooperation with the Chair for Ergonomics (Faculty of Mechanical Engineering, Technische Universität München), a partner in the TUMMIC

[1]Cooperation partner: BMW Forschung & Technik GmbH

project, mechanical, software-related and evaluation-related issues were addressed. A rapid prototyping environment for AR schemes was designed and implemented to guarantee efficient development and testing of AR schemes and other interaction concepts of the TUMMIC project.

User Studies

In this testing environment, several user studies have been conducted, examining issues for minimally distractive driver assistance systems. These studies concluded the TUMMIC project. Mainly these studies covered controlling a car driver's attention and implicit presentation of the dynamic behavior of the car. Further studies were conducted as part of the TUMMIC project but are not covered in this thesis. Brief references are given at appropriate positions in the text. Analysis of measured objective and subjective data brought many useful insights about the effects on AR. Among other things, one finding showed drawbacks of the used simulator environment. Driving simulators, for instance, can indeed simulate contact-analog, environmentally related AR through rendering the presentation schemes on the same projection wall and thus do not require the eyes to do focal adaptation. The glance behavior still is affected through further factors, such as optical size or focal distance. Through these effects, driving simulators do not proof fully useful for the evaluation of AR. The virtual environment of the driving simulator compensates the effects of superimposing virtual objects into reality.

Evaluating Anticipation

A follow-up project, called *Anticipation* project, investigated how assistance systems differ from human behavior. A major issue in this project was situated in the development of traffic scenarios for simulated environments. Therefore a laboratory setup using a table-top environment for collaborative creation and experience of traffic scenarios has been realized. The system also enables prototypical expert evaluation of AR schemes which usually must take place in collaborative and reality-near setups. Work on the investigation and development environment based on the work of Sandor [130] who investigated miniature cars on table-top environments as simulation tool for car motion. The system thus reduces roundtrip engineering cycles.

AR in Reality

In subsequence, a third project with industry was conducted. The so-called *SensorVis* project focused on an evaluation platform for any kind of sensor related data. Besides a laboratory version has it been incorporated into a real car. The system can deal with any spatial data, ranging from raw sensor data over aggregated data to AR schemes in driver assistance systems. The setup in addition brought along a recent part of the data flow from sensor data over three-dimensional transformations to AR-enabling presentation.

1.6 Contribution

Contribution in Four Areas

The interdisciplinary work mainly is located in the area of AR. Strong coupling exists to the communities of ergonomics and human factors while lower dependencies exist to other fields of research. Thus, not only one major contribution is presented in this thesis, but different, covering all areas in varying levels of relevance. Through the participation in different projects and the combined focus between different areas of research (ergonomics, optics, ...), I contribute in four areas of interest, mainly supporting the development process of AR ADAS systems. These four areas cover principles for such assisting systems, provide tools, tool-sets and working environments for efficient development processes of ADAS systems and investigate automotive AR in usability studies.

Classification Guidelines for Spatial Alignment of AR One general issue while developing user-related content for AR besides the shape of the scheme itself is the dependency to the remaining space for placing the object. The visible area, especially for car drivers, and the dependence on the associated task have a strong influence onto the appearance of the presentation. Feiner et al [55] defines the concept of window into the world which uses a 2D display to examine the 3D world behind. This model was applied in form of the *Sphere of Vision* to issues concerning the development of automotive AR interfaces. The *Sphere of Vision* therefore defines a classification model of tasks and their dependent presentation. The relationships between a task, the associated objects and the visual area and focal distance can be classified through this approach. Thus the developer only has to focus on the appearance of the scheme and the appropriate presentation device. Through further incorporation of communication models for group interaction, defined by Fahlén and Brown [53], a general model for development and investigation of metaphors in AR is developed and explained. Application of this model and demands distilled of the previously collected fundamentals of car driving and 3D user interfaces lead to a summarizing set of guidelines for AR in automotive environments.

Design, Discussion and Evaluation Environments The new possibilities of three-dimensional information presentation raise new issues for design and experience of such presentation schemes. Incorporation of new approaches for AR schemes into a car equipped with a large scale Head-Up Display (HUD) only allows the driver to have a personal experience. In addition, most AR presentation schemes require sophisticated sensor systems that still are under research. New development environments are necessary to enable early experience to designers, how an AR scheme can look like and if it really has the potential to bring a benefit. Thus a driving simulator has been extended in two steps to meet the requirements of AR and their easy incorporation and subsequent testing of concepts in user studies. A rapid prototyping environment was developed using facilities of the DWARF framework whose middleware, enabling dynamic ad-hoc interconnections of components, was developed by MacWilliams who published experiences in [107]. This environment enables development and comparability of various AR schemes and interaction metaphors. The next step incorporated the driving simulator into a rapid prototyping environment for development of any kind of assistance system, but with main focus on AR systems. The subsequent step developed a new laboratory table-top setup integrated with a driving simulator. The system enables rapid development of traffic scenarios with natural human behavior. This table-top environment was inspired by the CAR project of Sandor as published in [130]. It is suitable for personal and collaborative experience of applied AR schemes.

Usability of AR Schemes for Car Drivers Minimally distractive driver assistance systems are the main intention of the application of AR in cars. Reduced glance times and mental workload contribute to higher situational awareness and thus contribute to safety aspects. Several user studies have been conducted, covering topics as guiding a car driver's attention and implicit continuous information about the intrinsic behavior of the car. Concepts for these studies, among others, are based on the work of Sullivan et al [145] who investigated pathway predictors and Bubb [34] and Assmann [4] who examined braking distance indication for car drivers. Further applications focus on an increase of situational awareness. Situational awareness had been investigated by Wickens [167] and Chittaro and Burigat in

[41], whose work built a foundation for the reported studies. Significant results of diverse user studies give various information concerning dependencies in response time for spatial detection tasks combined with the effects of AR on driving performance. The contributions through the studies allow designing concepts of human-centered ADAS systems as well as for fundamental application in various other application domains of AR. For AR in general, the results contribute to the question, if its application *can reduce mental and visual workload?*.

Towards Mobile Setups To smoothly port solutions from simulators into real life setups in cars, a new system for in-car presentation using a LCD display and a Head-Mounted Display (HMD) has been developed. The system is an implementation of the *Sphere of Vision* and provides a window into the augmented world as initially described by Feiner et al [55]. This system also allows for collaborative experience and discussion. It also provides a laboratory setup for off-line development and investigation of AR schemes and prerecorded sensor data. To generate correctly aligned AR schemes on the displays, the development of this system required the definition of a structure of spatial relationships. This spatial data flow can completely be reused when AR schemes are ported into real cars.

1.7 Structure of the Document

Bottom-Up Structure

In contrast to the chronological approach of my work, this thesis is structured differently. To present the results of the work, first fundamental definitions and issues are given and general related work is listed. The structure represents a bottom-up approach, beginning with driving simulator environments. Then achievements for management of spatial relationships in the surrounding of the car are investigated and a solution is introduced. Then top-level AR applications and user studies conducted to test the effects of AR schemes on car drivers and the behavior are presented. Finally steps towards incorporation of AR in cars are examined.

Fundamentals

In the beginning, chapter 2 investigates a driver's workplace and informs on principles of user studies used in context of this work. Definitions of terms and classifications of a driver's tasks are illustrated. This section also identifies the issues when designing user interfaces for the time-critical environment of driving, especially issues arising through the application of AR. Analyses of related technical issues of information presentation lead to a third examination of automotive environments. The collection of fundamentals enables the development of a general concept for the application of AR in cars. Constraints of visible areas as well as dependencies to tasks in a car and related technical issues lead to the definition of the *Sphere of Vision* in chapter 3. The *Sphere of Vision* defines a general concept for the application of AR in automotive environments. Afterwards, a look on related work is given in chapter 4. The chapter contains work on AR applications that have been implemented by others. The focus is placed on research that is put on automotive AR in general, while later sections in other chapters investigate related work concerning the topic of the corresponding chapter.

Rapid Prototyping

The next chapters in this document have its focus on development cycles for AR schemes, their incorporation in driving simulators, and later in real cars. Each of the chapters goes into detail on an aspect of the development of AR schemes and adjacent issues in different stages of the development process. Chapter 5 first illustrates the efforts made to extend a driving simulator to a rapid prototyping environment for AR schemes.

Spatial Issues

A subsequent issue lies in the generation and management of the surrounding of a car, all objects in the environment, the spatial context. The first part of chapter 6 illustrates the differences between real world and simulator environments. The sections cover issues of generation of traffic scenarios in driving simulators and provide a solution using a table-top environment combined with a driving simulator. The second part of chapter 6 focuses on federation and analysis of spatial relationships. A reasoning system on spatial data allows for high-performance and non redundant delivery of base information to the user interface of driver assistance systems.

Usability

The next part of this document investigates the top-level, the user interface of AR applications. My third contribution is defined by two AR applications for car driver assistance. The first application examines a driver's awareness of the physical behavior of his own car. Chapter 7 explains the concept, the approach and the user study. The second application investigates issues of guiding the attention of a car driver to certain directions, i. e. to the direction where an imminent danger comes from. Chapter 8 gives information about the concept and the user study.

Into Cars

A further problem for the design of AR schemes is found in current available presentation technology. No real large scale contact-analog HUD is available in a real car at this point in time, therefore chapter 9 presents a solution to experience AR schemes without such a display. A mobile in-car solution enables collaborative experience and discussion. In combination with an off-line laboratory version of the system, both variants enable evaluation of new metaphors and estimation of their general applicability in the automotive sector.

Conclusion

In the end, chapter 10 concludes this document, summarizes the contributions and the experiences of the work conducted for this thesis. It gives an overview on further research. The appendix finally lists the questionnaires and the non-significant results of the usability studies.

2 Fundamentals of a Driver's Workplace and Usability Studies

Survey of fundamentals, evaluation principles and analyzes leading to a classification model for Augmented Reality schemes in dependence to spatial placement

Automotive Constraints

Automotive environments define several constraints for user interfaces. Design processes need to face these constraints, to ensure legal and applicable interfaces between the in-car systems and the driver. Like user interfaces, which became standardized over the last years, AR interfaces have to fulfill these demands in the same way. AR interfaces in addition have to enforce stronger constraints in some cases, since their presentation does not appear in an environment where designers have full control of function placement. The in-car environment for conventional interfaces can be structured according only to the needs of such interfaces. Thus, often used or important functions and interfaces can be placed in near distance to the driver. Placement of any of these functions and interfaces stays fixed. In contrast, AR schemes are associated with objects in the environment and are placed in the outside surrounding. Through driving, their placement becomes dynamic and can overlap with other important information in the vicinity of the car. Such effects of dynamicity generate new constraints for the design of AR schemes.

Fundamentals Structure

To meet all requirements for in-car user interfaces in a human-centered approach, constraints and dependencies of human factors, ergonomics, interfacing in computer science and optics are investigated. Findings then are mapped to automotive tasks and the application of AR. These mappings are separated into different sections in this chapter. First, tasks of car drivers are classified and associated with areas of interface placement. The main task of a car driver, the task of driving, is analyzed and levels of automation are illustrated. All these classifications and analyses enable the first mapping of AR to automotive tasks. In subsequence, issues related with 3D user interfaces are put in correspondence to automotive environments. 3D input, 3D output principles and interaction techniques of 3D user interfaces are investigated with focus on assistive systems. The second mapping relates 3D user interfaces to their application in cars. A following brief analysis of technical issues for AR displays in cars combined with human glance behavior leads to the third mapping which defines constraints of information presentation in AR. The final section of this chapter lists fundamentals about usability studies. AR user interfaces need to be evaluated to capture the effects pertaining to driving performance and mental workload. A brief survey about methodologies for evaluation and a introduction to formal usability studies concludes this chapter.

2.1 Classification of Tasks

Kinds of Tasks

The driving task can be decoupled from further interaction tasks in a car to provide a clear description of the conditions of this problem domain. One way of classification separates tasks into primary, secondary and tertiary tasks. A second classification aims on the effect of in-car systems and separates pure informative systems from assistance systems. The task of driving a car can again be classified to different subtasks. The classifications then enable an investigation of effects leading the driver to neglect safety aspects. An investigation of automation levels then allows for a matching of AR to application boundaries within the automotive environment.

Definition of Terms

This section provides several views on the workplace of a driver. Thus, all terms and definitions that are relevant for later chapters are collected.

2.1.1 Primary, Secondary and Tertiary Tasks

Obligation and Luxury

Interactive tasks in cars can be divided into three classes: primary, secondary and tertiary tasks [59]. *Primary tasks* describe how to maneuver the vehicle itself. The driver controls heading and speed of the car, as well as the distance to other cars or objects. *Secondary tasks* are mandatory functions such as setting turning signals or the use of the windshield wiper. This class encompasses all actions that necessarily increase safety for the driver, the car and the environment. *Tertiary tasks* cover entertainment and information functionality. These do not have any direct relationship to the driving task. Rather, they provide luxury services which are in high demand of buyers of modern cars, and thus a mandatory asset in modern cars.

Functionality Distribution

Fig. 2.1 illustrates how primary, secondary and tertiary tasks can be placed in physically separate areas of the cockpit. Users control primary tasks via devices (gas pedal, steering wheel) that are in a comfortable distance for arms and legs – the anthropometric distance. Thus, the area directly in front of the driver constitutes the main input area for primary car driving. Since primary tasks directly interact with the outside world, feedback is gathered through the windshield. Information related to such primary tasks is best shown in the windshield (HUD). Secondary user interfaces by majority remain in a distance that is still easily reachable and that is close to the focal perspective of the driver. Here, the area around the steering wheel below the windshield suits well. Tertiary functionality is placed next to the secondary area but to the center of the car. There it is still accessible, but it does not interfere directly with the area most relevant for car driving. Additionally, this location enables the co-driver to interact with the tertiary functions too, thereby relieving the driver.

Overlappings

Exceptions can be granted for functionality that is used very often. For instance, radio volume or air-conditioning usually are adjusted frequently. Access to this functionality must be provided immediately without traveling through complex menu structures. It is better to place such functionality within the area of the primary or secondary region. Therefore, the layout of interactive regions also depends on the frequency of usage.

Figure 2.1: Distribution of Primary, Secondary and Tertiary Tasks

2.1.2 In-Vehicle Information Systems versus Advanced Driver Assistance Systems

ADAS vs IVIS

In-car driver support systems can be categorized based on their goals towards comfort and safety. Such systems distinguish between driver information systems (In-vehicle Information Systems, IVIS) and driver assistance systems (Advanced Driver Assistance Systems, ADAS). Driver *information systems* are designed to inform and entertain the user while driving. Examples are air condition control, radio control and multimedia systems. Driver *assistance systems* explicitly support drivers in their driving task. Examples are heading or distance control (Adaptive/Active Cruise Control, ACC, e.g., [82]). ACC systems increase the comfort of driving through releasing the driver from active longitudinal control and putting him into a supervisor role. Yet, they are primarily designed and introduced in cars to enhance active safety.

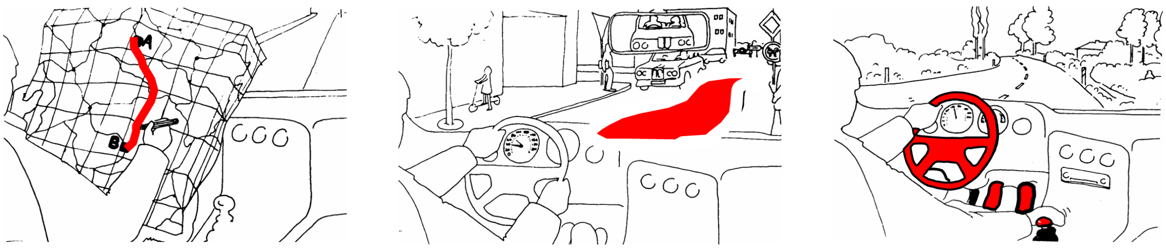
Tasks vs Systems

IVIS systems are closely associated with tertiary tasks. Driver assistance systems cannot be classified to tasks that easily. When drivers provide input to an assistance system, they interact within the tertiary area, since the minimum requirements of common maneuvering are already fulfilled by the steering wheel and the pedals. Yet, the feedback from assistance systems is inherently tied to the primary driving task – in particular if the car has means to actively control the pedals and the steering wheel. For instance, ACC systems actively decrease the speed of the car, when a slower car comes into closer distance in front. Drivers notice the decreased speed through kinesthetic hints. Nevertheless car drivers are able to overrule every intended action of the ACC system. The driver always is the strongest instance in the car and is able to decide against every action of the system.

2.1.3 The Primary Task and Control Circuit of Driving

Subtasks of Driving

The primary task of driving can again be split into three responsibilities a driver has to maintain [23, 35]: *Navigation*, *Maneuvering* and *Stabilization*. Fig. 2.2 illustrates these subtasks in sketches. To get to a destination, the driver always has to know about the route. The navigation task in fact is a static task that can be accomplished without driving but may require corrections of the route depending on traffic situations or closed roads. Within the current immediate traffic environment, the driver has to maneuver safely, to prevent collision with any obstacle and to stay within the actual speed limit. Finally he has to stabilize his car by transcribing actions to the in-car control devices, such that the car does not get off the road, keeps in its lane and has the correct distance to leading cars.



(a) Navigation (b) Maneuvering (c) Stabilization

Figure 2.2: Three Responsibilities of a Driver in the Primary Task; courtesy of [35]

Another Classification

A different definition is given by Wang [166]: not direct activities of driving are classified, but the understanding of the relationships in the environment. Here the driving task is presented with respect to global awareness and local guidance.

Global Awareness

Global awareness pertains to knowledge regarding the route to the destination. It requires large scale knowledge associating streets and distances, as taken out of a map. Global awareness describes the process of wayfinding.

Local Guidance

Local guidance includes tasks that involve controlling the vehicle and knowledge about the environmental situation. Dealing with local guidance means keeping the car on the road and not colliding with other cars or obstacles. Drivers have to know about the exact spatial relationships of their near environment. In local guidance tasks, car drivers control the steering wheel and the pedals.

Control Circuit

These activities can be compound into a control circuit for the task of driving. To execute the major activities for driving, the driver has to perceive input with all senses. The input is processed mentally to plan the corresponding action and then transcribed into manipulations of the steering wheel, the gas and brake pedals. Fig. 2.3 illustrates this circuit. This is a continuous procedure, because the change on the in-car control devices directly affects the 3D relationship between all objects participating in traffic. The changes in the spatial relationships then are perceived again and new adjustments are planned by the driver.

2.1.4 Incidents for Out-of-the-Control-Circuit Events

In the Loop

Management of the concurrent activities from all subtasks of the primary task require a sig-

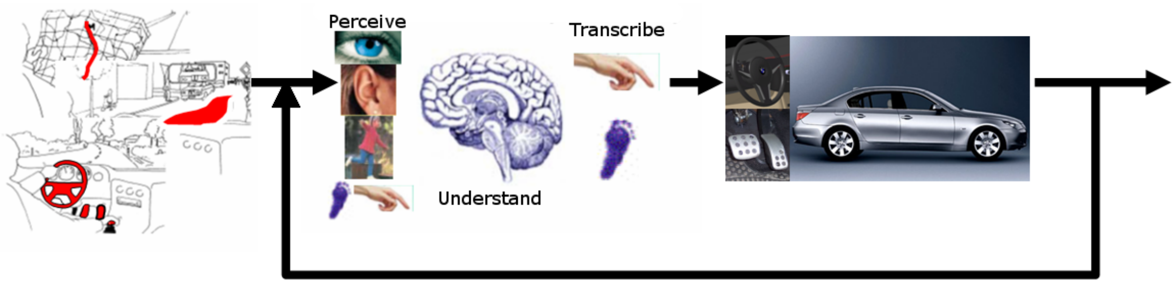


Figure 2.3: The Control Circuit of Car Driving; adapted from [35]

nificant amount of human physical and mental capabilities. In general, there is no problem for trained car drivers to execute the control circuit correctly. The driver then is *in the loop* of the control circuit.

Leaving the Loop

Various events or situations can bring a driver *out of the loop* of the control circuit. A list of separate causes is difficult to generate, because all can be generalized to *absent-mindedness* in the end. Thus a general list contains these causes:

- Interaction in secondary or tertiary task of driving (i.e. IVIS)
- Reaction to event of ADAS system
- ADAS system actively performs task or parts of the task of driving

The two middle items in this list in effect can lead to absent-mindedness of the driver. The last entry in this list puts the driver in a supervisor role. The focal change of the state of the driver bears the risk that he gets absent-mindedness.

Absent-mindedness The most general cause to take a driver out of the loop of the control circuit is mental absence. Personal or business problems at every point in time can appear so important that the driver looses the focus on the task of driving. The driver then thinks through the problem and neglects to manage at least parts of the control circuit. As mentioned in the introduction chapter 1 on page 1, also external factors, as advertisements or just too much information can lead the driver to leave the loop. Information overload can also be triggered through unexpected traffic situations as cars appearing spontaneously or sudden unexpected behavior of other participants in traffic. Communication with co-drivers, phone calls to others, smoking or searching activities can also lead to the effect that the driver is absent-minded.

Interaction in secondary or tertiary task of driving To differentiate and to satisfy mandatory and personal demands as well as needs of comfort, modern cars are equipped with a large set of functionality that is not directly necessary for driving a car. Either these functions are mandatory secondary tasks or are optional tertiary tasks. Secondary tasks in general only require short activities of the driver, such as checking the speed indicator or activating the turn indicator. Especially tertiary functionality can require the driver to invest more time to finish an activity. For instance, alphanumeric input of the destination of a navigation system can require some time. Even if that process is, and it must be, interruptible, the selection process takes time and requires the user to concentrate on that task. During this time, the driver has to switch his concentration between both tasks and thus has to leave the loop of the control circuit repeatedly.

Reaction to event of ADAS system In both cases, when absent-minded or when interacting with additional functionality, a critical constellation of traffic can come up. This is the point, where ADAS systems come into action. They monitor the environment of the car and deduce safety relevant factors, such as the Time To Collision (TTC). The ADAS system then warns the driver about the certain situation, event or obstacle. Current state of the art systems from major car manufacturers include, for instance, lateral assistance systems that warn drivers about unintended lane departures or longitudinal systems that adapt to a leading cars speed (the ACC). Alerts of such systems usually use multi-modal warnings to gather a driver's attention. What is left to the driver is to draw his attention to the warning, to interpret the warning accordingly and to transfer it back to the current outside situation. This process also takes a driver out of the loop of the control circuit.

ADAS system actively performs task or parts of the task of driving Some ADAS systems also can take over control of certain parts of the primary driving task. For instance, the ACC system manages the longitudinal part of the driving task depending on leading traffic. The driver then is taken out of the loop and is put into a supervisor role that has to monitor the activity of the ADAS system. Such systems comprehend a certain risk: that the driver tends to trust the system and does not concentrate enough on the supervision task.

2.1.5 Levels of Automation

The task of driving is a continuous process and repeats itself in a loop. The term *driver in the loop* still allows a certain amount of automated assistance. The driver still has to perform all of the tasks of the control circuit: perceive, analyze, and act. On contrary, the term *driver out of the loop* is used when drivers are no longer participants in the activity loop. Their role rather shifts to reacting on supplementary systems, supervision of the whole system and regaining control when necessary. The definition of Bainbridge [9] is still valid for modern driving support systems: normal operation can be performed automatically by the system, while abnormal conditions are to be dealt with manually. Important issues to be considered when introducing automated systems that put drivers out of the loop are whether drivers trust automated vehicles, whether they actually reclaim control if required, and whether they accept supervising an automated vehicle instead of driving [83].

Endsley and Kiris defined a typology of automation [52].

1. Perceptive cooperation mode

2. Mutual control cooperation mode

   a) Warning stage
   b) Action suggestion stage
   c) Limit stage
   d) Correction stage

3. Functional delegation cooperation mode

4. Fully automatic cooperation mode

Perceptive Cooperation Mode In the perceptive cooperation mode, the driver is only informed about current or approaching situations. However, the interpretation of the signals as well as which action to take is completely left to the driver.

Mutual Control Cooperation Mode In the mutual control cooperation mode the driving support system presents not only information, but also guides the driver through certain stages which help to accelerate the process of performing an action. At the warning stage, the driver is informed about upcoming situations. At the following action suggestion stage the system suggests what should be done in this particular situation. At the limit stage the system behavior changes so that the driver is guided towards the desired action which is calculated as the proper one. However, it is still up to the driver to either follow the recommendations of the system, or to overrule it and enforce his own action and therefore enter the correction stage.

Functional Delegation Cooperation Mode In the functional delegation cooperation mode the driver delegates parts of the driving task to the system. Delegation of driving responsibilities significantly reduces a humans workload, because the operator does not have to participate in the control loop anymore. However, if the automation is no longer needed or if the safety margins of the system are exceeded, the system gives manual control back to the driver. At this mode automation systems are said to be adaptive. Adaptive interfaces are intelligent systems that monitor the environment for changes in task demand, and regulate the level of automation to maintain an optimal state of system control for the operator at each particular situation [81].

Fully Automatic Cooperation Mode In the last level, the fully automatic cooperation mode, the whole control over the system is taken by automated systems. This mode might be needed in critical situations in which the system recognizes inability of the driver to react on time physically. It might be useful in situations where the sudden return of the control responsibility back to the driver might cause an accident, because the driver fails to overtake the charge immediately. Thus the system can avoid or at least mitigate an accident.

The first two types of cooperation modes keep the driver in the loop of the control circuit while the two last types take the driver, at least in parts, out of the control circuit.

2.1.6 Potential for Augmented Reality at Different Application Levels

Mapping Augmented Reality to Tasks

The previous sections collected different classification models for the tasks of driving: the investigation of the activities of the primary driving task, the definition of the control circuit and the classification of levels of automation. These collections enable a mapping of the AR paradigm to an area of application for further interaction and information concepts.

Assistance in Primary Task

AR technology can be applied to any task in a car. Helper systems for tertiary and secondary interfaces can guide a passenger or the driver to the interface and can give further hints on the usage of the interface, thus reducing traffic glance-off times and distraction. Inside the car, information no longer would have to be displayed in the limited space of in-car displays, but could use the whole surface or even the space in the car. The strong dependency of AR to spatial relationships in extent makes AR a promising notion for assistance in the primary task of driving. The outer surrounding of the car, where spatial relationships change continuously and quickly, generates a fertile environment for AR concepts. Aspects of safety surely apply for in-car helper systems as well as for assistance in the primary task. Demands for safety are higher in primary tasks because here assistance directly can affect the behavior of the user.

Ambiance in the Control Circuit

There are various approaches to transmit the message of an assistance system to the driver. Aside from active systems that directly affect the driving behavior of the car, most systems use human sensory channels, such as the visual, the auditory or the tactile sense to transmit their messages. The most used channel for information transfer remains the visual channel. Especially head-down displays in the instrument cluster and the central information display pull a drivers attention off the road. AR can incorporate new metaphors to embed information, thus transforming system warning to continuous information. Such information must use ambient ways of presentation, not providing too much cognitive information and mental workload to the driver. One area for application can be the operational safety margins of existing ADAS systems. Many ADAS systems only operate within certain safety margins and turn themselves off automatically, if they can no longer maintain their task in an appropriate manner. For instance, the ACC system has a predefined brake-force value. When another car changes onto the own lane and has a differential speed, high enough to reach a brake force beyond the defined threshold, the ACC turns off and transmits that action via acoustic and visual hints to the driver. AR can present spatial relationships to avoid a driver to come into a situation where a warning becomes necessary. Spatially embedded information about safe distances could then inform a driver about the spatial behavior of other cars nearby. The driver thus can intuitively realize the upcoming critical situation and can take over control before the ADAS system starts warning.

Shorter Out-time

Some critical situations cannot be anticipated in the described way. Dangerous situations can occur outside of the field of view or can require additional information to be understood. The driver then has to get out of the loop of the control circuit to gather the information and to adapt it to the situation. The time span, during which the control circle is left, must be kept as short as possible. A major part of time out of the loop is invested to determine the actual location of a critical occurrence. Especially, when information is placed in another frame of reference, the driver has to transform mentally into that frame of reference, understand the spatial relationships and then has to project this information back to his own frame of reference. Information presentation in the own frame of reference reduces the efforts necessary to understand the spatial relationships [167]. Such efficient perception is facilitated through the paradigm of AR.

Level of Automation

The discussion finally can map AR concepts to levels of automation. Systems on the level of fully automatic cooperation modes in the end could take over control of the driving task completely, letting the car drive autonomously. Such fully automated and trusted automotive systems will be a topic of research for several years until such systems become more reliable and make fewer errors than a human [105]. If drivers can trust such autonomous systems, no need for driver support and AR does exist anymore. All lower levels can incorporate AR concepts to either directly support the driver in the primary task or to facilitate the supervision role of ADAS systems. The functional delegation cooperation mode can use AR presentation concepts to deepen the understanding of ADAS systems and to shorten the switch back to manual control of the car through presentation of information in the own frame of reference. The mutual control cooperation mode can apply AR to intuitively guide the driver through certain stages of assistance. Information about critical situations can highlight the location and the action necessary to avoid an accident. AR systems in the perceptive cooperation mode finally can only inform the driver about the location of a critical situation or about an action to take.

Rationale for Augmented Reality

As discussed, the rationale to apply AR is driven by two factors. First, AR has the potential to increase information perception in the loop of the control circle and second, to apply information presentation in the driver's own frame of reference. Research in assisting systems should focus on integrated approaches that manifest the driver's placement in the loop of the control circuit.

2.2 Interaction of Car Drivers

Investigation of Interaction

After classification of tasks in cars, a deeper investigation of interaction principles in cars allows for further mapping of application areas of AR.

Mapping 3D User Interfaces to Cars

Man-Machine-Interfaces in cars are constrained by strong requirements specified through ISO-Standards [78, 48, 49] and recommendations of the automobile industry [2, 42]. The standards state various compliance procedures for in-vehicle visual presentations and principles for dialog management. The standards do not yet cover the application of 3D user interfaces. 3D user interfaces tend to discard traditional user interfaces as keyboards and mice and aim at incorporating of new interaction metaphors, such as gestures or glance-based interaction. Communication principles between humans are driving forces for 3D user interfaces. Such principles open up new implicit and intuitive interaction ranging from virtual environments to AR systems and ubiquitous applications. To investigate which novel 3D user interaction paradigms from the computer domain can be mapped under which conditions into the more restrictive automotive domain, this section reviews all aspects of 3D user interfaces regarding the environment, the interior and the interaction in cars. A wider survey also covering the application of IVIS related 3D user interfaces has been published in [153].

Investigation Approach

Recently, quite a number of 3D user interfaces have been systematically analyzed and categorized w.r.t. computer applications in purely virtual environments [31]. It remains to be determined whether these new methods make secondary displays and additional manipulation unnecessary, and whether they generate no – or just minimal – influence on a driver's capabilities.

The discussion on general concepts of 3D user interaction is combined with the fact that cars are no longer pure mechanical objects. Rather they become complex computer systems with very particular input and output devices and mobile functionality. Following this new view, familiar control devices in cars, such as the steering wheel and the gas and brake pedals become reconsidered as input and output devices to a very special three-dimensional computer application with strong connections to the real environment. Such interaction devices serve as well-designed 3D user interfaces for computer-based navigation.

Car becomes 3D User Interface

After shortly illustrating relevant ISO-standards and recommendations for man-machine interaction in cars, the next sections provide a survey of classifications about interaction domains. They discuss the use of common 3D interaction techniques in cars. Findings concerning the design of 3D user interfaces in cars are reported and guidelines regarding the amount and the spread of 3D user interfaces across a driver's cockpit are given and their cognitive interference is discussed. The classification and mapping is structured into detailed explanations for the area of input, output and interaction techniques.

Structure of Investigation

2.2.1 International Standards and Further Recommendations

Interaction principles changed through the development of computer systems. New experiences were gained and collected in guidelines and developed to international standards. Several standards and further recommendations, especially of car manufacturers apply for interaction design in cars. This section collects the standards beginning with general ergonomic dialog design for computer systems. Subsequent standards for automotive systems and further recommendations for automotive computer interaction systems are then illustrated.

Ergonomic Dialog Design The DIN standard 66 234 part 8, which in the meantime became integrated into the ISO standard 9241-110 [78] gives several ergonomic design principles for dialog systems:

Suitability for the task: Interaction with a system must not generate more difficulties than the task itself.

Self-descriptiveness: Every step in interaction must be understandable through self-descriptiveness without additional instructions. Otherwise declaration must be available immediately.

Controllability: The user must be able to have influence on speed, selection and order of the interaction steps or must be able to affect kind and amount of input and output. A timely clocked cycle is to avoid.

Conformity with user expectations: Interaction must be conform to the expectations and the operational procedure hitherto or it must be known through user instruction.

Error tolerance: A goal must be reachable despite identifiable incorrect input with low effort for correction. Errors, for that purpose, must be made comprehensible to the user for correction. No input must lead to undefined system state or system crashes,

Suitability for individualization: A dialog system must be adjustable to individual needs and preferences of a user.

Suitability for learning: The user must be enabled to learn interaction with a system by using it without having to use system help functionality.

System Ergonomic Rules System ergonomics [35] define nine rules for ergonomic design:

1. Concurrently or simultaneously never more than nine selection opportunities must be presented to the user. These, if required, must be distributed over sequential steps.
2. If possible, concurrent or simultaneous presented selections should be sorted by priority.
3. At maximum one unnecessary sequential interaction step can be inserted.
4. An interaction step which in principle is unnecessary must fit into the logic of application.
5. Simultaneous interaction must not be presented sequentially. Only if more than nine selection possibilities are presented, an exception, according to rule one is possible.
6. Sequential interaction must not be presented simultaneous.
7. Software-tasks in general must be designed statically.
8. Feedback must be given in 200 ms.
9. Tertiary tasks, designed for supervision must be easier to interact with than possible active variants and must reliably achieve their task.

Interaction Design Aspects

Automotive Computer Systems In the last years, computer technology has entered automotive systems, and ISO standards (especially EN ISO 15005:2003 [48] and EN ISO 15008:2003 [49]) have been established to give recommendations on the interaction design aspects and to enforce them. Among other things, the ISO states the following principles to be important:

Transport Information and Control Systems

Information and control systems in transportation environments must be suitable for use while driving. They have to be applicable to tasks related to Transport Information and Control Systems (TICS, [79]). Furthermore, they must be convenient for the driver.

Primarily Driving

In-vehicle systems should not distract the cognitive skills of drivers. Drivers have to react primarily to the current driving situation – even when they are interacting with the in-car system. The driver must always be in charge. He should never take both hands off the steering wheel to provide input to the in-car system.

Timing Issues

Some more issues that are especially enforced by the driving task are timing – presenting information in small, understandable pieces – interruptibility and the requirement for no continuous visual attention as well as immediate reaction and conformity with driver expectations. Common issues such as simplicity, consistency, controllability, self-explanation and fault-tolerance are further important requirements for interactive systems in cars.

Automobile Manufacturer Experiences Automobile manufactures in addition published collective declarations of intent. The Automotive Association Manufacturers (AAM) published a set of guidelines [2] and recommendations such as the European Statement of Principles (ESOP, [42]). General statements explain, that the primary driving task consumes visual attention to guarantee safety in traffic. Thus, visual interruptibility of further activities again is a major requirement. Every in-car system must have a minimal distractive impact so that the maximum cognitive attention aims towards the driving task. Efficiency has an important role but is subordinate to visual interruptibility. Car drivers with respect to demography, culture and education define a very heterogeneous group. Thus intuitive learnability must have a central role in any kind of in-car system. Animations and continuously moving presentation schemes are considered as bothersome and distractive. Moving presentation schemes attract visual attention [62] and should, as far as possible, be avoided, except they serve for learnability. The ESOP furthermore requests, not to place displays more than 30 degrees below a driver's horizontal line of sight.

Further Recommendations

Glance Related Recommendations Glance behavior is one major concern of the automotive industry. The AAM [2] among other things, lists constraints for glance behavior. They give a recommendation of $2.0\,s$ for each glance as upper duration limit. Every visual scheme must be perceivable within that amount of time. Perception time can shrink when one gets familiar with a system and thus allows for more content over time. That raises the risk, that changing content may again lead to overloading cognitive skills. Further on, AAM defines a maximum amount of glances to 10 glances for an activity. So, an overall activity must not require more than $20\,s$ for the total glance time. To reach this, every activity must be interruptible, so that a user can draw his attention back to his main task. After controlling or adjusting the primary task, the secondary perception task can be resumed, thus alternating both tasks until the second is finished. In addition, the AAM request to have $85\,\%$ of all glances required to fulfill an activity to be shorter than $2\,s$. Green [66, 67] in contrast defines a 15 second rule that specifies the recommended maximum time for drivers to complete navigation-related tasks involving visual displays and manual controls in a moving vehicle. Another definition, where glance duration is dependent on the number of glances is stated by Zwahlen [172]. Zwahlen puts the amount of glances and the duration together and defines combined thresholds, see Fig. 2.4.

Glance Requirements

2.2.2 3D Input in Automotive Environments

Three areas are covered by 3D user interfaces, input, output and interaction techniques. The next sections separately investigate dependencies and mapping opportunities for ADAS systems. As ADAS systems may also be controlled in the tertiary sector, IVIS systems are considered in this investigation when necessary. In similarity to Bowman [31], input devices are physical tools used to implement various interaction techniques. This section distinguishes between input devices for primary, secondary and tertiary tasks in a car, according to general design guidelines.

3D Input

A number of existing requirements restrict the options of three-dimensional user interfaces in cars: input facilities in cars cannot request drivers to take both hands simultaneously off the steering wheel. User input should require as little visual attention as possible and should

General Design Guidelines

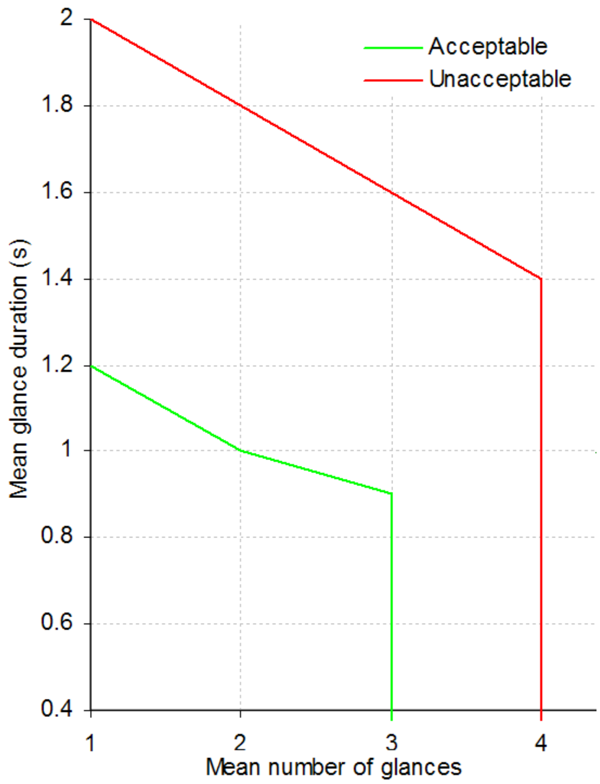


Figure 2.4: Dependency between Glance Duration and Amount of Glances; adapted from [172]

not require an explicit learning phase. It must be fast and easy for drivers to understand the underlying functionality of an input device, such that the driver does not have to think long about the process of telling the car what he wants the system to do. Focusing the driver's thoughts onto understanding something new, such as a new input device or its relationship to other functionality, could lead to a loss of attention to the environmental situation and could therefore cause an accident. Furthermore, it is important for drivers to be able to act without supplementary equipment. Thus, input devices, such as data gloves or ring mice are not suitable. All input devices that require the use of both hands, such as two handed joysticks and tablet computers, are not acceptable.

Primary Input Devices

Primary devices are devices that have direct influence on controlling the heading and speed of the car. Usually, these are the steering wheel and the gas and brake pedals. They must have a direct one-to-one mapping to their functionality, without a chance of being in a wrong input mode. In addition, they must generate immediate feedback whenever they are used. Maneuvering a car is a task that highly depends on 3D relationships between the own car, other cars, and the environment with all its obstacles. An intuitive mapping between the shape, the degrees of freedom and the associated action must be kept, in order to generate no secondary incompatibility [35] which could cause ambiguity with respect to their use. For example, rotation of the steering wheel transforms directly and uniformly into car rotation.

Since secondary tasks are not as important as primary tasks, immediate accessibility does not play such a fundamental role. Direct access should be granted, but access to the devices must not be as direct as for primary controls. Tertiary devices do not have a direct relationship to the driving task itself or to safety issues. Immediate and direct access is not necessary. Multi-functional controllers can be incorporated because no one to one mapping is required. Secondary & Tertiary Input Devices

2.2.3 3D Output in Automotive Environments

With regard to human senses, output can be classified into visual, auditory, haptic and olfactory displays [31]. Findings and issues concerning these displays w.r.t. to their use in cars are discussed and their multi-modal combination is considered. 3D Output

2.2.3.1 Visual Output

Visual attention is crucial for driving. It is the main input channel for a driver to maneuver a car. Thus, it must be handled very carefully. Drivers must be able to retract their visual attention from optical displays to the driving task any time. Visual Displays

To this end, displays of instruments which are the most important for driving are located in the secondary sector (see Fig. 2.1). Most of them are analog displays providing well defined output such as the actual speed or the current oil temperature. Bulbs and Light Emitting Diodes (LEDs) indicate activity of further functionality like the turn signal or lights. Analog Displays

Monitors and projecting displays have high potential for being used in cars, since they can present information more dynamically dependent on the current situation. But they have to be well positioned. Drivers need to be able to look at them without problems. They may not be placed more than 30 degrees below a driver's horizontal viewing direction [42]. Placing a display too low inside the car would require drivers to turn their heads and eyes too much, thereby increasing the overall glance time. In the current setup of cars, there are two regions where displays can be placed: directly in front of the driver behind the steering wheel or to the right of the steering wheel in the tertiary sector. All other regions either have the potential of being occluded by the driver's or co-driver's arms, or they are obstructing the driver's view through the windshield. To date, central information displays (CIDs) have been integrated into car models of many manufacturers. They typically present tertiary information content. View control is provided via hierarchical menus. LCD Displays

3D virtual environments provide many more visual display options, such as large workbenches and surround screens. Such devices are not suitable for in-car use due to the limited space, and because they draw too much visual attention, thereby distracting drivers. Concepts, such as fully immersive virtual reality displays are not applicable since they would occlude the reality. As mentioned before, drivers must be able to drive and interact with additional systems without use of supplementary equipment. For this reason it is not possible to integrate video-based head-mounted displays. A technical failure could have fatal consequences. 3D Virtual Environments

In contrast, semi-transparent approaches have high potential. HUDs present information mirrored into the windshield. The HUD is arranged close to an average driver's horizontal line of sight and in general shows speed, distance and navigational information (see Fig. Semi-Immersive Visual Output

2.5). One of the promising advantages of HUDs are shorter glance times. Through its design, a HUD reduces off-road glance times by faster focal adaptation and smaller saccade angles. Since available HUDs are designed to project information to a position about 2.5 m in front of the windshield, the accommodation time for drivers is faster than when they need to focus on displays in the dashboard at a distance of approximately 50 cm. Currently available HUDs provide a field of view of approximately 6 °. Therefore, they can display only very limited amounts of information, such as the current speed or icons representing navigational arrows. The importance of HUDs in cars grows significantly, if it is technically feasible to project large amounts of information in high resolution with a wider field of view. Technology to track the driver's eyes enables AR to embed dynamic illustrations into the environment, thereby minimizing glance distraction time. Such large scale HUDs can superimpose spatially related information and enable a new field of concurrent information visualization. Heavily transmittable values of the driving state, such as braking distance or the direction towards safety critical objects become displayable in a new way. Spatial relationships between objects can be visualized with appropriate AR schemes.

(a) Speed and Navigational Information are shown in most HUDs

(b) Some HUDs also show Distance Information. The bright Display also is visible under Daylight Conditions

Figure 2.5: Head-Up Display in a BMW 5 series, courtesy of BMW

New Issues Generated

This upcoming technology generates new questions and problems pertaining to information overload, perceptual tunneling and cognitive capture.

Information Overload refers to the state of having too much information to make a decision or remain informed about a topic. Large amounts of currently available information, a high rate of new information being added, contradictions in available information, a low signal-to-noise ratio, and inefficient methods for comparing and processing different kinds of information can all contribute to this effect.

Perceptual Tunneling is a phenomenon that originally comes from aviation and in which an individual becomes focused on one stimulus, like a flashing warning signal and neglects to attend to other important tasks/information such as driving the car.

Cognitive Capture refers to the situation where the driver may be totally ”lost in thought,” a condition which, in particular, could impair situational awareness. Where emotional content (i.e., personal involvement) in a conversation is high, such as arguing with someone over the phone, the likelihood of cognitive capture is increased. Instruments that require some level of cognitive involvement and thereby could lead to a loss of situational awareness are viewed as increasing the risk of a crash.

Non-computable Information Density

When embedding additional visual information into the real world, information density is not computable anymore, because the outside environment of the car is continuously changing during travel. If many events that are relevant to driving occur at the same location of the windshield, they can generate one or more of the problems listed above.

2.2.3.2 Acoustic Output

Auditory Displays

Auditory displays provide an attractive second communication channel, reducing load on the visual channel. Yet, minimal interference with the visual channel occurs since some attention is drawn to the perception of acoustic signals. The auditory channel can be used to issue informational or alarm signals and for speech based communication. Alarm signals are given, for instance, when the environmental temperature is below a certain threshold or when the ACC works outside its operating range (too high or low driving speeds) and thus turns itself off. Such sounds inform the driver about a contextual change that can have influence on the safety of the driver.

Spatial Sound

Sounds can be directionally encoded to provide spatial cues. In this respect, 3D sound displays have the potential to support drivers in locating objects in the environment, thereby warning drivers about imminent dangers of collision. An auditory hint can inform about the direction of the danger and further information could be provided in another modality. Such application of spatial sound can be classified to AR.

Auditory Limitations

However, there are limitations to the use of auditory displays. Some types of information are transmitted faster and more understandable in a visual representation. Spatial information, such as distances to environmental obstacles, are generally easier to perceive visually than aurally: due to the sequential nature of spoken words, such continuous information is easier presented in the visual channel. In addition, the use of different sound frequencies can result in inaccurate interpretations. Auditive output furthermore interferes with the driving capabilities to a certain degree [136]. When auditive output is given only if a difficult driving situation occurs, the driver’s attention can be captured by the acoustic output and the imminent danger might go unnoticed. Speech output also is not recommended for warnings and alerts [99]. Warning sounds have to be understood immediately, but in case of speech output, the driver has to listen to the whole notification. Sound output quickly becomes annoying since it disturbs other auditive activities like listening to music or conversations. Furthermore, drivers may feel embarrassed, if comments on driving mistakes are overheard by fellow passengers.

2.2.3.3 Haptic and Tactile Output

Haptic and Tactile Displays

Haptic and tactile output do not need visual attention and are user-centered. Most likely, haptic output is not suitable to convey complex information, but it is predestined to catch the driver's attention.

Modality Interferences

Lee et al [100] examined how well auditive and haptic alert modalities affect drivers' perception of collision warnings when the car ahead of them unexpectedly brakes. One of their experiments found that haptic alerts, in this case a vibrating seat, were perceived as less annoying and more appropriate.

2.2.4 Interaction Techniques in 3D

3D Interaction Techniques

According to Bowman [31], interaction techniques are methods used to accomplish a given task via the existing interfaces. Since interaction techniques are strongly related to the goals and tasks of a system, interaction techniques are distinguished in this section according to the driving task and to ADAS systems. Interaction techniques for IVIS systems are illustrated where appropriate, i.e. when application in IVIS generates certain interferences to interaction in other domains. All methods are discussed with respect to these systems and their relationship to tasks in a car. The classification of interaction techniques in the following sections has been introduced by Bowman [31] who distinguishes between *Manipulation*, *Travel*, *Wayfinding*, *System Control* and *Symbolic Input*.

2.2.4.1 Manipulation

Different Manipulations

Manipulational tasks can be divided into selection - acquiring a particular object from a set of objects, positioning - moving the object to another location and rotation - changing the orientation of an object [31].

Manipulations for Driving Driving is an interactive task in itself. Since driving is the primary automotive task which is associated with real danger, manipulators that are relevant to this task are rather physical than virtual.

Isometric Mapping

Drivers change the orientation of a car by turning the steering wheel, which thereby controls one degree of freedom. Steering manipulations can be mapped isotonically to the real behavior of the car: a right rotation of the steering wheel corresponds to a right turn of the car.

Singular Degrees of Freedom

The position of a car is manipulated by pressing or releasing the gas pedal or the brake pedal. In this setup, every pedal has its own degree of freedom. Yet, together, they control only one degree of freedom. The gas pedal provides an isotonic mapping from foot position to car motion. The deeper the pedal is pressed, the faster the car goes. The brake pedal works inversely. The more the pedal is pressed, the slower the car gets. Drivers need to envision a higher order technical concept to obtain a compatible intuition for this manipulation: the stronger the force on the brake pedal, the higher the braking force. We have a case of secondary incompatibility [35] where input is not directly compatible with the desired result. This higher level of abstraction needs to be experienced and acquired by novice drivers when they learn to drive a car. Alternative approaches have been researched, such as steering with a joystick [142]. Manipulations should directly reflect their influence on car dynamics.

Manipulations for Driver Assistance Driver assistance systems provide additional support for the driving task. Examples are automatic distance control and heading control. A well defined assistance system panel is needed that can easily be distinguished from luxury devices. Assistance functions influence the driving task itself in changing the position and orientation because of contextual information. Sensors are scanning the environment around the car and the assistance systems react to these information. The heading control e.g. changes the orientation of the car and is therefore altering the rotation.

Defined Panels

To date, manipulation and control of driver assistance systems is provided by physical devices. Information showing the current state of these systems, and devices for manipulating their state are placed in the primary or secondary area of the cockpit (Fig. 2.1). Longer-term concepts consider presenting distance information three-dimensionally in the HUD and using gaze-based pointing [118] in combination with speech to select and alter system parameters.

Gaze Interaction

2.2.4.2 Travel

Bowman defines travel as the motor component of navigation [31]. It defines the actions that are performed to move users from their current location to a new target location or in a desired direction.

Motor Component

Traveling is similar to Bubb's definition of stabilization, and to a certain degree, the definition of maneuvering [35]. The technique also is similar to Wang's definition of local guidance [166]. For the task of driving, this means to manage the car motions through the actual (real) environment. In this respect, the process of turning the car is divided into a series of small actions: activate the turn signal, slow down, look into the mirrors, look over shoulder, turn the steering wheel with the appropriate angle and operate the gas pedal. Maneuvering requires both, primary and secondary tasks. Therefore, interaction with all of these primary and secondary controls must not interfere with one another.

Primary and Secondary Interferences

Interaction with driver assistance systems interferes with the task of driving – in particular when such systems, if activated, enhance driving performance. Interaction time has to be as short as possible. Generally, interaction with assistance systems should be provided by use of a kind of *on/off*-switches. Easy selection concepts for configuring parameters require dedicated devices. The use of dedicated devices ensures that no modes have to be changed.

Activity Modes

2.2.4.3 Wayfinding

Wayfinding is the cognitive process of learning and understanding a path through an environment [31]. The wayfinding task is to know how to get from a starting point to a desired destination. This concept is discussed in relationship to techniques regarding ADAS systems and IVIS, because both areas of application construct different environments for route planning.

Environmental Paths

Knowing the Driving Route to a Destination This part of the cognitive component can be mapped to Bubb's definition of Navigation [35] and to Wang's definition of global awareness [166]. For instance, when drivers are approaching a crossing, wayfinding capabilities enable

Driving Routes

them to know whether to go right, left or to keep the direction. It is important whether drivers know a certain route or whether they drive it for the first time. In the latter case, a higher workload is necessary since they have to build up a cognitive map of the environmental spatial relationships in parallel [63].

Primary and Tertiary Interferences

The amount of knowledge about a route has implications on the degree of interference between primary and tertiary aspects of driving. If drivers know the route to their destination, they can focus on the primary driving task and then can fulfill secondary functions. If they do not know the route, they may want to request assistance from a navigation system. The driver implicitly interacts with a navigation system by driving his car. Car motion is sensed by the navigation system via GPS, resulting in an update to the current state of the car. Feedback from the navigation system to the driver is generally provided both via the optical and the auditory channel: a bird's eye view (map) of the car and its current surroundings are presented (at an adjustable scale) in the central information display (CID). Furthermore, speech instructions tell the driver how to proceed through a crossing. As an extension, symbolic navigational arrows can be presented in the CID, in the dashboard display, or in the HUD, thereby minimizing glance times, reducing ambiguities and enhancing driving performance.

Wayfinding in Menus

Knowing where to find Functionality Driver information systems are currently typically organized in hierarchical menu structures. In this context, wayfinding means that drivers have to internalize this menu structure in a mental model, knowing how to get to a particular (sub)menu when required.

Unknown Environment

To some extent, menu navigation in IVIS systems is dual to real navigation on roads: drivers have to build up cognitive maps of an unknown environment over time. 3D spatial design of in-car menu interfaces is not feasible in tertiary menu structures, because wayfinding issues then can interfere with the primary driving task. Interaction techniques both with respect to primary road navigation and with respect to tertiary menu control would have to share the same valuable cognitive resources of spatial understanding. This could generate interferences with the driving task and handicap users in distinguishing between the spaces of the real world and the IVIS system's virtual world.

Spatial Motion in Menus

This hypothesis is approved through a study that investigated motion principles in 3D menu structures [33]. The study evaluated different types of animation and motion in a 3D menu displayed on the central information display of a car in an easy driving simulator test. The different submenus have been aligned according to walls, ceiling and floor in a room. Five submenus were available. The front wall of the virtual room was missing so that the user could look into the room. Three different types of motion were evaluated. First, on selection of a submenu, one wall turned into the user's field of view, stopping in a position that the user has a perpendicular look at the wall. Second, on selection, the whole room moved and turned so that the selected wall stopped perpendicular in the user's field of view. Third, on selection, the user's point of view moves into the room and then turns until the selected wall stops in the center of the display. The third variant can be seen as egocentric movement through a 3D world.

Study Results

Results of this study [33] indicate usability criteria being worse for the third variant compared to both other variants in effectivity and compared to the first variant in efficiency. Subjective estimations judging rapidity, learnability, operability and clarity resulted in chain priorities placing the first variant best and the third worst. Lane deviation measures generated no significant differences, but all factors of usability lead to the assumption that a negative influence on driving performance could exist. The negative influence could occur because both mental models, the one of the real world and the model of the virtual world differ but have to be traversed in parallel.

Yet, it is important to ensure that drivers can easily build up a clear cognitive model of the system, helping them to remember paths to specific functionality. Clear Cognitive Model

2.2.4.4 System Control

In System Control tasks users issue abstract, non-spatial commands to request the system to perform a particular function, to change the mode of interaction or the system state [31]. Abstract Non-spatial Commands

Abstract concepts of system control are not suitable to tasks involving car driving: devices of the primary task, as mentioned in the 3D input section 2.2.2 (see page 23), must not provide opportunities to be in another state. Implicit changes however are possible. Active steering for instance, where the turning angle of the steering wheel adjusts to the front wheels according to driven speed is such an implicit system control. Implicit Mode Change

Abstract system control tasks may be amenable to ADAS systems. Such systems require abstract settings – e.g. to adjust reactions to distance measurements to the car ahead in the ACC system. In modern cars, assistance systems are isolated from other car functionality – thereby ensuring fast and direct access. However, as a consequence, drivers have to adjust functionality separately for different system components. To date, drivers receive a minimal amount of visual feedback to recent adjustments. It is unclear, whether it is reasonable to provide systematic system control output presented as graphical menus, voice commands or gestural commands. With technical progress enabling more and more assistance systems, it seems not to be feasible for long to provide individual system feedback to individual system adjustments. There will be a need to think about suitably integrated system control techniques for driver assistance systems. Isolated Systems

2.2.4.5 Symbolic Input

Users need symbolic input facilities to enter symbolic information (text, numbers and other symbols) into the system [31]. It is not necessary to provide specific symbolic input facilities for the driving task itself. Text and Numbers

ADAS systems do require symbolic input in some cases. The ACC system needs a velocity specification for the desired speed. Drivers are allowed to make minor adjustments via some button-oriented input device – e.g. by turning a control knob. The favored distance can be set by a throttle, providing different spans. As a consequence, symbolic input is only supported on a very abstract layer. Abstract Input

In IVIS systems, symbolic input is very important for systems like navigation systems. Current systems for alphanumeric input typically accept symbolic input via multi-modal controllers, requesting drivers to manually select each individual letter in a *speller*. Automatic name completion provides some support for input. Other approaches include full or mobile phone like keyboards, or handwriting recognition on a touch-pad [134]. Voice could Detailed Input also be an adequate solution [133]. Yet, speech recognition systems deal with issues concerning full and correct understand of the required large variety of phrases spoken by people in different dialects.

2.2.5 Mapping In-Car Interaction to Augmented Reality

Mapping 3D UIs to Cars

In accordance with the tasks of driving and the control circuit of driving in section 2.1 (page 13ff), an analogous mapping to AR (section 2.1.6 on page 19) can be conducted for interaction. The investigation of 3D user interfaces in this section allows for identification of interactivity in cars portable to AR techniques.

Automotive Situation

The potential and the problems involved in bringing 3D user interfaces and interaction into automotive driving environments define the important issues to deal with when AR is intended as a means for driver support. The automotive situation is very special because users are executing another task of higher priority – car driving – parallel to providing system input. As a result, only limited cognitive and motor capabilities are available for interaction tasks, requiring an extension to the list of usability criteria for interactive systems: minimal distraction from the driving task.

Used Interaction Techniques

The driving task has limited similarities to interaction with a computer system: drivers provide input to cars via pedals and the steering wheel, and they receive output via spatial and kinesthetic cues. They are performing interaction techniques mostly by object manipulation – positioning and rotating – traveling and wayfinding. It is essential to keep this workload in mind when designing user interfaces for in-vehicle interaction systems.

Summary over Tasks

Input devices for primary tasks must be provided as simple one-to-one mappings. They have to be placed in adequate anthropometric distances. Since secondary tasks are strongly related to the driving task, their input devices should be positioned next to the primary input devices to ensure fast access. Tertiary tasks are not relevant for basic safety. Therefore, their input devices can be placed in a comfortable distance. They should not interfere with primary and secondary devices. Exceptions can be made for frequently used or favorite functions.

Modalities

Visual output has to be handled carefully since the driving task needs visual attention. New technologies, such as HUDs provide promising potential since drivers do not have to turn their heads or eyes to glance at a screen. Yet, they also bring up new questions, such as the effects of perceptive tunneling and cognitive capture. Auditive and tactile output does not demand visual attention. Nonetheless, there are technological problems as well as user interface-related ones. Multi-modal approaches have high potential to provide adequate interaction systems.

Important Techniques

User interaction while driving consists mostly of manipulating, traveling and wayfinding. To avoid interference between the driving task and system interaction, manipulation, traveling and wayfinding techniques must be interruptible and kept as simple as possible. Since the driver's cognitive load is already high due to driving, additional high workloads complicate these interaction techniques.

Mental Maps

AR can support cognitive requirements of car drivers. Mental maps are easier to generate, because the effort for interpretation of symbolic icons is reduced when information is displayed in familiar 3D shapes. This also reduces the amount of in-car control displays.

Hierarchies, as generally used in central information displays and their menus can become smaller and do not require the driver to memorize an extensive structural layout.

2.3 Presentation of Augmented Reality Schemes

Towards Presentation Areas

Tasks applied in cars, their roles in the control circuit of driving and levels of automation enabled a mapping of AR to general application areas (see section 2.1). Through investigation of interaction techniques of 3D user interfaces in automotive environments the techniques, important for incorporation of AR (see section 2.2), were collected. Both examinations specified important factors contributing to psychological design dependencies. After investigating such issues, a third look from another perspective rounds up dependencies of AR application in cars. This third perspective covers dependencies of information presentation in different modalities under physical and technical constraints.

Presentation Modalities

AR can use different modalities to present content to the user. While techniques for presentation using the visual, acoustic and haptic senses are of relevance for investigation to date, tactile, gustatory and olfactory senses are not yet mature enough.

Structure of Presentation Constraints

The structure of this section follows the order of the previous sections. After briefly discussing realization concepts for the important modalities, the main focus is placed on visual content. A brief introduction to glance behavior illustrates benefits of HUDs and AR presentation concepts. HUD principles and concepts are shortly illustrated to be able to analyze dependencies between glance behavior and hardware issues.

2.3.1 Presentation Modalities

Human Senses

All human senses can capture information. Some are of higher importance for research towards ADAS systems as others. Of minor importance are the gustatory, the olfactory sense, and the sense of touch. The gustatory and the olfactory sense require deep research about a human's understanding and mapping to current situations in the environment. The sense of touch requires deep investigation towards ambient information presentation and according understanding.

Haptics

In contrast, the haptic (or tactile) sense can be applied in cars directly. Two main operation areas exist here. First, the driver's seat can transfer information and second, the devices controlling the primary task (i.e. steering wheel, gas, brake pedal) of driving can transcribe information to the user. An in depth classification of presentation content and application can be found in [96] and thus is not covered here.

Acoustics

Acoustics in contrast is of certain interest here. Acoustic presentation concepts can spatially embed and transcribe information to the driver. Accordingly placed loudspeakers and appropriate sound calibration enable simulation of spatially embedded sound, appearing to originate either from the inside or outside of the car.

Optics

The main channel for information transfer is the visual channel, which in fact already is the most used and loaded channel for car drivers. The visual channel also is the most complex channel to present information accordingly. The following sections therefore dig into detail, first investigating human glance behavior, then illustrating the general principle of HUDs and after all investigating demands for information presentation. As mentioned, such constraints are generated by the physical structure of the car and its motion behavior.

2.3.2 Human Glance Behavior

Optimized Recognition Time

Human glance behavior defines several delimitations for the presentation of AR schemes. The human eye has regions with different grades of perception wherefore glance movements occur to bring objects in a region of clear perception. Glance movements and subsequent focal adaptation to the objects distance require certain time intervals for execution and must be considered when designing HUDs and AR presentation schemes. The knowledge later can be applied to guarantee optimized recognition time of AR schemes.

Foveal Areas

The human eye has different areas of perception with different degrees of sharpness. The *fovea centralis* (yellow spot) is the area, where the eye has the sharpest perception. It is located at the intersection point of the retina and the extension of the central glance axis. Its field of view is about $2\,^{\circ}$in a cone. Only objects in this cone can be seen sharply. Sharp and clear vision is important, when, e.g., the speedometer is read. To gather information, the foveal field of view must be turned to the direction of the information. The *parafoveal field of view* furthermore is a second cone, surrounding the central foveal field of view and ranges from $2\,^{\circ}$to $10\,^{\circ}$. The *peripheral field of view* starts in angular values greater than $10\,^{\circ}$to the central glance axis. Peripheral perception enables static and dynamic orientation as well as perception of movements and changes in brightness. Size and direction of objects can be estimated through perception in the peripheral area [90]. Fraisse [69] found the threshold for peripheral perception of movement between $1\,^{\circ}/s$ and $2\,^{\circ}/s$.

Resolution

The angular resolution of the human eye is a further factor being important for HUD and AR presentation scheme design. Vince [163] reports about a study placing two light sources of 1.5 - 2 mm diameter in various distances. Decomposition of both light sources was possible up to 10 m distance, being equal to 40 arcsecs (0.01 °) for the average eye. Barfield [10] results in 30 arcsecs for the angular resolution.

Depth Perception

Important for HUD design is also perception of depth which uses binocular and monocular cues. Binocular cues use the slight displacement of the two retina images which especially is important for depth perception in near distances. Monocular cues [71] use static or dynamic properties of objects and their relative movement. Knowledge about the common size of an object (static) allows estimation of the distance. Occlusion (static or dynamic) through other objects and shadows (static) on other objects also allow for depth estimation. Perspective decrease of size (static) and changes in parallax during movements (dynamic) conclude the monocular depth perception cues. A car driver thus is able to control a car even with one eye. This is possible under the proposition that an increased amount of head and glance movements due to the reduced field of view becomes necessary.

Stereoscopic Threshold

While monoscopic depth perception enables depth estimation at any distance, binocular depth perception does suffer with increasing distance. This effect is explained by very small changes of angular values between both eyes in higher distances. A certain threshold for the maximum distance, stereoscopic depth perception ends cannot be defined. Literature provides different values for this end. Values range from 12 m [87] to 30 m [163]. Goldstein [62] states binocular criteria to be the dominant criteria of depth perception up to distances of 65 m and reports about effective distances of up to 450 m.

Focal Accommodation

Presentation in different distances requires the human eye to accommodate to the specific distance. The time required for focal accommodation is an important foundation for the introduction of HUDs to cars. Instead forcing the driver to focus to the dashboard (i.e. 80 cm), he now only has to focus to the focal plane of the HUD (for BMW, to 2.2 m). The time required to focus from large distances of the road scenery thus decreases significantly. Duration for focal accommodation takes between 0.5 s and 1.0 s [110] and increases with age. Thus the speed of accommodation ranges between 4 dpt/s and 15 dpt/s [110] and decreases with age.

Eye vs. Glance Movements

Coming back to perception movements, a distinction between eye and glance movement is necessary [129]. Eye movements can be determined by monitoring the eye, for instance by duration of jumps from one direction to another. Glance movements also require interpretation of the viewed objects. When, for instance the driven speed is checked, the driver has to turn his eyes and has to focus on the speedometer. Both movements can be classified to three groups:

Saccades

Adjustment of Fovea to new Objects An object determined by peripheral perception leads to a jerky jump of the glance direction so that the object gets into the foveal center. Such jumps are called saccades and are in the range of angular degrees. They can reach a speed of about $500\,°/s$ [71]. A saccade already initiated cannot, like a ballistic projectile, lead astray from the defined course. Thus saccades are also named ballistic eye movements. Between two saccades a fixation of focus is executed. Each saccade is characterized by its amplitude and its glance jump time (saccade duration). The approximate duration of a saccade is $D = D_0 + dA$; where $D_0 = 21\,ms$; $d = 2.2\,ms/°$; and A is the amplitude $[°]$. Angular values below $10\,°$in general only require the eyes to move [71], while larger glance amplitudes occur in conjunction with head movements.

Fixation

Eye Movements that enable Fixation of Objects Eye movements that allow information capture are fixations and tracing movements of glances. The aimed object in both cases remains in the foveal area of the retina. The special case of glance following movements (smooth pursuits) lets the eye move with the fixed object at a maximum angular speed of $60\,°/s$. Here no relative movements of the image on the retina occur. In general, both terms are considered as fixations.

Mental Workload

In road traffic, fixation durations in general range from $80\,ms - 100\,ms$ up to some seconds. Information perception below the lower threshold cannot consciously be captured [170]. Very short fixation durations are a hint to high mental workload.

Micro-movements

Micro-movements The eye continuously performs very fast micro-movements in the range of arc-minutes. These movements are called tremor- or drift-movements. They occur due to supplying new impulses to the receptors on the retina that primarily react on changes. Without these movements the eye would not see anything.

2.3.3 Head-Up Display Technology

AR depends on HUDs

AR content requires sufficient presentation technology. The drawbacks of inappropriate presentation devices otherwise could prevent the benefit of the AR concepts due to presentation in, for instance, wrong focal depth.

History of HUDs

The HUD technology originates from aviation. First HUD systems have been developed in the 1940 s and were applied in military aircraft in the 1960 s. First HUDs have been introduced in cars in 2001 in the United States and were introduced 2003 in full-production in Europe by BMW. Today many premium car manufacturer provide HUDs.

Combiner

HUDs use a combiner to fuse the rays of light from the outside environment with the light coming from a display, in general built behind the dashboard. The combiner has a special coating so that the light of the display, which mostly is monochromatic is reflected to a higher degree, while the other light from the outside can still pass through the combiner. In airplanes, often a planar glass plane is used to combine the two images. In cars, such extra glass planes are not accepted by drivers so that the windshield is used as a combiner. The windshield has an uneven surface and therefore the HUD hardware requires optical elements to correct the image to appear undistorted.

Focal Depth

The image of the HUD appears in the distance summarized of the distances of the driver's eyes to the windshield and from the windshield to the display. To extend the distance between the driver's eyes and the virtual image, several mirrors and lenses are used to place the image in a larger distance. Thus the time, the human eye needs to refocus to the distance of the HUD decreases. The common distance acquired with such HUDs is the distance of the front bumper, which is about 2.2 m (in cars of BMW) away from the driver's eyes. The mirrors and lenses generally also correct the image distorted by the combiner. Fig. 2.6 illustrates the general setup.

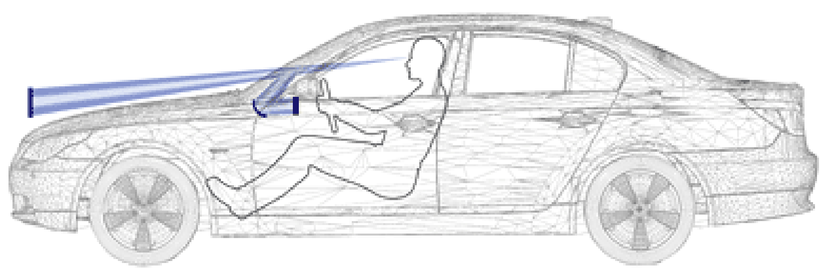


Figure 2.6: The principle of a HUD, a bright display behind the dashboard generates the image that is mirrored into the windshield and appears in distance of the front bumper (courtesy of BMW)

Field of View

Yet, these displays require a certain volume behind the dashboard to generate a virtual image in the desired distance. The size of a HUD with an approximate volume of 2 liters behind the dashboard enables an image that reaches about 6 °field of view in about 2.2 m (in cars of BMW) distance to the eye. Such HUDs are not sufficient for full-blown AR presentation schemes, they only enable the presentation of symbolic information. To really enable AR, a HUD must have a wider field of view and a larger focal depth to present the virtual content on the road or superimposed on other objects. An examination of values necessary for AR follows in section 2.3.4 on page 37.

Other Approaches

Approaches for HUDs with a larger field of view and a greater focal depth generally rely on the combiner concept. They require larger optical elements to cover a wider area on the windshield. Such large field of view HUDs require more space behind the dashboard. Most of these displays use TFT technology to generate the HUD image. Some other approaches use laser technology to project onto the windshield, a screen or directly onto the retina. Specialized HUD systems incorporate light sources, such as soffit-lamps to generate images for certain applications [37].

HUDs Everywhere

Further approaches place Organic Light-Emitting Diodes (OLEDs) wherever a display is required. The location of a HUD thus is independent from form factors of the car or the dashboard. A HUD can be installed wherever display area is required. Through the placement of the OLEDs on the window, the focal distance of the HUD lies on the windshield, thus only enabling superimposition of objects but still enforcing the eyes to focal accommodation.

2.3.4 Constraints for Information Presentation

Impact of HUDs

Conventional HUDs generate a significant impact on glance behavior. First, they reduce angular values of glance movements and second, they reduce the duration of focal accommodation. The HUD is placed very near to the straight line of sight above the dashboard and therefore reduces the angle of the turn for the glance, the driver make. The second factor reducing glance time of HUDs is given through the greater focal depth of the HUD image. Instead of the driver's eyes to accommodate to the distance of the dashboard, the eyes only need to focus on the virtual image plane of the HUD. The adaptation from infinity to $2\,m$ requires significantly less time than accommodation down to $0.8\,m$

Perception of AR

Conventional HUDs currently only enable symbolic information. The field of view is too small and the covered area is below the area important for information presentation. To reach HUD capabilities for AR, two issues are necessary to aim on: large scale HUDs and larger focal distances.

Large Scale HUDs

First, the size of HUDs must be increased. The optimal solution surely would be a full windshield HUD, but smaller sizes already enable a wide range of AR applications. Monitoring the area of the windshield looked through while driving, most traffic relevant glances pass the windshield in an area of the approximate size of an A3 paper sheet (see Fig. 2.7). The size is estimated by investigating fixation distributions under several road conditions [171]: on US highways with an average speed of $83.1\,km/h$, with over $90\,\%$ the large majority of glance fixations resided in a horizontal file dof view of $14\,^\circ$ and a vertical field of view of $18\,^\circ$ under different wheather conditions. Non highway driving in curves with relatively small radii ($73\,m$) kept the covered area in equal size, but moved the center of the field about $14\,^\circ$ aside, reaching a maximum deviation of $24\,^\circ$ the straight horizontal forward line of sight for the $90\,\%$ covering area. Specific AR applications surely may require a wider field of view or other areas for presentation such as the side or rear windows but then have to face the issue of guiding the driver's glance to that direction.

Focal Depth

Second, to reach minimal glance time, not only glance angles, but also focal accommodation must be reduced or, in best case, become unnecessary. AR information associated with an object thus should be displayed in the same distance as the object. Increasing the size of conventional HUDs is not sufficient for achieving minimal glance time. The human eyes still would have to adapt to different focal depths.

Contact-analog HUDs

So called contact-analog HUDs conceptually incorporate solutions for these two issues.

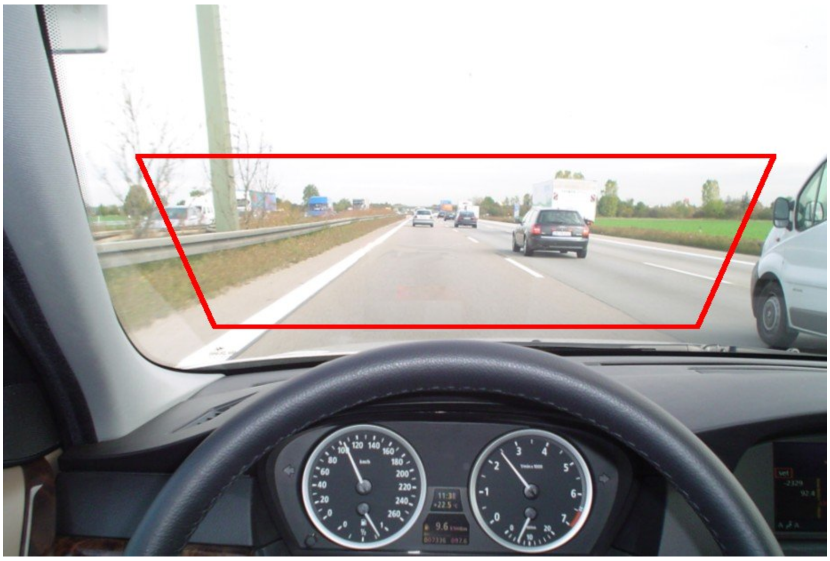


Figure 2.7: A Driver's Frontal View with outlined minimal Area for a Large Scale HUD

The general idea of contact-analog HUDs is not to display symbolic content, but to spatially relate information to the environment – in other words – enabling AR. Such contact-analog HUDs must have a large scale presentation area to display the content. They furthermore must display the content in the appropriate distance. Thus, OLED based displays mentioned in the previous section 2.3.3 on page 36 are not sufficient, even if they provide the easiest way to build large scale HUDs.

Definition of Term *Contact-analog*

Thus a definition for the term *contact-analog* with respect to AR and HUDs can be as follows.

> Contact-analog AR *is an extension to the paradigm of AR. Besides interactive integration of registered virtual 3D content into reality, further constraints are required to reach contact-analog AR.*
>
> - *In a classification of AR presentation schemes between* symbolic *and* naturalistic *content, contact-analog AR has a strong dependency to realistic and naturalistic presentation.*
> - *Contact-analog AR has a strong dependency to the physical state and behavior of the environment. AR schemes smoothly integrate into the environment.*

Contact-analog AR applied in the automotive sector thus places AR schemes in different mountings. Besides classical mount-points for AR schemes, such as location-fixed and head-mounted, car-mounted information presentation defines a new mounting point. Screen-fixed AR presentation no longer is counted to contact-analog AR as the smooth integration into the environment is missing.

> *A* ***contact-analog HUD*** *is the display system that enables contact-analog AR by combining virtual and real content accordingly. Independent from the actual head position*

does the mixed scenery look correctly aligned to the driver. Besides vertical and horizontal alignment, the presented virtual scheme also has the correct focal depth. Virtual objects seem to smoothly integrate into the real world at the exact position and with the exact motion.

2.3.5 Types for Information Presentation

The main intention of the paradigm of AR places virtual information spatially related to real objects. 3D information or objects are placed in the user's personal field of view and appear in correct position and orientation, and are shown perspectively correct. The virtual objects seem to be part of the real world.

Egocentric Presentation

AR technology offers a wider range of application. In general, any information can be displayed anywhere. Thus, additional information from another perspective, such as bird's eye maps, can be placed anywhere in the user's field of view. Such bird's eye maps implement the concept of the *world in miniature* (WIM) [144].

Exocentric Presentation

At this point it is on time to take a look on information, ADAS systems can present to the driver. The main intend of ADAS systems is to give advance notices to the driver. Otherwise, the system could take over control and perform the necessary task autonomously. *Advance notices* (in German „Voranzeigen") provide information about the most likely future event or progress. Information about future events or progresses bear the benefit of mental discharge, improved performance and reduced study time. Such information is provided adjacent to the actual situation.

Advance Notices

Pursuit and Compensatory Displays ADAS systems can present supportive information about the task or how to achieve the task. Such presentation can be presented via AR in the natural environment (in general in an egocentric frame of reference) or via alternative cues (in general in an exocentric frame of reference). In the first case has the user to care for the full data processing. The mapping from the required task to the required action is left to the user. A so called *Pursuit Display* (in German „Folgeaufgabe") does not give a hint on the desired action to perform. The second case presents extra information, about how to fulfill the task, to the user. The ADAS system precomputes some future situation and gives hints on the most likely action. The difference between the task and the task fulfillment is indicated. Such presentation of additional information is called *Compensatory Display* (in German „Kompensationsaufgabe").

Pursuit and Compensatory Display

The use of AR enables both types of information presentation. Situations can be highlighted with *Pursuit Displays*, such that the driver has to care completely for the actual task fulfillment. Solutions for tasks can also be presented with *Compensatory Displays*, so that the driver has a hint on task achievement. *Compensatory Displays* provide presentation schemes in a frame of reference coupled to the user.

Frames of Reference

Egocentric and Exocentric Presentation Information presentation in the field of computer graphics can also be classified according to a *continuum delimited by egocentric and exocentric* information presentation. The egocentric end is defined by the classic idea of AR. Information is fully embedded in the user's personal frame of reference and shown from the

Definition of a Continuum

user's own point of view. 3D information thus is seamlessly embedded into the surrounding world. The exocentric end of the continuum is defined by information presented from a completely different frame of reference. Usually this different frame of reference is rigidly mounted to the world surrounding the user. In between these two boundaries, information presentation varies depending on the number of altered degrees of freedom. Objects and viewpoints have six degrees of freedom, three translational and three rotational. The localization in the continuum changes depending on the number of degrees of freedom altered. Starting on the egocentric end of the continuum, all six degrees of freedom between the user's point of view and the point of view of the AR system correspond to each other. The translational degrees of freedom can be assumed to be located nearer to the egocentric end of the continuum, because translations are easier to deal with than rotations. Moving the point of view of the AR system along one translational axis is the first step away from the egocentric end. The user now has to transform between both frames of reference. When the AR viewpoint of the AR system differs from the viewpoint of the user, but shows the user with an avatar, a *tethered viewpoint* is used. Fully egocentric presentation for instance, can show an AR scheme from a car driver's point of view. Moving the point of view of the AR representation backwards some of meters then can show an environmental view of the scenery, including an extra AR scheme of the own car. The more translational and rotational degrees of freedom are altered, the further moves the representation of the AR scheme to the exocentric end of the continuum. A well known alteration of three degrees of freedom often is used in 3D computer games. Besides the fully egocentric view on the scenery, a tethered viewpoint can be chosen. This viewpoint lies some meters behind and some meters above the own character. The camera is facing slightly down. Here, three degrees of freedom are altered.

Continuity

The continuum is not only defined by the 6 discrete degrees of freedom, but also by the continuous values of each degree. Location between both ends also depends on the range, each single degree is altered. For instance, moving some meters along an axis has less effect than moving some hundred meters.

Mental Workload for Transformation

The more AR presentation schemes are located to the egocentric end of the continuum, the less mental workload is required to transform the information to the personal frame of reference. At the egocentric end of the continuum, no mental translation between both frames of reference is necessary. At the exocentric end of the continuum, most effort for translation is necessary, because the user has to know about the position of the virtual viewpoint relative to the own position and mentally has to transform between both frames of reference.

Complex Transformations

Complex transformations between two frames of reference are necessary, when the direction of the AR scenery is fully turned around. When, for instance, one sees his virtual character face to face from a leading viewpoint, doing a left turn leads to the character walking right (on the screen).

Camera Mounting

Egomotion in Displays The community of ergonomics maps the type of mounting of the virtual camera presenting the information display in *exocentric* or *egocentric* manner to *Pursuit* and *Compensatory Displays*. *Pursuit Displays* in general use an exocentric frame of reference. Here the point of view is rigidly bound to the environment. *Compensatory Displays* in contrast are coupled to the frame of reference of the user but do not necessarily have to present the information from an egocentric point of view. The point of view of the display can rather have a rigid tether to the user, mounting the camera in a way that it follows the *egomotion* of the user [111].

Dynamic Tethers

A special role of a *Compensatory Display* is defined by mounting the camera not rigidly to the user, but dynamically. Milgram and Colquhoun [111] describe such systems with the camera having a certain mass (and thus a certain inertia). A spring then mounts the camera to the user. Changes to the physical state of the user thus no longer directly and rigidly change the state of the display. The mass-spring-system smoothes the effects of the transformation and in particular compensates large translations, a rigid tether would generate due to rotations of the user. Lamb and Hollands [94] investigated this kind of display and compared it to conventional displays. Their results show a high potential for egocentric spatial awareness.

2.4 Formal Usability Studies

Necessity of Studies

Interaction or presentation concepts must be tested whether they generate a benefit when compared to traditional approaches. Such tests for AR schemes require improvements in driving performance and situational awareness. If such systems generally improve certain factors in other application domains, but are not compatible with the automotive constraints, the system must get discarded or rethought to meet the demands.

Study Environments

As explained earlier in this chapter, the automotive environment strictly has to enforce management of the primary task of driving. Any system providing supplementary information thus must be tested under circumstances of a primary task to be performed in parallel. Just giving an extra task to solve is not sufficient, because assistance systems affect driving behavior. ADAS systems aiming at improved performance and situational awareness therefore require driving simulators or real test setups to evaluate coincidences between driver reactions.

Objective Measures

The effects of the ADAS system on driving quality and mental workload can then be measured by comparison to test drives under the same circumstances but without the ADAS system. By this approach, objective data, such as lane and speed keeping behavior, reaction time, or glance behavior times, can be measured. Analysis of this data allows assessing assistance systems in reference to criteria of usability, distraction and understandability.

Subjective Measures

Subjective measures in addition can be gathered through questionnaires. They can support objective measures or can give information about acceptance, pleasure or joy of experience.

Descriptive Statistics

Descriptive statistics then are used to describe the basic features of data from a study. In case of usability studies, different systems are tested and descriptive statistics show how the systems differ. Basic approaches calculate mean values and standard deviation of measured values. To generate results over different systems, these values also have to undergo a statistical comparison to compute the likelihood of a wrong hypothesis.

2.4.1 Evaluation Methods for Assistance Systems

Used Methods

This section shortly introduces two methods that are applicable for usability studies as conducted in the context of this document: driving simulator environments and the glance tracking system Dikablis (German abbreviation: Digitales Kabelloses BlickerfassungsSystem; digital wireless glance tracking system). Further methods to test the effects of AR systems include occlusion tests, Peripheral Detection Tasks (PDT, [119]), pupilometrics [127] and physiological measures [84], such as heart rate, respiration rate, skin resistance or number of swallows. Such methods have not been used in the studies and therefore are not explained here.

2.4.1.1 Driving Simulators

Levels of Fidelity

Driving simulators range from simple desktop based systems with gaming controllers over fixed-base driving simulators to full-motion systems. Each simulator environment generates a certain level of fidelity. Each system which has to be tested in a driving simulator requires its own level of fidelity, a simulation environment must meet.

Simple Systems

In general, IVIS systems, specifically systems in the tertiary task of driving only require low levels of fidelity as they only enforce to have a mandatory task. This mandatory driving task can be established in simple desktop based systems. The *Lane Change Task* [109] is such a system requesting the driver to drive at a certain speed and to change lanes according to passing traffic signs. Secondary tasks have influence onto the capability to maintain the lane changes. Analysis later can incorporate objective factors of lane keeping behavior and total task times.

High Fidelity Systems

ADAS systems and specifically AR-based ADAS systems in contrast require higher levels of fidelity. The general need for more immersion comes from the dependency to the road scenery. ADAS systems are developed to improve driving performance. Thus driving simulators must enable a higher degree of realism so that a driver can really drive through the virtual world. Such simulators must provide wide field of view environments and correctly calibrated presentation systems. Rebuilding a natural view onto the scenery is necessary to keep the impression of speed and sizes.

Fidelity Classification

A classification model for driving simulators and mapping principles are currently under investigation by Tarr (RAPTER group, Institute for Simulation & Training, University of Central Florida). Usability studies in the context of this thesis were conducted with a fixed-base driving simulator with a single projection wall, generating about 40 °field of view. See section 5.1, page 81 for details about the driving simulator and its successor. The setup in a real car and the large projection wall provided a simulator environment mature enough to test AR schemes for the front windshield.

2.4.1.2 Glance Tracking System Dikablis

Dikablis

Dikablis [95, 97, 98] is a glance tracking system developed and improved over several years at the chair for ergonomics of the mechanical engineering faculty of the Technische Universität München. Its first versions, previously called Janus used a helmet to carry the glance recording hardware. In improved new variants, the helmet was replaced by swimming goggles and later by a frame similar to normal eyeglasses. The system now is available in different configurations, e.g., in a wireless version, transmitting the camera images via wireless links to the recording computer.

The construction itself uses an infrared mirror to record both, a camera image of the wearer's eye and to record a second image of his frontal field of view. A recording and analysis software allows blending and scaling both videos relative to each other so that the two streams can be calibrated to a certain focal depth. Hardware

The recorded videos have to be analyzed manually, but part-automatic analysis is under development, so that certain regions of interest can be marked and categorized automatically. Then only moving objects need to be identified manually. Video Analysis

Glance behavior involves information about mean, maximum and cumulated glance times. Glance frequencies and amounts, and all factors contributing to the identification of distraction are cumulative. Such factors are illustrated in the paragraphs concerning issues about visual output in section 2.2.3 (page 26). Glance tracking systems thus are excellent applicable tools for the evaluation of ADAS systems. Glance Revelations

2.4.2 Methods to Collect Subjective Data

This section briefly lists methods used in the later usability studies to gather subjective data. All methods use questionnaires to obtain data. Subjective Questionnaires

2.4.2.1 General Questionnaires

Each usability study contains a demographic questionnaire, asking for gender, age, level of education and experience with related systems, i.e. automotive assistance systems. Such data helps to categorize results into different groups, e.g., people dealing with computers and 3D computer graphics for a long time or people new to superimposed computer graphics. Such questionnaires in general are filled out before the usability study is conducted. Demographic Questionnaire

Further questionnaires collect data about the test participants' experience during the study and in general inquire about factors such as pleasure, feeling of safety, feeling of capabilities to maintain speed or lane keeping, or they ask test participants to rank systems relative to one another. Other Questionnaires

2.4.2.2 NASA Task Load Index

The NASA Task Load Index (NASA-TLX, [74]) is a multi-dimensional scale designed to obtain *workload* estimates from one or more operators while they are performing a task or immediately afterwards. Workload is a term that represents the cost of accomplishing mission requirements for the human operator. The NASA Task Load Index consists of six subscales that represent somewhat independent clusters of variables: Mental, Physical, and Temporal Demands, Frustration, Effort, and Performance. The assumption is that some combinations of these dimensions are likely to represent the workload experienced by most people performing tasks. Fig. 2.8 shows the six questions, for each the participant has to mark his opinion on a 0 to 100 scale. NASA TLX

Since its introduction, NASA-TLX has been translated into more than a dozen languages, administered verbally, in writing, or by computer, and modified in a variety of ways [73] and became a quasi standard to measure an overall workload index. 20 Years of NASA TLX

RATING SCALE DEFINITIONS		
Title	**Endpoints**	**Descriptions**
MENTAL DEMAND	*Low/High*	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	*Low/High*	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	*Low/High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
EFFORT	*Low/High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
PERFORMANCE	*Good/Poor*	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
FRUSTRATION LEVEL	*Low/High*	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Figure 2.8: The six questions of the NASA-TLX. Ranking takes place on a scale which is not shown here

2.4.2.3 AttrakDiff - Method to Measure Attractivity

Semantic Differential

AttrakDiff [76] is a measurement method for attractivity of interactive products. The method is based on the principle of the semantic differential. Adjectival complements are used to measure a user's perception of a system. Test participants use Likert adjectival complements, for instance between ugly - nice or between confusing - clearly arranged. Different dimensions of judgment are classified:

Pragmatic Quality: Pragmatic quality characterizes usability and clarifies how a user can reach his goal with the system.

Hedonic Quality - Stimulation: Hedonic quality of stimulation shows how an interface supports further development of a user by providing new, interesting or stimulating functionality, content, interaction techniques and/or presentation schemes.

Hedonic Quality - Identity: Hedonic quality of identity describes to what extent a user can identify with a system.

Attractivity: Attractivity measures a global benchmark of a product based on perceived quality.

Judgment of Attractivity: Pragmatic and hedonic quality are independent, but contribute almost equally to the judgment of attractivity.

2.4.3 Descriptive Statistics

Further Reading

In subsequence, statistical fundamentals are summarized which were used for the analysis of usability studies. For further reading, the work of [7, 30, 54, 124] should be consulted.

Towards Significance

A usability study generates data either in protocol log files or through questionnaires. Thereby, measured values of different data clusters are collected. The data then must be analyzed statistically to allow for comparison to predefined hypotheses. Applied computations then allow for significant conclusions about the tested system.

2.4.3.1 Preparation of Data

Data Conversion

Data from questionnaires first is put into tabular representation for the use in Excel or SPSS. Protocol log files are also converted for application in analysis software. Glance behavior movies are analyzed and mapped to tabular representation.

Minimum, Maximum, Arithmetic Mean

Easy computations, such as maximum, minimum and arithmetic mean are computed on all data sets. Minimum and maximum values are the smallest and largest values of a set of values. The arithmetic mean $\overline{x}$ is the sum of all values of a measured value set, divided by the amount of values.

$$\overline{x} = \frac{1}{n}\sum_{i}^{n} x_i;$$

Standard Deviation

The standard deviation is a measure of the spread of the values of a measurement set. It is a measure to compare a variability of distribution. The standard deviation σ is the positive result of the square root of the variance var. The variance is computed from the sum of the quadratic deviation of all measures to the arithmetic mean divided by the amount of all measures.

$$var = \sigma^2 = \frac{1}{n}\sum_{i}^{n}(x_i - \overline{x})^2;$$

$$\sigma = \sqrt{var} = \sqrt{\frac{1}{n}\sum_{i}^{n}(x_i - \overline{x})^2};$$

2.4.3.2 Formulation and Verification of Hypotheses

Hypotheses

To verify theories and to answer questions about a system, hypotheses are predefined before an evaluation is conducted. The evaluation then delivers measured values which are analyzed statistically. The analysis provides statements concerning the questions to the system.

Null Hypothesis

Statistical analyses distinguish between an *alternative hypothesis* (H1) and a *null hypothesis* (H0). The alternative hypothesis tells that a difference between the examined attributes exists. The null hypothesis in contrast assumes both systems as equal with respect to the independent variable. *Independent variables* are the objects which are studied by the experiment. The work at hand studies different system variants of ADAS systems in later chapters. There the different variants of the systems state the independent variables. Driving without any assistance system is a separate variant, the so called baseline. Differences between tasks or groups of the sample are not focused in this work and thus are not examined. Undirected alternative hypotheses only tell about existence of a difference. To get statements about preferred system variants, directed alternative hypotheses are applied.

Study Designs

To check hypotheses, samples from the population are selected. The test participants should meet the target group as close by as possible, which in case of driver assistance systems in first order aims at people buying cars from the premium sector. Samples can be depended or independent. Independent samples only exhibit test participants to one variant and use a between subject design. Dependent samples put all test participants through all variants in a so called within subject design. To avoid learning effects, the order of the variants is counterbalanced over all test participants. Best results are gathered when such studies are conducted in multiple sessions where in one session only one variant is provided to the test subjects. Due to the common problem of getting test participants at all, most usability studies are conducted in single sessions. Studies conducted in this work used within subject designs with single session study execution.

Probability of Wrong Decisions

General statements concerning the population are derived from the test results of the samples. It must be decided, which of the hypotheses must be declined and which can become accepted as correct. Besides correct decisions, for which a right decision was taken based on the test results, possibilities for wrong decisions exist. Table 2.1 gives an overview over all possible decisions.

		In population applies:	
		H0	H1
Decision based on sample in favor to	H0	Correct Decision	β-Error
	H1	α-Error	Correct Decision

Table 2.1: Statistic opportunities for decisions; courtesy of [30]

α-error

The α-error indicates an alternative hypothesis as accepted even though a null hypothesis applies for the basic population. The β-error in contrast indicates the effect that an alternative hypothesis is discarded wrongly and that the null hypothesis is considered as correct. The probability to commit an α-error is named probability of error. A probability p is computed which indicates the probability indicating that the data determined in the experiment match the situation in the basic population. If this p-value lies below the probability of error, the result is titled as *significant*. Fig. 2.9 shows the α-error in a sketch. All usability studies conducted in context of this work applied a significance niveau of $5\,\%$. Thus all p-values below 0.05 are significant.

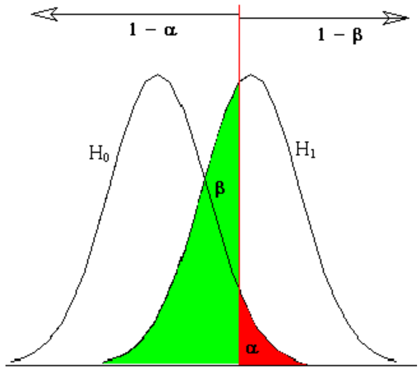


Figure 2.9: Sketch explaining distribution and probability of an α- and β-error around a mean value

β-error

The β-error cannot be defined by a fix threshold. The β-error can, according to [124], be estimated in dependence to the α-error: p must be larger than 0.25 to accept the null hypothesis as correct. The interval between 0.05 and 0.25 thus generates no statistical utilizable results. Fig. 2.9 shows the β-error in a sketch. β-errors have not been investigated in this work.

2.4.3.3 Significance Tests

Amount of Variants

Depending on the scale niveau, sample attributes and distribution of data, a significance test must be chosen to analyze the relationships of the measured data statistically. For metric scales and normally distributed data, parameterized tests can be applied. The T-test for independent samples and the analysis of variance (ANOVA) have been applied for analyses of usability studies.

T-test The T-test for independent samples is applied if only one independent variable becomes altered, for instance, when test participants perform the same task with two system variants.

$$\hat{x}_i = (x_i - \overline{x}); \hat{y}_i = (y_i - \overline{y});$$

$$t = (\overline{x} - \overline{y}) \sqrt{\frac{n(n-1)}{\sum_i^n (\hat{x}_i - \hat{y}_i)^2}};$$

ANOVA If the same set of test participants performs tests on more than two different system variants, analysis of variance (ANOVA) is used for analysis. The ANOVA compares the variances of multiple mean values and generates statements about significance covering all tested system variants.

First, the common variance var_G of all measures is computed.

$$var_G = \frac{n_1\, var_1 + n_2\, var_2}{n_1 + n_2};$$

Second, the F value is computed. The F value is a probability variable with a $F_{k-1,n-k}$ distribution where k is the number of groups and n the number of values in the samples. The samples must have equal sizes.

$$F = \frac{n_1\, n_2\, (\overline{x}_1 - \overline{x}_2)^2}{(n_1 + n_2)\, var_G} = \frac{n_1\, n_2\, (\overline{x}_1 - \overline{x}_2)^2}{(n_1\, var_1 + n_2\, var_2};$$

The value of the F-distribution is read from a Fisher table with use of the probability of error. The null hypothesis can be rejected if the computed F value is larger than the F value from the Fisher table.

The computation of the pair-wise α-values then uses the T-test.

There are many derivates of the ANOVA. These are used under the circumstances of different sizes of samples or inhomogeneous variances.

2.4.4 Presentation Style of Results

Tables and graphic diagrams are used to illustrate all aggregated results.

The tables are structured as follows. The lower part of the tables shows mean values and the standard deviation. Here, the best mean value is highlighted in green, while the worst mean value is highlighted in red. The upper part shows a cross mapping to that reports the $\alpha-$values of the analysis. Significant values are presented in green. Table 2.2 gives an example of three variants analyzed with ANOVA.

α-**Values**	Variant 1	Variant 2	Variant 3
Variant 1		0.255	0.017
Variant 2			0.102
Variant 3			
Mean [km/h]	5.06	6.65	8.83
Std.dev [km/h]	7.02	8.05	7.91

Table 2.2: Example for Tabular Presentation of User Study Results

The graphic diagrams presenting the results use vertical bar diagrams. Fig. 2.10 gives an example with values similar to table 2.2. The vertical Y-axis shows the values of the arithmetic mean. The horizontal X-axis displays the different variants that have been compared. The vertical error indicators on top of each bar show the standard deviation. The horizontal markings visualize the results of the statistic analysis. A double arrow on the top end of the diagram indicates a significant difference between two variants. Variant 1 and 3 in example Fig. 2.10 differ significantly. A simple bar directly on top of the bars indicates variants with no statistical difference. Variant 1 and 2 in example Fig. 2.10 have no statistical difference. If no marking is placed between two variants, no statistical statement can be given because the α-value lies in the interval between 0.05 and 0.25. Variant 2 and 3 in the example Fig. 2.10 do not have a statistical statement.

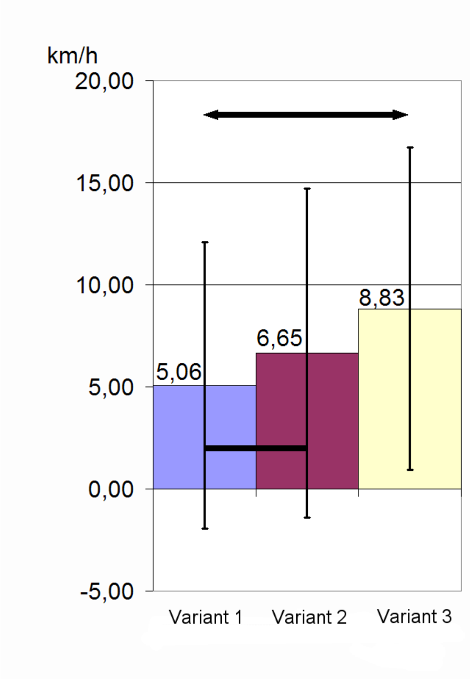


Figure 2.10: Example for Graphic Presentation of User Study Results

3 General Augmented Reality Concept

Models for interaction and presentation of Augmented Reality content based on technical, interactive and perceptive constraints leading to guidelines for Augmented Reality in Advanced Driver Assistance Systems

Foundation hitherto

Augmented Reality still is a relatively new field of research and has not yet been investigated deeply in automotive ADAS systems. Presentation and interaction with AR differs from conventional systems. Guidelines for applications therefore require some extensions and redefinitions compared to available design guidelines for conventional systems. The first mappings of AR to application levels (section 2.1.6 on page 19), mappings of 3D user interfaces (section 2.2.5 on page 32) and constraints for information presentation (section 2.3.4 on page 37) provide a foundation for the collection of guidelines for such a general AR concept related to car driver assistance.

Dependency Pooling

This chapter revisits some of the fundamentals from the previous chapter 2 puts them in relation to technical and interactive needs and in consequence summarizes guidelines for automotive AR in general. Especially areas visible for car drivers in dependence of exploration mechanisms for AR presentation are examined. An interaction model applied to automotive interaction then generalizes human perception which is mandatory for ADAS systems to transmit their information. The initial exploration model is revisited under the influence of the general interaction model. This enables an investigation of technical issues of HUD design, which in subsequence contributes to the AR concepts. The contributing factors are now briefly illustrated before they are investigated subsequently.

Available AR Space

To develop a general concept for the incorporation of AR into automotive environments, several further constraints and dependencies of space available for AR presentation must be taken into account. The available space for information presentation must be examined and defined. The space depends on form factors that restrict the visible area from the driver's point of view and on outer delimitation such as the maximum distance required to present AR content. These factors are explained in the following paragraphs in detail.

Externally Constrained Presentation Spaces The visual sense is the most important sense for AR and for automotive tasks. Information not only is presented inside the car, but can, and in most cases of ADAS systems is, presented in the environment outside the car. Here, presentation areas are, among other things, constrained by the physical structure of the car frame which occludes certain areas from possible presentation. Focal Distance of AR presentation schemes plays another important role for perception with optimized glance time. The *Sphere of Vision* as a conceptual model establishes awareness for these dependencies.

Interactive Spaces The *Sphere of Vision* defines a conceptual model for exploration of available visual presentation spaces around the car. Another model, which is derived from interaction principles between different entities, describes another view on spaces around cars. Combinations and overlappings of these spaces enable communication and situation-related information presentation. This interactive model is explained and mapped to automotive environments. This mapping then leads to a classification of different awareness ranges of automotive sensor systems and car drivers. The difference between these awareness levels is defined as a delta in knowledge between car drivers and automotive sensor systems.

Internally Constrained Presentation Spaces Presentation of AR content is not only constrained by external factors such as occluding parts of the car, but also by technical dependencies. To present AR content in a certain focal distance in the HUD, a suitable apparatus is needed to bring the virtual content to the required position and distance.

Space Combination

All these exploratory, technical and communicative factors combined form the space dependent volume for information presentation. This volume dynamically deforms in conjunction to motion and defines requirements for systems enabling windows into augmented worlds.

Design Guidelines

By knowing the available space for the application of AR, fundamentals of chapter 2 can be applied to define guidelines for the incorporation of AR. These guidelines in combination with a multi-modal interaction concept lead to a general concept for the application of AR.

Chapter Structure

The structure of this chapter is aligned with the structure of this section. First, the *Sphere of Vision* is defined, followed by the interaction concept. Revisiting the *Sphere of Vision* and combining it with the interaction model finally leads to guidelines for AR integration and the general multi-modal concept for AR application.

3.1 Exploring the Available Presentation Space – The *Sphere of Vision*

Space for AR

One general issue in the development of user-related content for AR, besides the shape of the AR scheme itself, is the dependency on the space the scheme can use for its presentation. It has to be determined, where and how a presentation scheme can be placed. The visible area, especially for car drivers, and the dependence on the associated task have a strong influence on the appearance of the presentation. The *Sphere of Vision* therefore defines a classification and exploration model for task dependent schemes and dependent presentations. The relationship between a task, associated objects, the visual area and the focal distance can be classified through this approach. Using this, the developer only has to focus on the appearance of the scheme and the appropriate presentation device.

2D Spatial Displays

This model originates from the difference in research and in final applications. In research, presentation devices are used to generate stereoscopic 3D schemes. To present AR schemes in applied applications, many of these displays cannot be used. The result is, that on the one hand, special stereoscopic displays need to be incorporated to still present the schemes in 3D, or on the other hand, that spatially decoupled 2D displays are applied to put the virtual content in open space. Especially in this case, where only one focal distance exists for the virtual content, developers often have to keep in mind that also this distance has to be adjusted depending on changes in the presentation depth. In addition, if a display is not head-mounted, the presentation area of the display can get out of the viewer's range. A further constraint is defined through the available space to render virtual content. Every area of application, specifically in dependence on the position of the user, has areas that are occluded by objects. For instance, the front-pillar occludes a certain area in the outside environment for car drivers.

Sphere of Vision

To generate an assisting model for the development of AR schemes, the following assumption is necessary: in general, virtual content can be displayed everywhere. In fact, depending on form factors of the car, this space is restricted. The conceptual model of the *Sphere of Vision* places a virtual sphere around the user. This sphere is never visible in an ADAS application, it rather is a means for the development process to indicate the area a scheme can use at a certain focal distance. Fig. 3.1 shows a sketch of such a sphere. Here, approximately, the focal distance of the car driver is set to about 2.5 m, as indicated by the radius of the sphere.

Figure 3.1: Sketch of the *Sphere of Vision*: An invisible sphere on which virtual content can be rendered

Application Domains

As general as this idea is, so are its areas of application. The sphere generates awareness of presentation issues and enables exploration mechanisms for AR concept developers. Even HUDs with a large field of view cannot enable presentation everywhere around the car. Only a certain field of view towards a certain direction can be superimposed with AR schemes. Although these displays are not yet available, exploration becomes possible by instantiation of the sphere by portable displays. Such displays can visualize certain parts of the sphere and can superimpose AR schemes in any direction. Another perspective onto the sphere from a larger distance furthermore enables exploration of the constraints generated through the shape of the car frame. Visualization of areas on the sphere occluded by car components thus becomes possible.

3.1.1 Exploration of Presentation Areas

There are no HUD technologies that can cover the whole area around a car for information presentation. The concept of the *Sphere of Vision* can be applied in car setups to explore possible display areas for AR content. Special environments like CAVEs [44] can present information in every orientation around a user but are not large enough to place a car inside. It would require each new car to be brought to the exploration environment, thus complicating development processes. Another approach, using a portable tracking system can reverse the transportation problem by installing such a system where it becomes necessary. This can be either in driving simulators or in real cars. A tracking system placed near or in the car in combination with a trackable TFT display can enable the display to render spatial information correctly aligned in location and orientation of the display. The display therefore must have a defined virtual point of view rigidly placed in front of the screen. It then enables a view into the augmented world and presents a certain section of the *Sphere of Vision*.

Tracked LCD Display

The concept of this sphere can be extended to adapt different sizes dynamically. The size only depends on the placement of the display relative to the position of the driver. This approach allows examining where any kind of AR content would potentially be presented. Designers of AR schemes can examine the full area around the car and can test if and how information is perceivable from the driver's point of view.

Space Examination

The setup can be extended by an outside visualization of the design area. An additional camera system can film the development process and dynamically overlay the scenery by a visualization of the sphere of vision. The scene visible on the secondary system then shows how the *Sphere of Vision* adapts to the distance of the LCD display. As a consequence the required focal distance for correctly perceivable presentation is visualized and supports monitoring issues for the technical development of HUDs. Fig. 3.2 shows in a sketch, how information presentation can be facilitated through such a tracked TFT display by perspective alignment of the presented AR scheme. The figure also provides an impression of how the sphere adapts its size to the distance between the driver's head and the display.

Monitoring Design Processes

3.1.2 Constraining Visible Areas

Every design of a car, even a convertible, has a roof and some columns for passenger protection. These restrict the passenger's view to the outside and also restrict the displayable area for AR schemes. Depending on the information concept, a certain risk exists that a presentation scheme might fully or in parts be occluded through car parts and thus might not be perceivable any more.

Restricted Views

The *Sphere of Vision* enables investigation and awareness for these restrictive areas. The areas which are visible through the windows of the car can be highlighted by different colors on the sphere. Thus developers not having the exact application environment, or in other words, not having the right car to develop their concept, can use 3D models to visualize and test, if their proposed solution does fit into the remaining space. The example of a car driver in Fig. 3.3 shows which areas on the sphere remain for AR content.

Indicating Visible Areas

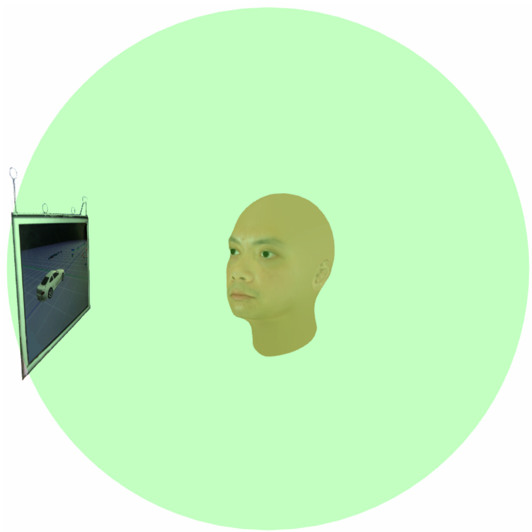


Figure 3.2: The *Sphere of Vision* adapting to a tracked LCD display: The nearer the display gets to the head, the smaller the sphere but the wider the field of view

3.1.3 Fully Aware Design

Laboratory Development

The concept of the sphere of vision facilitates interaction design such that dependencies of applications in real setups can be brought to the laboratory. Factors are more present during early development. Visualization of various constraints of the application domain facilitates the design process of spatially registered interfaces. The *Sphere of Vision* allows experiencing the constraints of

- focal distance
- field of view
- occluded areas

and thus enables interface design combining

- the task to execute
- the appearance of the interface
- the placement of the interface.

Focus on Interaction Concept

Thus the developer only has to focus on the interaction and the appropriate device but still can keep track of the constraints.

Figure 3.3: The *Sphere of Vision* highlighting non-occluded areas: Here the windshield and the driver side window field of view are highlighted

3.2 Interactive Communicative Dependencies

Interaction Mechanisms

A second approach to determine boundaries of important space around a car can be defined by investigating interaction in groups. Not only groups of people, but also groups of objects are considered in this approach. The original model was developed by Benford et al [18] for group interaction in large virtual environments but is applicable for real environments as well and thus for automotive environments in particular. The interaction model provides mechanisms for conversation management in every modality by adopting spatial approaches. In doing so, the underlying philosophy has been to encourage individual autonomy of action. The model provides mechanisms for constructing highly reactive environments where objects dynamically react to the presence of others.

Aura

The first problem in any large-scale environment is determining which objects are capable of interaction with each other at a given time. *Aura* is defined to be a subspace which effectively delimits the presence of an object within a given medium and which acts as an enabler of potential interaction [53]. Objects carry their auras with them when they move through space and when two auras intersect, interaction between the objects in the respective medium becomes possible. A flow of information between both objects is established. The kind of information depends on the type of the aura. For vision, the photons of the light emitted or reflected from one object move towards the receiver. An object typically has different auras (e.g. size and shape) for different media. As, for instance a car approaches another car, one might be able to see the car before one can hear it because the visual aura is larger than the aural aura.

Focus and Nimbus

Once the aura has been defined to determine the potential for object interactions, the objects themselves are subsequently responsible for controlling these interactions. This is achieved on the basis of quantifiable levels of awareness between them [19]. The measure of awareness between two objects not need to be mutually symmetrical. As with aura, awareness levels are medium specific. Awareness between objects in a given medium is manipulated via *focus* and *nimbus*, further subspaces within which an object chooses to direct either its presence or its attention. More specifically:

- The more A is in the focus of B, the more A is aware B.
- The more A is in the nimbus of B, the more A is aware of B.

Quantifiable Level of Awareness

Awareness levels are calculated from a combination of nimbus and focus. More specifically, given that interaction has first been enabled through aura, the level of awareness that object A has of object B in medium M is some function of A's focus on B in M and B's nimbus on A in M.

Basis for Interaction

The resulting quantified awareness levels between two objects can then be used as the basis for managing their interaction. Exactly how this is achieved depends upon the particular application. One approach might be to allow objects to actively react to each other's presence depending on specified awareness thresholds. A car, for instance, might automatically generate a collision warning for the driver once a certain direction and distance threshold has been passed.

Different Levels

Levels of awareness now can be distinguished in more detail. Considering two cars, A and B, we can now evaluate three possible levels of awareness as sketched in Fig. 3.4:

- A is *fully aware* of B if B is within A's focus and A is within B's nimbus. In this case, A would receive information about B. See Fig. 3.4(a).
- A is *not aware* of B if B is not within A's focus and A is not within B's nimbus. In this case A gets no information about B. See Fig. 3.4(b).
- A is *semi-aware* from B if either B is within A's focus or A is within B's nimbus, but not both. In this case A would not receive information about B, but could be notified that B exists nearby. See Fig. 3.4(c).

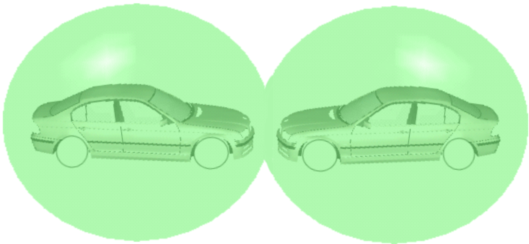
3.2.1 Auras in Automotive Environments

Automotive Interaction

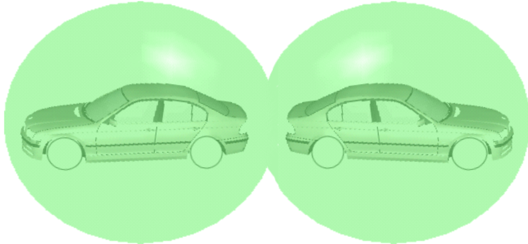
When applying this interaction model to automotive environments, the three given levels of awareness get varying importance for driving tasks. Car drivers being fully aware of each other in general will not come into any dangerous situation. Both drivers being unaware of each other in general do not generate a risky situation, if their paths do not intersect. If paths intersect, critical situations can occur similar to semi-awareness. Both can lead to specific risks, as, for instance at intersections where one or both drivers might not be aware of the other car. Then interaction must make use of further assisting systems informing the driver or the drivers about the situation.

Different Auras

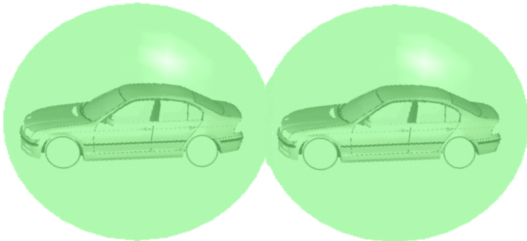
The example enforcing assistance systems to inform the driver shows the existence of different auras. Each human sense has another aura and car-mounted or environmental sensor systems bring their own auras. Some auras which are important to deal with are described here:



(a) A (left) is fully aware of B (right)



(b) A (left) is unaware of B (right)



(c) A (left) is semi-aware of B (right); back mirrors neglected

Figure 3.4: Levels of Awareness when Auras overlap

Visual Aura The visible area each car driver has. This volume is constrained by the own car and every obstacle in the visible environment. The possible shape is a indefinite sphere with large indentations created through the objects in the environment. The initial visual aura is specified by the Sphere of Vision (section 3.1, starting on page 51), where only automotive components constrain the field of view. The actual shape of the visual aura furthermore is constrained by the current viewing direction of the driver. Here three further auras can be differentiated, according to human glance behavior (section 2.3.2, starting on page 34):

Foveal Visual Aura The foveal aura defines the clearly perceived area, a driver has at a certain point in time. The general shape of this aura is defined as a long sharp cone. The foveal viewing cone has an opening angle of about 2° and is constrained in distance by the maximum perceivable distance, but in most cases by objects in nearer distance occluding more distant objects. The actual aura is smaller. This decrease in size depends on the focal accommodation of the human eye. Only objects near the adapted focal distance appear sharply. For near distances, the cone thus has two conic sections, one defining the nearest and the other defining the largest distance, the human eye can capture without accommodation. The foveal aura can change quickly in dependence to focal accommodation and to glances to other directions.

Parafoveal Visual Aura The parafoveal aura uses the same central line of sight as the foveal aura but has a larger opening angle. It ranges from about 2° to an average of 10°. The shape of the parafoveal aura has the same boundary constraints as the foveal aura except for the wider opening, but only enables perception of movements.

Peripheral Visual Aura The peripheral visual aura is the largest aura a human has for perception. It is constrained equal to the other auras but covers the whole field of view. Perception in this aura only enables estimation of size and direction of objects. Perception in automotive environments suffers, especially at high speeds through the relative speed of passing objects. The fast motion generates many different images on the retina. The cells on the retina get overstimulated through these fast changes. Tunneling effects appear, reducing perception of objects the further they get off the center of the central line of sight.

Auditory Aura The size of the shape of the auditory aura strongly depends on the acoustic insulation of the car. It furthermore is deformed by noise reflections of other objects, such as tunnel walls or other cars. Also speed deforms the shape of the aura minimally and decreases its size due to the increasing noise of the own car, especially from the tires. Occlusion has not as direct an effect as it has for visual auras, but reduces acoustic perception.

Mental Aura A very complex aura is the mental aura. This aura is defined through cognitive awareness of humans. It can be seen as the compound aura of all other human auras but reduced in size through a cognitive filter. This cognitive filter reduces perception. One can see something but not notice it cognitively. This aura becomes important, if it does not intersect with the foveal visual aura. Then, one is cognitively captured (see section 2.2.3.1).

Sensor Aura The perceptive field or area of a sensor system also generates an aura. Size and shape differ in dependence to the applied technology and range from few meters to lower hundreds of meters. The coverage of a sensor systems aura must be wider than a human's senses aura or must reach areas occluded for drivers to enable ADAS systems to really be assisting systems.

Motion Aura The motion of a car can also be interpreted as an aura. Two different shapes can be applied to this aura. Either the aura has the width of the car and is aligned along the direction of he heading of the car or the aura has the shape of the possible directions the car can currently have. Bubb [36] defines the latter interpretation in combination with the current braking distance as „Hirschgeweih“ (in English: deer antler). It was named according to a deer antler because of its outer shape having strong similarities to the shape of an antler. Especially for the first interpretation concerning the trajectory of the car, these auras, in contrast to all other auras, should never intersect. Intersection would lead to an accident. In case of the second interpretation which indicates the available field for steering, intersections of two auras restrict the available space for maneuvering.

3.2.2 Interaction between Drivers and Assistance Systems

Driving Alone

Driving a car is possible without any consideration of auras. The sense of sight sufficiently enables a car driver to perform the driving task. The driver only has to perceive his environment to plan according actions.

Other Drivers

When other cars get into the surrounding of the own car, a car driver can still perform his task. But in certain situations, interaction with other drivers can become necessary. For instance at a four way crossing, drivers have or should have eye contact. Only when a driver knows that he is seen by the other driver, can he be sure not to risk an accident when entering the crossing.

ADAS System Interaction

The same applies to ADAS systems. They monitor the environment. When a dangerous object enters an aura of an ADAS system, the ADAS system can determine a dangerous situation. They then have to communicate that information to the driver to warn him about the danger. In this case, the ADAS system has to determine the focus of the driver to display the information in according manner. To enable interaction of ADAS systems with drivers, both of their auras require to overlap so that the driver can gather the information.

Anticipation

The problem of ADAS systems is to determine the aura and especially the focus of the driver to present the information. ADAS systems, as a matter of fact have a wider aura than car drivers have. Thus both auras differ in shape and range. Sophisticated ADAS systems (will) have an advantage in anticipation of traffic behavior. Because both auras differ, the designers of ADAS systems have to face the problem of transmitting the knowledge that is unknown to the driver, in an understandable way. Invisible areas in a narrow crossing, for instance, can let another car appear spontaneously.

Delta between Awareness Levels

The difference of both auras generates a delta in knowledge about a traffic situation. The task of the ADAS system is to reduce that delta so that the driver knows about the upcoming situation. Three issues can be distinguished here. First, an aura of the driver can be used to indicate a situation. Second, an aura can be used to indicate an invisible situation. Third, an aura can be used to gather attention concerning the general existence of a situation.

Indicating a Situation Dangerous situations often occur within the field of view of the driver. In some cases, a driver's attention is focused on another stimulus and the driver does not capture the danger. Then, direct indication of the situation using, for instance the peripheral aura by generating an AR scheme around the critical object can draw the driver's attention towards that object.

Indicating an Invisible Situation As in the above example of the narrow crossing, the dangerous situation can be occluded, but would be in the driver's field of view if the occluding object, for instance a parked truck, would not be there. Then the ADAS system can give a hint about the existence of an approaching object.

Drawing Attention towards a Situation Due to the forward motion of the car most dangers come out of the frontal region. Yet, dangerous situations can also come from aside or from the backside in some cases. The driver's field of view then cannot be used to indicate the situation directly. Thus no visual aura can be used to transfer information about the danger directly. Instead, information about the existence and location of the critical situation must be transmitted to the driver. Either another aura, such as the aural aura must transfer that information or an indirect hint must be presented to the driver. Here the issue is to guide a driver's attention towards the direction of the imminent danger.

Movement of Auras

ADAS system design processes have to determine the most suitable aura for information transfer and the most intuitive presentation scheme for declaration of the information. A further issue for the determination of the suitable aura lies in dynamic movement of auras. Especially the foveal aura can reach high speeds: when the driver refocuses to near distances or when the eyes perform a saccade, the foveal aura can move rapidly to another location. The same effect applies for the other visual auras accordingly but due to their greater size with less effect.

Mental Aura

Special consideration must be placed on the mental aura. The mental aura specifies cognitive awareness. Especially in combination with the foveal visual area, design of ADAS systems must face further issues. When a car driver has the foveal aura placed accordingly, he might still not capture the flow of information from the nimbus of the other object to his own focus (of the foveal aura). Here, mechanisms to capture the cognitive attention must be incorporated.

3.3 Combining the *Sphere of Vision* and the Interactive Model

Display Technology

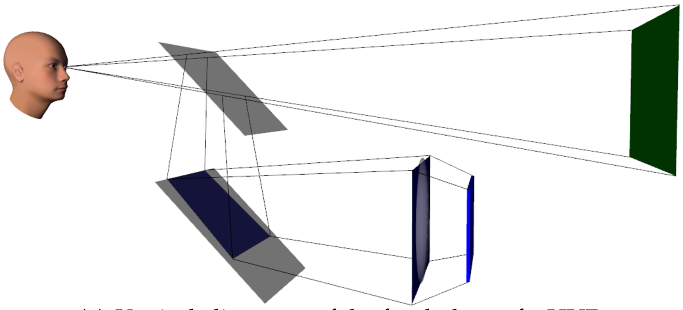
In addition to presentation distances, visible areas and interactive dependencies also technological aspects constrain presentation spaces. Such car internal constraints define further issues AR concepts must face. Technological issues to reach adequate focal depths by minimal form factors of HUDs behind the dashboard and pixel resolutions in correspondence to large fields of view are the main factors having influence on appropriate AR presentation. This section illustrates the dependencies AR concept developers must face due to the limitation of display technology.

Influence of the Sphere of Vision

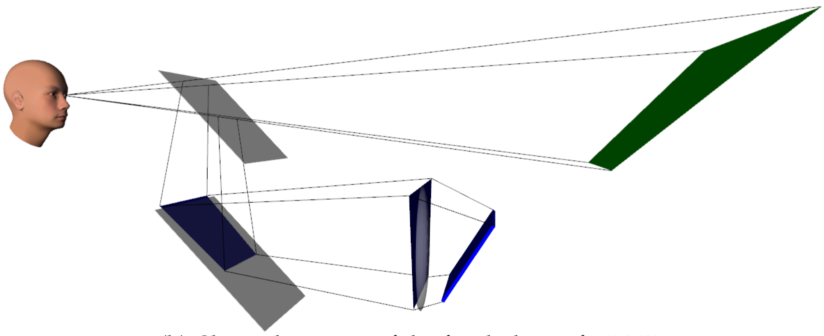
The interaction model of Benford [18] and its application to automotive environments can be used to investigate correlations to the Sphere of Vision. Visual AR presentation only is useful and applicable when the surface of the Sphere of Vision lies inside the targeted presentation aura of the driver. The AR scheme otherwise would have a wrong focal distance so that the driver's eyes would have to refocus from the related real object.

Focal Depth

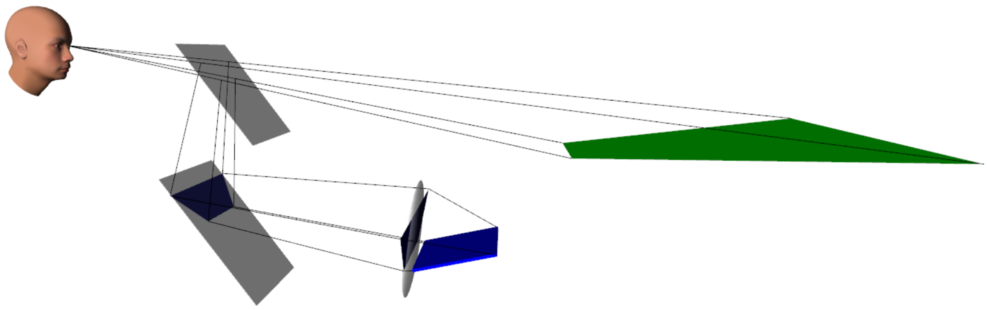
A HUD must provide capabilities to present superimposed AR schemes in the correct focal distance. As described in section 2.3.3 starting on page 35 the focal distance of the virtual image in a HUD is the sum of the distances between eye, windshield and display. This length can be stretched through incorporation of mirrors into the path of the light between windshield and display. Additional incorporation of a lens can stretch the focal distance in accordance to the focal length of the lens, but distorts the image of the display. A second lens with opposite optical factors can be used compensate the distortion again. More complex lens systems using aspherical lenses can correct the distortion of the windshield if it is used as a combiner. Every additional lens increases the volume of the HUD system, making it more difficult to place the whole setup in the car. The 2D display restricts the virtual image to have only two dimensions. Only the alignment of the image plane can vary (see Fig. 3.5): the display placed perpendicular to the driver's line of sight generates an image with a fixed focal depth (see Fig. 3.5(a)), while any horizontal tilt to the line of sight also tilts the virtual image (see Fig. 3.5(b)). Each line on the display in any case has its own fixed focal length. Tilting the display so far, that the focal plane is aligned to the street (see Fig. 3.5(c)) finally enables AR presentation with correct focal depth on every position on the ground.



(a) Vertical alignment of the focal plane of a HUD



(b) Slope alignment of the focal plane of a HUD



(c) Horizontal alignment of the focal plane of a HUD

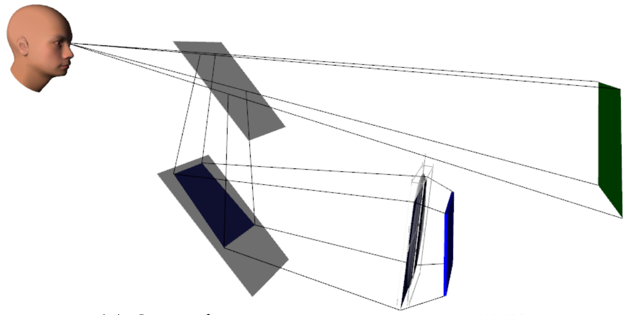
Figure 3.5: Different Alignments of Focal Planes to the line of sight of the Driver generated through different HUD Setups. Tilting the Display (blue) tilts the Focal Plane (green). Next to the Display is a Lens to stretch the Focal Distance. A Mirror (lower left) eases the Setup and the Windshield (upper left) combines the Views

Infinity

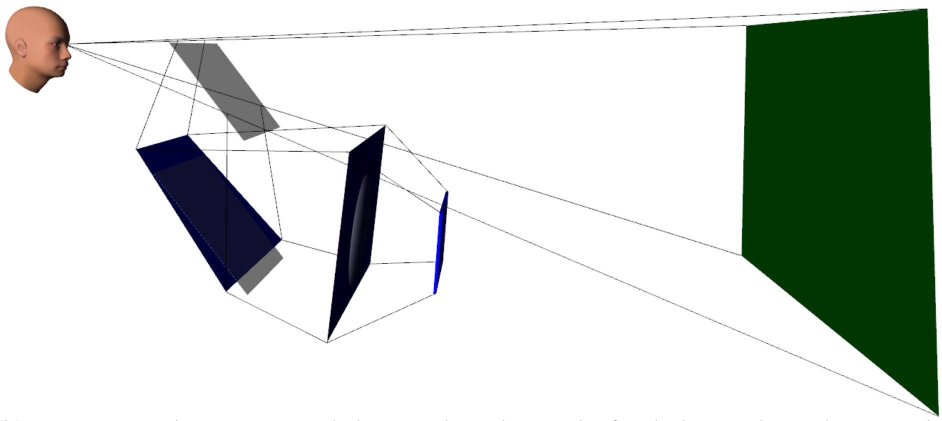
Neglection of focal accommodation is only possible through the fact, that the human eye does not perform any focal accommodation in distances larger than approximately 30 m (see section 2.3.2 (page 34), because the light rays are nearly parallel when they reach the eye and the lens therefore does not have to adjust anymore. Any AR scheme presented nearer than this threshold must use a HUD correctly placed in the focal plane.

Large Virtual Images

A second effect generated through application of lenses is the size expansion of the virtual image of the HUD. Depending on the setup of the optical components, the field of view keeps its angular value with increasing distance of the focal plane or even widens it. The image thus covers a wider area the further it is away from the driver (see Fig. 3.6). Such a wide field of view is necessary for contact-analog AR.



(a) Setup for near presentation in a HUD

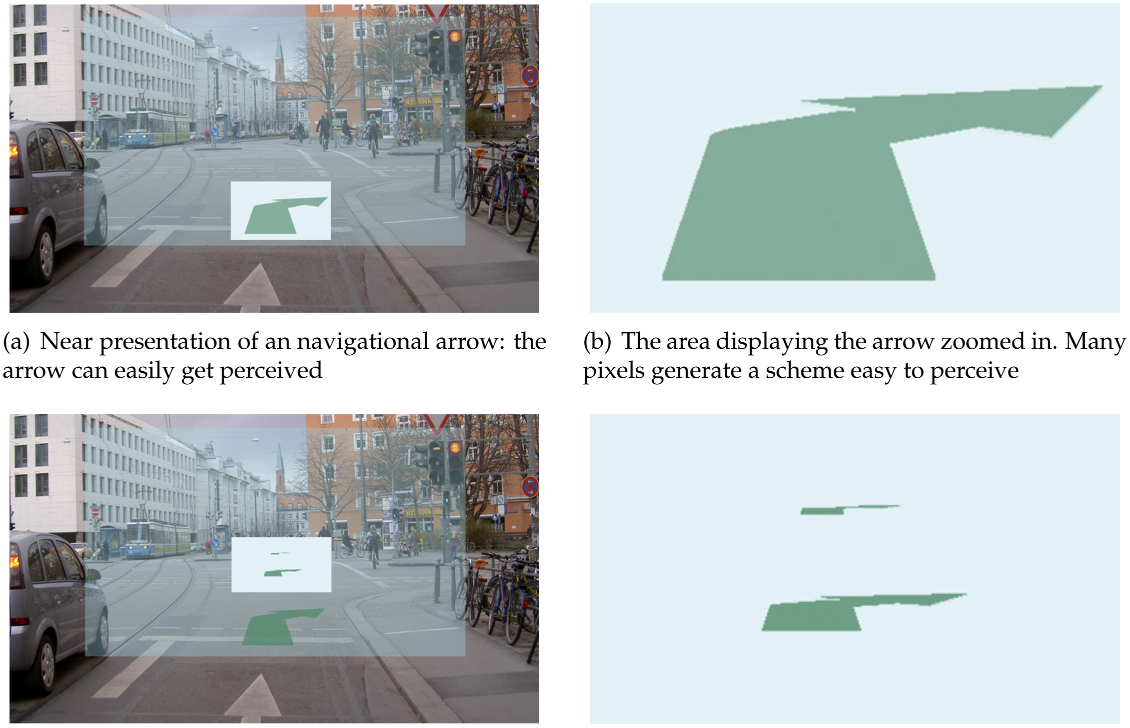


(b) Setup using the same optical elements but placing the focal plane in large distance: the field of view became wider

Figure 3.6: Dependency of Field of View and Focal Distance

Less Pixels

Every pixel displayed in the image therefore covers a larger area in that distance. AR schemes in contrary become smaller the larger the distance to the driver is. An AR scheme in greater distances becomes too small to be perceivable any more (see Fig. 3.7). The transparent rectangles in the left images indicate the display area of the HUD and would be invisible in real application. The white rectangles also would not be visible in ADAS systems but has been added here to ease perception of the arrow schemes. Depending on the exact construction of the HUD and on the AR scheme, it is necessary to define a maximum presentation distance.



(a) Near presentation of an navigational arrow: the arrow can easily get perceived

(b) The area displaying the arrow zoomed in. Many pixels generate a scheme easy to perceive

(c) Distant presentation of an navigational arrow: the most distant arrow cannot get perceived any more

(d) The area displaying the distant arrows zoomed in. Only few pixels generate a scheme hardly to perceive

Figure 3.7: Dependence between Size of HUD and AR schemes in large distances

3.4 Guidelines for Interactive Augmented Reality Concepts

Through the Lab

Experiences gained through investigation of a driver's workplace in chapter 2 and the constraints and interactive dependencies collected in this chapter enable collection of general guidelines for AR concept design. The issues of HUD technology already need to be applied during early development phases which normally take place in simulated environments. The first set of guidelines therefore has its focus on the development and design phase. The subsequent section then collects guidelines for the application of AR concepts. These guidelines in any case must already be applied in laboratory development.

3.4.1 Development and Design Phase

Volume Examination

AR concept design as an iterative process investigates scheme design, activity duration and the application context of AR content. An initial issue is to determine, which presentation volume an AR scheme requires. Laboratory setups often do not have appropriate space for visualization of AR content as it would be displayed in a real HUD. The presentation scheme then would often lie beyond the bounding borders of the simulator room.

HUD Placement

Another question in early concept phases is found in the issues of HUD placement. Investigation of new metaphors can require HUDs not only in the area above the steering wheel in the windshield, but also in other regions.

Concept Investigation AR content often must meet the issue of large distances in conjunction with large fields of view. Investigation of display concepts can therefore apply tracked LCD displays showing a window into the augmented world in driving simulators. To visualize how content would look like on the surface of the Sphere of Vision (see section 3.1, page 51) which indicates the focal depth of the presentation scheme, an appropriate set screen resolution can show presentation schemes as they would appear in a real HUD.

Display Placement Visualization of any area around a driver and his car also is enabled through the model of the Sphere of Vision. Required presentation areas as well as volumes can easily be evaluated through the application of the Sphere of Vision in driving simulators.

3.4.2 Concept Design

Summary of Guidelines

The design of AR concepts has to face issues ranging from minimally demanding visual and cognitive workload to enhancing effects on driving performance and safety. The following summary of guidelines has been collected to guarantee the general requirements of beneficial ADAS systems.

Minimal Content A major issue of AR is occlusion of relevant information. AR content therefore must use as little visual (or auditory) space as possible. The design of schemes only is allowed to incorporate visual features that support fast perception and understanding [62, 63].

Little Animation AR schemes should not use animation [62]. Animation only should be used in time-critical situations to catch attention or when they state disambiguate ambient cues. Thus only two kinds of schemes are to be applied:

- Schemes not placed in the foveal aura that require imminent attention in case of time-critical dangers (see section 3.2.2, page 59).
- Continuous visualization of spatial dependencies in ambient manner (see section 2.1.6, page 19).

Personal Frame of Reference Information presented in the driver's frame of reference reduces the time to interpret the spatial dependencies between the car and the indicated location (object).

Glance Behavior AR schemes must not require additional glances to another direction (see section 2.3.2, page 34) except for guidance to that direction (see section 3.2.2, page 59). Information transmitted via AR thus must be displayed at exactly the direction and focal depth, where the driver looks (see section 2.3.4, page 37). Warnings and especially alerts that require a driver to look towards another direction either have to be displayed where the driver looks (immediate information capture) or at the location (direction) where the driver has to look (guidance of attention).

Enhanced Tracking Many activities of driving can be considered as tracking tasks. A driver for instance has to track the boundaries of the own lane to keep the vehicle within the proper lane while driving. More prevision of a driver results in better tracking performance. Better tracking performance results in more accurate driving performance within the proper lane. AR schemes for driving performance should aim at enhancing such human tracking activities [171].

Interactive Auras Presentation depends on interactivity between the driver, the car and the object or information indicated through AR. AR presentation always must apply to at least one aura of the driver (see section 3.2.1, page 56). To facilitate interaction between all participating instances of a situation, ADAS systems must know about the actual shape and size of the driver's auras.

Capturing the Mental Aura When car drivers have at least one aura intersecting with aura of an object, they still can cognitively neglect the flow of data from the nimbus of the other object. The issue to relocate or widen the mental aura then is the main issue for the ADAS system.

Reduction of Delta between ADAS and Driver The sizes of auras of sensor systems differ from the size of the auras of the car driver. If an aura of a sensor system is larger than the aura of a driver, the sensor system has an advance in knowledge about the environment. The delta generated through such larger auras of sensor systems then is unknown to the driver. To facilitate intuitivity of the wider surveillance of such sensor systems, ADAS systems must compensate that delta (see section 3.2.2, page 58). AR presentation therefore has to incorporate hints about the further knowledge of the ADAS system that are unknown to the driver.

Hybrid Concepts Concept design processes also have to focus on issues in presentation technology. AR schemes approaching from large distances should use hybrid concepts for presentation (see section 3.3, page 60). Early information about an upcoming activity initially can be displayed through symbolic HUD schemes. By approaching the location dependent to the information, the information then can become an AR scheme. Such hybrid concepts guarantee early knowledge about the upcoming action, but can then directly show the action in the personal frame of reference of the driver.

Meanings of Modalities

Finally, a general classification of modality-related action content can be proposed: different modalities can transport information of different levels about required activities.

> *Optical displays tell the driver what to do, and haptic displays convey how this should be achieved. [96]*

Nature of Human Senses

For instance, an icon change on a visual display can inform the driver about an upcoming change of the allowed speed, while the gas pedal adjusts a pressure point to propose a comfortable deacceleration phase. This classification is based on the intrinsic nature of human senses. While the visual channel provides information about the area beyond the human skin, the haptic sense range is limited to the human's body surface, the skin. Reactions, a car driver must execute therefore are modeled equally to perception. The visual channel alone does not enable any activity except by use of glance tracking systems. The human body where the haptic sense is located, in contrast, enables the transcription of actions to devices.

4 Related Work

Research of others on assisting Augmented Reality in cars

AR Applications

A broad spectrum of research towards AR in cars came to life over the last years. This area developed from a new side field to a direct and active field of research. The flow of experiences now is bidirectional: in the one direction, monitored effects of perception contribute to AR and psychology, while in the other direction, human factors have strong influence on the design and selection of metaphors. Both areas of research now fertilize each other.

Structure of Related Work

This chapter gives an overview of the application of AR in ADAS systems. Two different classifications of AR systems are used to structure the chapter. The main classification separates ADAS system concerning their deployment to real cars and HUD systems. Here, one category is specified through systems not implemented in real cars with HUDs, while the other category collects all systems that are fully deployed to real cars. The minor classification only defines categories for the ADAS systems that are not incorporated in real cars. The two minor categories distinguishes between simulation environments, such as driving simulators and ADAS systems that do not incorporate HUD systems but already incorporate AR technology.

Major Classification

The major classification defines a threshold on an one-dimensional continuum between simulation and reality. HUDs are often simulated in driving simulator systems. Either HUDS are completely simulated or use easy workarounds. In some systems, the projection wall that shows the computer generated environment also shows the AR schemes. Other systems use prototypical HUDs to generate the impression of a spatially decoupled virtual image. Such systems are classified as simulated environments and thus belong to the first category. The separation between simulation and reality can also be applied to AR technology. Any ADAS system that applies only parts of the AR paradigm therefore belongs to the first category. Every system localized on the continuum between simulation and reality defines the categorization. Whether an ADAS system belongs to one of the two classes depends on the ability of the ADAS system to work with a HUD in a car on the road. ADAS systems of the first category (simulated car or no application of a HUD) are reported in the first subsequent section 4.1. All systems that are installed in conventional cars with a HUD are collected in the second subsequent section 4.2.

Minor Classification

The first subsequent section 4.1 has two subcategories. Here, a second categorization distinguishes between simulated environments and application in cars, but without full application of AR paradigms and AR technology. When the system was set up in a driving simulator, is was categorized to the first subsection 4.1.1. When an ADAS system was installed in a real car, but applied the AR paradigm only partial, it was categorized to the second subsection 4.1.2.

On Usability Studies

When usability studies have been conducted, the most relevant results are mentioned together with the description of the ADAS system.

4.1 Simulated Environments and Partial Augmented Reality Systems

Cheaper Simulator Tests

Before a system is put in the real environment of application, its general usability is evaluated. This evaluation is a stepwise process: after a first mock-up expert tests, laboratory setups for application-near tests follow. Not until the artificial tests show promising results, real prototypes are built for further testing. Research communities often stop investigation in laboratories and leave further examination to industry. Some approaches for AR have been tested in driving simulators and are illustrated in this section.

Simulated Augmented Reality

A further approach, to simulate AR, is sometimes necessary when certain parts of technology are not yet available. Developers and usability testers still can examine effects of AR to a certain extent. Simulation then takes place under a specific proposition, either a simulated environment, like a driving simulator, or by reducing a whole system by one necessary assumption of AR. Showing a superimposed video on a secondary screen from the perspective of a camera and not from the user's egocentric frame of reference still can bring useful insight for a proposed AR application. Here in this example the difference to full AR would be the different perspective. Some approaches intend to provide car driver assistance and use certain elements of AR, but do not implement full AR systems. These systems have also been collected under this section.

4.1.1 Augmented Reality Systems in Driving Simulators

Holistic System

Trivedi and Cheng [161] built a holistic sensing and display system for intelligent driver support systems. Their main focus aims at user-centric information presentation. They intend to generate a stress-free environment. In potentially dangerous and continually changing traffic conditions they try to guide the driver to make corrective decisions without getting strained under stress [161]. They therefore built a system to meet three major issues. First, the context is captured with a holistic environment, vehicle and driver related sensing system. Second, model-based approaches with safety metrics are used for analysis. Third, precise safety control is maintained to give feedback to the driver.

Dynamic Active Display

For the studies on driving behavior and corrective information, a so called dynamic active display has been built in a fixed-base driving simulator. It consists of a multifunctional integrated imaging and sensor array, an analysis system for driver intention and situational awareness and a windshield-sized HUD. The sensor array collects input from various sensors in the environment, from the vehicle and from the driver. Besides vehicle dynamics, the driver's head position, eye location and hand positions are sensed. The system for analysis of driver intention and situational awareness then processes information about the driver's state and situation to determine what, where, and when to display appropriate warnings. The HUD has been incorporated to provide an informative interface that has reduced glance angles.

HUD Setup

The system has HUD with a large field of view spanning the entire windshield (field of view: approximately 67 °at the bottom edge, 100 °at the top edge). This large area is reached by placing a highly transparent acrylic screen made for laser projectors directly over the windshield of the test vehicle. Fig. 4.1 illustrates the general setup. Through head tracking, the HUD allows for spatially registered information presentation.

Figure 4.1: Full Windshield Head-Up Display in Driving Simulator; courtesy of [161]

Safety Critical Warnings

The integrated holistic sensing and display system projects safety-critical warnings in three ways:

- in a constant single location,
- at or near the driver's line of sight, and
- on top of obstacles as perceived by the driver.

Display Modes

Fig. 4.2 a shows a static visual alert indicating the presence of a vehicle in the driver's right-side blind spot. The information is projected in the HUD so that the driver can maintain control over the road ahead in the peripheral field of view. In Fig. 4.2b, the system uses an attention-capturing line and icons to direct the driver. The driver, who is originally looking ahead, has to turn his gaze to the right to notice a vehicle backing out of a driveway. In Fig. 4.2c, overlay graphics call out roadway markings and a pedestrian ahead.

4.1.2 Partial Augmented Reality

Nearly Augmented Reality

AR superimposes the user's environment. The user's position in space is used to place vir-

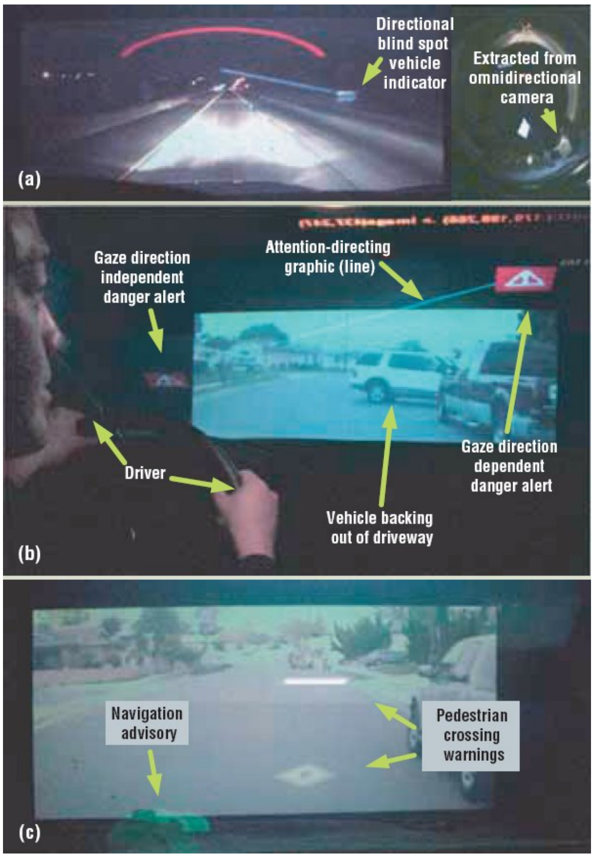


Figure 4.2: Display Modes of Holistic User-centric System: (a) in a constant single location, (b) at or near the driver's line of sight, and (c) on top of obstacles as perceived by the driver; courtesy of [161]

tual content correctly aligned into his field of view. When, for instance, instead of the user's own point of view, the point of view of a fixed camera is superimposed, AR technology is applied, but not to the full extent. Such partial AR can already bring insights about the use of AR. Some research has been conducted on such systems. The following sections illustrate work that does not completely comply with the original definition of AR, but uses, at least some ideas of AR.

4.1.2.1 Siemens Navigation System

AR in Dashboard Display

Siemens AG and the University of Linz [139] presented a bus navigation system incorporated into a shuttle bus information display. The researchers have installed a camera behind the rearview mirror of the shuttle. This camera films the road from the driver's perspective and projects this view of the road like a television image onto the navigation display. On the basis of the stored cartographic information and the GPS signal the on-board computer calculates a route which appears as a transparent yellow stripe placed exactly over the camera picture – the route is displayed in color on the live image of the road. In this way the driver can take in the route with just a quick glance and, thanks to the camera has the road in view at all times on the display. Fig. 4.3 shows how GPS information and 3D topography information are used to compute a 3D model of a navigation path which is superimposed on the camera image on the in-car display of a navigation system. A user study has not been conducted.

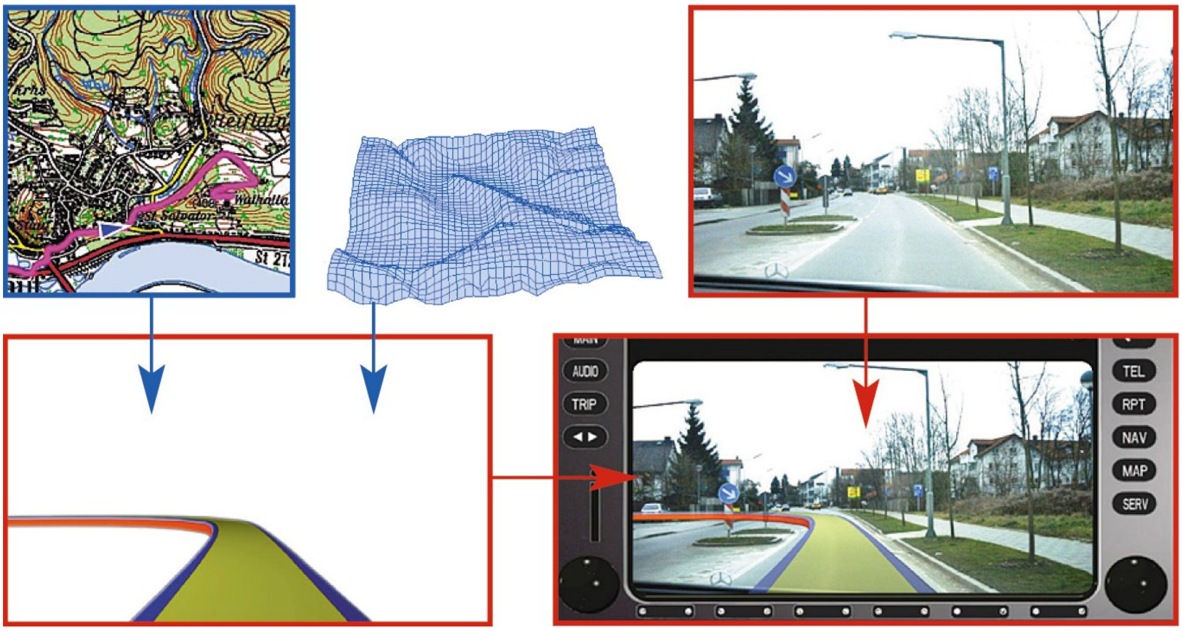


Figure 4.3: GPS information and 3D topography information are used to compute a 3D model of a navigation path which is superimposed on the in-car display of a navigation system; courtesy of [139]

4.1.2.2 Carnegie Melon Navigation System

Another approach for navigation systems has been developed by Wu et al. [168] at the Carnegie Mellon University in cooperation with General Motors. They built a multimedia system for route planning and video-based navigation. The driver has the possibility to share routes in the trip planning process. Driving instructions are given by an live-video image overlaid with navigational arrows and with additional synthesized voice instructions. Two different designs for route guidance information were tested, where perspective arrows (see Fig. 4.4(a).b and 4.4(a).d) resulted as the preferred style compared to icon-based navigational arrows (see Fig. 4.4(a).a and 4.4(a).c). They tested their system in indoor (see Fig. 4.4(a)) and outdoor (see Fig. 4.4(b)) context. They mentioned that video-based navigation reduces the cognitive load in some cases. They mentioned also that such approaches have also limitations: in the outdoor context the cognitive load from watching the video of a night route could be higher than reading a map. In the night route, details are difficult to perceive because of low-light conditions and the size of the screen in the experiment.

(a) Indoor navigation: icon-based arrows (a) and (c), perspective arrows (b) and (d)

(b) Outdoor navigation

Figure 4.4: Video-based navigation; courtesy of [168]

4.2 Applications in Cars

Full AR Systems

Incorporating AR systems in real cars requires not only working applications, but also presentation environments capable of displaying the AR content in an appropriate manner. Often certain trade-offs in the presentation system have to be taken into account to enable at least good registration on the image of the HUD. The following sections illustrate approaches to embed AR in real cars.

4.2.1 Virtual Cable

Volumetric HUD

The Virtual Cable Volumetric Head-Up Display (MVS, [115, 64]) is a system with small packaging available on the market. It can be installed behind the dashboard of a car. The principle of this HUD uses a laser projector to render shapes on a built in screen. The image of this screen then passes two lenses, stretching the focal distance and then leaves the enclosure of the HUD to use the windshield as a combiner.

Field of view

The radius of the rim of the projection screen is 35 mm, allowing the driver 160 mm of head movement without blanking out the virtual image. The transversal magnification of the viewing optics results in a binocular horizontal field of view of at least 27°, i.e. the field of view comprising the field seen together by both eyes (in 3-D) as well as flanking left and right fields seen only by the left and right eye, respectively.

Volumetric Presentation

The main difference to other HUDs is given through a movable screen, whose range of motion is almost 3 mm. The front limiting surface of the working volume is conjugated to the optical distance of approximately 10 meters and reaches almost to infinity.

Line Display

The laser projector focuses the beam in dependence to the distance of the movable screen so that a dot of about 3 mm in diameter is generated. In combination with the motion of the projection screen, the laser can paint lines in fix or in increasing focal distance, allowing presenting depth-based presentation. The current implementation of the system enables presentation of information only when the screen moves away or is held in position.

Navigation System

This display is used in combination with a navigation system to render a virtual cable on the windshield. It appears as if suspended over the road, similar to the power and guidance cable of a trolley. The image is in 3D and appears as part of the landscape. The driver only has to use peripheral vision to follow the Virtual Cable. Fig. 4.5 shows two photographs of the Virtual Cable.

(a) Photography of the Virtual Cable doing a right turn at the end of the street; courtesy of [115]

(b) Photography of the Virtual Cable doing a continuous right; courtesy of [115]

Figure 4.5: Two photographs of the Virtual Cable; adapted from [115]

4.2.2 Windshield HUD

Research Large Scale HUD

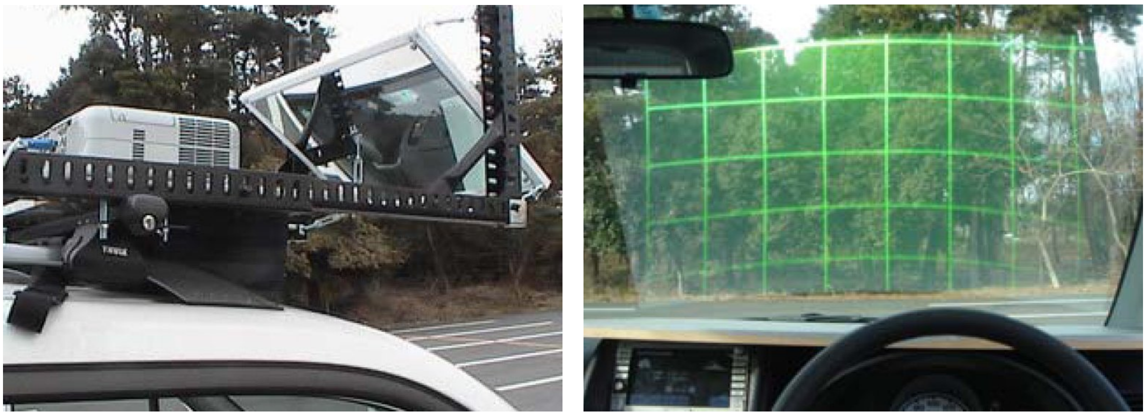
Sato et al built a full windshield HUD [116, 131] for research purposes. Their approach uses the concept of conventional HUDs: a screen generates an image which uses the windshield as a combiner. In contrast to conventional HUDs, their system uses a video projector on the roof of the car that projects the image over a mirror onto a retro-reflective screen placed directly on top of the dashboard. The system generates a HUD with a display area of almost the size of the whole front windshield. Fig. 4.6 illustrates the system in two photographs. Fig. 4.6(a) shows the video projector and the mirror mounted on the outside roof. Fig. 4.6(b) shows the inside of the car with the screen horizontally placed on the dashboard and the size of the generated image.

Optical Path

The HUD generates an image bright enough for daylight use. The retro-reflector on the dashboard returns the light to the direction it comes from. On its way back to the projector, some of the light is reflected by the windshield. The reflected light converges on a single point that is an optically symmetric position of the projector, but, through the reflection of the windshield, lies inside the car. By arranging the position of the projector close to the position of the driver's eyes, the driver can see the bright image from the screen together with the outside scene.

Optical Factors

The windshield distorts the image of the HUD. Therefore a distortion correction has been integrated, generating an inverse warping function which is applied to the image before rendering. Presentation schemes in the HUD thus can superimpose the outside scenery. From a fixed driver's viewpoint the presentation schemes in the HUD appear in a focal distance of about 1 m.



(a) The image shows the setup on top of the car consisting of a video projector and a mirror; courtesy of [131]

(b) The image shows the screen that generates the virtual image and shows the wide display area of the HUD; courtesy of [131]

Figure 4.6: Overview of the Windshield HUD

This windshield HUD has been used for various applications. An overview of these applications is presented in [85], while the applications are illustrated in the following sections. Many of these applications make strong use of surveillance cameras placed in the environment.

Application

4.2.2.1 Navigation Information

Sato et al implemented a visual navigation system [131] as an application that uses the windshield HUD system. Fig. 4.7 shows that drivers can see two types of visual information, navigation flags and directional signs, in the HUD. Navigation flags show the name of a destination and the distance to it. The position of the navigation flag directly indicates the orientation to the destination, such that drivers are able to recognize the direction to follow.

Flags and Signs

The navigation flags are shown in upper or lower region of the HUD. There they do not hide important portions of the driver's view on the road scene.

Presentation Areas

4.2.2.2 Virtual Back Mirror

To confirm safety around and behind a vehicle when driving a car, Miyamoto et al designed a virtual mirror to visualize the area behind the car [113]. This mirror floats in front of the driver in the HUD. The image on the virtual mirror is formed by applying a geometric transformation to the image taken by a surveillance camera. The camera usually is environmentally fixed on a signal pole near crossings and transmits the camera image to the car. Since its image is shown in the HUD, the drivers need to move their eyes slightly to see the virtual mirror. This slight glance turn is necessary because the virtual mirror is placed just above the road or intersection to which the driver pays attention. Fig. 4.8 shows a photography through the HUD. The white car in the image is the driver's own car. He can see his own car and other cars nearby and thus can estimate the relations between the cars.

New Placement

Figure 4.7: Navigation Information through navigation flags and direction signs; courtesy of [131]

4.2.2.3 Lateral View Enhancement at Crossings

Blind Areas at Crossings

Using the windshield HUD, Fumihiro et al designed an assistance system for crossings. Two virtual mirrors shown in the HUD allow reducing blind areas at crossings. They tested their system in a driving simulator [57]. Further an implementation in real life setups [89] has been conducted.

Figure 4.8: Virtual Back Mirror floating in the HUD showing the correctly transformed view of a fixed camera on the street; courtesy of [113]

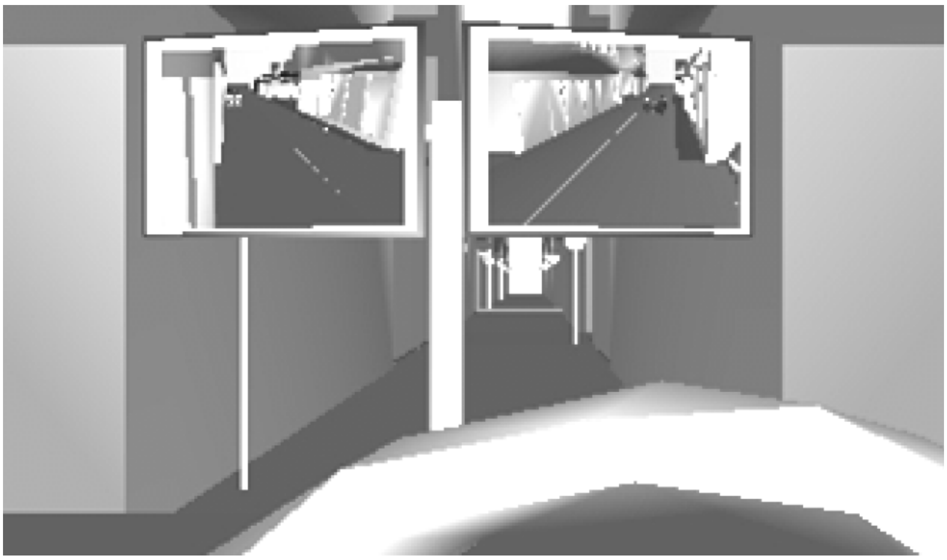


Figure 4.9: Virtual Side Mirror in the HUD showing the view to the left and right, thus reducing blind areas; courtesy of [57]

Two Mirrors

Fig. 4.9 shows a screenshot taken from the driving simulator. The image shows an intersection with two additional mirrors in the HUD aiming to the left and to the right.

Environmental Cameras

According to the previous application, the system makes strong use of cameras in the environment. The cameras must be placed appropriately to record the oncoming traffic, but minor distortion with respect to the driver's own viewpoint are correctly applied by image warping.

User Studies

User studies, but without analysis through descriptive statistics, have been conducted on the virtual side mirror systems. In the driving simulator they investigated time of appearance and location of the virtual mirrors, both in comparison to the response time of drivers for vehicle detection. The users had their head in a fixed position and looked through the HUD onto the virtual scenery. The HUD used a plasma screen and a combiner to synthesize the image. The measured response time has been counted from the time when the subject's vehicle stopped at the stop line and the time when the subject determined a coming vehicle. Mean values of their results indicate earlier detection of crossing vehicles when the own car is still far distant, but almost no difference when the own vehicle is near the intersection. Measures testing the time of appearance revealed that virtual mirrors should be displayed as early as possible to shorten recognition delays. A test on the location of the virtual mirrors has been conducted. The position with the shortest response times was determined in location, horizontally centered, but located above the straight forward road.

4.2.2.4 View Enhancement for Opposite Traffic at Crossings

Blind Areas in Front

Another application making use of the windshield HUD has been implemented by Taya et al. Here they proposed a visual assistance system that can visualize the blind area behind other large vehicles. The system visualizes the blind area as a virtual slope [146] and thus intends to reduce collision accidents when traffic crosses at intersections or turns across opposite lanes. Fig. 4.10 shows a photography through the windshield HUD where one can see the opposite lane at the crossing tilted up.

Elevated Cameras

Taya et al utilized surveillance cameras to capture the required videos from an elevated location. Instead of showing the camera image in a dashboard display, which could require the driver to invest time into understanding of the spatial relations, the cropped and warped camera image becomes superimposed over the upcoming road-view.

4.2.3 Contact-analog Head-Up Display with Braking Bar

Distance Indication

Assmann and Bubb [4, 34] have investigated a visual presentation scheme for longitudinal anticipation of the speed of the car and safe distance to a leading car. They have built a HUD by use of a fresnel lens. Thus the focal length had been stretched to distances up to infinity. To generate the image, they incorporated a double-ended tubular lamp in the HUD. The lamp generated an impression of a bar in the HUD. This lamp was mechanically linked to the speedometer and moved in the HUD depending on the speed of the car. The plane which the lamp covered was tilted against the vertical focal plane, thus generating an image with varying distance. When the car drove slowly, the image of the lamp appeared in near distance to the driver. The higher the speed of the car, the farther got the focal distance of the mirrored image of the lamp. An additional mask in the HUD let the width of the lamp

Figure 4.10: Virtual Slope Visualization in the HUD showing the opposite lane at an intersection tilted up so that occluded vehicles become visible; courtesy of [146]

appear smaller width by increasing speed and focal distance. This increased the perception of perspective distance of the virtual bar. The faster the car drove the farther away and the smaller the lamp appeared. This bar showed the braking distance adjusted to an average braking coefficient. A knob on the dashboard allowed to change the adjustment to slippery roads and to a leading car follow mode, both cases where the safe distance either must be increased or can shrink down. The lamp only moved along a straight axis, thus correctly operating only on straight roads.

Improved Feeling of Safety

Studies indicated that test participants felt safer when driving with the HUD. The braking distance indication let test participants drive safer for a longer time and and more often. Measurements stated an improvement in driving safety of about 15 % and a prolongation of unsafe distances in platooning traffic of 30 %. The average speed did not increase through the HUD and no influence on longitudinal and lateral acceleration and fuel consumption was measured. Subjective measures could be classified to two groups. Skilled drivers do not think that they can drive safer with the presentation scheme. Unskilled drivers think that such presentation enables safer driving and reduces amounts of accidents.

4.2.4 Contact-analog Head-Up Display for Night Vision

Placement of Focal Plane

Bergmeier [21, 20] developed a HUD with a vertical focal plane. With a prototype he evaluated depth perception in a laboratory [21]. He determined that the best placement of the focal plane is in a distance of approximately 50 m. There, most test participants of a study conducted with 24 subjects judged the estimated distance of presented test icons correctly.

Parallax Errors

The large distance of the focal plane reduced the need for parallax correction of AR schemes

Figure 4.11: The Braking Bar displayed with a Contact-analog HUD; courtesy of [34]

on the HUD. AR schemes presented in a distance of 50 m are aligned correctly and horizontal or vertical head movements do not generate swimming effects of the AR scheme. Presentation in larger distances than the focal plane has a minor impact. Also presentation nearer to the driver has minor effect. Only AR schemes presented near to the driver suffer under swimming effects. Bergmeier thus did not have to incorporate any head-tracking functionality to test his system.

Porting to a Car

Bergmeier ported the HUD setup to a car [20]. He used a flat glass plane, mounted at the sunshade of the driver, as a combiner and mounted the optical elements of the HUD at the seat of the co-driver (see Fig. 4.12(a)). This setup generated a horizontal field of view of 30 °and a vertical field of view of 10 °.

(a) Photography of the internal setup of the HUD system; courtesy of [20]

(b) Photography of the mounting of the infrared camera; courtesy of [20]

Figure 4.12: Two photographs of the contact-analog HUD; courtesy of [20]

Night Vision

To enable a night vision system, an infrared camera was integrated to provide images for target object determination. To avoid parallax errors as far as possible, the camera was mounted as near to the driver's egocentric viewpoint as possible. The best location was determined slightly above (not to occlude the driver's field of view) the straight forward line of sight outside the windshield (see Fig. 4.12(b)).

Object Highlighting

Computer vision algorithms determined the brightest spots on the infrared camera images and highlighted them with 2D bounding boxes. Fig. 4.13 shows two persons on both sides of a rural road in different distances.

(a) Target objects in 120 m distance; courtesy of [20]

(b) Target objects in 80 m distance; courtesy of [20]

(c) Target objects in 60 m distance; courtesy of [20]

Figure 4.13: Three photographs of the night vision system taken through the HUD; courtesy of [20]

Effects on Perception

A comparative study has been conducted with 27 test subjects. The variants tested were a regular night vision system in the central information display (CID), an extension with a warning icon (either in the CID or in the CID and the HUD) and the AR variant showing the 2D bounding boxes. The warning icon was displayed when a target object was determined by the ADAS system. On average objects are perceived at a distance of up to 50 m without assistance, which corresponds with the beam length of dipped headlights. With the contact-analog night vision system and the warning in the HUD, objects tend to be recognized 10 m earlier in average, at a distance of 60 m, but this effect is not verifiable objectively by significant statements. The fastest and most efficient reaction time was recognized with contact-analog HUD with a value of 0.3 s. Showing the warning in the HUD, test subjects needed 0.65 s in average and with the warning in the CID, test subjects needed 1.3 s to recognize the warning. In summary, the contact-analog HUD presentation generated significantly best results.

5 Rapid Prototyping in Driving Simulators

Flexible system architecture for highly experimental multi-modal interaction concepts in driving simulator environments

Testing in Real Cars

In order to explore and evaluate the concept of the *Sphere of Vision* (section 3.1, page 51) for car driving, a suitable test environment is needed. Ideally such evaluation would take place in a real car on real roads. Yet, for several reasons, this is not possible today. First, no large scale HUDs or contact-analog HUDs (see section 2.3.4, page 37ff) are available in real cars for evaluations conducted in this thesis or do not have official approval and homologation for road service. Second, live testing in real environments cannot be performed as systematically as in virtual environments because critical situations cannot be provided on demand and tests are thus irreproducible across multiple test persons. Third, the risk of serious accidents cannot be neglected. Instead, in collaboration with LfE, we have conducted systematic evaluations of ADAS systems in a fixed-base driving simulator.

Testing in Simulation

Fixed-base driving simulators have been available for a number of years. However, use of such simulators in experimental settings involving the use of very novel multi-modal 3D interaction concepts is very demanding since many realtime input and output devices, including 3D rendering in HUDs, need to be considered. Thus the driving simulator must be provided as a very flexible rapid prototyping environment.

Simulation of HUDs

Simulation of HUDs

Initial tests therefore must rely on driving simulators. HUD functionality can be simulated in driving simulators. AR schemes can be designed and implemented there, can get tested in usability studies and can be refactored since they meet the demands of the underlying concept.

Driving Simulator

The chair for ergonomics at the faculty for mechanical engineering provided a fixed-base driving simulator with a level of fidelity high enough to examine effects of AR. Some extensions had to be made to this simulator to enable user studies of this kind. Later, a complete substitution for the driving simulator with a new driving simulator was considered and performed. The new driving simulator was built, and here again software architecture concepts were applied and integrated.

Rapid Prototyping

To meet the wider range of design and implementation issues of AR concepts, not only the driving simulator itself required adaptation of its components, but also the development infrastructure had to be extended. Development processes require design and implementation iterated with testing procedures. Such roundtrip engineering issues usually need system wide startups of software systems. To enable a rapid prototyping environment in combination with the driving simulator, component architectures and dynamic ad-hoc networking principles and systems have been applied. Thus the different versions of the driving simulator became enabled to meet the requirements of rapid prototyping in AR.

This chapter illustrates the modifications made to the initial driving simulator and the new driving simulator. The extensible and modular architecture of the rapid prototyping environment is explained afterwards. Finally, the implementation of both simulators and, in parallel, the impact of the rapid prototyping architecture is illustrated.

Software Architecture

5.1 Driving Simulators

Driving simulators are used to conduct tests of new in-car systems to determine if they are suitable to be finally tested in real cars. Tested systems range from new devices to in-car display interaction systems. The incorporation of AR now brings new requirements to driving simulators. The 3D rendering functionality must also be accessible to the developer so that AR content can become integrated in the scenery – simulating HUDs.

Access to 3D

During the cooperation in a large industry driven project, TUMMIC, an existing driving simulator was reused for some user studies and a new one was set up. This section illustrates the initial driving simulator, the necessary changes to the testing system and the step to the new driving simulator.

Section Overview

5.1.1 Initial Setup

The driving simulator initially installed at the LfE recently had been used for several other projects. Each project made extensions to the source code. Thus a monolithic system had evolved that consisted of the following components.

Monolithic System

The Car The central real part of the simulator was a BMW 325i convertible (E30) with automatic transmission. Engine, transmission and extra equipment were removed. To gather data for the driving simulator, sensors were been connected to the gas-pedal, the brake-pedal, the steering wheel and the turn signal lever.

Driving Dynamics (PC, Windows 95) The devices in the car were connected to a computer running under Windows 95. The computer ran a driving dynamics based on a single track driving model which computed the position of the car for the 3D virtual world. Dependent parameters such as „rounds per minute“ and „speed“ also were computed on that machine.

Virtual World (Onyx) The positional data then was transmitted via a serial link to an Onyx „Infinite Reality II“. The Onyx machine computed the driver's view into the 3D world. In addition, the Onyx computed further traffic, 10 cars driving in the same or the opposite direction on a rural almost circular road course. When a car in the vicinity left the visible area it was automatically relocated so that there appeared to be more than ten cars.

Presentation of Virtual World A video projector mounted on the ceiling finally generated a 40 °field of view scenery into the virtual world. The projection wall was mounted at about 3 m in front of the driver.

Fig. 5.1 shows a view on the driving simulator from the test coordinator's seat behind the car, as of May 2005.

Figure 5.1: The initial Driving Simulator at the Chair of Ergonomics

5.1.2 Setup in Second Generation

New Simulator

The experiences with the driving simulator led to the construction of a new fixed-base driving simulator with a new software platform. Reasons for the new driving simulator were found in the following facts:

Joy of Use Even if secondary for some simulator studies, test participants must have a feeling of pleasure when participating in a study. Thus a driving simulator with a state of the art car had to be installed. A BMW 6series (E64) convertible was chosen to be installed in the driving simulator room.

Optical Feeling of Presence To increase a feeling of presence in a virtual world, a large field of view was necessary. Therefore a three channel presentation system, covering up to 160 °field of view was installed.

Haptic Feeling of Presence To face the setup of a fixed-base driving simulator, but to increase the feeling of driving, a bass pump, a bass speaker without membrane was installed under the driver's seat, giving a feeling of engine and road vibrations.

Dual-Track Driving Dynamics To allow for a more sophisticated handling of the virtual car, a dual-track driving dynamics was considered for integration into the new simulator. Such a physical model also modulates drift and swimming effects of the simulated car.

Improved Control over Neighboring Traffic The previous driving simulator used a specific hard-coded simulation model for neighboring traffic not allowing test scenario dependent behavior of the cars in the vicinity. To enable better control of the additional vehicles, a new simulation model was considered for the new driving simulator.

Improved Control over Virtual World The previous simulator used a virtual world that encoded a proprietary world model. Extensions were complicated to incorporate and existing structures were immutable. The new simulator had to enable construction of new worlds to ease the application for specific test runs.

Fig. 5.2 shows a photography of the new driving simulator as it was almost finished in January 2007.

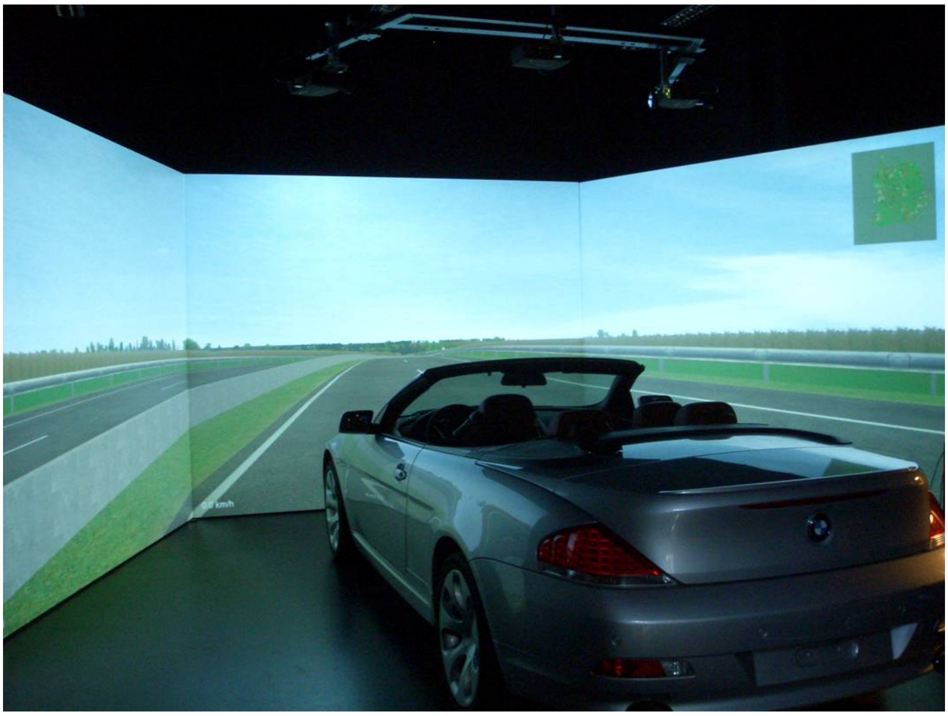


Figure 5.2: The new fixed-base Driving Simulator at the Chair of Ergonomics

Software Adaption

The step to the new driving simulator allowed to adapt the software designed and implemented for the old simulator to the new needs and to discard obsolete design decisions.

5.1.3 Requirements for Flexible Integrated Systems

Component Decoupling

Not depending on driving simulators in general, but on development issues of new AR concepts in detail, system architectures must face a number of new issues. Fast and efficient realization of various concept variants requires accessibility to many more parameters of the system than classic driving simulators provide. Modern systems with a strong relationship to the outside environment of the car require the driving simulator system to transcribe sensor data as well as contextual parameters of the dependencies to the environment. To display AR content in the simulator environment, positional data as well as accessibility to the 3D rendering engine are mandatory.

Distributed Approaches

Development and testing of the system furthermore require a broader spectrum of accessibility than final applications. Due to trials on design approaches and varying hardware connections, distributed approaches on the whole software system are necessary to provide the required computing power.

Issue Collection

The following items summarize the requirements for realtime driving simulators capable of AR content. Most of these items surely apply to driving simulators in general, but become mandatory for spatially registered AR application content.

Clear Definition of Interfaces and Components Already driving simulators enable classification of responsibilities of separate tasks. For instance, the driving physics model of the own car is separate from 3D rendering. Such system components or services require clear definition, so that all components can access required data from suitable interfaces. Thus data types for data exchange must be defined. One data type always required for 3D systems is location and orientation information. The *Pose* is one data type containing such information. In a pose, 6 dof data indicating an object's position and orientation is stored. Usually a 3D vector defines the euclidic position while a 4D vector defines the orientation with a quaternion. *Poses* per definition define relative coordinate systems of spatial relationships, but are treated as absolute placements relative to a world coordinate system. Other data types capable of the same or wider functionality are *Angle Axis* representations, *Euler Angles* and matrices (which also can give information about scaling or perspective adjustments).

Data Flow Access to a broad spectrum of runtime parameters, ranging from positional data of all objects participating in traffic to the status of the own car is required to generate AR presentation schemes. To prohibit redundancy in computation of aggregated values of different parameters, the extension from control-loops to data flow networks becomes mandatory.

Realtime Data Management Simulations in the automotive sector require response times in realtime. Software development often focuses on certain issues while performance is neglected. A component-based architecture assures efficient testing and debugging of bottlenecks.

Connectivity of Mechanical Devices Distributed architectures also ease the connection and the exchange of new devices. Specific computers can manage the connection of devices and then propagate the values to dependent system components. The rest of the system does not require further modifications, because only specific computers manage the devices. To ease connectivity issues, new technologies, such as National Instruments' LabView [1], can adapt various kinds of signals.

Flexible Exchange and Parameterization of Components As mechanical devices can be exchangeable, system components also need to be easily exchangeable. Thus, a component-based architecture appears to facilitate these requirements. Configuration mechanisms for separate components then can ease dynamic reconfiguration and thus can reduce roundtrip engineering times during development and design of new components and AR schemes.

Reduction of Competing Errors (Runtime Conditions) Often various input data gets aggregated to new contextual values. Such aggregations often are computed at different locations in large systems. When one value is recomputed, the whole system behavior can change, leading to unintended effects of the system. Graphical network visualization and editing tools can incorporate validation procedures for semantic network data and thus need to be integrated to ensure valid data and data flow. Validation of data flow and graphical editing can reduce redundancy of code and minimize error proning.

Porting to Mobile Setups When a system proves worthful for further testing, it normally gets integrated in a real life system. In case of automotive applications, the new system becomes integrated into a mobile carrier. To adapt to the different architecture in a car and to connect to the various bus systems (CAN, MOST, ...) minimal effort should be necessary. An architecture separating interconnection functionality from the dependent application facilitates such porting.

5.2 Component-based Architecture

Interfaces Levels

To design an architecture of a rapid prototyping environment in the automotive area for interactive systems, different areas of responsibility need to be identified. Each area takes care of different types of signals and values in the system and thus defines different levels of interfaces. Including input and output devices, a rapid prototyping environment has been layered into six levels of interfaces. Fig. 5.3 shows a graphical sketch while the next sections give a stepwise description of all levels.

5.2.1 User Input and Sensors

Hardware Connectivity

This level of interfaces focuses on schemes to connect hardware components to the system.

Data Delivery

A rapid prototyping environment requires many kinds of data. The required data either is generated through user input on the gas pedal, the brake pedal, the steering wheel or other devices, or it is delivered through sensors. Such sensors can be car-internal sensors tracking the driver and his gestures or outside sensors. Outside sensors can be mounted on the car or can be placed in the environment. Both kinds track the environment and, in general, deliver spatial sensor data to the in-car system. Especially data from outside sensors is simulated or generated systematically in driving simulators.

Interfacing

All devices, especially the ones for the primary task of driving must have their own interface to guarantee exchangeability and extensibility. The interface is connected to a measurement card in a dedicated computer. More complex devices, such as tracking systems often use standardized interfaces and are connected directly to a computer, using, e.g. USB or IEEE1394 FireWire specifications.

5.2.2 Low-Level Data Processing (Semantic Values)

Components at this interface level process data streams and signals of the input layer. Here primitive electromagnetic values are converted to semantic values for later use in the application logic of the system. For instance, a device delivering 0 to 5 Volts for the position of the gas pedal generates computerized floating point values ranging from 0 to 1.

Two areas of conversion can be classified: on the one hand real measured values are gathered and converted for further processing. On the other hand, some values are simulated to reproduce input from the outside of the car. Such values would be delivered by sensors in a real car but cannot be provided in the simulator. Thus all components generating virtual measurements are located in this layer.

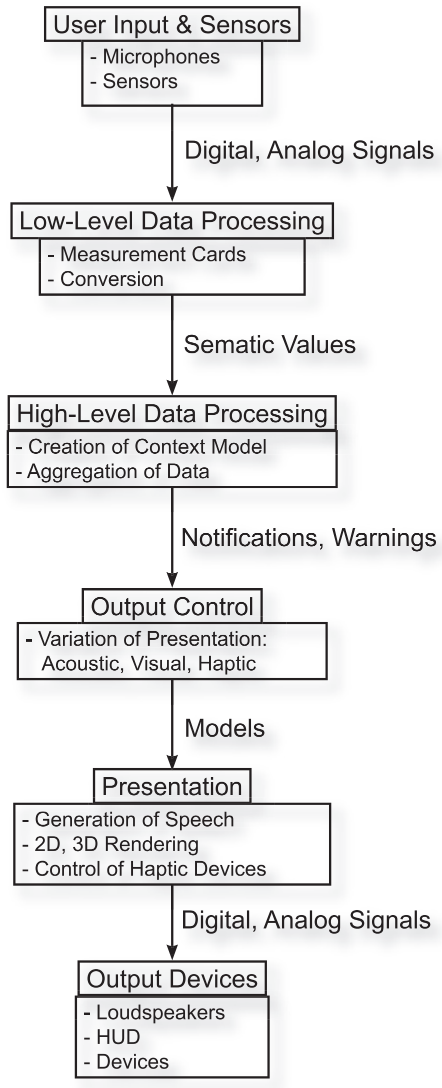


Figure 5.3: Levels of Interfaces in the Rapid Prototyping Environment

Conversion of Values The interoperability software of National Instruments, LabView [1] allows for easy connection of devices and propagation of measured values to other software components. LabView provides a graphical programming system to convert measures to semantic values. All proprietary devices thus are connected via LabView.

Precomputation of Semantic Values A driving dynamic model, based on a single track dynamics computes the parameters of the own car through measurement of all primary devices. Such values include the current position, driving speed and the currently set gear.

Simulation of Other Cars Simulation of other vehicles furthermore is an integrative component of low-level data generation. Any rapid prototyping environment therefore requires such data to enable usability testing of AR assistance schemes. Generation of positional data of other vehicles belongs to the low-level data provision layer.

5.2.3 High-Level Data Processing (Context)

This layer focuses on the deduction of context-dependent data. Such data is based on the low-level data. Here, various values are aggregated to values meaningful for spatial relationships and intended behavior between participating objects and the driver.

The problem domain of context adaption still is a matter of research. Approaches, among other domains, differ between car external geometrical context and car internal user-context [56].

Geometric Context The geometric context describes the behavior and spatial relationships of vehicles and obstacles relative to each other. Approaches for context acquisition range from car- and environment-mounted sensors to car-to-car communication. The geometrical context collects and fuses all providers of spatial context and builds a world model describing all spatial relationships. It supplies the other system components with information on how and to what extent in time an object will reach or hit another.

User Context The car-internal context [161] gathers information about driver behavior and deduces possible upcoming activities. Determination of a car driver's intention can enable early determination of activities neglecting important information. User context management systems often apply hand tracking and glance tracking systems. Especially glance tracking defines the interdependency between both classes of context. A user's car internal context is, to a certain degree, influenced by the external geometric context. Perception of outside events leads to certain reactions of the driver. The user context furthermore has to incorporate the driver's preferences and wishes to deduce specific personal demands of the driver.

5.2.4 Output Control

The output control layer decides how information is presented to the driver. It determines which modality or which modalities (optical, haptic, acoustic) to use. Components in this layer also specify where, how and how long information is presented. This especially becomes necessary when many concurring pieces of information must be given to the driver and some kind of information overload to the driver is to be expected.

Variation of Output Components in this layer have a strong dependency on concepts of presentation. Developers here can compile different concepts and test them on performance with the user. Developers can configure concepts to investigate different modalities or multimodal approaches. Especially for visual content, developers can set up different presentation based on 2D or 3D, or how acoustic output can be displayed.

Computation of 3D Presentation Especially for optical and acoustical output different output locations can be interesting for presentation. Here, input data for such kind of presentation is given via the position and orientation of vehicles in the vicinity and obstacles and Points of Interest (POI). Such data must be converted in dependence to the output location of the presentation device in the car. So called filter networks can serve here as a notion for non-trivial spatial transformations. Well defined sets of predefined spatial transformations can provide many necessary computations for the automotive sector. Based on driving dynamic models, spatial relationships can be modeled to present information accordingly. Such components can be activated in dependence to the kind of presentation and either can deliver spatial data to visual, acoustic or haptic presentation components.

5.2.5 Presentation

Output can be presented to the driver in different modalities. Optical, acoustic or haptic output modalities are the most common in the automotive sector. Control about the modalities of the output is managed in the presentation layer.

Components in this layer concentrate on the issue of generating and presenting 2D, 3D spatial visual, acoustic or haptic output. The final presentation devices are managed in this layer and presentation schemes are generated and presented through components in this layer.

5.2.5.1 Optical Presentation

Optical presentation differs between symbolic and spatial content. Both aspects require different approaches and solutions.

The Driver's Front View The 3D environment of the own car requires spatial information about location, orientation of all necessary objects and the surface of the world. 2D images are rendered from 3D data generating a perspective image as when looking through a window into a virtual world. Such rendering requires information about the position of the own car in the 3D world.

HUD-View Systematically decoupled from the rendering of the 3D world is the rendering of the visual AR presentation schemes. Spatial, contact-analog HUD content, similar to 3D world rendering, requires *Pose* information about the own car, but often may require additional information about environmental context. ADAS approaches also may require 2D rendering of symbolic content. Thus functionality must satisfy a wider spectrum as the rendering of the virtual world which then can focus on performant 3D rendering. Generation of AR schemes in a separate component later eases porting to other driving simulator systems and real car presentation systems.

5.2.5.2 Acoustic Output

Acoustic output nowadays can also be provided in a spatial arrangement. Modern surround sound systems enable spatially encoded sound. Components to display spatially encoded information can manage the speakers in the car and can provide 3D information to the driver.

5.2.5.3 Haptic Output

Haptic output in general requires many output devices, all placed in accordance to the exact output location. Such interfaces to the driver can range from the primary motion control devices to the driver's seat. The presentation layer has to choose the according output device and has to determine which kind of force or moment to apply by the device.

5.2.6 Output Devices

Components in this layer finally generate the output to the user. The output can occur in all modalities, either optical, acoustic or haptic, even through other modalities.

The virtual world of a driving simulator generally is rendered by a separate computer. Such a separation is necessary due to complex worlds with various high detail components, such as the animated wheels of other cars, turn signals and massive use of textures to render cities, rural areas and various kinds of roads. Depending on the field of view, at least one, often three, but sometimes more rendering engines on different computers generate sceneries for the front, side or even back mirror views.

Acoustic output can be incorporated into the spatial visual rendering systems as such software systems often also allow for spatially encoded sound output. Purely informative content, such as warning signals or speech output, can be delegated to other machines thereby enabling more complex software routines via decoupling to other computers.

Active responsive devices generate haptic or tactile output in the end use the same infrastructure as their input in the lowest layer.

5.2.7 Support for Evaluation

To execute user studies, several values from all levels of interfaces need to be monitored and to be recorded for further analysis. Each implemented concept brings new components into all layers of interfaces. To enable recording of those values, an orthogonal logging mechanism, covering all layers through a generic mechanism has to be integrated. Such an infrastructure then can capture any data with respect to any experiment. Such data can range from actual adjustments of input devices over deduced corrections, e.g., steering wheel reversal rates, up to data on driving performance, e.g., offset to the center of the own lane or distances to other cars and times to collision.

The application of data flow networks allows for easy access to data on all levels of the architecture and therefore facilitates easy incorporation of dependent and configurable recording mechanisms. Chronologically time-stamped log files can easily be generated, written to disk and later transformed to synchronized tables. Such logging data can also contain discrete signals such as activation of ADAS systems and thus can even facilitate automatic analysis: start and stop tokens in log files define delimiters for important data to analyze.

5.3 Implementation

To incorporate this architecture in the driving simulator for a useful rapid prototyping en- Stepwise Approach vironment, a stepwise approach was chosen to concurrently support development of interaction concepts. The modifications to the existing source code were performed in two steps, each resulting in a state that enabled the incorporation of the interaction concepts developed so far.

Interfacing DWARF

The first step decoupled the central components of the driving simulator and introduced interfaces to the DWARF [13] data flow network developed at the AR research group at TUM. The second step took care of further decoupling and new distribution of software components. Software was ported to modern computers and access to input and output devices was ported to extensible interfacing software.

Lightweight Approach

After the completion of each step, a number of interaction concepts were evaluated and the next step was prepared. After the tests following the second step were finished, the driving simulator was renewed and replaced by a BMW 6series convertible. At this point in time, the driving simulator architecture was also completely renewed, leading to the issue of reimplementing the rapid prototyping environment to support the dependencies of the new software. Experiences from the preceding system led to an implementation using a more lightweight approach than the initial data flow network had been. This became necessary because not only computer scientists, but also non-experts had to implement components of new interaction concepts. The learning curve of the previous data flow network initially was very steep, because it was developed for ubiquitous AR applications and incorporated extremely generic mechanisms which were unnecessary for driving simulator systems. Thus the framework did not perfectly fit to the requirements of a rapid automotive prototyping environment.

The following sections illustrate the two steps performed on the initial driving simulator. Afterwards, the implementation for the new driving simulator is explained.

5.3.1 Refactoring Step 1: Decoupling and Integration of Data Flow Networks

Incorporating DWARF

To have a rapid prototyping environment that is capable of easy integration and testing of interaction concepts that range from new devices up to AR schemes, the initial integration of components of such kind had to be eased. The driving simulator was therefore integrated with the DWARF framework [13, 106, 107] developed at the AR group since 2000. DWARF is a framework for distributed realtime AR applications. It especially suits the 3D presentation of virtual objects on different AR presentation devices, thus also on HUDs. The framework is also suitable for dynamic and multi-modal incorporation of input and output devices and dynamic reconfiguration of functional mapping. A generic mechanism for dynamic parameterization completes the short summary of functionality, facilitating rapid development of user interfaces and AR applications.

5.3.1.1 Basic DWARF-based Architecture

User Input and Sensors

The hard-wired connection between the car control devices and the driving dynamics has been kept intact during the initial refactoring step. Only the proprietary connection between the two cooperating computers, a serial link, was opened for additional passive reading of transmitted data.

Low-Level Data Processing

To integrate new hardware devices, National Instruments' LabView [1] was used. Analog and digital signals can be read from a measurement card and sent back to the devices. LabView provides a graphical programming language to manipulate data or to transcribe data to computer system network ports. A service component in DWARF was implemented to access LabView bidirectional. A clear separation between mandatory interfaces of a driving simulator and optional devices was drawn. One instance of the adapter to LabView only handled data of the primary control devices of the car, i.e. the gas and brake pedal and steering wheel. A second instance of this adapter was configurable to handle additional devices, such as the turn signal lever and optional knobs and sliders.

To access data from the car, a separate adapter was implemented as a DWARF service, accessing the serial link for reading. The adapter reads the positional information of the car and adapts the data to the DWARF data flow. This conversion allowed for access from all other DWARF components to the data flow of the initial proprietary driving simulator.

Access to the data of the other vehicles in the simulated traffic was established via an extension in the existing software on the Onyx machine. Here, the data of the simulated cars was put on a network connection which could be accessed from a further DWARF service component that provided the data to the DWARF network.

The structure of the interfaces can be seen in Fig. 5.4.

5.3.1.2 Management of Geometric Context

High-Level Data Processing

Management of geometric context is an issue on its own for any kind of AR application. Spatial relationships must be computed to anticipate possible collisions for immediate prevention or at least mitigation of accidents. The implementation was realized in a subframework, named `Spatial Context Ontology Reasoning Environment (SCORE)` [56]. The components are fully integrated into DWARF and thus allow for event driven approaches for realtime information delivery and subsequent performant presentation. The framework is rule-based and allows for the dynamic extension of new requirements. SCORE receives positional data from all dependent objects at runtime, computes their trajectories and applies references to the intermediate results. If a rule applies, related events are delivered to all registered follow-up components of the output control. Computations of this kind are extremely time-critical even in rule-based systems, because such systems generally do not scale according to the number of objects participating in the computation. The implementation has an average latency of 18 ms, which results in an overall runtime below 30 ms depending on the whole data path through the system. It thus suits the defined realtime approach of 30 ms.

Because of the central importance for AR applications either in simulation or in real incorporation in real cars, this framework is illustrated in more detail in a later section. Chapter 6 investigates spatial dependencies of objects. The second part of the chapter, section 6.2, page 125 specifically investigates the mentioned SCORE framework.

5.3.1.3 User-attentive Objects

Output Control

A concept that has been investigated and applied for some time in the AR community deals with user-attentive objects. Such (virtual) objects are equipped with input and output functionality and decide on their own, what and how they provide their information to the user [118]. An important issue for the combined use of such objects is the limited presentation resources and the limited attentional capabilities of the driver. To this end, all user-attentive objects must communicate with one another and negotiate for the presentational resources [17]. A rudimentary implementation that allows for easy presentation, manipulation and relation to locating algorithms in the HUD had been used for presentation of objects in the HUD. A wide range of 3D models (e.g. from Catia or 3D StudioMax) could be integrated to give a representation to the user-attentive objects. Such objects could be linked to *Pose*-data sources. The output control established facilities for activation, control and use of such informative objects in the 3D space of the HUD.

2D symbolic information in a conventional HUD, so called „screen-fixed information" in addition used conventional 2D layouting algorithms ported from standard graphical user interfaces of modern programming languages.

This approach allowed separating control and placement of any kind of user-attentive objects. High-level data processing service components can activate objects while other services take care of placement. Placement depends on the location of the situation to inform about, the available space and the line of sight of the user.

Because different concepts for the same issue were to be evaluated against each other on different output modalities, an extra service component was introduced to control and link the different implementations for the concepts. The implementation, the so called TUMMIC Output Controller (*TOC*) incorporated selection and combination mechanisms for different concepts and presentation approaches. The *TOC* provides a graphical user interface for the user study executor to configure specific experiments.

5.3.1.4 Spatial Control

Spatial control of the output objects requires location and orientation information. To enable efficient computation of such positional data, a part of the DWARF data flow network was dedicated to flow of *Pose*-data. For instance, the computation of a braking point is not implemented in the user-attentive service component that manages the control for, e.g., activation, but is implemented in a separate component as a positional data filter. This separation enables easy exchange of algorithms and reduces code complexity, since 3D transformations in general require deep understanding of the corresponding mathematics. Linking of spatial filter objects and user-attentive objects can be achieved by parameterizing service component interconnection attributes. These connection attributes allow for $m : n$ connections between components and thus enable the placement of multiple objects according to one or more spatial filters, no matter if output occurs through visual or acoustic channels. [1]

5.3.1.5 Output Generation

Presentation The already existing visual presentation service allows for perspective rendering of 3D ob-

[1]Various filter system components and the dependent architecture have been realized in the system development project of Michael Schlegel: *Filter Framework for DWARF* http://campar.in.tum.de/Students/SepSchlegel

jects designed in the Virtual Reality Modeling Language (VRML) or in the Inventor (IV) format. Such perceptive rendering, if viewed through a see-through display and correctly aligned to the real world, generates contact-analog AR presentation schemes. Virtually in front of the perspective rendering system, orthogonal rendering is possible, thus allowing for the inclusion of screen-fixed symbolic content in the same window.

To present acoustic content, an implementation had been integrated into DWARF as a separate service, allowing putting standard WAV files on the sound output.

Output Devices

Since the rendering engine of the 3D world in the old simulator did not allow for integration of animated objects, a separate video projector was mounted on the ceiling to generate the spatial, contact-analog HUD content. The presentation service was adjusted to the perspective parameters of the field of view.

Acoustic output used a Dolby surround sound system with two front, two back and a bass speaker.

5.3.1.6 Data Collection

Support for Evaluation

To record runtime data protocols, an easily configurable service component was developed. Through the architecture putting all necessary data on the component network, only specific needs for the required data had to be put into the configuration file of the logging service. When logging was activated through a button on a graphical user interface, all received data automatically was written to a specified log file. All data was extended with a time-stamp and stored sequentially.

Hardware Distribution

The original two computers, the Onyx and the driving dynamics computer, were extended with three new computers. Fig. 5.4 shows the general architecture of the system, the computers and the components running on the five machines. One computer handled the connection to the new devices and the listening to the old driving dynamics. A second computer ran the DWARF network and a third machine managed the acoustic output.

DWARF Service Structure

Fig. 5.5 shows the DWARF service components according to the rapid prototyping system in detail. Some of the components belong to specific user studies. Thus it does not appear to illustrate these here, where the focus lies on the implementation of the general architecture. Only the component *TUMMIC II* on the left side needed to be started as a program. It then automatically started all dependent service components. The *OnyxSocketClient* and the *FahrdynamikAdapter* on the right side of the diagram provided data from the own car and from the other cars in the vicinity. The data was delivered to the components for the high-level data processing: the *SpatialContextProvider* and the *ContextServer*. The *LabViewAdapter* at the lower right connects the *LabView* hardware driver to the DWARF network and sends the current speed and the rounds per minute back to the instruments on the dashboard of the car. The *LabViewAdapter* also connects all in-car devices to the DWARF network, with the *TOC* activating icons on the symbolic *HudStatusBar*. The *TOC* also activates sound output via the *Audio* service and it controls the activation of concept-dependent services (*BubbscherBalken*, *LangscherFahrschlauch*). Such spatially embedded presentation schemes are rendered through the *HudSphereViewer*.

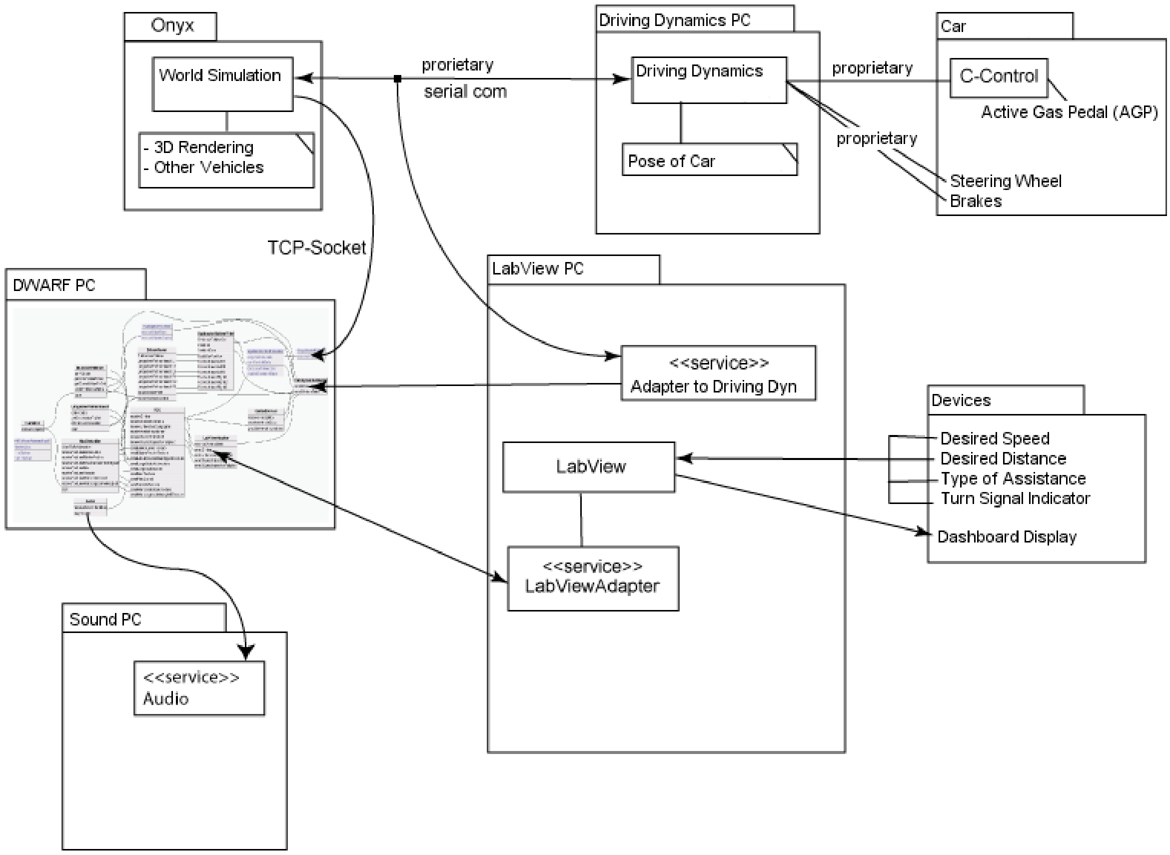


Figure 5.4: The Rapid Prototyping environment after the first modification step

5.3.1.7 Summary of first Refactoring Step

First Outcome

The modification and extension steps of the first refactoring phase established a usable rapid prototyping environment that enabled first investigations and discussions of various presentation and interaction concepts. Existing components and software was reused as far as possible, thereby allowing for a quick realization of setups for first experiments. Short development cycles in the first phase quickly enabled development of first ADAS systems. Already after a few months of development the first refactoring and extension steps were completed and the first usability studies could start. Among many expert discussions about possible ADAS systems, the following ADAS systems were designed and refactored and tested in subsequent user studies.

- The pilot study for the AR ADAS system to guide a car driver's attention towards imminent dangers (see section 8.3, page 164).
- Expert studies on visual longitudinal and lateral assistance (see chapter 7, page 142).
- A study about design issues and glance behavior when interacting with ACC controls (the master thesis of Thompson [148] and two publications [150, 149] about the study give more details).

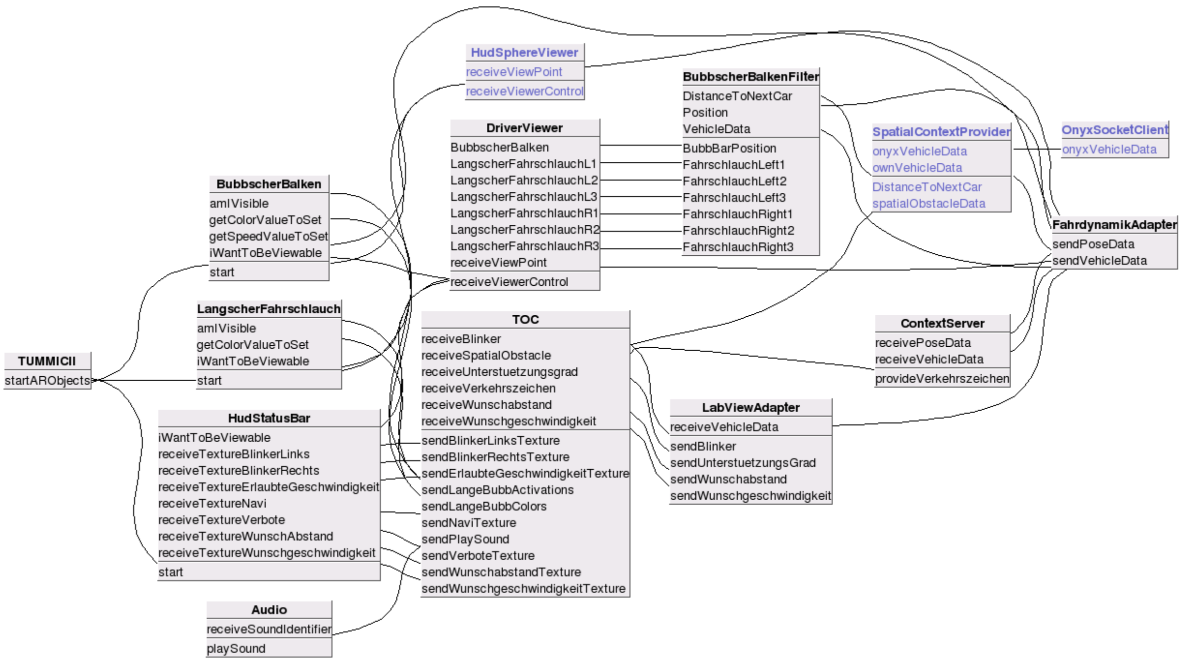


Figure 5.5: Screenshot of the DWARF network mainly running on the computer dedicated to DWARF. The boxes are the service components and the connecting lines show the data flow between the components.

- Traffic sign assistance in a symbolic HUD array displaying currently applying traffic signs. The visual memorizing assistance and the depended layout has been established in cooperation with Lange [96].

5.3.2 Refactoring Step 2: Porting Legacy Software and Hardware Access

New Demands

Experiences in dealing with the rapid prototyping environment, the conduction of first trials for user studies and first user studies generated demands for further extensions to the rapid prototyping environment. This section investigates these demands, illustrates the necessity for their realization and explains the changes and extensions made to the system.

Driving Simulator Assimilation

The first refactoring step covered only code refactoring issues, generated new interfaces and accessed data from the driving simulator to provide it to the rapid prototyping environment. The driving simulator had not fully been integrated into the rapid prototyping environment. Timing issues with upcoming user studies lead to this intermediate dual-system. The resulting heterogeneous setup had several deficits in system control and operability distribution.

Startup DWARF provided a mechanism to start all components of an application with respect to the dependencies of the components to one another. This mechanism worked across networks of computers and could start up the entire infrastructure of a system. Yet, the driving simulator components were only integrated into the system by use of service component adapters and thus had to be started separately. Developers and test executers were required to walk through the whole laboratory to start the system. Four computers had to be visited and seven different programs had to be started, thereby unnecessarily lengthening development and test cycles.

Furthermore, all programs had to be started in specific order. By fully incorporating the driving simulator into the networked architecture, such startup procedures can be shortened so that the system is easier to work with. Development cycles are optimized and higher numbers of iterations of concepts can be reached.

Adjusting Parameters of the Driving Dynamics Some concepts developed in the project required close control of internal parameters of the driving dynamics model. DWARF service components can provide such a mechanism, but the available program code of the driving dynamics model did not. Integration of the driving dynamics code directly into DWARF could alleviate these drawbacks.

Network Communication The serial link between the two driving simulator components was a legacy interconnection not providing access to the data flow. Modern communication mechanisms allow reading as well as writing to such connections as well as delivery to multiple clients. Access to this data flow becomes necessary to simulate modern assistance systems, such as the ACC [82], by injecting intervention at exactly the position into the data stream where it would be placed in a real car.

World Model Distribution Knowledge about the road layout is necessary for the computation of a vehicles position in the virtual world. Functionality such as automatic steering (easing ADAS system development and testing) of the own car and the vehicles in the vicinity required information about the placement of roads. Curve-angles and orders of road intervals are used to compute the position of a car relative to the defined waypoints of the road-course. Such data was redundantly distributed above all computers of the driving simulator. The redundancy of this world model complicated ADAS system development, because consistency issues between the different storage locations consumed time and effort and often led to inconsistencies.

Control of Other Vehicles The rendering subsystem of the driving simulator contained the code responsible for control of the neighboring vehicles. Strong coupling to the road layout led to this integration during system design for the Onyx computer. Steering functionality directly accessed world model information leading to the effect that the proprietary format of the world model only allowed black-box control of the neighboring vehicles. Up to 10 neighboring cars either could drive in both directions with the own car or in the opposite direction. Cars in the direction of the own car only could be in front of the own car. Leaving the field of sight, the other cars were randomly relocated. The inaccessibility of the control mechanism and the strong coupling to the world model information prohibited the development of more complex traffic scenarios.

The realization of newly developed assistance concepts led to further extensions to the rapid prototyping environment. These also are introduced in the subsequent sections.

Porting Code

To meet the demands of system startup, adjustment of parameters and network issues, the old computer running the driving dynamics was taken out of the system. The code was ported to another computer, which ran the hardware connection to the devices. Device interaction thus did not have to use an extra network link, thereby decreasing unnecessary network lag. The code was ported to a new integrated development environment and was decoupled from the direct access to the hardware devices (gas, brake pedal, steering wheel). The code was integrated into a DWARF service component and all parameters necessary to adjust were moved to the DWARF authoring infrastructure.

Hardware Devices

Decoupling of connections to devices and modules for the driving dynamics on the one hand eases the exchange of components and on the other hand eases the reconfiguration of parameters concerning the data flow and logging of objective values for user studies. To have an easily usable interface for incorporation and access to hardware devices, the LabView software therefore was brought into the rapid prototyping environment in the first refactoring step. According to the architecture where two adapters for the primary devices and all other devices had been designed, two subsystems were realized in LabView. This guaranteed independent data flow that was unaffected in processing time. The first subsystem only accessed devices for the control of the primary driving task. The second subsystem managed interconnection of all devices belonging to certain user studies. Thus any errors during system development did not affect the control of the own car. Debugging times were reduced, because any malfunction could clearly be attributed to the interface and the dependent data flow. All hardware devices were ported to the LabView system. This enabled any component to get bidirectional access to any hardware device. As a consequence, response channels towards the driver could also use haptic and tactile modalities.

Run-time Protocolling

The first refactoring step incorporated a chronological logging mechanism for objectively measured data of driving experiments. To ease the analysis of this data, the range of responsibility of the components was extended.

The amount of loggable and measurable data provided in the DWARF network increased due to deeper incorporation of the driving simulator. Data became more complex and allowed for deeper analysis. The exact computation of mean values requires such data to have all measurements in fixed time intervals, e.g., logged with 40 Hz.

The DWARF data logger was extended by a mechanism to convert chronological logs to tabular structures. As long as no computer in the system and no network connection in the while system reached a workload of 100 %, continuous data like the current position of the own car in the own lane could be recorded properly. Data, for instance generated at the specified frequency, satisfy this demand, but can differ in logging time, because due to the phase shifts between different components. Other components, like the implementation of the vehicles in the vicinity, generate their data with 30 Hz. To convert such data to a timely ordered set with fixed time intervals, the conversion mechanism had to read the preconfigured recording interval. When the logging was started, it stored the start time and then always placed an entry containing the currently logged values with fixed time-stamps into the log file.

Discrete data such as button clicks or slider settings were defined as states of adjustment, and were recorded in defined state values shown in separate columns of the tabular representations. Thus, intervals, in which one or more certain states were active, easily could be taken out of the log-file. The timely synchronization additionally allowed parallel framewise analysis of glance behavior movies which were generally recorded by a frequency of

40 Hz [98].

To reduce the risk of overloading the network in the rapid prototyping environment, multiple instances of the data logger were run on different computers. Thus data generated on one computer did not necessarily have to use the network just to notify the data logger on another machine. The central starting and synchronization mechanism of DWARF guaranteed time synchronization between all different logs.

Resolution of Conventional Head-Up Display

The projector on the ceiling that produced the HUD presentation schemes covered almost the whole windshield. Running at a resolution of 800x600 pixels, fine grained presentation schemes, especially symbolic data on the conventional HUD appeared pixelized and were difficult to perceive.

To keep the advantages of a large scale HUD that covered the whole windshield, a second projector was added to the system. This video projector, mounted in the front of the car under the hood, enabled high resolution projection of the symbolic HUD status bar and simulated a conventional HUD with increased field of view.

The existing DWARF service was reconfigured to be startable in a single computer – the one connected to the HUD projector. The area covered by the status information bar in the HUD now had to be larger on the screen to consume the same area as before. The configurability of the 2D layouting service easily allowed for the required reconfiguration.

Spatially Encoded Acoustic Presentation

To enable the full spectrum of AR user interfaces, also spatial sound-based presentations can be integrated. Besides optical, haptical and sound in general, spatially encoded sound extends the range of hints and cues, human-centered concepts can make use of.

The already existing sound player capable of playing sound and speech required an extension to spatially place sound sources of a Dolby Sound System in the lab. The player thus was extended to also receive positional data for sound sources played from different directions.

The Open Audio Language (OpenAL), an acoustic extension of the OpenGL graphics library, suited this demand well. Through this implementation, sound could be generated through all speakers ubiquitously or encoded spatially. Multiple sound and speech files could be played concurrently from different positions. Such sources could receive spatial data from filter networks computing *Pose* data. Sound sources thus can be placed in accordance to output using other modalities.

To ease calibration of the speakers, all four speakers responsible for perception of direction (high frequency speakers) were placed at the same distance from a driver's average head position. The first two speakers were integrated in the dashboard while the two back speakers were on the back shelf. Both right speakers were placed near the center line through the car.

Management of Assistance Systems

With increasing numbers of assistance systems in different concepts it became necessary to manage output control of these systems in more detail. Previously, each assistance system could access each output modality and interface. Depending on the input each service component received, it could trigger different output connections to present different content in different modalities. This could lead to components competing for one output device, e.g., a certain field in the HUD status bar.

To coordinate device access, all handlers receiving input signals were realized as separate objects inside the *TOC*, notifying the central internal scheduler when assistance systems sent their data events. The *TOC* was extended by a queuing-mechanism to store back all requests for presentation. Not until all concurrent events were stored, the queue checked competing output modalities and areas and then sent out the up-to-date notifications to the DWARF service components. When a conflict was determined, an error was sent to the developer or test coordinator, informing him of the inconsistent situation. Such errors had to be corrected before the final user study could be conducted.

The warning mechanism was a pragmatic approach, not allowing assistance systems to compete at different priority levels, it only supported consistent system development. Later extensions for priority queuing were enabled through this implementation.

System Authoring

DWARF is a self-organizing framework allowing for dynamic reconfiguration of context parameters. Attributes and parameters could be specified separately for services, but could also be accessed beyond service boundaries. Thus, e.g., timing parameters only had to be specified once but could apply for the whole system. Such attributes could be changed during development or even at runtime of the system. A specific tool called *DWARF Interactive Visualization Environment* (*DIVE*) allowed for modification of these parameters by use of a graphical interface showing the network structure of the current system. Services and parameters could be selected and changed. This tool only allowed for textual parameters and did not allow depositing alternative values.

These restrictions complicated dealing with complex parameters, such as positional information. Two approaches therefore were applied to the rapid prototyping environment. First, DWARF service components that had to be adjusted frequently and had complex parameter settings were equipped with graphical user interfaces for parameter modification. Second, management of Points Of Interest (POI) were realized in a separate DWARF service.

Graphical user interfaces, now controllable by mouse and keyboard, were mainly generated for the *TOC* to easily change appearance and activation of different assistance schemes or to select content of the HUD status bar.

Management of POIs focused on specific places that trigger system behavior. Such triggers serve as placeholders for sensor systems as they, for instance, simulated the detection of an obstacle on the road or changes in the allowed speed. The newly introduced component allowed to place POIs on a graphical bird's eye map and to link these POIs with certain activities and events to be sent to the DWARF network. When a driver passed such a POI, the corresponding event was triggered and resulted, e.g., in a change of street signs. [2]

New System Structure

Fig. 5.6 shows the system architecture of the rapid prototyping environment after all modifications and extensions were finished. The figure also shows the components that were refactored to DWARF service components, indicating to which computer they moved or where they were implemented.

In the new version, the computer running LabView signed responsible for hardware and driving dynamics simulation of the own car. The DWARF components now almost completely ran on their machine, except for the adapters, the driving dynamics and the sound system. The Onyx still managed generation and rendering of the 3D world and the neighboring traffic.

[2]The corresponding service component has been developed in cooperation with the chair for Systems and Software Engineering, Computer Science, TUM. Details are given in the system development project of Dimitri Alexeev: *Development of a Component for the Analysis and Management of Positional Data*

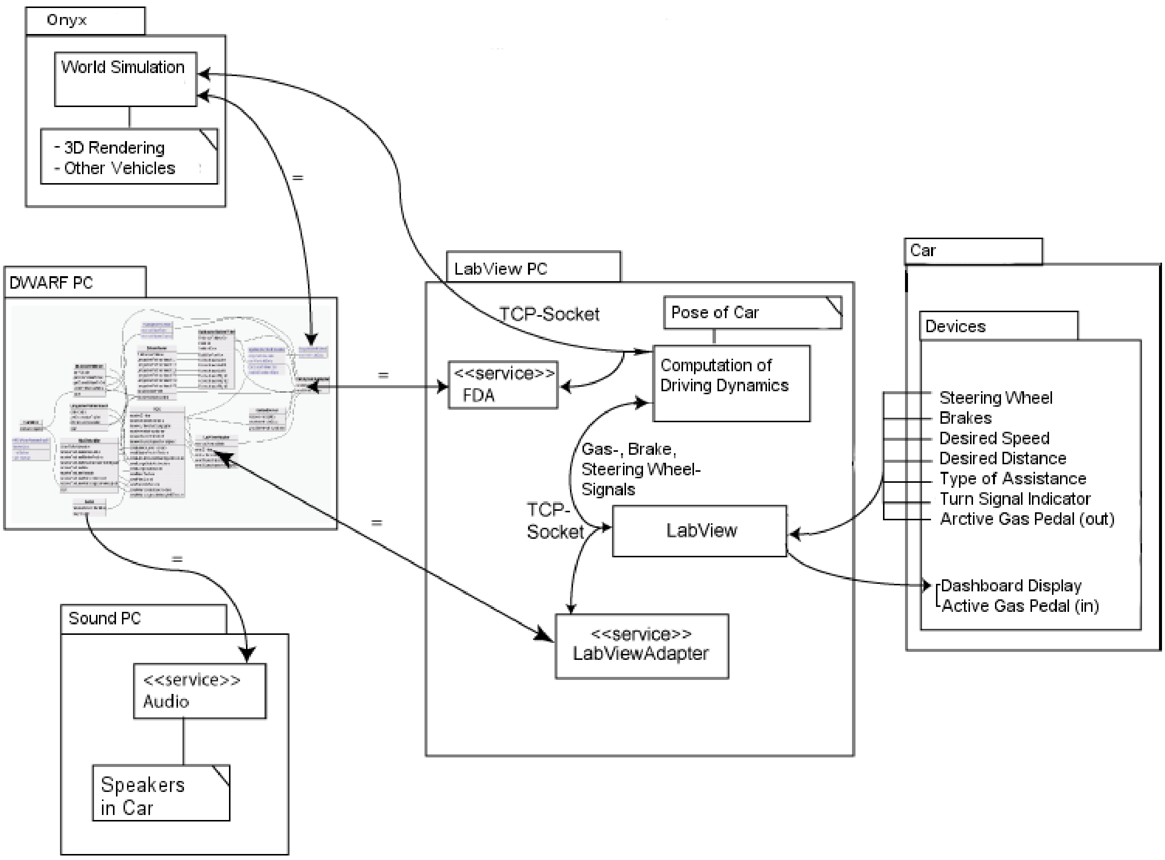


Figure 5.6: The implementation of the final rapid prototyping environment in the first driving simulator

The amount of DWARF components increased, now including the full implementation of the high-level data processing framework. Fig. 5.7 almost shows the same structure as after the first refactoring step but now includes the service components of the SCORE subframework (reported in detail in section 6.2, page 125ff).

A further refactoring step could have been made, to take the legacy Onyx computer out of the system and to set up two new components, specifically managing the simulated world and the other vehicles. Due to new project responsibilities at the LfE, a completely new driving simulator was acquired instead, making further efforts unnecessary.

5.3.2.1 Summary of second Refactoring Step

Similar to the outcome of the initial refactoring phase, a broad spectrum of user studies has been conducted with the final version of the old driving simulator and the encapsulating rapid prototyping environment. The most relevant usability studies conducted in the rapid prototyping environment are listed here.

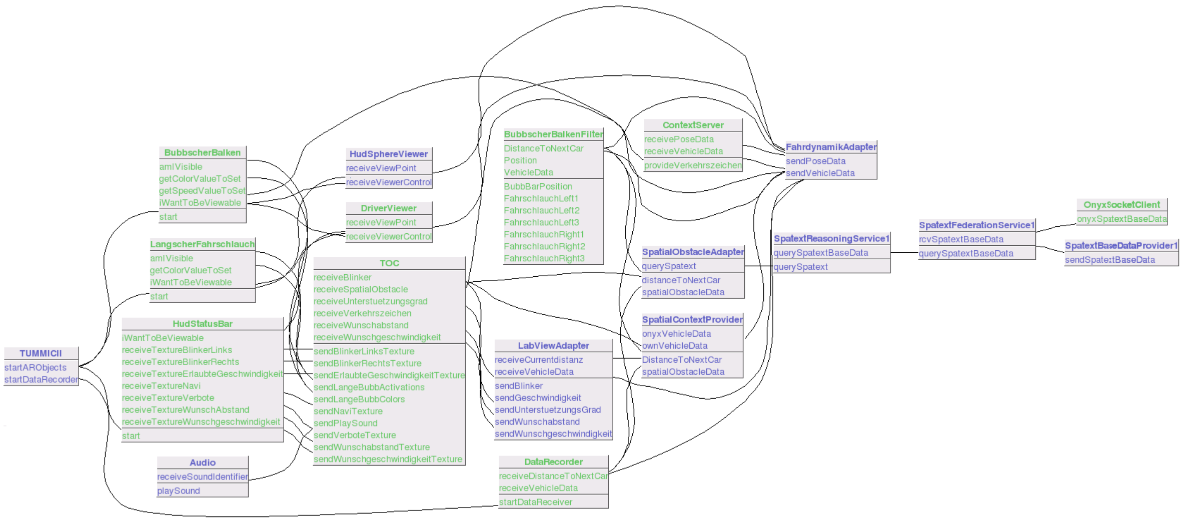


Figure 5.7: The DWARF service components of the rapid prototyping environment after the second refactoring step now incorporating the full implementation of SCORE

- The main study for an AR scheme to guide a car driver's attention to imminent dangerous situations outside the driver's field of view (see section 8.4, page 171). - The study concerning visual longitudinal and lateral assistance with an animated AR braking bar scheme (see chapter 7, 142).

- A further study examining additional AR schemes for visual lane departure indication. Presentation schemes, their spatial dependencies and algorithms have been developed in cooperation with the work of Lange [96].

- A study investigating haptic assistance for lateral assistance. Force functions applied to the driver's steering wheel have been examined. In cooperation with the work of Lange [96], programmatic data distribution algorithms and interconnectivity issues have been solved.

- Building site assistance and general location approaching information systems have been tested for effectiveness. To support the work of Lange [96], symbolic presentation schemes have been integrated into the HUD and triggered according to location and speed of the own car.

5.3.3 Rapid Prototyping Augmented Reality with the New Driving Simulator

At the end of the second refactoring phase of the driving simulator, plans for a completely new driving simulator became topic to the LfE. Some major reasons for the complete exchange of the driving simulator have already been listed in section 5.1.2 on page 82. Simulator Replacement

Besides incorporation of new hardware ranging from a completely new car to new input and interaction devices, new simulation software was introduced as well. Software that is Simulator Software nowadays developed for driving simulators provides a wider range of access to data necessary for development of interaction concepts and conduction of user studies. To have a rapid prototyping environment for AR schemes and other functionality, existing self developed software required to be adopted to meet the new interfaces.

Streamlining Development Systems

Experiences gained from the rapid prototyping environment of the first driving simulator also brought insights into deficits of the infrastructure used hitherto. In detail, mainly the DWARF system proved to be complex and overqualified for the requirements of a rapid prototyping environment, because its original design was oriented towards highly dynamic systems. ADAS concepts, for instance, do not require highly dynamic ad-hoc networks, which in fact was a central goal in the development of DWARF. Efforts to streamline the implementation and to throw unnecessary parts overboard led to the decision to keep the well suiting component-based architecture, but to exchange DWARF with a more light-weight component framework.

Jakarta Components

A light-weight component-based framework enabling the implementation of the architecture for the rapid prototyping environment was found in the Jakarta Components Project Fortress [3]. It allows for independent, (re-)configurable components to be interconnected in m:n network structures. Components can run in different threads, thus enabling the execution of various independent data sources, such as input devices, simulated sensors or other vehicles.

Computer Setup

The new driving simulator incorporates a larger set of computers. Fig. 5.8 shows the structure planned by the colleagues from the chair for ergonomics: as in the final state of the first simulator, the in-car devices are connected to a computer running LabView. Only the steering wheel is connected to a separate computer. Force feedback generation on a steering wheel requires complex calculations, depending on the driving speed, the curve radius and many other factors, and thus requires a separate computer. Devices of assistance concepts also use a separate computer in the new setup. This computer is also running the components of the specific implementation of the concept. The conventional HUD is, as in the first driving simulator, connected to a computer by its own. The same applies for the large scale contact-analog HUD. The driving dynamics, using a new dual-track model, also uses an own platform. The world scenery, now incorporating three visual channels, finally is rendered on three separate machines.

5.3.3.1 Integration with Driving Simulator Software

Third Party Software

When the hardware installations were nearly finished, first versions of the software were available, provided through cooperation of two software companies. The software provided rendering of the 3D world, a driving dynamics model, interconnection to standard USB-steering wheels for gaming applications, simulation of other vehicles and a so called shadow database generating basic context information, such as the position of the own car on the road and deviation from the center of the own lane or distance to other vehicles. Data was exchanged through proprietary implementations using standard network connections. System components had to be started separately.

Requirements for AR

As already mentioned, short roundtrip cycles facilitate rapid development of assistance systems. To further enable different configurations of assistance systems independent of each other, certain further requirements in the new software had to be faced.

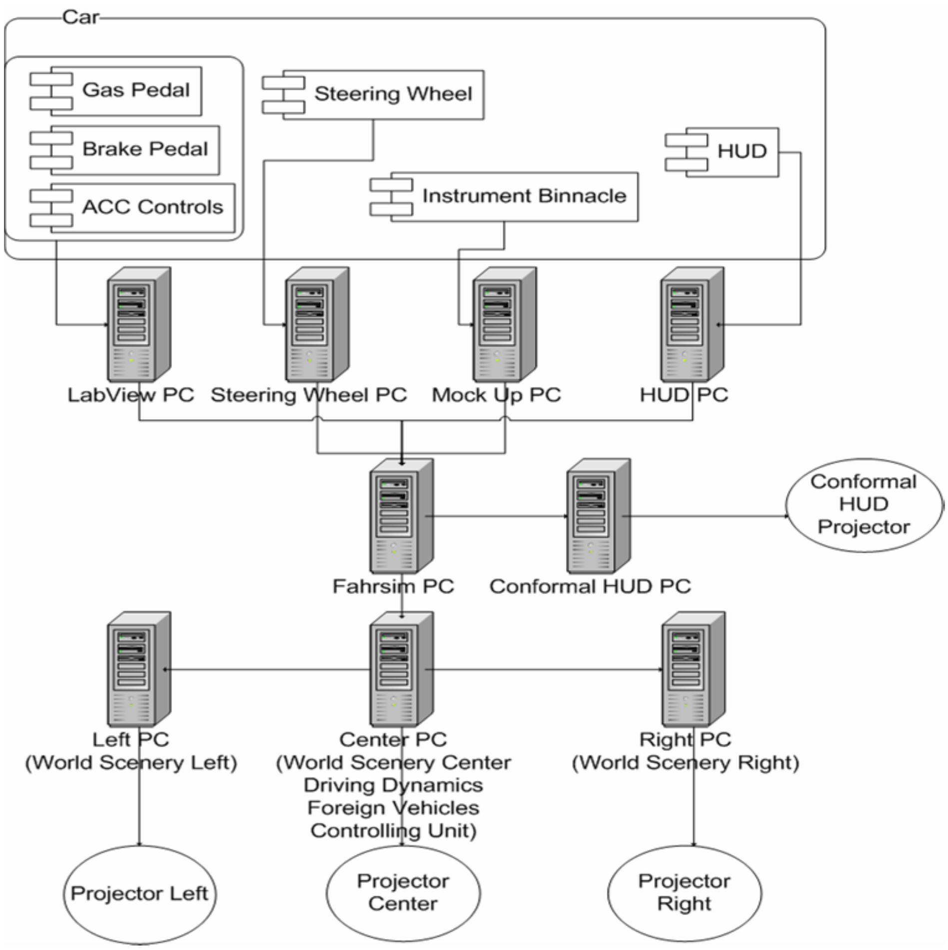


Figure 5.8: The Hardware Architecture of the new fixed-base Driving Simulator at the Chair of Ergonomics

Centralized remote startup Long roundtrip cycles during system development and conduction of user study especially lengthen and strain efficient work. Accessing different computers to start various components of the simulator and the testbed, as described in the implementation of the first rapid prototyping environment, are a major factor. A mechanism is required that covers not only the startup of the components of the rapid prototyping environment, but also the subsystems of the driving simulator.

Distribution of components As in the first implementation of the rapid prototyping environment, where distribution of components was necessary for load balancing and minimal network load, components in the new system must have the possibility to be distributed among different computers. DWARF provided a generic mechanism. It had strong dependencies on third party software libraries, generating a steep learning curve, even if dealing with these parts was encapsulated as much as possible. A new implementation had to ensure that non-expert developers without expertise in special software can easily handle such matter.

Easy integration of new components Each new concept brings new components to the rapid prototyping environment. Integration mechanisms must be easy and must not affect interoperability of existing solutions.

Easy configuration of combinations of components Combinations of assistance systems lead to integrated systems. To test such integrated systems, full applications must be configurable without interfering with existing applications.

Previous Requirements

All other requirements of the previous rapid prototyping environment still apply to new implementations. Especially realtime management and parameterization of components are among such requirements. Easy portability of already realized components and assistance systems therefore played a major role in the implementation of the new framework for the rapid prototyping environment.

New Implementation

The new implementation of the framework uses the Jakarta Apache component framework *Fortress*. The main concepts of this light-weight extensible and configurable framework are listed in subsequence.

Inversion of Control Pattern The Inversion of Control (IoC) Pattern is used when tight coupling of the components endangers system functionality. This often is the case in component-oriented software architectures, when the implementation of each component should be more or less independent from the implementation of other components. Changes in the implementation of a specific component should not affect other components that cooperate with it. Initialization and reference handling of components must be decoupled. Clearly structured interface hierarchies define general responsibilities of components and require no other component for initialization. Dependencies between components based on the interfaces allow for the placement of retrieving components and the setup of references between these components. Fortress is based on the IoC pattern and sets the references according to the principle of loose coupling. It allows the developer to efficiently integrate and test new components, not having to care about how to implement and inject the needed references to the cooperating components.

Separation of Concerns Pattern The principle of the separation of concerns pattern is to be able to distinguish between the main concerns with which components have to deal. Fortress realizes the concerns in form of interfaces. The framework provides a number of basic interfaces as a hierarchy allowing the framework to correctly initialize and link the components with respect to the inversion of control concept.

Component Lifecycle To establish the communication between the relevant components, and to manage the behavior of components, containers are used. Containers include groups of components. To create a communicational network, each container first initializes required components. Afterwards they call methods of each component, as necessary for a component to initialize the service expected by other components. These methods form the lifecycle of a component and range from initialization to starting and stopping. A container is required to take a component through certain stages of its lifecycle. The lifecycle specifies which method must be called in exactly which order.

To enable the whole system startup from one computer, general runtime execution clients have been deployed on all computers in the system. A specific generic component was implemented to be integrated on the central management computer. This stub component can be configured to dispatch events to other computers, such that programs like the world scene rendering can be started and stopped from remote computers.

Centralized remote startup

The new component framework did not allow for distribution across multiple computers. Therefore, generalized default components for continuous data flow and discrete events have been implemented for incorporation into data flow networks. Such components provide sinks and sources of any kind of data flow and encapsulate network structures. In combination with the functionality for remote component startup, component networks now can be distributed among any kind of computers.

Distribution of components

To place the focus on assistance system development, components must have easy interfaces for integration into the system. Generic base implementations must provide such functionality on each level of the architecture. General functionality for any kind of components have been identified as the needs for data logging, communicational networking (servicing), configurability, initializability, and startability. The corresponding interfaces provided by the component framework were assembled into a basic service component structure. To gain more control of the data flow, some new interfaces were aggregated into the infrastructure. Components handling data became a qualifying interface for general declaration. This interface was extended for components providing, retrieving or processing data. Components separately creating data on their own became extended by a threadable interface so that separate data flow could be established.

Easy integration of new components

As in the first implementation, the rapid prototyping infrastructure had to provide functionality to run different applications with respect to different user studies conducted concurrently. Each application uses the driving simulator components. A general configuration file for definition of an application for the startup process has been developed to only run the simulator environment. Any assistance system or interaction concept using the default setup can copy and extend this basic definition. Concepts altering functionality of the simulator, such as active driving dynamics intervention assistance system, still need to exchange certain components or have to extent the data flow interconnection by a further mediating component.

Easy configuration of combinations of components

The component architecture of the new simulator and especially its implementation has been executed in cooperation with Popiv who reports about more details in her master thesis [121].

Cooperation

5.3.3.2 Integration with Software of the final Driving Simulator

The new driving simulator software did not fully satisfy the needs and requirements of the chair for ergonomics. It therefore was replaced by software that is now provided by a software company focusing especially on driving simulator environments. The new software, called SILAB [169] uses a design centered on realism, scalability, application-oriented design of scenarios, expandability and transparency. The new software incorporates its own data flow model, using so called data processing units (DPU). Components can access data from any source and even can add presentation schemes under certain circumstances to the virtual world.

To incorporate already realized functionality of the first implementation of the new simulator, which was missing in the new SILAB software, the Fortress component framework was ported to the new driving simulator. In early 2008 some central features, among others, the generation of the sound (loud speakers and driver seat bass pump) and braking bar schemes are still implemented in the component framework.

5.3.3.3 Summary of Refactoring Step to Final Driving Simulator

The new driving simulator, since its establishment has already served for several usability studies, where some still have been developed with assistance of mine.

- A study concerning semi-automatic longitudinal assistance with ACC and active gas pedal functionality. The master thesis of Popiv [121] and the dissertation of Lange [96] report in detail on the experiment.
- Explorative expert discussion studies on designing systems for ADAS systems. These ongoing examinations are based on Bubb's work [36].
- In preparation is a further usability study investigating AR assistance at crossings. The study will be conducted in 2008 as a cooperative project between FAR and LfE.

5.4 Experiences and Future Recommendations

Wide Variety of Systems

The different versions of the driving simulators and the rapid prototyping environments served for a wide variety of systems that have been developed. Section 5.3.1.7 (page 94) and section 5.3.2.1 (page 100) report on systems and studies conducted with the initial environment while section 5.3.3.3 (page 106) report on some systems developed with the new infrastructure. Components on every layer of the architecture have been implemented, extended and used in different ADAS systems in different combinations.

Broad ADAS Spectrum

After escorting and investigating driving simulator systems on the hard- and software side for a wide range of ADAS system development processes for several years, some experiences, especially when facing AR-related system development issues, can be described. Many of the gained experiences are strengthened through repetition. Their consideration can optimize and and speed up the design and development phase of AR ADAS systems. Other experiences faced calibration requirements that often reduce the quality of perception and understanding of spatial relationships in experiments. Such experiences become recommendations to enable fair comparability between different, classical or AR-based ADAS system approaches.

Fields of Experiences

The experiences and recommendations cover three areas. First, efficient development cycles were investigated for different ADAS systems. Here strategically integrated computer infrastructures can serve for consistent, deficit-free, documented system development. Second, knowledge transfer between different fields of research and their interoperatibility enables deeper cooperation. When software infrastructures leave opportunity for non-programming experts to modify and generate new ADAS system blocks independently, multiple systems can be built in parallel without inconsistencies. Third, in virtual environments, imprecisely set parameters for the perspective presentation of a scenery indeed have less effect on first impression as in optical-see-through AR, but in AR they can reduce the interpretation of AR schemes through incorrect aligned animation and even can cause simulator sickness.

5.4.1 Design and Development Environment

Copying

Design and development processes of ADAS system like any kind of system development process require iterative testing cycles. A system developed on a separate machine must then be deployed to the simulator environment and spread across several computers. Usually this is a manual copying task. Other activities where software or code fragments are copied occur during redesigning tasks. Often, a previous design, e.g., the appearance of an AR scheme is discarded in favor of a new and better one, but should not get thrown away. In this case the respective file is copied to a new name. Testing of different variants then requires replacement of files and renaming. The history of the development process and the variants later tends to get lost. The new code is then extended, also affecting other files, leaving the old scheme in a state that is inconsistent with the running environment. Each such replication task bears the risk of errors. Software components do not meet the requirements of the current state of development of the whole system because they are inconsistent. Deployment tasks are time-taking and also bear the risk of inconsistent systems if a target is forgotten.

Folders and Versioning

Strategically integrated computer infrastructures can serve for consistent, deficit-free, documented system development. Two infrastructure systems are applicable: remote network folder integration and versioning systems.

Remote Network Folder Integration User-dependent mounting of server directory folders in fact reduces data transfer rates through the network but it integrates development and testing. Code can be developed anywhere and accessed with higher consistency. For instance, configuration files often contain directory paths to refer to other files. When absolute paths have been used here, exactly the same folder structure must be available on all other machines. In addition, all files must be copied. When different systems are developed at the same point in time, the selection of files to be copied can become complicated. Server-side folders overcome a lot of these issues because they can be integrated on every client accordingly, enabling transparent data access over the whole system and not requiring copy tasks.

Versioning Systems Variant development and bug-fixing are two examples why access to different versions of software blocks is necessary. Different variants need to be altered or exchanged, while bug-fixing often requires comparison to earlier versions of the code to evaluate and test the changes. File copying tasks bear the risk of inconsistent file history. They complicate comparison and may lead to incompatible code fragments.

Access to any revision and version of multiple system histories is guaranteed through the application of versioning systems. Such systems provide a server-side repository automatically maintaining the chronological history of every file. Versioning systems furthermore provide capabilities for development in different branches of a system concurrently and functionality for later merging of branches and the main system.

Such merging functionality also supports team development where multiple people modify multiple files concurrently. While the code of a developer simply can be overwritten on file copy, the versioning system merges files automatically or immediately reports a conflict before code is lost.

5.4.2 Interdisciplinary System Development

Component-based software development takes the task of component integration into the system from the source-code level to the configuration level. Only the component itself has to be developed, while existing interfaces are linked by the component framework. Several components have been developed or modified over the last years. Experiences have shown that the DWARF infrastructure and the component-based architecture of the initial version of the new simulator enabled non-programmers to quickly acquire small portions of necessary programming knowledge to efficiently develop their ADAS system. The clear separation into different layers of responsibility and data preparation enabled easy overview and knowledge of available data. The separation from activity management, mathematical spatial computation and visual or acoustic representation also reduced the complexity of system development. Cooperation and distributed development were thus possible.

5.4.3 ADAS System Instantiation

Incorrect Calibration

An important factor noticed several times refers to the correct visual replication of virtual sceneries. Experiences here range from the replay of recorded videos, their overlay with AR schemes to correct setting of driver viewpoints in driving simulator environments and the adjustment of video projectors for HUD presentations. Incorrect adjustments of projector systems (or of displays) lead to tunneling effects and wrong estimation of the speed and size of objects. Such effects must be eliminated, because already the monoscopic representation of 3D sceneries in simulator environment complicates depth perception. Two examples will explain these issues.

Camera Angle

When videos are recorded with a car-mounted camera, the camera has a certain opening angle, that defines the field of view of the camera. When such a video is replayed in a driving simulator, that same angle must be used to present the video. The angle between the left edge of the projected image on the screen, the driver's head and the right edge of the projected image on the screen must have the same value as the opening angle of the camera. If the replay angle is too large, speed appears higher since the scenery appears to move faster away from the center of the screen. The relative size of objects then seems larger than in reality. When the angle is set too small, speed appears to be slower and objects appear smaller. According to videos replayed in a simulator, rendering of the 3D world of a driving simulator has to face the same issue. Wrong alignment of the real driver's viewpoint and the virtual viewpoint of the rendering system often lead to more occurrences of simulator sickness and nausea. Here, both systems, the hardware setup of the projection walls and the field of view in the virtual 3D scenery, must be harmonized.

Visual Overlay

Similar to the issue of correctly aligned sceneries, AR superimposition must be carefully adjusted. The field of view of the AR projection system must fit the rendering of the virtual world and the field of view of the rendering system must incorporate these values. If not adjusted correctly, the same effects occur as described above, but in extent to the above consequences, the understanding of spatial relationships is handicapped. Location-fixed schemes will have an unintended movement and distances will be unclear leading to the effect that speed recognition is tangled even more.

Consequences for Development Tools

In consequence, development processes in driving simulators must adopt principles of applied software engineering. Structured development cycles and consequent incorporating of supplementing software maintenance tools guarantee efficient development and reproducibility of decisions. Changes can be tracked and sources of errors can easier be eliminated. When software system sizes as in complex modern driving simulators are reached, responsibility of code fragments must structurally be decoupled. The use of packaging mechanisms or component frameworks becomes mandatory to ensure understandable code complexity.

Experiences

After almost four years of experience in ADAS system development in driving simulators, I can conclude that the development of the rapid prototyping environment and the continuous teaching of supplementing development tools lead to a new era of structured software development with simulator systems.

6 Creation and Understanding of Spatial Context

Behavior management of neighboring vehicles in simulated environments and applied reasoning of spatial sensor data

Open Issues

Chapter 5 developed a rapid prototyping environment for ADAS systems in driving simulators. The description of the implementation left some issues open concerning the spatial environment of the car. This chapter focuses on these issues and provides two systems that extend the rapid prototyping environment.

Knowing Context

One major issue of ADAS systems is that they require detailed knowledge about the spatial context of a car. Sensor systems acquire spatial data of the environment and generate models of the spatial context. ADAS systems then query the spatial context to deduce critical events for driver presentation or automatic reaction.

ADAS Development

During the development phase of such ADAS systems no real sensor data is available, but simulator environments in general allow generating simulated sensor data. To test the applicability of assistance systems, low-level data must be simulated to test the context analysis functionality in combination with the ADAS system. Deductions on this data, so called reasoning must then be realized with respect to the application.

User-generated Context

Generating realistic sensor data to test new ADAS systems is a major problem. Programmed simulations of traffic follow exactly specified trajectories. Such motion algorithms either follow predefined waypoints or they are implemented by a priori algorithms. Testing assistance systems against such algorithms neglects individual behavior of humans. ADAS system development requires already in early phases non-random movement of traffic participants, but dynamic uncertainty, reflecting natural behavior. I have therefore developed an integrated table-top and driving simulator system. This system simulates sensors and thus maps to the first layer of the architecture of the rapid prototyping environment: *User Input and Sensors* (see section 5.2, page 85ff). The setup enables test participants to create traffic scenarios on a table-top workbench with a tangible miniature car. The driving simulator part of the system provides the direct experience of the generated scenarios. This system can be used to perform case studies to reason about human principles of anticipation. Test participants create traffic scenarios and subsequent analysis can derive principles of human behavior.

Context Understanding

Such traffic scenarios reflect low-level sensor data, gathered with perfect sensors. The second and third layer of the architecture of the rapid prototyping environment deal with *low-level data processing* and *high-Level data processing* (see section 5.2, page 85). In the second and third layer, a context management system provides generic functionality for a wide range of ADAS systems. The decision to implement such a context management system independent from specific ADAS systems is based on the principle of avoiding functionality duplication. If different systems use different algorithms to provide data for different ADAS systems, each system might react different. Thus, competing or conflicting information could be provided to the driver. Centralized management of all algorithms in a separate system ensures validity of reasoned data and ensures that all user interfaces of ADAS systems are notified with the same information and simultaneous. General rules, such as computation of the time to collision are realized. Further ADAS systems will require a wider set of rules.

Structure of Chapter

This chapter illustrates the solutions for both issues, starting with the first issue, creation of traffic scenarios through direct user behavior. In subsequence, the second issue, federating spatial sensor data and reasoning on spatial data, is investigated.

6.1 Generating Spatial Context

Intense Coupling

Driving simulators are worthful environments in the development cycle of in-vehicle information systems. ADAS systems, as a part of such in-vehicle systems, often have user interfaces and require to be tested in driving simulators before they can be tried out in real tests. In contrast to IVIS systems where interface design is affected through the existence of a primary driving task, ADAS systems have an intense coupling to the actual traffic situation. To test ADAS systems in a simulator, a traffic scenario must be available that looks occasional. In general, traffic scenarios in driving simulators are somehow artificial or depend on a certain application logic controlling neighboring cars relative to the own car.

Tangible Miniature Car

To generate traffic scenarios with more human behavioral content, I have developed an intuitive system to enable traffic scenario development for user study subjects. The system uses a *tangible miniature car* (see Fig. 6.1) with a *table-top back-projection workbench* that is connected to a *driving simulator virtual environment* (VE). The approach follows the idea of Sandor [130] who investigated the use of table-top miniature cars for the development and testing phase of user-attentive objects [118]. The system enables collaborative discussion, easy intuitive and rapid traffic scenario generation and multi-view experience. The system enables analysis of human behavior to facilitate the development of semi-automated and especially in-car assistance systems that are accepted by the driver. The system architecture and experiences from monitoring people while they are using the system to generate traffic scenarios are reported. A publication on the system can be found in [152].

Towards the Generation System

The following sections give an overview of the foundations of such a system. The sections explain, why no other approaches for the generation of realistic traffic scenarios provide the same ease of use. Minor differences in perception between automated and human recognition systems illustrate the delta between the different levels of awareness. This delta was introduced in section 3.2.2 (page 58ff) and indicates the importance of the existence of such minor differences. After showing how the system can be incorporated in a driving-simulator environment, a number of issues and experiences concerning object registration of new virtual 3D car models and traffic scenario creation on a fixed size table-top are discussed.

6.1.1 Comparison of Traffic in Real and Simulated Environments

Driver Acceptance

For the development of ADAS systems for semi-automated cruise control it is not only neces-

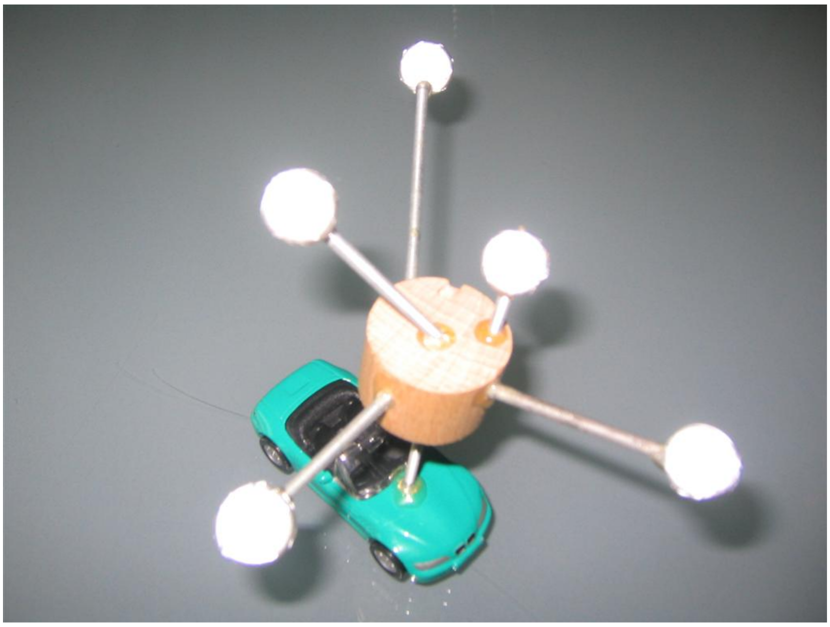


Figure 6.1: The tangible miniature car: A small green BMW Z3 series in a scale of 1:100 with attached 6 dof marker tree.

sary to ensure and enhance safety, but also driver acceptance. The Adaptive Cruise Control (ACC, [82]), for instance, is such a system. It supervises the distance to a leading car and adjusts the speed of the own car, so that a safe distance is kept. When, for instance, a leading car is slower than the own car, the automatic distance control system starts decreasing speed at a certain distance. Aggressive drivers may estimate the distance to be too large and the relative speed difference to be too low, thus perceiving the decrease in speed of the ACC as annoying. In contrast, cautious drivers may often get nervous, if the system reacts too late in regard to their personal habits. People then tend to turn the assistance system off, since it does not fit to their own behavior, thereby loosing benefits of the assistance system.

Impact on Personal Habit

Future assistance systems will not only monitor longitudinal behavior, but also lateral and environmental settings. Hence the problem of acceptance becomes even more complex. To test the impact of such systems on personal habits, it is generally required to deploy the system in a real car and to test it on real test courses. This is an expensive and time consuming process.

Minor Changes in Behavior

To enable evaluation and insight into individual behavior at an early stage of development, a system for laboratory environments must generate appropriate traffic scenarios. Yet, computer generated traffic settings can not reflect all potential occurrences in traffic behavior. For example, drivers of other cars may initiate an upcoming right turn by gently reducing their speed without hitting the brake immediately. An experienced driver can anticipate future traffic development from such very subtle changes in the speed of the other car. A traffic generation system under direct human control that can capture and present such subtle changes is required.

Roundtrip Measuring the Delta

An environment to illustrate and discuss traffic scenarios for psychologists and sensory researchers enables live experience. In addition, such a laboratory system enables test subjects to easily generate traffic scenarios on their own. Comparison of the reactions of the ADAS system and the behavior of the human can be compared with such scenarios. Other test subjects are placed in an interconnected driving simulator to experience setups with and without the ADAS system. If reactions to both variants show a difference, a delta between the reaction of the ADAS system and the human can be measured. This delta has been introduced in section 3.2.2. The ADAS system must be refactored until its reactions are appropriate.

6.1.2 Traffic Scenarios

Differences in Scenarios

Traffic scenarios play a major role in the development of driver assistance systems as they define the baseline for concepts to react on traffic behavior. This section illustrates how scenarios differ and why ADAS systems have to adapt and react to these differences. This section starts by explaining the necessity of repeatable scenarios in user studies and discusses approaches to generate traffic scenarios.

6.1.2.1 Repeatability of Traffic Scenarios for Comparison

User Studies

Repeatability of traffic scenarios is an important issue for user studies. Only when a certain situation is fully and clearly repeatable, is it possible to use it in user studies. Certain factors can then be altered separately. A user study to distinguish significant differences can then be performed. If more than one factor is changed at a time, results can not be attributed clearly to the originating cause. Thus traffic scenarios require explicit repeatability to compare one to the other.

Alternatives

It is possible to gain insights into human behavior for comparison in two ways: first, test persons can be exposed to real traffic. Second, simulated traffic in a driving simulator can be used to gather data from scenarios. Both approaches enable the comparison of reactions of the assistance system and the driver. By recording the driver's actions as well as the actions of the ADAS system, both behaviors can be analyzed and compared.

Non-comparability

The approach to monitor real traffic allows for analysis of general reactions of drivers, but does not allow statistical comparison of groups of scenarios, because effects can not be attributed clearly to reasons. Even if the same scenario occurs again, there is always more than one small difference, at least in the trajectories of the cars, prohibiting exact comparison to other scenarios.

Into Simulated Environments

The non-comparability of the real-street setup enforces to move into simulated environments, where traffic scenarios are repeatable with adjustable single factors. Trajectories of cars can be generated as absolute movements or as movements relative to the own car. In addition, passing certain points on the road can trigger certain activities and behavior of other cars, e.g., to brake abruptly. Further extrinsic factors as different car types and colors are adjustable as well. Scenarios are repeatable as often as required. Various factors in the setup can be modified and general rules for ADAS system behavior can be deduced.

Programmed Traffic

Here, the benefit of computer systems enables comparison of scenarios, which would not be possible in real traffic. In contrast, computer generated trajectories are reproducible. A simulated car always follows a perfect course, in general interpolated between predefined points on the road. Drivers often react to minor changes in another the trajectory or speed of a car. Such minimal changes in behavior are *somehow* noticeable for humans. These are difficult to generate with simulation systems and never reflect natural behavior. The minimal differences between simulated traffic and real traffic are necessary for a driver's visual input.

Human Traffic Design

Thus it is not only necessary to test subjects through behavior in traffic scenarios, but to include people into the design of traffic scenarios. Only through this early integration, traffic scenarios reflect not only pure computer generated road-courses, but also required human inexactness.

6.1.2.2 Scenario Development by Test Subjects

Creation of Traffic Scenarios

Rather than merely asking test persons to react on prearragned traffic scenarios, test persons can also be asked to provide their own experience in real traffic by creation of traffic scenarios for driving simulators.

Practicability of Tools

Here certain predefined boundary conditions of the scenario are given to the test subjects and they are requested to build their own scenario in a virtual driving simulator environment. Collecting several solutions for the same given boundary conditions allows for analysis of similarities and differences in behavior. As test subjects are normally not requested to build traffic scenarios on their own, tools to support this activity vary in practicability. Non computer-skilled people have to use a traffic development tool, which often requires them to handle with mathematical equations and to program.

Programming Scenarios

The most general opportunity for development of traffic scenarios is general programming. Here test participants would need to learn the corresponding programming language, which apparently is not possible for every test person. Applied tools such as OpenFlight [122] and Dynaware [147] include sophisticated driving dynamics, traffic models and even sensor simulation environments. They apply for testing of ADAS systems and provide predefined procedures for certain maneuvers. These procedures base on mathematical equations and always reflect an exact route. Every maneuver can be integrated into a complete driving course and can be overlayed with any type of car, even new 3D models. A similar approach is used in the Iowa driving simulator [43]. Here dynamic and behavior models are separated and use a state machine to control dependencies between different vehicles. The Iowa system allows focusing on behavior modeling without taking care of a realistic driving behavior. Still the development of scenarios is a time-consuming process and does not reflect a test person's individual manner. Finally, those systems are difficult to distribute onto complex architectures using more than one computer. Cars on one computer would not know about cars controlled by a second computer.

Laboratory Setups

Other approaches try to generate car movements with tangible objects. The Tangible Pathfinder [137] is a TUI based orientation and mobility trainer for visual impair. The Tangible Pathfinder is intended to allow detailed, autonomous learning of a new physical setting and self-assessment of the resulting cognitive map. It allows for gaining information about objects and route layouts by touch but is not intended to generate traffic models.

Physical Car Model

Kanec et al [86] use a physical car model, moved by hand to maintain a virtual reality representation of the environment and to use it for producing additional views and to provide guidance to users in a parking situation.

Novak et al [118] use a miniature car in a table-top environment to generate a driver's personal view. The table-top environment is a bird's eye map, enabling test coordinators to move the miniature car through a city environment. Their system allows for evaluation of attentive in-car user interfaces.

Test Coordinator Driven Evaluation

6.1.3 Concept – A Table-Top based Tangible Car

This thesis suggests using a tangible miniature car to generate car trajectories for driving simulators. Test participants now can enact their traffic experiences in a tangible play area. To provide a view on the environment, the car is shown, not only in the driving simulator from the driver's field of view, but also on a table-top from a bird's eye perspective. This approach allows for fast and intuitive traffic scenario development. Fig. 6.2 shows a photograph of the integrated system.

Integrated System

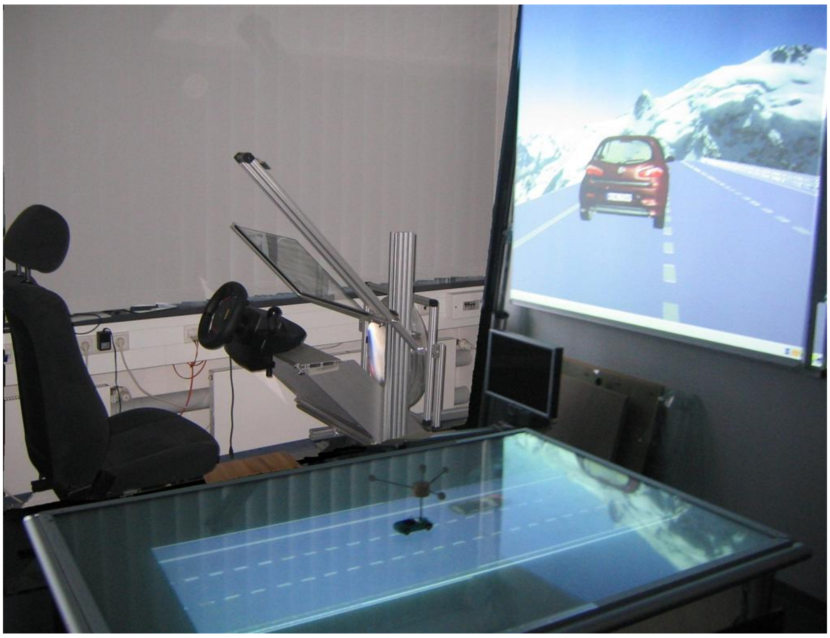


Figure 6.2: The system setup: The table-top environment in a tracking volume, where the tangible car can be moved around. The system is connected to a driving simulator

Tangible user interfaces [80] use objects from the real world as metaphors in augmented or virtual environments. Typically, one aspect is selected and transferred to the new application domain. In this concept the main aspect is car motion. Moving the car directly affects the table-top presentation, where a virtual representation, a virtual 3D car model, moves around. The driver's view is also directly affected. People sitting in the driving simulator immediately receive the visual feedback as if they were driving. Working at the table-top environment allows perceiving both views simultaneously, thus facilitating front view as well as environmental experience.

Metaphors for Tangible User Interfaces

The main intention of the tangible miniature car is to reflect a real car. Already children

Natural Motion

playing with cars move them almost similar to real cars. They seldom move them sidewards, mostly for naive simulation of future parking systems. The main use is to drive them through the environment, and in children's case to make races and accidents. This takes place in a straight forward or curved manner, similar to real cars. Except for producing accidents miniature cars are promising for use in VE.

Visual Surprise

Interaction affected by such a miniature car is enhanced by a concurrent generation of a personal view, as if the driver were sitting in a driving simulator. Driving there and seeing another car spontaneously appearing and quickly approaching can have an effect of surprise. This leads to a reflex, in general, drawing aside. This reaction is similar to a driver's action to avoid a crash in a dangerous situation. One can imagine the situation, when one forgot to look in the back-mirror or missed to check the dead-angle before starting a lane change and then realizes another car on that lane. The driver is alarmed and immediately pulls back to his own lane. The pull-back action is given by an immediate shaking with both hands on the steering wheel. The steering reaction is transformed to a shaking action when using the miniature car.

Collaboration

Collaborative experience and discussion also is enabled by this concept. As every virtual car has a real representation, it is not possible to move a second, later integrated car at exactly the same position. Collisions are producible, but full intersection of the virtual 3D models will be prohibited.

Complex Traffic Scenarios

Not only the behavior of a single car, but also complex traffic behavior can be generated. After a first car has been recorded using the tangible miniature car, a second trajectory can be recorded by associating the real to a second virtual model. Here in fact, overlappings are possible, but in general will be avoided, as adult people participate in experiments and are not requested to play.

6.1.4 System Setup and Architecture

System Components

The system is a hybrid multi-view setup incorporating a driving-simulator and a table-top environment. Fig. 6.2 and Fig. 6.3 show the setup in the laboratory. The driving simulator consists of a projection wall with a 40 degree field of view and a driver's cockpit on an aluminum frame (see Fig. 6.4). The second area of the laboratory contains the development and discussion environment. It consists of a table-top environment, placed underneath a tracking system to enable tracking of the miniature car (see Fig. 6.5). The tangible miniature car (see Fig. 6.1) can be moved on that table, while the road scenery is projected onto the workbench.

6.1.5 Object Registration

Preferred 3D Models

The system allows test participants to bring in their own, preferred virtual car models. Every major format is accepted by the system. To effectively use these models, a user has to register the virtual model to the 3D car. This procedure should be performed by the user of the system and not by the test coordinator. If the test coordinator performed this activity, the test participant would be pushed away from the system for the meantime and could feel superfluous. It is necessary to keep tested persons in the system at all times to have them

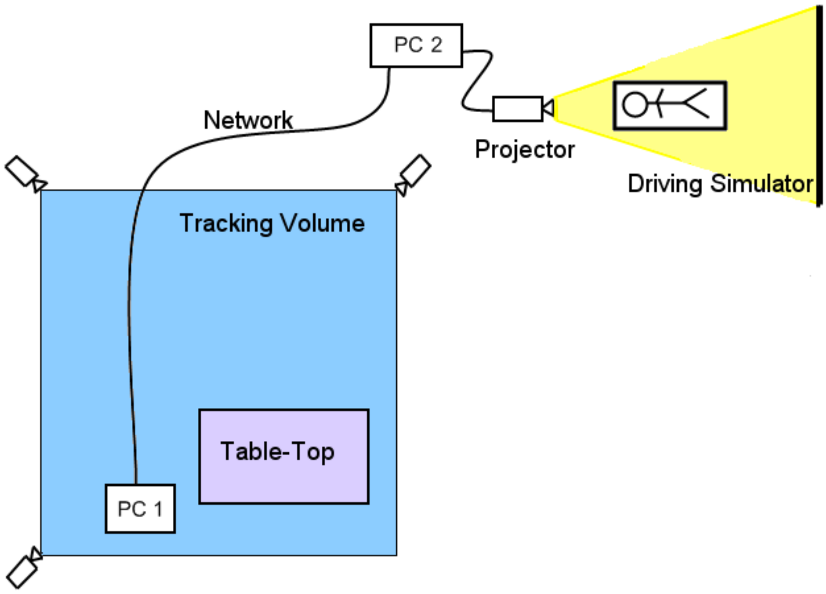


Figure 6.3: The Miniature Car Table-Top Environment – Sketch of the Setup

Figure 6.4: The driver's cockpit is build on an aluminum frame and has the same relationships as a common driver's cockpit (distances and sitting height)

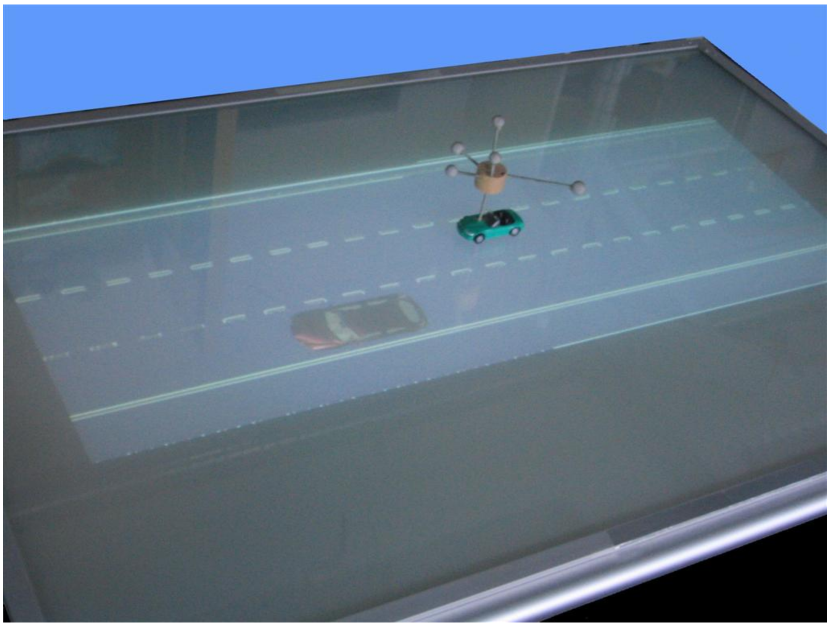


Figure 6.5: The table-top environment is built with a back-projection workbench and is placed in an infrared tracking volume

familiarized with the system such that they feel comfortable later when generating scenarios. Thus an easy to use registration method was required in the system.

6.1.5.1 Object Scaling

Size Adjustment

The first decision to make is about scaling. A newly integrated 3D virtual car model has to be scaled to fit into the environment. Its size has to fit to the road model and to the size of the tangible miniature car. To this end a slider has been integrated in the central controlling GUI.

Size Relationships

In early tests, test participants had no problem to deal with that slider and could adjust the size of the 3D model easily. An interesting problem regarding the relationship between lane size, 3D model size and the size of the miniature car: during the first system usability tests, not even the lane size was predefined. Test subjects could adjust all sizes of virtual models relatively to the miniature car. In the first trials, the size of the virtual 3D model was accurately adjusted to the size of the miniature car (see Fig. 6.6(a)), generating the effect, that the virtual model was nearly occluded completely. Thus the virtual 3D model appeared unnecessary for scenario development. After adjusting the size of the virtual car, the road section was scaled to fit to the size relationship of the real and the virtual car, making the road relative small. The visible road section on the table-top environment got a length of about 70 m (in real life).

Equal Scaling

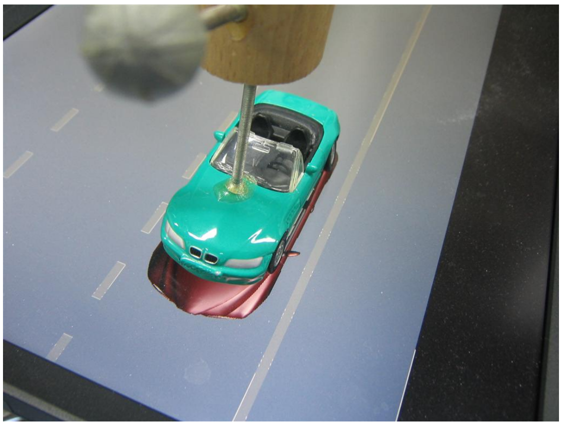
In this setup, test participants could use the system, but they generated strong lateral errors in the trajectory by shaking the car when they moved it around, and they could not understand the movement of the virtual car, even if the real car directly gave position and orientation.

Different Scaling

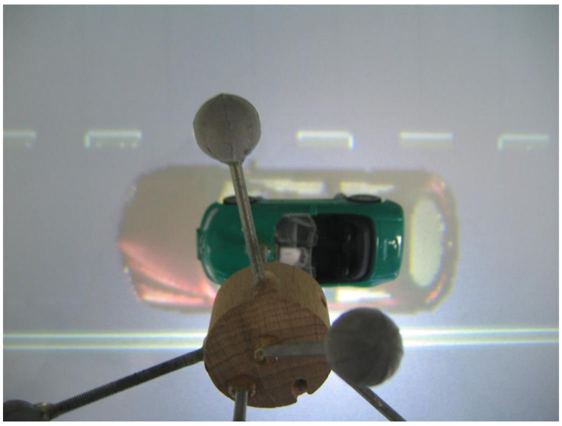
In further tests the road section was made wider, reducing the length of the road section to 40 m. Now, the miniature car was about 60 % of the size it should have to fit the lane. A virtual car model integrated into the scene now was about 1.6 times larger than the real car (see Fig. 6.6(b)). Now test participants could directly see the virtual representation of the miniature car and they understood how their manipulations of the toy car induced motion in the virtual world.

Larger Virtuality

This intentional skew in scale eased use of the system. Moving errors of the real car had less impact on the jitter in the virtual world. Perception of the virtual car gave better understanding of the behavior of the virtual world and test participants felt more comfortable when using the system.



(a) Photography of a 1:1 scaling



(b) Photography of a scaling with unequal size. The virtual car model is about 1.6 times the size of the miniature car

Figure 6.6: Different Scalings of the Virtual Model relative to the Miniature Car

6.1.5.2 Object Alignment

Pose-based Approach

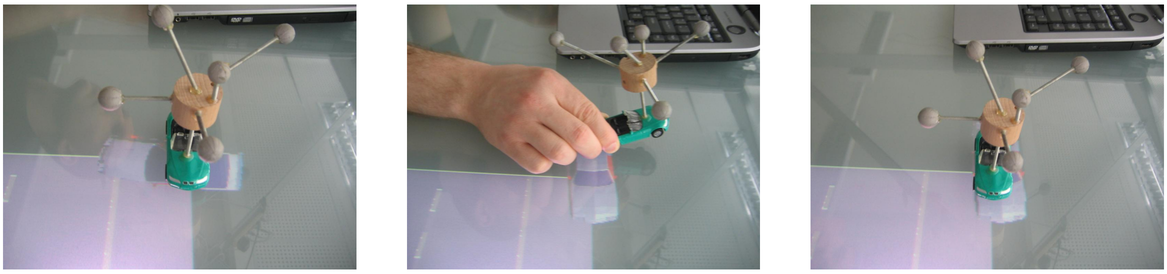
The second and more complex activity involves correctly aligning the virtual model with the toy car. Approaches to use GUI-based manual alignment facilities for the underlying scene-graph-based 3D transformations are not easy to understand by novices. An easier alignment algorithm only requires users to manipulate the toy car.

Two-click Procedure

The alignment method requests users to place the miniature car somewhere at the table (see. Fig. 6.7(a)). After a click the system stores the current position. Now the virtual model must be aligned to the position and orientation of the real model (see. Fig. 6.7(b)). A second mouse-click stores the transformation of the virtual model and activates the registration routine. Here both stored transformations are composed (Composite Model Transformation) to result in the final registration transformation. The result is a representation of the 3D virtual object aligned to the real miniature car (see. Fig. 6.7(c)).

Vertical Alignment

Working on a table-top environment in a bird's eye view can lead to misalignments in 3D



(a) Placement of the real miniature car (b) Manual alignment of the virtual model (c) Resulting registration

Figure 6.7: Calibration of a new 3D Model to the Tangible Car

w.r.t. object heights. The 3D model seems to be correctly aligned in the bird's eye view, but can be aboce the ground, appearing to float in the air. The 3D models might also be slightly tilted. Here a gravity algorithm could force the virtual object to „fall" to the horizontal plane and to tilt until three points of the bottom side touch the horizontal plane. The resulting offset and rotation then is stored, so that no second registration is needed, if the 3D model is used again to simulate a second car.

Applicability

The registration algorithm has been tested with a small number of subjects to guarantee applicability of the algorithm. The principle of the algorithm is shown in the controlling GUI and people could easily deal with that subsystem. Only associating the tracked car with the virtual model sometimes confused test participants, as they wondered, why the virtual model immediately jumped to the position of the tracked miniature car.

6.1.6 Creating Complex Traffic Scenarios

Iterative Process

Generating a scenario involving several cars is an iterative process, where the trajectories are recorded one after another. After a first trajectory has been recorded, a second car is incorporated and its trajectory can be recorded in dependence to the course of the first car. All other movements of cars are recorded subsequently.

New Issues

To effectively deal with the system and the available space, certain further issues arose in the development, such as the limited space of the table-top environment. These are discussed in the subsequent sections.

6.1.6.1 Controlling the Tangible Car

Equal Orientation

The setup in the laboratory enabled users of the table-top environment to also monitor the driving simulator view while interacting with the table-top view. Both perspectives helped people to perceive changes made to the trajectory of the controlled car. Both views followed the same orientation: pushing the tangible car in a forward direction changed the view of the driving simulator in the equal manner, making the driver's view going into the same direction in the laboratory.

Operator Location

People can control the car from every side of the table-top environment. In general, right-handed people preferred to use their right hand and left-handed people used their left hand to control the car (see Fig. 6.8). Few people tried to stand on the small side of the table. Controlling the car from the small side was neglected immediately, because the driving simulator then was in the back of the user. Controlling the car from the other small side, where the cars come from, allowing people to get a view similar to a third person view as in 3d-action games quickly was given up, because it became difficult to reach over the whole table (length over all: 1.1 m). Thus the tangible car was controlled from the two long sides of the scenery, allowing people to face the same direction as if they were sitting in the driving simulator.

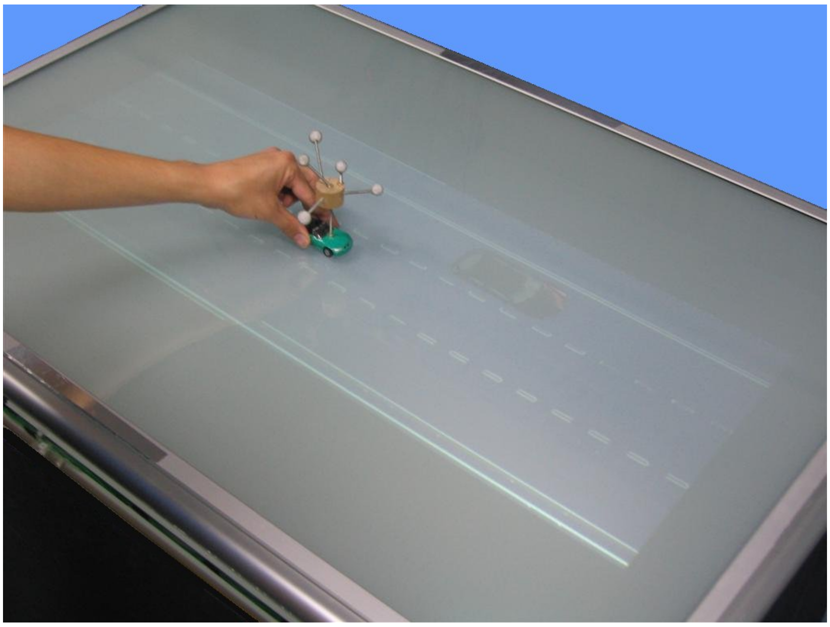


Figure 6.8: The tangible miniature car can be controlled from every side of the table allowing test participants to get into their preferred maneuvering position

6.1.6.2 Iterative Recording

Animation Recording

To generate traffic scenarios, a user can use predefined road setups or generate new setups with new road sections. A road model is placed on the table-top and in the driving simulator. The generation starts by loading and registering a 3D car model. After that, the real car movements control the virtual representation. Simply pushing a record button stores every transformation of the real car in a *PoseStream*. After the recording has been stopped, the *PoseStream* is stored and associated with the 3D model of the car as its data-source. Now another 3D model can be associated with the car. Replaying the scenario and concurrently recording the trajectory of a second car enables generating complex traffic scenarios. A screenshot taken from a scenario is given in Fig. 6.9, it shows a double passing situation using all three highway lanes.

Reassigning Miniature Car

The iterative approach to develop traffic scenarios was easy to understand and apply for the test participants. After registering their first car, they immediately could start and record

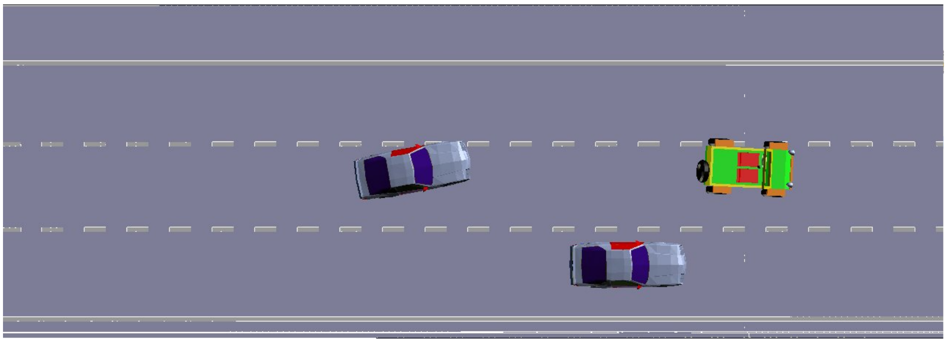


Figure 6.9: A screenshot of a scenario: a car (left) is going to pass another car (right) that just passed a third car (middle)

the trajectory. People then had to reassign the tracking system to track a second car. As the system at the moment relies on a GUI to control the system itself, people had to activate scenario playback an trajectory recording concurrently. Here a security mechanism had to be integrated to ensure that each virtual model only gets one associated trajectory. Otherwise a virtual model could have two sources for animation: the tracked tangible car and the already assigned *PoseStream*. Not having that mechanism, often resulted in people wondering why the car continuously jumps between the two positions of the toy car and the predefined trajectory.

Getting Familiar

Test participants in general used the table-top environment to generate a new *PoseStream* and then used the driving simulator view to check the recorded path. In the beginning, people often were not satisfied with the recorded route and rerecorded the path. After a while, when people became familiar with the behavior of the miniature car on the virtual road, the first trajectory was good enough to satisfy test participants' wishes.

Future Modifications

Only the step from the system control GUI, where the test participants had to activate and stop the recording, disturbed them, because they had to turn between computer and table. Future extensions will have to add a record-stop-facility on the table surface.

6.1.6.3 Limited Interaction Space

Relationship Table to Road

The used table-top environment had a width of about 1 m to 0.7 m. The road course, a three lane highway, used about half the width of the projection area, thus having a real size length of about 40 m. This range would only allow for development of parking scenarios.

To allow for longer stretches of traffic, the system allows the highway to scroll forward underneath the car. To this end, the bird's eye camera can be attached to a *PoseStream*. One *PoseStream* is provided with the system. At a speed of 80 km/h, it leads straight along the highway. If this *PoseStream* (or any other later generated *PoseStream*) is attached as a source to the camera, the whole scenery becomes animated on replay of a scenario. Within the system, the *PoseStream* recording facility composes the position of the camera in the scene and the position of the tracked car on the table-top. Thus every movement of the tangible car reflects the correct position on the moving ground.

Car Relative to Bird's Eye Viewpoint

Fig. 6.10 shows the part of the whole dataflow in the system, responsible for this composition: the Camera *PoseStream* (top left) controls the *Camera* (right). For the camera, a static *Offset* (middle left) is fused (two *Fusion Handlers*) into the resulting transformation. Tracking data (*DTRackPoseSource*, lower left) is transformed to the scale of the system (*DTRackToParentTrafo*) and fused (two *FusionHandlers*) with the *„Kamera PoseStream"*. The fusion is performed by the *CameraZTrafo* and provides the *Pose* of the *Controlled Virtual Car*.

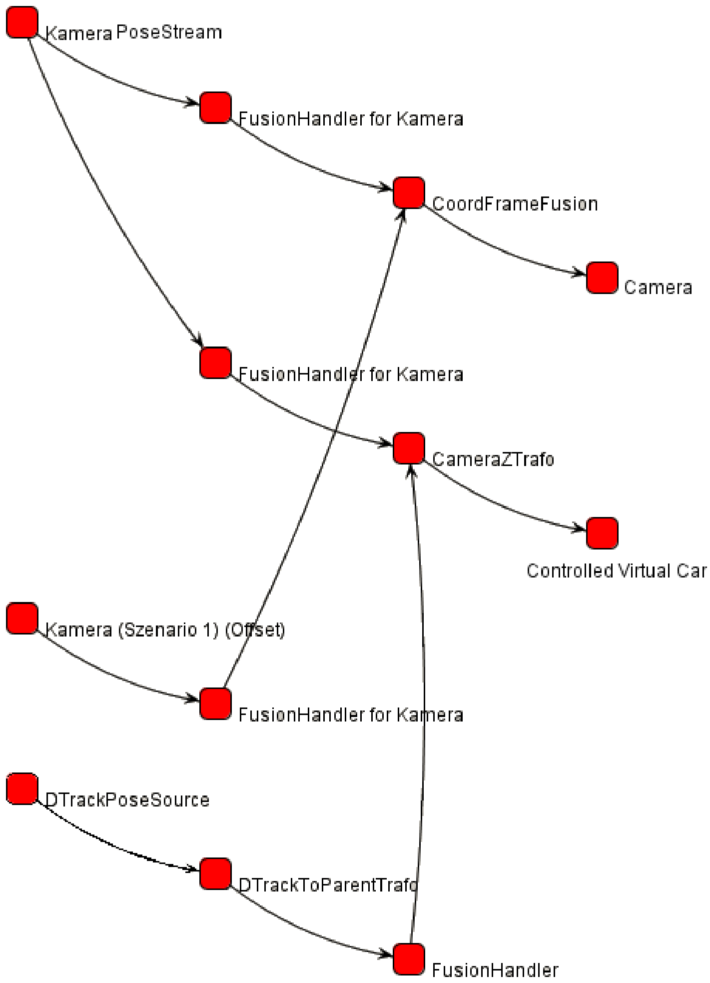


Figure 6.10: The part of the dataflow network responsible for the base speed of the tangible car

Curved Roads

Given road courses with curves, the remaining free space on the table-top can be used to allow for curved scenarios by use of the one given *PoseStream*. To use not only a straight line through the environment, further *PoseStreams* (at best associated to the road course) should be predefined. Alternatively, any other road course can be used in the system. Users only have to record a curved *PoseStream* which follows the road. This *PoseStream* then is attached to the bird's eye camera. The camera will then follow this trajectory and always stay above the road. Repeated new recording and attachment to the camera can reach every point on the simulated surface.

Flying Camera

Test participants understood the concept of the flying camera well and knew intuitively, that their car now has a base speed, the speed of the camera above the scenery. Moving the car forward increased the relative speed of the car and moving it backwards decreased the relative speed. These facts were understandable to all test participants and, especially in highway scenarios, they could efficiently develop any kind of scenario. Further scenarios to deal with crossings will definitely require suitable camera-PoseStreams to allow for useful anticipation of the crossing interval of the road. These *PoseStream* will have to follow a general crossing-speed-behavior, which decreases speed when approaching the crossing and later increases speed when the crossing is passed.

Animation Delay

Here by use of an animated camera, the turn-over from the computer to start and stop the recording mode generated delayed reactions of test participants, because they immediately had to take over control of the miniature car. Right after clicking the record button on the GUI, the car started driving at the base speed of the camera. Introduction of a delayed activation or a table-top controlled start-stop-mechanism will solve this issue.

Collaboration

Although the system only incorporates one tangible car at a time, collaborative work is enabled. Various *PoseStreams* can be recorded per car. Traffic scenarios then can be altered by dynamically associating different trajectories to the same or different cars. Teams of psychologists can discuss human behavior and illustrate behavior to developers of sensors. They can explain, where and to what extent a sensor has to track certain areas that are more important to supervise than others.

More Miniature Cars

Further integration of more than one tangible car can have a wider impact on scenario development and team discussion. Each participant can control his own car and can contribute to a particular traffic behavior.

6.1.7 Summary of Context Generation

Capturing Human Behavior

A system to intuitively and easily develop human behavior based traffic scenarios has been illustrated. The system allows to collaboratively work in a hybrid table-top VE. It can deal with various high quality graphic models (see Fig. 6.11).

Rapid Scenario Development

Test participants easily understood how to generate scenarios, but sometimes had problems using the GUI. Recording a trajectory was easy for any tested subject. It took some recording to get a feeling for realistic rotation angles when changing lanes. Trained people can generate a scenario including five cars on a one minute highway course in about 8 minutes, excluding object registration. Every recording of a trajectory takes as long as it takes to drive that trajectory. Only some seconds on the controlling GUI extend the time to generate a scenario.

ADAS Discussion

The system allows for intuitive and rapid development of traffic scenarios. It further enables a new field of research, where test subjects are integrated into an analysis of human behavior. Collaborative aspects are met, e.g., in discussion, about „when should a system react how“ or in general discussion where multiple tangible miniature cars are directly used to present certain traffic situations.

Further Extensions

Future work focuses on integration of a physical model of a driving dynamics to correct pose streams after recording. Correction is necessary because humans tend to turn the miniature car too much, thereby generating too extreme, unrealistic turns of the view of the

Figure 6.11: A screenshot taken from the driver's perspective. The system allows for high quality virtual models and textures

driving simulator. At the moment the system only supports car (and camera) trajectories. To have a system that can provide a more realistic world, also additional visual stimuli will be integrated, such as turn-signal lights. Finally, the pedals and steering wheel of the driving simulator will be connected to the system to enable roundtrip scenario development. Then we will bring the system into a user study to completely evaluate its facilitation for rapid traffic scenario development and transmission effects of factors human behavior.

6.2 Understanding Spatial Context

Towards Computer Understanding

Building on top of the context generation system for laboratory environment of the previous section, this section investigates context understanding systems. In contrast to laboratory setups, where human behavior is investigated, ADAS systems must understand environmental setting under real circumstances.

Wider Environment

Currently available ADAS systems monitor certain areas around the car. The ACC system [82], for instance monitors a 16 °field of view to the forward direction and maintains the speed of the own car under well specified criteria of safe distances. ADAS could monitor a wider environment and thus could deduce more complex traffic situations or other drivers' behavior. These systems then could provide a wider range of information for the driver about timely and accurate safety-related information to use it in automatic course adjustment or even to intervene in emergency situations. Such concepts were explored in a system that supervises location, speed, and trajectory of other vehicles and deduces relevant behavioral traffic data to be used within a vehicle-centric service-oriented architecture.

Rich Sensing System

Mandatory basis for the analysis of traffic behavior is a rich sensing system. GPS, Galileo as well as in-car dead-reckoning systems indicate that car motion will be trackable within individual lanes of a road. Stationary systems along the road will be available to gather such data from passing cars and integrate it into local traffic models. For the area of pervasive computing, challenges of a highly dynamic environment in conjunction with dynamic short range network connections are addressed through such an approach. It is the responsibility of the individual cars to gather and interpret accumulated traffic data from such stationary providers along the road – enhanced by data from on-board sensors such as radar, near and far infrared, and range scanning devices [164].

ADAS System Underlying Infrastructure

ADAS systems then need to infer critical events from such traffic data and provide appropriate feedback to the driver. Among other types of feedback, those systems have to provide intuitive and minimally distractive information to the driver of a car. To enable focusing on the user interface, such systems require underlying deduction of the spatial context of the car. The concept of an underlying infrastructure is supported through the need of multiple ADAS systems to guarantee that all systems in case of activity react at the same point in time and not independent of each other. To enable ADAS systems to receive such spatially related information about traffic situations, a distributed system was designed and implemented to meet the general issues of such systems. The work has been executed together with the diploma thesis of Fischer [56] who designed and implemented the system and reports on more details.

SCORE

The context deduction system, *SCORE*, a Spatial Context Ontology Reasoning Environment, constitutes, what pervasive distributed systems need: a peer to peer middleware in conjunction with an applied contextual deduction system. The system consists of separate autonomous components which federate and reason about contextual data that is related to spatial properties [47, 93]. SCORE shows that Semantic Web technologies and logic/rule-based systems are applicable to a spatial context. Federation components collect explicit spatial data coming from distributed information sources. To support applications that access structured information, reasoning systems deduce spatial knowledge by querying data from the federation components. Multiple instances of this system can set up short range ad-hoc networks and can thereby maintain up-to-date models of moving cars in the vicinity.

Description Structure

The SCORE system has helped to overcome the limitations of sensory equipment in current cars through enabling dynamic incorporation of multiple sensors – real or simulated. The following sections illustrate the approach of the context deduction system and the underlying middleware. The system is illustrated in the context of its own dependencies [154]. The work of the FAR research group in underlying sensor systems is presented together with other approaches on top level ADAS systems for future use in intelligent transportation systems. Especially the way from sensor data to ADAS systems, that use Augmented Reality for egocentric and therefore minimally distractive information presentation is described. The illustration closes with a description of the implementation, results from applying and testing the SCORE system, and ends with an outlook of future work.

6.2.1 Related Work

Car to Car Communication

Research projects such as the project INVENT [38] deal, among other things, with the subject of car to car communication. Stationary sensors as well as mobile sensors mounted to cars acquire data for use in a traffic routing system. Diverse and heterogeneous sources of data are combined to obtain a prognosis of traffic state. In this manner, a comprehensive knowledge base is built up to support optimal individual route guidance. To reconstruct the traffic state based on fused data coming from different sources, methods such as computer simulation of traffic flows are used. Route planning then is performed using a roadway network with dynamic attributes. The network combines criteria from a static digital map with attributes obtained from a reconstruction of the current traffic state, from a forecast of the future traffic state, from knowledge of traffic management, and control strategies. Waypoint- and graph-theory algorithms are used in an in-car computer system. Here each car deduces its own information relevant for use in 3rd generation navigation systems.

Network Protocols

The goal of the work of Kosch [91] is to provide precise and up-to-date information to car drivers, according to the needs of their individual situation. The developed CARISMA system independently and autonomously self-organizes direct wireless transfer of sensor data between automobiles. Various system analysis and simulations clarify the behavior of the resulting vehicle ad-hoc network and provide insight to its characteristics. By adding new protocols below and besides the TCP/IP stack, the used protocol design takes special network properties and very dynamic topology into account. The developed methods allow targeted exchange of information between vehicles on the road. The system assesses the situation-dependent benefit of information and decentrally controls the communication with its distributed components.

6.2.2 Tracking and General System Architecture

Car-mounted Sensors

To reason about the current traffic situation, cars need a long-ranging detailed overview of cars in their surroundings. Many sensors, such as GPS, radar, infrared, range, and ultrasound sensors, are integrated into next generation cars [164]. Thus valuable information about the immediate surroundings becomes available to on-board automatic analysis and reasoning. Yet, such tracking data might not to be sufficient since directly adjacent cars may be occluding further cars that contribute significantly to the total traffic conditions.

Hybrid Sensor Concept

The SCORE approach uses a hybrid concept towards gathering and maintaining up-to-date traffic models. The approach involves continuous communication between car-based (inside-out) mobile tracking equipment in cars and road-based (outside-in) stationary tracking equipment along the road. Of course, the system cannot expect all cars to actually provide positional data, since older cars may not have such functionality. Thus, the analysis of traffic context data must always assume that there are more cars than reported (false negatives).

Stationary Spatial Context Providers

To provide ubiquitous support along the road, the street network is separated into road sections, with each of them containing a number of vehicles at a certain point in time (see Fig. 6.16). For each road section, a logically related tracking system observes the explicit spatial context states of all vehicles within that area. When a car crosses an areal border, it becomes associated (based on its GPS-based position) with the next road section. These components serve as *stationary spatial context providers*.

Two Layers of SCORE

Bearing the prerequisites of such ubiquitous information management [58, 140] and high dynamics of spatial data in associated scenarios in mind, SCORE was designed to support applications on two separate layers that set up on the observed reality. In the *federation* layer, all data of a certain area is federated in a spatial context model. Components of the federation layer are intentionally associated to certain road sections. From the next layer above, ontology-based *reasoning* components can access the spatial context model. The reasoning components then intentionally reside in each car so that each car can deduce its own view. Fig. 6.12 shows a sketch of this architecture. This approach is based on work by [16] and supports the combination of spatial context models for efficient processing of low-level spatial data with ontological context representations for information deduction on the top layer.

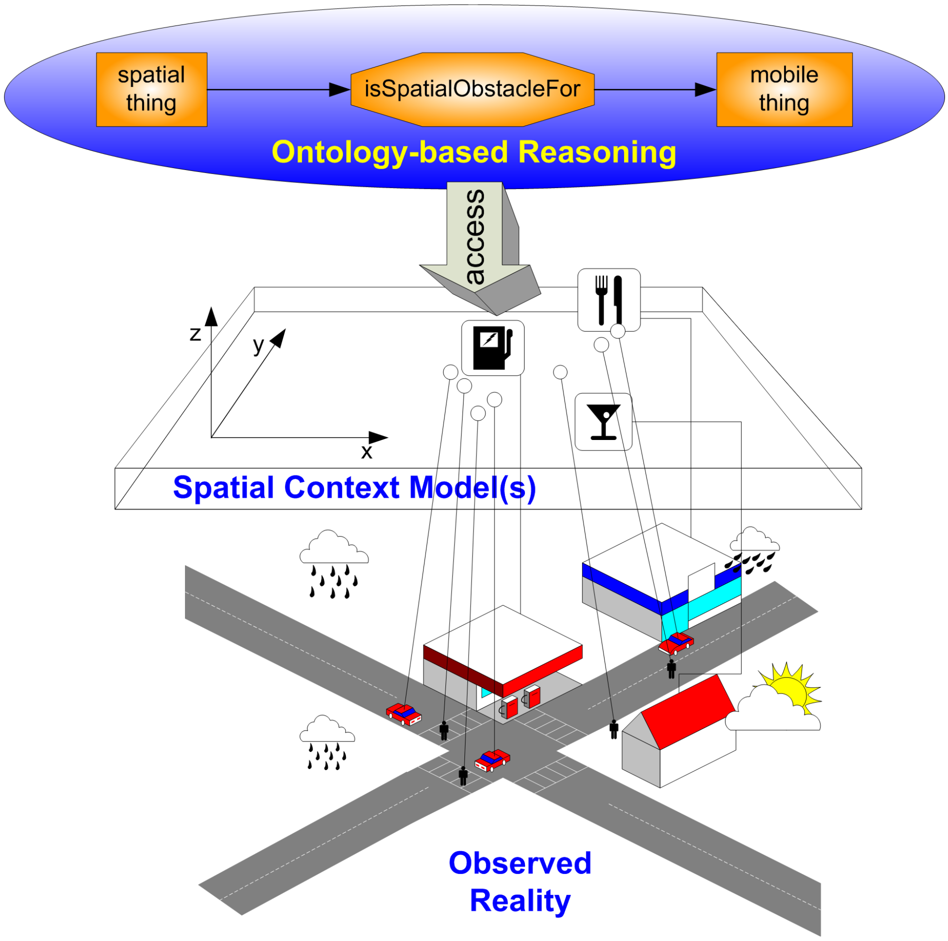


Figure 6.12: Combining Spatial Context Models and Contextual Ontologies

Clear Separation

The two layers clearly separate highly dynamic assertional knowledge in traditional coordinate-based models from terminological information of real world concepts within interpretable ontology spaces [56]. Multiple instances of software components are allowed to run on each layer to warrant high availability of the system and avoid single points of failure.

From Entities to Context

In the federation layer explicit context data is aggregated in spatial context models as attributes of entities. Implicit information is deduced in the reasoning layer by ontology-based interpretation modules. Here high-level spatial context is represented by binary relations between the entity classes of the domain and range of the relation. The decision whether such a relation is executed in particular situations is based on information observed at this moment. The concept strictly distinguishes between continuous acquisition of context and its usage by aware applications. This enables facilitated access to context data and also its sharing between applications [60].

Data Access

Applications, such as ADAS systems, can access the components of the reasoning layer by querying for certain information (pull) or by being automatically notified (push). All components of the architecture act as autonomous services. Fig. 6.13 illustrates the general architecture.

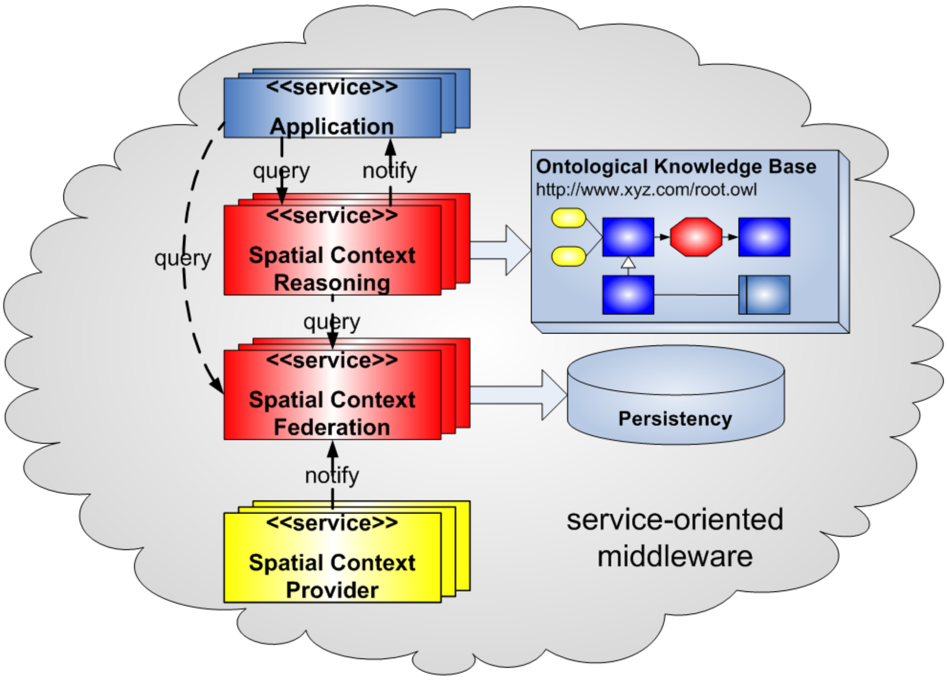


Figure 6.13: Architectural Overview of SCORE: Trackers define Spatial Context Providers that update Spatial Context Federation components. These are queried by components for Spatial Context Reasoning. ADAS Applications on top specify the user interface for the driver

The approach combines advantages of coordinate-based models with those of ontological knowledge representation. Therefore SCORE profits on the one hand from the flexibility regarding spatial scope, an extensible spatial detail. On the other hand, SCORE profits from scalability with respect to dynamics of context acquisition [128]. In addition, it provides ontology-based reasoning capability, information sharing and reuse. Flexibility and Scalability

6.2.3 Federation

In the layered architecture of SCORE a federation component mediates between various information sources and reasoning components and beyond that, the ADAS systems. Regarding the volume of communication traffic, several stationary computers – each logically related to one road section – run federation components that collect spatial data within the respective areas. Trackers act as *spatial context providers* (see figure 6.13). These inform the federation layer about spatial data with frequencies high enough to permit realtime use in safety-relevant applications in ubiquitous computing and in Augmented Reality-based applications in general and for visual support in cars in particular. Feeding Federation

When the so-called *broker* of the federation subsystem is notified, it instantly accesses the Data Aggregation *warehouse* to aggregate attributed data items. Such items are each linked to a unique entity within the real world.

Primary and Secondary Context

Each data item describes exactly one entity and contains information about its primary and secondary spatial context. The primary context of an entity covers its unique name and its positional and orientational values at a particular time. The federation component uses this information with the class membership of the entity to identify each entity. The secondary context depends on this identification and – among other things – includes a number of valid spatial context attributes such as position, orientation, velocity, acceleration, distances and trajectory angles. Since a federation component may serve multiple applications at a time, namespace statements are supported to uniquely name entities and their class memberships.

Data Storage

The *warehouse* organizes an efficient volatile data structure to continuously index and cache those data items to optimize query response times and to provide quick information retrieval. Among other things it also computes distance values for efficient range-based queries.

Persistency Mechanism

An additional persistency mechanism is represented by connections to relational database management systems which store snapshots of the contextual configuration in discrete intervals. The federation component also provides query mechanisms for applications requesting mere explicit information such as reasoning components used for deduction of context. The querying component can request current and past contextual information about a number of specified entities. Applications and reasoning components also issue range-based queries to obtain data of entities that are in a specified range to a special entity.

6.2.4 Reasoning

Applying Ontologies

To deduce relevant information from federated data, the reasoning system uses an ontology rule-based approach. In each car a reasoning component dynamically connects to one or more federation servers in range to access spatial data necessary for interpreting the situational information of the vehicle. Therefore the principal task of the reasoning component of SCORE is context interpretation for queries from applications running at this moment. Similar to the *broker* of the federation component, the central *controller* of the reasoning system manages the control flow. The controller mediates between the interfaces of the component, the subscription component, the query parser, the reasoner subsystem and the persistence manager.

Timed Intervals

Using the *query handler* interface, applications can directly request deduced spatial context from a reasoning component or can subscribe to notifications regarding static queries. These queries are then executed in defined intervals. The subscriber is notified only if contextual changes regarding the observed entities occur.

Querying

The query language is declared to be easy to use, so that non-programmers can define their own queries for use in additional ADAS systems. Each query consists of a triplet comprising an ontological object property. Later, its domain and range are dynamically mapped to entities by the reasoner. Hence, the important prerequisite for the functionality of SCORE is the automated matching of entity classes to ontological classes, entity class relations to ontological binary relations between classes, and entity class attributes to ontological properties, that assign data types to ontological classes. The following two examples show the request of contextual information for queries whether vehicle "car007" overtakes "car001', and which lorry represents a spatial obstacle for the motorcycle "bike27". To support multiple applications at the same time, optional namespace declarations can be stated in a query.

```
Vehicle=car007 overtakes Car=car001
Lorry=* isSpatialObstacleFor
                          Motorcycle=bike27
```

The controller invokes the *query parser* only upon the arrival of a new query. At that point in time, the query is parsed, transformed into a processable abstract syntax and afterwards cached due to efficiency purposes. Abstract Syntax

Next the abstract query is handed to the reasoner subsystem, where it is processed by the description logic-based reasoner (*DL-reasoner*). T-box information contained in ontologies describe terminological entity relationships that are used by the reasoning component to understand how to interpret assertional spatial data that is collected in the environment of the entities [56]. Description Logic

The terminological interpretation process is based on ontologies [70] known from the *Semantic Web* [22, 46]. For defining static knowledge, a global *ontology knowledge base* plays a central role in the architecture of SCORE. It comprises extensible ontologies for a homogeneous application domain terminology as well as rules that describe the validity of binary relations between ontology classes. Ontologies are well-suited for logic-based reasoning, especially when description logic ([39, 6]) is applied. This is due to the similarity between the language constructs of description logics and those of ontologies. Additional information can be deduced automatically from pre-defined ontologies with properties such as equality, symmetry, transitivity, inversion, disjointness and others (see figure 6.14). For this purpose, an off-the-shelf ontology-based reasoning framework is accessed via the *DL-reasoner* interface. Ontology Knowledge Base

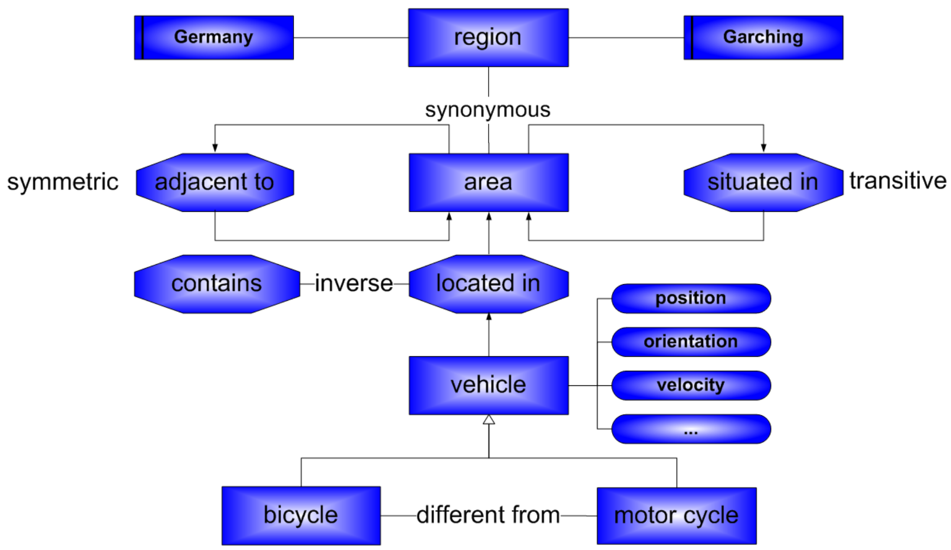


Figure 6.14: Example Ontology

A successful interpretation leads to a pre-defined instance of the ontology class "*rule*" (see Ontology Relation Domain figure 6.15). To identify the correct rule definitions for an object property, the domain of the query relation and range classes are mapped to the domain of the ontology relation – i.e., to the range classes or to the proper subclasses, if either the domain, the range or both classes in the query inherit from those declared by the relation in the corresponding ontology. As mentioned before, the rules themselves are instances of the ontology class *rule*. They are defined by application developers in a generic way, such that they can be reused in various application domains. Rules are specified in the custom-defined RDFS-based language SRL (**S**patext **R**ule **L**anguage, *Spatext* abbreviates *Spatial Context*) [32].

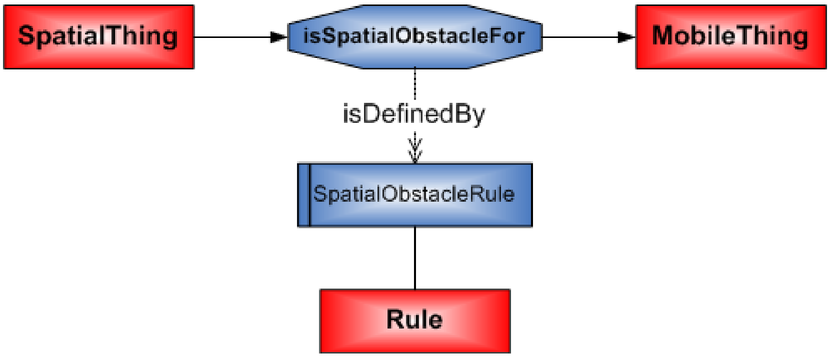


Figure 6.15: Reasoning about Ontological Object Properties

Condition Definition

For each rule derivations are defined similarly to "if" statements of programming languages. Conditions can be expressed using subconditions, boolean operators, comparison operators, and *reasoning functions*, where the latter ones are defined within an extensible *function repository*. These functions can also be nested, and are used to compute spatial relations between entities. For instance there are functions returning angles, distances or the time to collision (TTC) between entities.

Internal Caching

The interpretation process results in a set of rules that just define the binary relation referenced in the query. Similar to the query that is parsed by the *query parser* the rule set is transformed by the *rule parser* of the *rule-based reasoner* into an abstract syntax and cached internally to speed up succeeding operations.

Generic Invocation

To execute the rules, the *rule invoker* invokes those functions declared in the rule conditions together with the explicit spatial context of entities matching the query. Here the federation layer plays an important role as it is accessed for obtaining this information.

Highly Dynamic Data

Ontological knowledge bases are not well-suited for maintaining a detailed history of highly dynamic assertional data due to the continuous growth of information resulting in inefficient data management. In spite of that and to cope with the increasing amount of data without giving up the benefits of an ontological representation of concept knowledge in application domains dynamic spatial context data is managed on the federation tier and only requested for interpreting situational information. The reasoning process is rule-based since it addresses the objectivity of spatial relations, e.g., traffic rules, that in its own sense disregard a scope of varying interpretation [56].

Persistency

Each successful rule invocation of the *rule-based reasoner* results in interpreted spatial context, returned to the central *controller*, where it is cached as well and forwarded to the *persistence manager*. The *persistence manager* of the reasoning component can be compared to the one of the federation subsystem. It handles the storage and retrieval of spatial context. In this case it only manages implicit data, not low-level context. Hence the *persistence manager* of the reasoning component only enables storage of those location-based information, that it can deduce. Alike the *persistence manager* of the federation layer the persistence manager of the reasoning layer does not implement persistent storage on its own. Instead persistent storage is dependent on an additional component providing persistence management of interpreted spatial context.

Supplying ADAS Systems

Finally the interpretation result is provided to those applications that have subscribed to the corresponding query or actively issued the query. Besides the implicit information deduced from a binary relation between certain entities the result also comprises descriptive information specified by application developers as well as corresponding explicit context data requested from the federation layer during the reasoning process.

6.2.5 Ad-hoc Networking

Dynamic Networking

Spatial context providers and federation components can be placed in the environment and therefore can be interconnected statically. Similarly, instances from the reasoning layer can have hard-coded interconnections to applications inside the car. Interconnections between the federation and the reasoning components require dynamic bindings to handle transitions between two federation sectors, when a car leaves one federation sector and moves to another. Then once more the built-in reasoning system of the car must get connected to the federation component of the forthcoming sector and disconnect from the previous one.

Incorporation in DWARF

For this kind of ubiquitous networking SCORE uses the DWARF [13] architecture to describe and interconnect all components. DWARF is the peer to peer framework originally used for the driving simulator rapid prototyping environment (see section 5.3.1, page 90ff). SCORE therefore perfectly embeds into any rapid prototyping environment based on DWARF and also serves demands for highly dynamic systems with strong dependency to performance. DWARF manages services to dynamically interconnect them depending on their contextual attributes [107]. For instance localization and tracking distances of services are specified by such attributes. The DWARF middleware supervises these attributes and interconnects corresponding connectors, therefore enabling the data flow. When the system is started, it establishes the interconnections between federation and reasoning components as well as between base data providers or applications that declare driver assistance systems.

Interconnecting Different Federation Services

If a car moves through the environment, it updates the contextual requirements of the reasoning service that specify its global position. When a car is going to leave the sector of a specific federation component, the DWARF middleware determines that another environmental federation service has contextual attributes that now fulfill the changed need of the reasoning service. The new connection between the federation component of the entered sector and the reasoning system of the car is established and the present connection between the two services is removed. Fig. 6.16 shows in a sketch how interconnection is executed while a car drives along the X-axis. While this operation is performed, some of the attributes of the reasoning service are automatically passed to the federation service, adjusting and configuring it for addressed queries and notification frequency [108].

Mobile Spatial Context Providers

To provide additional tracking data, among other various information sources a car built in GPS system can also act as a spatial context provider and therefore propagate the position of the own car to the federation service that is connected at this moment.

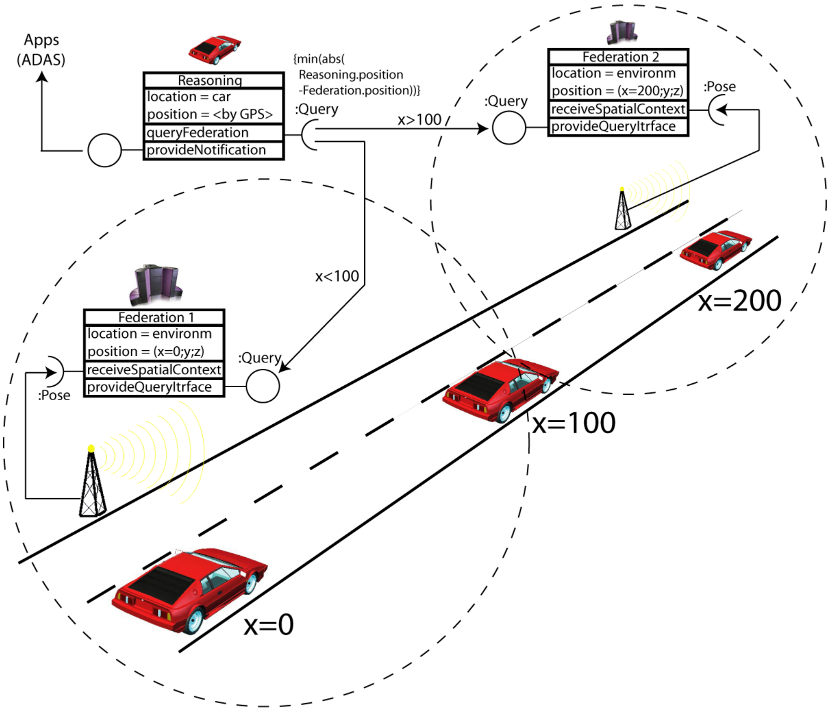


Figure 6.16: Sketch of dynamic reconnection of car internal reasoning service between two federation service sectors as car moves along X-axis

Current Delimitation

Inconsistencies that may arise during a hand-over from one federation service to another, which are similar to hand-overs of WiFi systems, are not dealt with at the moment. At the moment our work focuses on applied federation and reasoning, which we will investigate further on in the future.

6.2.6 Implementation

State of implementation

This section describes the current implementation state of the SCORE framework as well as the procedure for developing new applications on top of the SCORE system. Some missing functionality implementations correspond to the integration of an off-the shelf persistence management system on the federation layer as well as the implementation of the persistency manager on the reasoning layer. However the possibility of an easy extension of SCORE has been carefully considered during its design to meet these functionalities in future development.

6.2.6.1 Federation Subsystem

Performant Data Structures

Due to high performance requirements the federation service is implemented in portable ANSI/ISO C++. Thus efficient main memory management speeds up the *warehouse* of the service through fast memory (de)allocation. To meet fast response time requirements of ubiquitous computing and Augmented Reality applications, the warehouse of the service is based on an efficient and flexible indexing data structure combining *minimum binary heaps* and *AVL-trees*. Following a pointer from an item within an array of ontology classes to the corresponding heap, range-based queries can be executed quickly since the heaps are arranged by distances between tracked objects. For general queries also internal binary search trees pointing to items within heaps can be traversed. Indeed, for both indexing methods the worst case runtime for finding or updating an the contextual history of an entity has a logarithmic time complexity on the total number of items in the corresponding tree.

Communication Mechanisms

At this moment the federation service provides two interfaces for communicating with other system components. Spatial context providers use the asynchronous CORBA event notification connector of DWARF to match the receiver connector of the federation service to enable events regarding low-level location-based information about entities. Multiple spatial context provider services can simultaneously send notification events to a single service.

Event-Driven Communication

The decision for using an event-driven communication with the *need* interface of the federation service is founded upon the asynchronous property of this communication mode. In contrast to synchronous method calls we integrated context providers by use of continuously sent structured events of spatial information, therefore not enforcing the federation component to take care of multiple communication sessions but delegating this issue to the DWARF middleware. The asynchronous communication mechanism significantly increases the performance of context providers, especially when the frequency of context acquisition is high. Though there is no absolute guarantee for delivering events (they might get lost on the network if netload is too high) the benefits in the flexibility of asynchronous communication clearly surpasses this limitation.

Query Interfaces

The federation service also has a common interface for querying basic spatial context histories about contextual entities using synchronous communication via CORBA method calls. Here the service is capable of handling multiple queries at the same time. By use of the synchronous communication mode the calling system is blocked during query processing. In contrast to the need interface, where the federation service only receives events, here the communication is based on a client-server approach, where the client such as a reasoning service specifies additional attributes for constraining the possible results of its query. Events are far too inflexible and inefficient for the transmission of both the dynamically declared queries and the varying responses.

6.2.6.2 Reasoning Subsystem

Semantic Web

As a concrete ontology reasoner the reasoning subsystem uses the open-source *Jena2 Semantic Web framework*[1] at this moment. This Java-based framework is the second version of the Jena reasoner. It follows the *HP Labs Semantic Web Research Program*[2], and is now available under a BSD open source software license. Jena2 supports reasoning with respect to RDFS and subsets of DAML and OWL. The framework provides several Java APIs for accessing RDF models and ontologies. Besides an implementation of RDQL, Jena2 also allows for the

[1] http://jena.sourceforge.net/
[2] http://www.hpl.hp.com/semweb/

persistence of ontology models in relational databases. Though Jena2 restricts the programming language of the reasoning service of SCORE to Java, it nevertheless has been selected, because it provides an easy to use OWL API and both a volatile and persistent storage mechanism. Above all the OWL API facilitates the retrieval and reasoning about terminological information that is contained in the ontologies of SCORE.

Ontology Language

For describing this information in the central ontological knowledge base of SCORE the *Web Ontology Language (OWL)* was chosen. OWL is a powerful XML-based language, that has been recommended by the W3C in February 2004[3]. It is based on RDF features of data and meta data modeling, and RDFS capabilities of defining the corresponding vocabulary and constraints. OWL extends this first approach of knowledge modeling by specifying formal semantics with the help of additional restrictions in the usage of RDF. The decision for using OWL as the description language for ontologies not only allows for an uniform modeling of common knowledge about application domains. Furthermore it enables sharing of these information among cooperating applications and also other context management systems. Also the extensible structure of an OWL knowledge representation enables developers and system architects to understand ontology evolution.

Generic Method Invocation

Interpreting dynamic context is done by the *rule-based reasoner*. On the basis of globally defined interpretation rules, it transparently invokes functions that refer to the function repository - a special Java class designed for easy extension. These functions are identified at runtime and dynamically invoked via Java reflection by passing the explicit context that matches a certain application query and is subsequently requested from the federation layer. Java reflection is used due to the convenience for application developers, who just have to add new functions to the repository in the case they do not yet exist and afterwards can instantly use them in new rules. Since functions can be nested within conditional statements, more complex interpretation behavior is also achieved by piping spatial data through a set of functions. Independent from whether functions are added to the repository, composed during interpretation, or nested in complex conditional statements, because of the reflection mechanism, application builders do not have to think about how and when interpretation functions are executed by the reasoning service.

ADAS Applications

As mentioned before reasoning services query basic spatial information from the federation layer by calling methods in the corresponding interface represented by the federation ability of the service. Similar to the federation service also the reasoning subsystem of SCORE enables other services such as applications to query for spatial information about entities. In further development the reasoning service will also provide a subscription mechanism via event notification to send contextual events to its subscribers. Therefore aware applications are able to actively request or be informed about implicit context processed on the basis of a terminological context representation and the dynamically changing location-based context of those entities an application is interested in.

6.2.6.3 Developing Applications on Top of SCORE

ADAS system Extension

This section illustrates how the usage of SCORE in new applications is facilitated. In the requirements analysis phase application builders first identify entities, e.g., individual persons, locations and objects, that must be supported by the application. After unique names

[3] http://www.w3.org/TR/owl-features/

are provided for each entity they are mapped to common ontology classes, e.g., 'person', 'vehicle' or 'service station', for which binary relations are analyzed. If necessary corresponding ontology rule instances are defined properly for each relation using the XML-based *Spatext Rule Language*.

Function Repository

If a required reasoning function is still missing in the function repository, it is integrated additionally. Then existing generic spatial context provider services are configured or new ones are built depending on the requirements of the application.

Qualified Identifiers

In the last step the application is built. During the development, queries that were identified in the requirements analysis are declared using the query language of SCORE. It might be necessary to define classes and properties with fully qualified URIs if their short names raise ambiguities.

Error Tracing

Now the complete system can be started up. SCORE will automatically detect any errors related to misstated declarations in the terminologies, rules or in queries, for instance. Here it informs the application developer where and why errors arose.

6.2.7 Performance

Test Setup

To test the performance of the system, a driving simulator was used to simulate additional cars. Their number reflected an average frequented road. We developed an ADAS application that observes the *time to collision (TTC)* with various additional cars. To support this functionality it registers with respective events that are released if the TTC falls below certain thresholds. The positional data of the other cars is propagated by stationary spatial context providers to the federation layer running on another computer. Two federation services managed two areas (left and right of the vertical X axis dividing the world into two areas), see figure 6.17.

Computer Setup

The position of the own car in the virtual world was computed by a single-lane driving dynamics model – we simulated a GPS tracker. Depending on the the position of the own car in the virtual world, the reasoning service of the car (running on a Linux PC) was connected to one federation service, querying for spatial data. Depending on its location in the world, the reasoner updated its predicate for the selection of a suitable federation.

Dynamic Reconnection

The upper part of figure 6.18 illustrates a snapshot of the service structure of the SCORE subsystem. Within this snapshot, the car is on the positive (right) side of the simulated world and therefore is connected to the service named *Federation1*. The lower part of figure 6.18 shows the *predicate* that is adjusted in correspondence to the current position of the own car.

6.2.7.1 Performance of Single Services

Federation Performance

The federation service gives a response time below $10\,ms$ for up to five spatial context providers with up to 250 entities per provider. Compared to an average amount of cars on a road interval, these response times are acceptable. The reasoning service responds to n-to-n queries in $37.1\,ms$ seconds for 100 entities. This result is a worst case result, because general reasoning systems are intended to be integrated in each car and therefore only have to manage 1-to-n queries. Going down to 50 entities, which still is a lot on open fast traveled

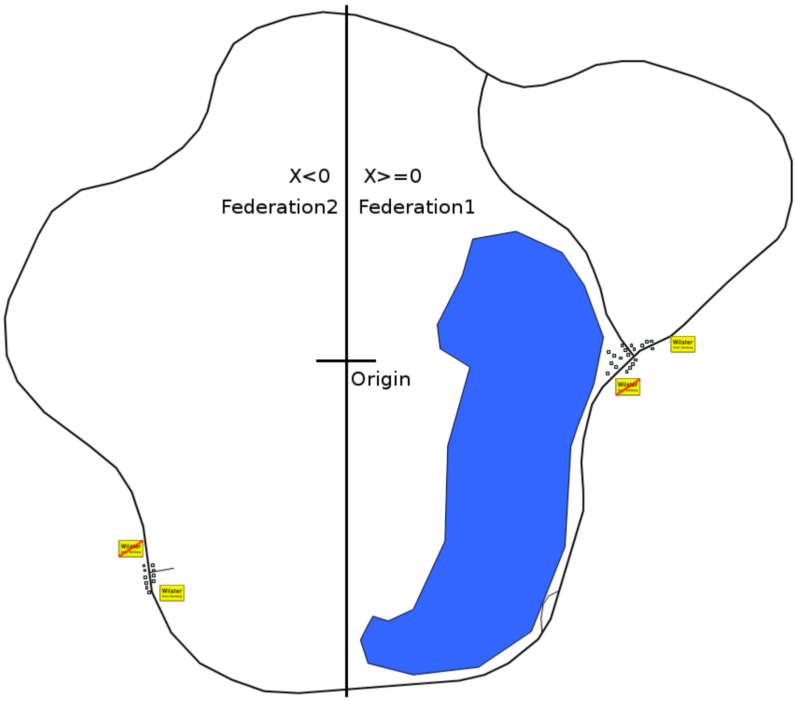


Figure 6.17: The road course of the driving simulator. *Federation1* manages the positive side of the X-Axis, *Federation2* the negative

roads like highways, the response time decreases to values around $10\,ms$, as shown in Fig. 6.19. Taking network delays of cabled installations into account, the cumulated response or notification time of the system is below $30\,ms$. These measurements do not match any wireless communication and also do not take any computation time of tracking systems into account.

6.2.7.2 Performance in Distributed Setups

Dividing Entities

When dividing up entities a single query will only span one subset of entities. Therefore entities in different subsets are not related to each other with respect to the relation stated in the query.

Amounts of Entities

Such an approach is depicted in Fig. 6.20 where 100 entities from the previous performance analysis are split into particular groups of entities so that the number of all entities in all groups equals 100 again. The diagram shows the decreasing number of comparisons while the number of groups is increased.

6.2.8 Summary of Context Understanding

Examinations

The SCORE system uses ontology-based reasoning, resting upon distributed federating components. As such a system requires a suitable middleware, the DWARF framework suited

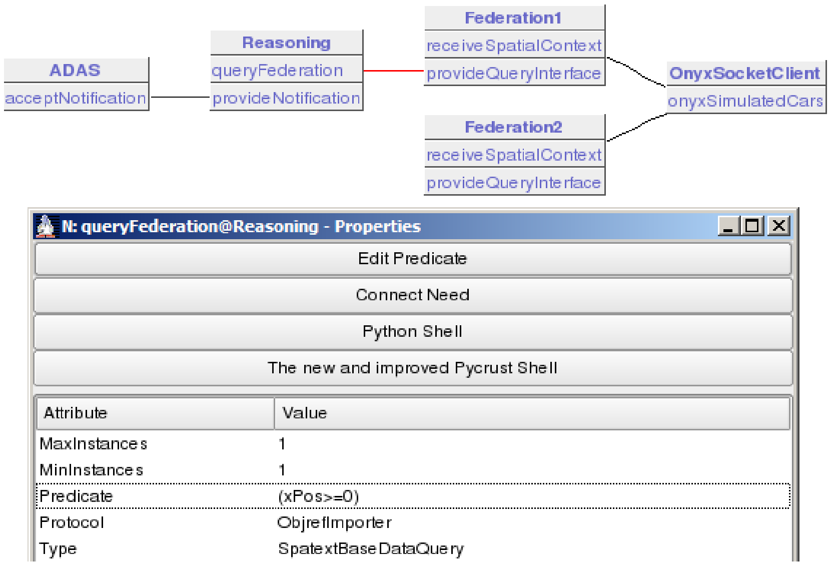


Figure 6.18: A snapshot of the interconnections of the services: The own car is in the positive side of the federation sector „border"

as foundation for this purpose and showed that, besides tracking infrastructure, such a system is capable of performing spatially related contextual reasoning. Application in a test workbench also showed that an overall highly dynamic traffic environment can be split into separate independent areas of stationary data acquisition, while traveling cars access this data and conclude information that is relevant for them. Dynamic short range network connections can get established to guarantee access to important data. The system shows how Semantic Web technologies and logic/rule-based systems are applicable to spatial context. Certainly additional focus must be laid on research in the field of networking when pursuing a system deployment in a wide area environment. However, before deploying the framework for use with a real world application, the function repository of SCORE requires extension to serve in proactive assistance for local guidance in road traffic scenarios.

6.3 Summary

Two Systems

This chapter illustrated system and software issues focusing on spatial context. Two areas dealing with context required investigation. First, laboratory setups need more influence of human behavior to generate realistic traffic scenarios. Second, development of ADAS systems requires a common underlying infrastructure to analyze spatial sensor data.

Table-Top Generation

A new approach for traffic scenario generation has been proposed and implemented in a working system. The system allows for a wide range of application, ranging from collaborative discussion about ADAS system behavior and demands to user centered traffic scenario generation. The system currently only is incorporated in a low-fidelity driving simulator and requires deeper investigation of its system usability. It therefore should be used in combination with projects investigating driver behavior to clean out possible undetermined ambiguities and complexities in usage and to test its applicability for the intended tasks.

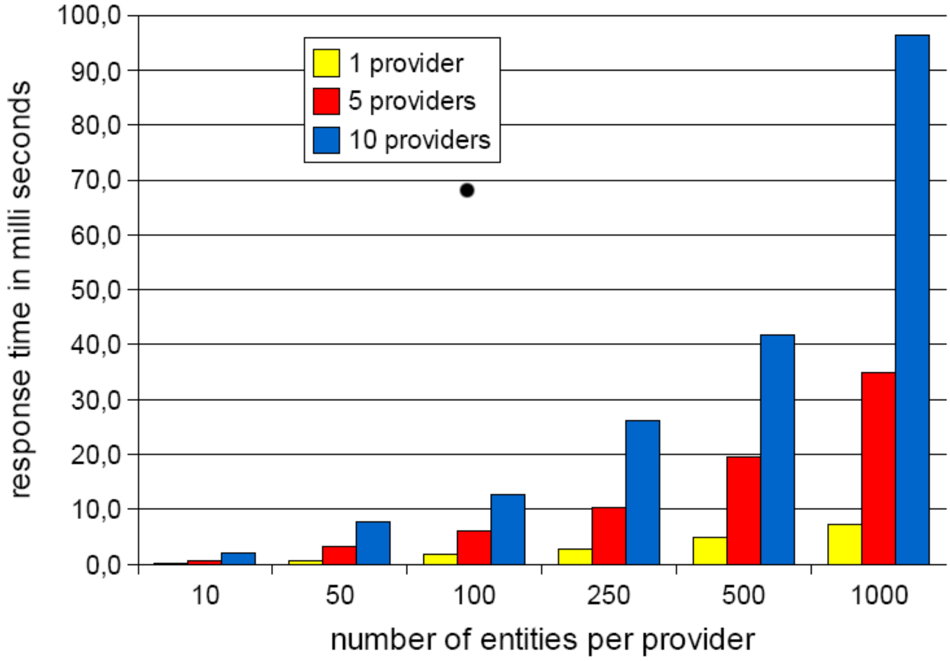


Figure 6.19: Overall response times of the entity histories of the access interface method of the federation service (n-to-n query)

Reasoning Anywhere

The second system developed, SCORE, aims at context understanding for a wide range of ADAS systems by providing a common underlying infrastructure. ADAS system development with this system can start in driving simulators while sensors are simulated but can be ported to cars without any further efforts, except for redefinition of sensors. Future development of ADAS systems should investigate the contribution of the multi-level architecture guaranteeing efficient and consistent information management and analysis.

Enabling Rapid Prototyping

Both systems serve as necessary components for a rapid prototyping environment as illustrated in the previous chapter 5 (page 80ff). Designers and developers of ADAS systems can both keep their focus of work and do no longer have to learn about data management and information distribution in software systems.

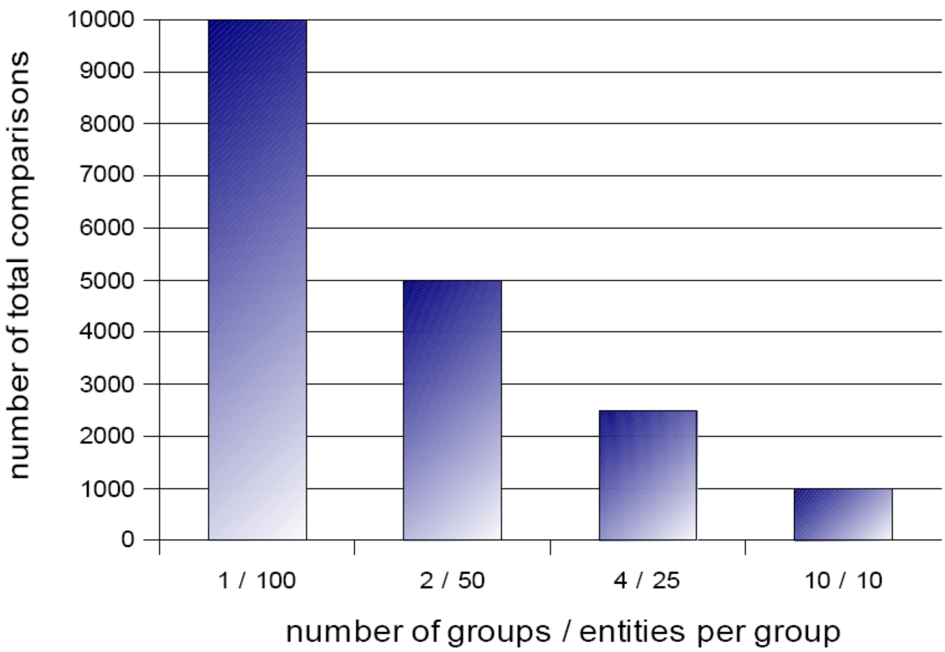


Figure 6.20: Reducing the complexity of queries by distributing entities over particular numbers of groups

7 Ambient Longitudinal and Lateral Assistance

Continuous visualization of the motion physics of the own car with an Augmented Reality braking bar and drive-path scheme

Foundation for Usability Studies

After realization of all necessary development and testing environments, usability studies for AR ADAS systems now can be conducted. Previous work established a driving simulator rapid prototyping environment capable of incorporation of AR interfaces and recording of data for analysis. A management system for spatial context enables application dependent reasoning and information delivery, so that ADAS system development can focus on design and usability issues without having to care too much for sensor systems and sensor data analysis.

Indicating a Situation

An ADAS application can be derived from interaction concepts between ADAS systems and car drivers. Section 3.2.2 (page 59) lists three opportunities for ADAS systems to inform the car driver about varying situations. The most direct approach for ADAS system assistance mentioned is *indication of a situation*: even if car drivers generally look forward, dangerous situations can occur unnoticed. An approach to increase awareness for the environmental situation can indicate the physical motion behavior of the own car. AR presentation schemes inform the driver about the actual trajectory a car drives and visually indicate safe braking distances.

Continued Work

The presentation concept for indication of safe braking distances has existed for many years and has originally been researched by Bubb [34] and later by Assmann [4]. Their approach used a sophit-lamp that was mechanically adjusted in a contact-analog HUD to indicate the safe braking distance. AR technology now can apply the concept by replacing the lamp-generated image by an AR presentation scheme. This approach enables more flexibility in design and animation of the scheme because no fixed form is moved mechanically. Instead, a computer generated 3D schemes provide the visual information to the driver.

7.1 Motivation

Accident Counts

The concept of indicating braking distances is motivated by the investigation of classified accident counts. Statistics on accident counts reveal that many accidents are caused by human errors in longitudinal and lateral car control, as seen in Fig. 7.1. Lateral accidents occur due to lane departure or collisions with lateral traffic, while longitudinal collisions occur due to obstacles, upcoming traffic or rear end collisions.

Secondary Displays

This is a main issue already addressed by many current driver assistance systems (like

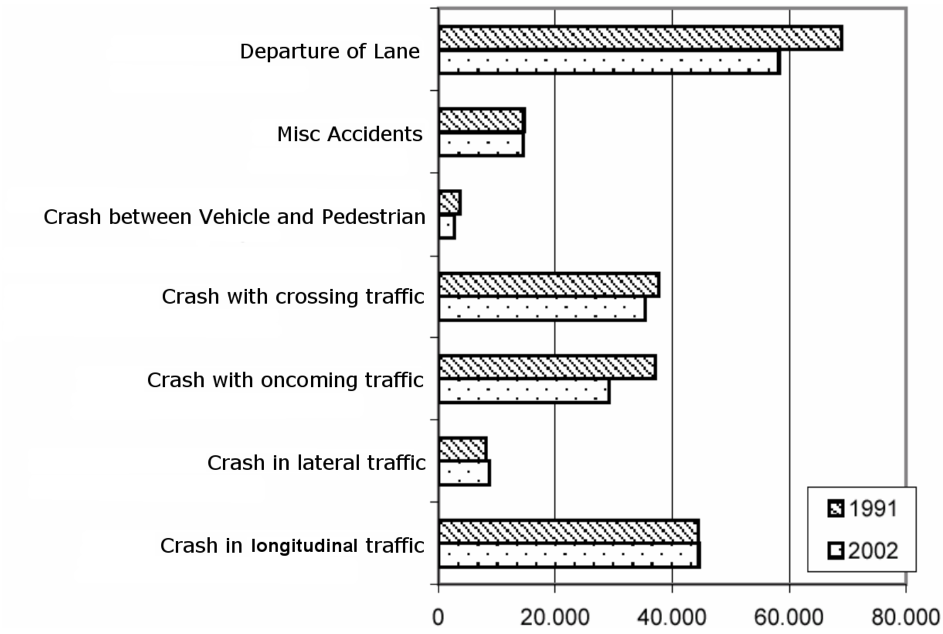


Figure 7.1: Distribution of Accident Counts in 2002 (Germany, adapted from [143])

the ACC [82]). They give warnings of potentially upcoming collisions when a safe distance to the car in front is not kept. Also warnings concerning lane departure are presented to the driver. In general, these systems indicate their warnings as symbolic icons in secondary displays on the dashboard. Even if such systems do increase environmental awareness, they require the driver to take his attention off the road, turn to the in-car secondary display, focus on it, interpret the message and then react to it.

Leaving the Control Circuit

Drivers act in a tight control cycle (section 2.1.3, page 15), in which they continuously perceive the environment, interpret the current situation and execute the most suitable action to control the car. Assistance systems with secondary displays are not integrated into this tight control loop. While looking at and reacting to a warning signal on a secondary display, drivers are taken *out of the loop* [83].

Car becomes 3D User Interface

The concept of visually embedded information presentation intends to keep drivers *in the loop* of the control circuit. The in-car control devices become extended control devices for AR presentation schemes that are embedded into the personal view of the driver (section 2.2, page 20). Such visual presentation schemes in the HUD of the car indicate how drivers are maneuvering through the 3D environment, specifically, where their car is heading at the moment. The concept assumes, that this kind of assistance is much less distractive than secondary displays, because it keeps drivers *in the loop* of the control circuit. Such a concept can be attributed to the perceptive cooperation mode (section 2.1.5, page 17), the lowest level of automation. This concept also allows for future integration of safe distance indication in platooning traffic where the risk of rear-end collision is increased.

AR Schemes

Two visualization schemes have been designed that present the intrinsic status of the car in the HUD. They present lateral and longitudinal properties of car motion in a *Compensatory Display*. The first presentation scheme consists of a single bar shown in front of the car on the street. The second scheme extends the first one by outlining the path that will be covered by the car (see Fig. 7.2). The bar indicates where the car would come to a halt, if the brakes were fully pressed at that instant. Depending on the steering angle, the bar turns left or right, according to the way the car will turn. The second presentation scheme shows the drive-path of the car. Here the right and left border of the bar are connected by polygons to the right and left front corner of the car. These lines surround the area that will be covered by the car. The drive-path-based presentation is intended to better convey the alignment of the driving path with curves in the road. Both visualization schemes have been implemented, tested in a driving simulator and are published in [157].

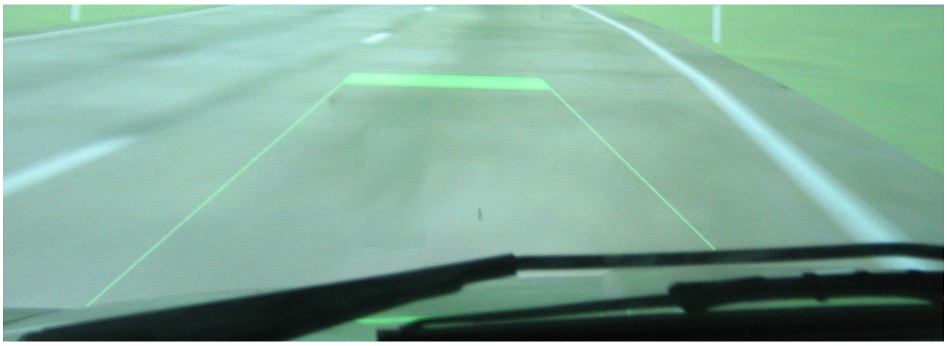


Figure 7.2: A Screenshot showing the Braking Bar and the Drive-Path

7.2 Related Work

Adjacent Research

There are various warning systems for rear-end collisions and lateral way-control available and under research. But only few approaches explore visual in-the-loop assistance, that concurrently superimposes the road performance of a vehicle. In non-automotive domains, diverse approaches for that kind of assistance exist.

Naval Pathways

Pathway predictors have been under research in several application areas, involving navigation on ships, cars and airplanes. Sullivan has investigated a pathway indicator for training surface transport of mid-sized vessels [145]. On-board a ship, steering is complicated, because it takes a long time for a ship to react perceptibly to steering changes. Here a path predictor on a secondary screen indicates where the ship will head in dependence of the current control stick adjustment. Usability tests with inexperienced as well as with experienced participants revealed that all participants were significantly better in pursuing the correct path when using the path predictor. The test furthermore showed that some test subjects focused on the secondary display, neglecting surrounding traffic.

Symbolic Systems

In the automotive sector, the MobilEye system [114] alarms car drivers to critical environmental settings and misleading courses. It uses a small secondary screen to show a stylized car on a symbolic road. The right and left lane boundary as well as the car icon can blink when a lane departure or an upcoming rear collision is predicted. Citroën provides a lane departure warning system that notifies drivers via vibrations in the left or right side of the seat of the driver when the car drifts to the left or right.

Efforts to improve situational awareness [75] with course support are under research by, for instance, NASA. Randall et al. have tested vision enhancement systems in the HUD of airplanes [8]. The experimental data has shown that significant improvements in situational awareness without concomitant increases in workload can be provided by the integration of synthetic and enhanced vision technologies. More specifically, pathway indications of a pilot's course have been investigated by Kramer et al. [92]. They have compared different visualization schemes regarding the shape and appearance of a virtual flight-tunnel and guidance metaphors. Results have indicated that the presence of a tunnel on a HUD has no effect on flight path performance but that it does have a significant effect on a pilot's situational awareness and mental workload. A visualization scheme showing a dynamic tunnel with a *follow-me* aircraft guidance symbol produced the lowest workload and provided the highest situational awareness among the tunnel concepts evaluated. Assistance in Aviation

In the automotive sector, Assmann and Bubb [4, 34] have investigated the visual presentation scheme for longitudinal anticipation of the car's speed. Their setup is described in detail in section 4.2.3 on page 76 and thus only briefly illustrated here. They have built a HUD and incorporated a double-ended tubular lamp such that the lamp works as an indicator for the braking distance. The faster the car drove the farther away and the smaller the lamp appeared. Studies indicated that test participants felt safer when driving with the HUD. Measurements stated an improvement in safety for about 15 % and a prolongation of unsafe distances in platooning traffic for 30 %. Concept Foundation

7.3 Concepts

When designing visual schemes for automotive applications, factors about other automotive systems must be kept in mind. The mobile application domain of automobile environments can also incorporate further visual aids, e.g., for navigation tasks. Design approaches therefore have to take care of a unique understanding of implemented presentation schemes. Multiple Systems

To illustrate the issue, dealing with unique understanding of presentation schemes, it is important that arrow-like presentation schemes are already and often applied in automotive context. Arrows are widely used presentation schemes. For example, they indicate heading directions of roads, give hints about navigational tasks and inform about existence of opposite traffic. Automotive environments require various concurrent tasks and thus have to deal with presentation schemes carefully [156]. Ambiguity of Arrows

Warning arrows can be used to indicate for lane departures. This raises several issues. First, such an arrow could be misinterpreted w.r.t. its direction. An arrow pointing right could tell to go right or that the car is departing to the right. Furthermore the fact that arrows are often used for navigation tasks can interfere with the intended meaning of an arrow for a lane departure warning. Does an arrow want the driver to go right or does it warn that he is leaving to the right? Examples

When applicable, ADAS systems should use AR presentation schemes without arrows. Other Schemes

ADAS system monitor the environment. In case of a critical situation, they can present the warning on a secondary display. The driver has to immediately look at the display and capture the information to avoid the accident. Secondary Displays

Continuous Information

Instead of requesting a driver to look at a secondary display, the concept for ambient longitudinal and lateral pathway assistance is based on an integrated approach. It shows where the car is heading and where it will come to a halt. Drivers can stay in the loop of the control circuit and continuously perceive the actual state of the car. The concept incorporates a predictor for the pathway, intended to improve driving performance directly and does not wait until a certain critical event, like a lane departure, has arisen. Drivers are no longer required to pull their attention away from the environmental settings to a secondary display. Rather, they can concentrate on surrounding traffic.

Concept Baseline

The concept uses an analogy to flight-tunnel-presentations [158] for lateral guidance in conjunction with a braking bar [4, 34] as an indicator of longitudinal distances. This concept allows for later alterations, e.g., in platooning traffic, where indication of following distance to leading cars can be incorporated into the presentation.

Porting Aviation Systems

Pathway assistance originates from aviation. Presentation scheme design can port some experiences already gathered there. Concept transferation has been discussed in [158], thus only the main differences are illustrated here. Surface transportation differs in certain factors from aviation environments. First, instead of 3D spatial movement, cars only drive on the ground, which is a 2D surface, even if bent across hills and bridges. Therefore only lateral and longitudinal assistance are necessary. However, vertical assistance could be provided for under-crossings and similar situations where height becomes an issue. Second, due to lower speeds and the option of always being allowed to bring the car to a complete stop, the presentation of the braking distance appears useful. This way, the driver can have better anticipation of the surrounding settings and can react to obstacles.

7.3.1 Braking Bar

Form Factors

The *braking bar assistance scheme* is a flat cube, $2\,cm$ high, shown with the same width as the own car (see Fig. 7.3). It is $50\,cm$ long such that the bar is visible, even when the car drives at high speed and the braking distance reaches large values, making the AR scheme smaller in perspective size. Due to the thin layout, the bar does not occlude a large area in the field of view of the driver, it only covers some area on the ground.

Color Design

The bar is colored in bright green, known to be well suited to the presentation in HUDs – where dark colors are invisible. The color has strong contrast to common gray scales on roads or unpaved brown country lanes.

Bar Motion

At startup of the car, the bar appears in the lower end of the windshield when the speed reaches about $5\,km/h$ – depending on the body height of the driver. The bar is rendered perspectively such that its size becomes smaller, when speed increases. Turning the steering wheel causes the bar to rotate and move left or right – according to the curved path the car will take at the current turning radius. The lateral placement of the bar in the HUD is computed according to a single track driving motion model, see Fig. 7.4. The bar, in addition, rotates around its vertical axis, so that it always shows the stopping line of the front of the car at every point in time.

7.3.2 Drive-Path and Braking Bar

Covered Area

To support estimation of curves and narrow road sections, visualization of the area through

Figure 7.3: A Screenshot showing the Braking Bar

which the car will drive on its current trajectory defines the extended, second presentation concept. The *drive-path* indicator extends the braking bar presentation scheme by two additional sets of polygons that connect the bar to the car. Each corner of the front side of the car is connected to the corresponding corner of the bar. Each of the two polygons uses four vertices between the car and the bar to generate a rounded shape. Therefore the drive-path presentation scheme always indicates the area to be covered in the next seconds of driving.

Scheme Appearance

Fig. 7.5 shows the bar and the drive-path in a light left curve where the car is left of the center of the own lane and started the curve, before the curve itself actually begins.

7.4 Hypotheses

The idea of visual longitudinal and lateral assistance in its two variants for car driver enables definition of the following hypotheses for usability studies:

1. *The braking bar scheme, informing about longitudinal motion, improves driving performance in longitudinal direction.*
2. *The braking bar scheme, informing about lateral motion, improves driving performance in lateral direction.*
3. *The drive-path scheme does not alter capabilities of longitudinal behavior.*
4. *The drive-path scheme improves lane-keeping capabilities to a higher degree than the bar scheme.*

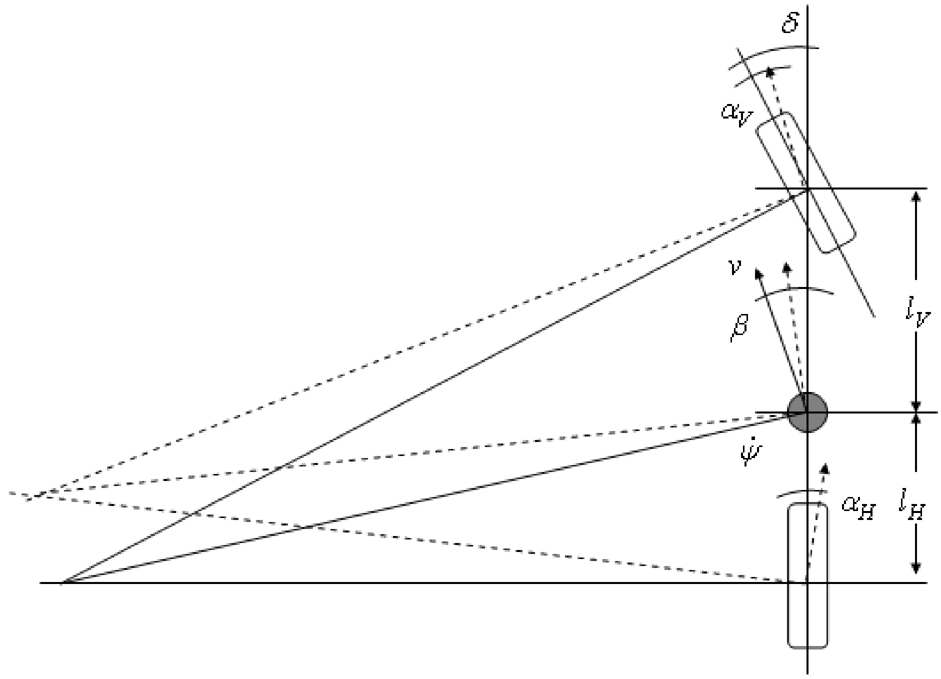


Figure 7.4: Principle of Single Track Driving Dynamics Model. A two wheeled vehicle follows a circle section

7.5 Experiment

Demographic Values

The experiment has been conducted with 27 test participants. The mean age was 41.3 years with a standard deviation of 14.8. These were 14 male and 13 female. None of the participants had taken part in a study of similar context before. All participants had normal or corrected to normal vision and held a valid driver's license. The participants were paid 30 Euro for the two hour experiment.

7.5.1 Physical Setup

Testing Environment

The experiment was conducted in the initial version of the driving simulator at LfE, see section 5.1.1 (page 81) for details about the simulator. This driving simulator used a single track driving dynamics perfectly describing the animation model of the braking bar scheme. Thus no ambiguity in motion behavior between the car and the bar could be noticed.

Concept Implementation

The software components were incorporated into the rapid prototyping environment in its first step of refactoring, see section 5.3.1 (page 90) for details about the development environment. Two additional service components were implemented. The first implementation is a filter component that computes the location of the presentation scheme. The second implementation is a presentation component allowing for independent design of the appearance of the presentation scheme.

HUD Simulation

The presentation concept uses a HUD with a focal plane lying congruent to the real street

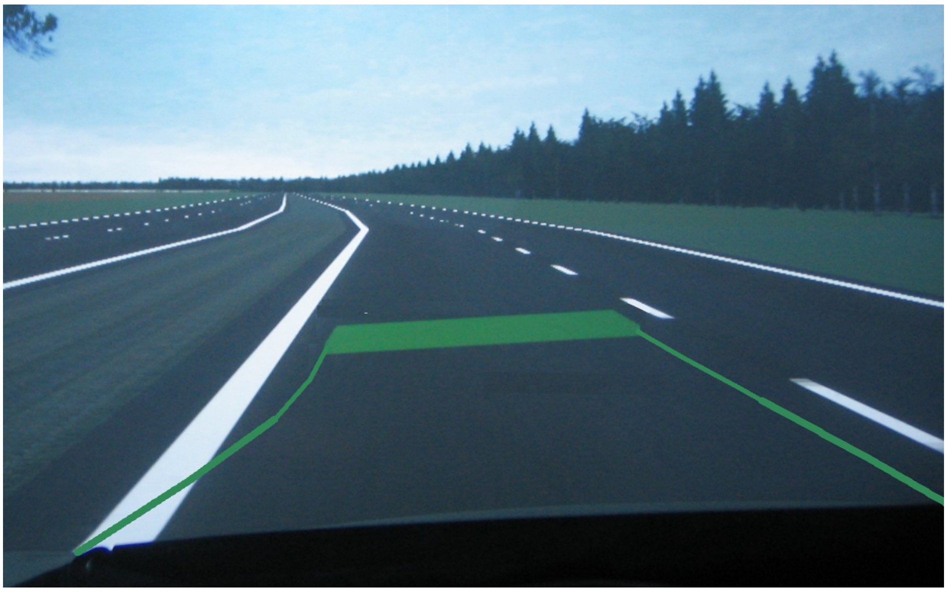


Figure 7.5: A screenshot showing the braking bar and the drive-path in a light left curve. One can see the car actually is slightly too far to the left and starts the left curve too early

surface such that the driver's eyes do not have to refocus between the distance of the real world and the AR presentation scheme – the contact-analog HUD. Such a contact-analog HUD is easy to implement in a driving simulator: the software system just renders the schemes onto the same projection wall. With this approach, no visual focus has to be obtained nor is any calibration of the vision system required. Humans of any body height will always see a view that is perfectly aligned with the scenery of the driving simulator. Head movements do not alter alignment.

7.5.2 Experimental Design

Topic Introduction

Upon arrival, the participants had to fill out a demographic questionnaire. To familiarize themselves with the driving simulator, each participant drove for about 10 minutes, thereby experiencing the slightly different driving behavior of the simulated car. The participants were requested to keep the allowed speed and adhere to the traffic rules.

Within-Subject Design

For the experimental trials, the participants drove the same rural road course as in a practice trial. In three trials they either saw no further information (baseline) or one of the two presentation schemes in the same rural road course. The order of the two concepts and the baseline was counterbalanced between participants. After completing the three experimental tasks, the drivers were interviewed about their subjective opinions. A within-subjects design was used, with all drivers using both presentation schemes and the baseline. The experiment was conducted in a single session.

Independent Variables

The *independent variable* in the experiment was the *concept*. Three different modes, *no assis-*

tance, *bar based scheme* and *bar and drive-path scheme* were compared to one another.

Dependent Variables

The *dependent variables* included driving performance and subjective measures. The *driving performance* measures were an indication of how well the driver could maintain proper speed (speed deviation and average speed difference) and lane position (lane deviation, lane departure time, time to line crossing).

7.6 Results

Descriptive Statistics

All data was collected at a frequency of $40\,Hz$ and analyzed. Data analysis followed the principle as illustrated in section 2.4.3 (page 45). Significances were computed for all results. First, ANOVA was used to compute, whether the results were globally significant per measured variable. The significance level used in all following statistics (objective and subjective measurements) is $\alpha = p = 0.05$. Second, a pair-wise t-test comparison was computed to get the exact $\alpha-$values.

This chapter only lists results that revealed significant values or results which state important evidence of influence on human cognitive demands. All further results of the study have been moved to appendix B.1 (page 250.

The style of result presentation follows the definition given in section 2.4.4 (page 48).

7.6.1 Objective Measurements

Classification

The illustration of objective measurements is classified according to longitudinal and lateral dependencies.

7.6.1.1 Longitudinal Behavior

Value Selection

To obtain results for speed behavior, not all measured values could be taken into account. All speed measurements close to traffic signs which enforced a speed change were discarded, since such dynamic driving action would falsify results. Four intervals were defined, depending on traffic signs that changed speed settings.

Four Interval Types

These intervals exclude road sections, where speed is changed and therefore no accurate speed could be taken as basis for analysis. The general rule for the definition of the road section is as follows: if drivers have to drive slower at the beginning or at the end of a road section, then there is a strict border, as defined by traffic rules, of which the indicated speed has to be maintained. Otherwise it takes some time to accelerate the car. A speed offset of $5\,km/h$ below the upcoming speed limit was defined as threshold for values included in the calculation. If this offset is reached, data is collected for analysis.

Increase Decrease Interval

The first road section is defined by a sign that allows drivers to increase speed. The interval ends with a sign to decease speed. After the first sign is passed, we wait for the driver to reach the new speed maximum minus $5\,km/h$. In our scenario, this meant that, after leaving a town, drivers were allowed to increase speed to $100\,km/h$. We started recording when the car reached $95\,km/h$. At the end of the interval, a sign requested drivers to decrease speed.

We stopped recording when the speed dropped below the $5\,km/h$ threshold, in our example $95\,km/h$.

The second road section is defined by a sign to decrease speed as an entry point and a second sign enforcing a further decrease as terminator. Here values are taken from the very beginning to the end, similar to the definition of the end of the first section.

Decrease Decrease Interval

The third section – a decrease in the beginning and increase at the end – takes all values, because the car has to maintain exactly that speed to follow traffic rules.

Decrease Increase Interval

Finally the fourth section requests a speed increase at the beginning and another increase at the end. Speed values are taken when the speed first reaches $5\,km/h$ less than the allowed speed and collects values until the end of the section, i.e., the sign is passed.

Increase Increase Interval

Fig. 7.6 illustrates the four classes of road sections in a diagram: first, increase-decrease section. Second, decrease-decrease section. Third, decrease-increase section and fourth, increase-increase section. These intervals were used to analyze differences in allowed speed, standard deviation and the excess in speed. All lateral measurements were analyzed independently from these intervals.

Graphical Intervals

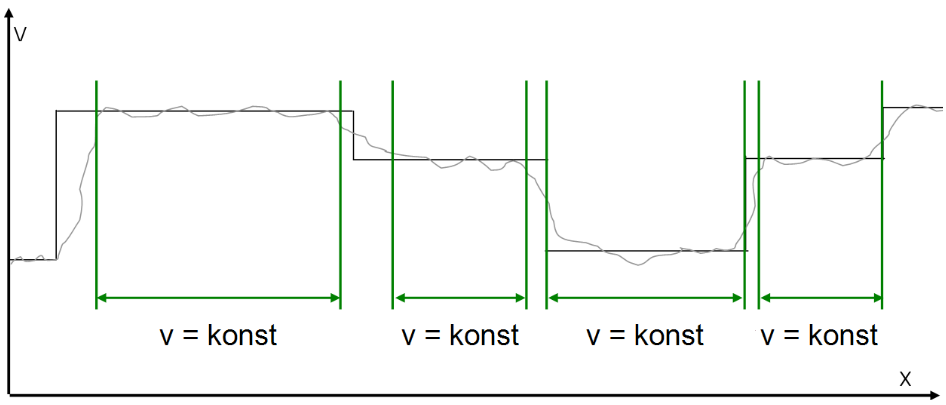


Figure 7.6: A sketch that illustrates the four intervals, where a constant speed should be maintained. The four intervals are constrained by increases or decreases of the allowed speed

Difference to Allowed Speed Based on the speed measurements that were selected for analysis, we computed the mean *difference between the driven and the allowed speed*. Results show that drivers drove faster with visual assistance than without it. In the baseline test drives, drivers were $5.06\,km/h$ (std.dev: 7.02) too fast on average. With the bar assistance, they were $6.65\,km/h$ (std.dev: 8.05) too fast. Participants drove $8.83\,km/h$ (std.dev: 7.91) faster than allowed when they used the drive-path presentation scheme. Specifically the speed difference between driving with no assistance and driving with the assistance of the drive-path is significant. Table 7.1 and Fig. 7.2 show all results for the difference between allowed and driven speed.

α-Values	Baseline	Bar	Bar & Path
Baseline		0.215	0.017
Bar			0.102
Bar & Path			
Mean [km/h]	5.06	6.65	8.83
Std.dev [km/h]	7.02	8.05	7.91

Table 7.1: Difference to Allowed Speed

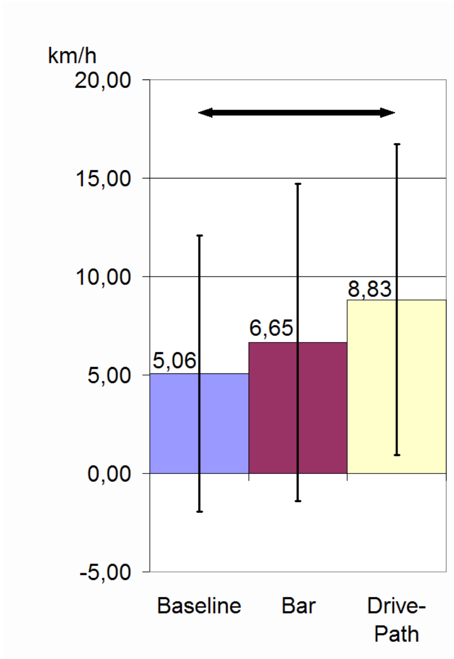


Table 7.2: Difference to Allowed Speed

Standard Deviation of Speed The *standard deviation of the driven speed* indicates, to what extent speed varied. Interestingly, a larger degree of visual assistance correlates with higher oscillations. The baseline shows a range of $6.40\,km/h$ (std.dev: 1.80), the bar assistance a range of $6.64\,km/h$ (std.dev: 2.14) and the drive-path scheme spans $7.36\,km/h$ (std.dev: 2.34). The drive-path scheme oscillates significantly more than both other schemes. Table 7.3 and Fig. 7.4 show the results for the standart deviation of speed.

Time of Speeding Violation An analysis of the amount of time during which a serious speeding violation (more than $10\,km/h$ over speed limit) occurred did not produce significant results. See appendix B.1.1 (page 250) for detailed results.

7.6.1.2 Lateral Behavior

Lane Deviation For the analysis of lateral performance, we first calculated the *lane deviation*. The experiment recorded the offset to the perfect trajectory in the middle of the own lane. In all three test drives, participants tended to drive slightly left of the center of their own lane. The data recording procedure recorded negative values for left side departures of the center line of the own lane.

Without any assistance, participants were about $0.51\,m$ (std.dev: 0.23) to the left of the central path. The bar assistance scheme helped people stay better in their own lane and reduced the offset down to $0.28\,m$ (std.dev: 0.23). The additional drive-path again shrunk

α-Values	Baseline	Bar	Bar & Path
Baseline		0.470	0.003
Bar			0.023
Bar & Path			
Mean [km/h]	6.40	6.64	7.36
Std.dev [km/h]	1.80	2.14	2.34

Table 7.3: Standard Deviation of Speed

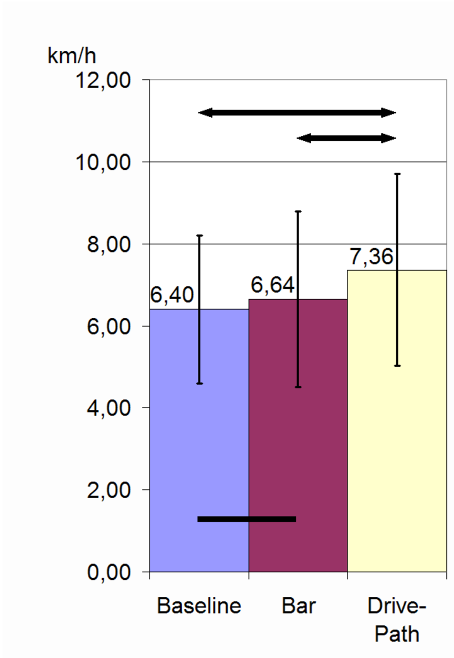


Table 7.4: Standard Deviation of Speed

the offset to $0.15\,m$ (std.dev: 0.20) off from the ground truth. Table 7.5 and Fig. 7.6 show that all pairs are significantly different.

Standard Deviation of Lane Deviation Regarding speed oscillation, the *standard deviations of the lane deviation* show that only the drive-path scheme (mean: $0.66\,m$, std.dev: 0.16) generates a significantly higher oscillation in comparison to the bar assistance scheme (mean: $0.63\,m$, std.dev:0.18). Even though the test participants performed better when they stayed near the perfect trajectory, they generated more steering activity. The baseline had a mean value of $0.62\,m$ (std.dev: 0.17). Table 7.7 show the $\alpha-$values, the mean values and the standard deviation. Fig. 7.8 shows the graphic diagram of the results.

Time to Line Crossing The measurements of lateral acceleration were used to compute the Time to Line Crossing (TLC), an indicator for lane keeping behavior. All resulting mean values ranged between $11.20\,s$ and $11.56\,s$ and had no significant impact on their pair-wise comparison.Results can be found in appendix B.1.2 (page 251).

15. Percentile of Time to Line Crossing Another indicator for lane keeping behavior is the 15. percentile of the TLC. Sorting all measured TLC values in ascending order and taking the value at the 15 % limit gives the 15. percentile [61]. No results were significant. Detailed results can be found in appendix B.1.3 (page 251).

α-Values	Baseline	Bar	Bar & Path
Baseline		0.000	0.000
Bar			0.000
Bar & Path			
Mean [m]	-0.51	-0.28	-0.15
Std.dev [m]	0.23	0.23	0.20

Table 7.5: Lane Deviation

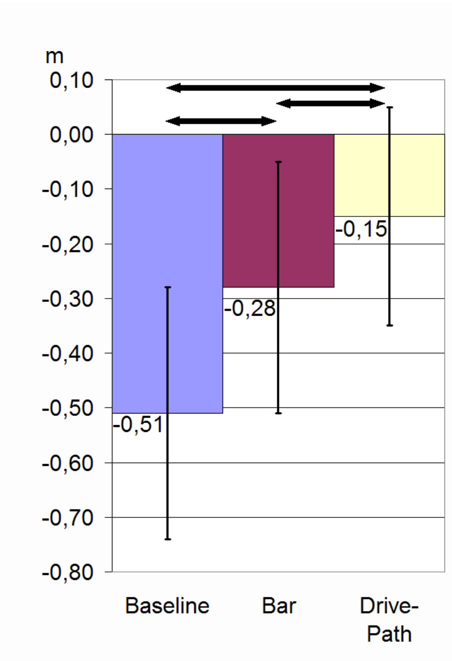


Table 7.6: Lane Deviation

7.6.1.3 Summary

Objective Findings

In summary, the objective measurements state that the test participants drove faster with a drive-path assistance scheme than with no assistance. In addition, the drive-path generates higher speed oscillation than no assistance or the bar presentation scheme. Lateral driving performance is improved. Test participants could better stay in their own track. Finally, compared to driving without assistance, the bar scheme raises the 15. percentile of the time to line crossing, which states that test participants really could stay in their own lane more precisely.

7.6.2 Subjective Measurements

Grading System

Where personal opinions were asked, measures according to the German school grade system, ranging from 1 (best) to 6 (worst) were collected. Here again, the significance level used in all following statistics is $\alpha = p = 0.05$.

Overall Workload Index The *NASA Task Load Index* (NASA TLX, [74]) computes an overall workload index from a short questionnaire. The result is a value between 0 (no workload) and 100 (full workload). The analysis shows that the test subjects had less workload when they used the bar assistance scheme (mean: 27.87, std.dev: 15.76). Despite the existence of an additional visual presentation scheme, the test drivers had less workload to deal with. The workload for the drive-path and for the baseline ranged around 32 (baseline: mean: 31.71, std.dev: 24.95; drive-path: mean: 32.08; std.dev: 20.88). This is consistent with various other experiments where the overall workload index remains constant across similar tasks [73].

α-Values	Baseline	Bar	Bar & Path
Baseline		0.879	0.112
Bar			0.033
Bar & Path			
Mean [m]	0.62	0.63	0.66
Std.dev [m]	0.17	0.18	0.16

Table 7.7: Standard Deviation of Lane Deviation

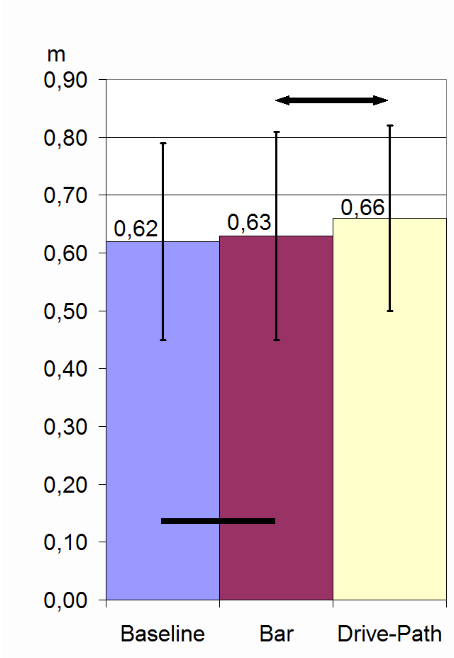


Table 7.8: Standard Deviation of Lane Deviation

The results show that the visual assistance does not increase the overall workload of test participants. Table 7.9 and Fig. 7.10 illustrate the computed results for the NASA TLX.

Ability to Maintain Speed Test participants also had to estimate their *ability to maintain speed*. They ranked the bar assistance scheme significantly better for keeping speed than the drive-path and no scheme. The bar received a grade of 2.85 (std.dev: 1.06), while the drive-path was graded as 3.56 (std.dev: 1.28) and no assistance as 3.22 (std.dev: 1.31). Comparing these subjective results to the objective measurements of speed deviation, the findings should be accepted carefully. Even if participants drove too fast in the objective measures, they here only state, that they could keep the speed they drove. Table 7.11 and Fig. 7.12 show the computed results for the question about the ability to maintain speed.

Overall Driving Quality To evaluate the *overall driving quality*, the participants were asked to grade their driving performance for the three assistance schemes. The bar scheme ranks at the top position with an average value of 2.63 (std.dev: 0.88). The difference is significant in comparison to driving without any assistance (3.00, std.dev: 1.00). Driving with the drive-path resulted worst with a mean value of 3.04 (std.dev: 1.22). Table 7.13 and Fig. 7.14 show all relevant values.

Concentration on Task of Driving When asked how well they could *concentrate on the task of driving*, the participants answered that they could concentrate the less the more visual

α-Values	Baseline	Bar	Bar & Path
Baseline		0.360	0.940
Bar			0.190
Bar & Path			
Mean	31.71	27.87	32.08
Std.dev	24.95	15.76	20.88

Table 7.9: Overall Workload Index (OWI)

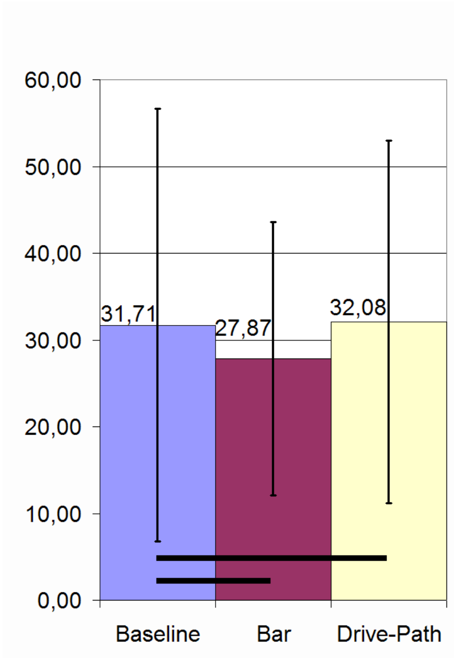


Table 7.10: Overall Workload Index (OWI)

content was in their field of view. Without any assistance, they could concentrate best with a grade of 2.19 (std.dev: 0.88). The bar presentation scheme reached second place with a grade of 2.33 (std.dev: 1.00) and the drive-path comes in last with a grade of 2.74 (std.dev: 1.35). The last result is significant in comparison to driving with no assistance. Table 7.15 and Fig. 7.16 show all results.

Further Questions Further subjective questions about *Pleasure*, *Wish for Realization*, *Relaxation*, *Ability to Stay within a Lane* and *Feeling of Safety* did not produce significant differences. The statistical values can be found in the appendix in sections B.1.4 through B.1.8 (page 252ff).

Subjective Findings

Summary In summary of all the significant subjective measurements, the bar presentation scheme is ranked top. The test subjects mentioned the improved lane keeping performance by use of the bar scheme in comparison to no assistance. They also think that they can keep their speed better by use of the bar assistance system, compared to no assistance or the drive-path assistance. Furthermore, the test participants think that they drive better with the bar system in comparison to no visual indication. Participants were equally pleased with both kinds of visual feedback and did not notice any increased workload with both schemes. Furthermore, participants mentioned that both assistance schemes had no impact onto the feeling of safety. Finally, the test subjects said that the drive-path reduced concentration on the task of driving in comparison to no assistance.

α-Values	Baseline	Bar	Bar & Path
Baseline		0.030	0.131
Bar			0.005
Bar & Path			
Mean	3.22	2.85	3.56
Std.dev	1.31	1.06	1.28

Table 7.11: Ability to Maintain Speed

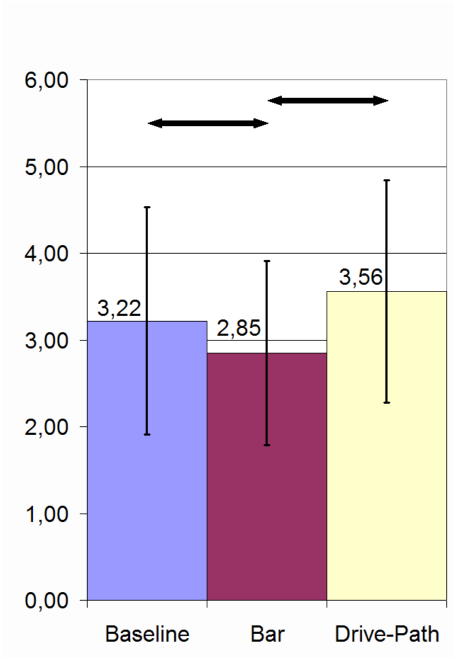


Table 7.12: Ability to Maintain Speed

7.7 Discussion

Results show, that the test subjects drove faster with increasing visual assistance. Driving simulators are safe environments. Except for simulator sickness, test participants do not suffer any harm. Thus, higher speeds could be expected, but the further increase shows, that the visual aid raises a feeling of safety to a larger extent. Another fact in longitudinal behavior is found in the standard deviation of speed. The drive-path scheme oscillates significantly more than both other schemes. Here the drivers seem to neglect their obligation to maintain proper speeds when they look at the animated presentation scheme of the drive-path. Thus hypothesis 1 stating that longitudinal performance is improved through the bar scheme must be rejected. Hypothesis 3, that the drive-path scheme does not alter longitudinal behavior, must also be rejected. Longitudinal Support

The lateral assistance appears useful for lane keeping behavior, because lane deviation decreases the higher the visual assistance is, but the drive-path scheme oscillates more than the pure bar scheme. Hypothesis 2, stating that lateral behavior becomes improved now can be assumed correct. Also hypothesis 4, assuming that the drive-path again improves lateral capabilities, can be accepted, but long term studies have to investigate, if habituation reduces oscillations to really accept the hypothesis. Lateral Support

Summarizing subjective measurements, test subjects judge an improved overall driving quality for the bar scheme in comparison to no assistance. Subjective Selection

Especially the findings, that the bar scheme does not increase overall workload, reduces lane deviation and does not increase oscillations in speed and lateral movement make this Scheme Selection

α-Values	Baseline	Bar	Bar & Path
Baseline		0.001	0.876
Bar			0.118
Bar & Path			
Mean	3.00	2.63	3.04
Std.dev	1.00	0.88	1.22

Table 7.13: Overall Driving Quality

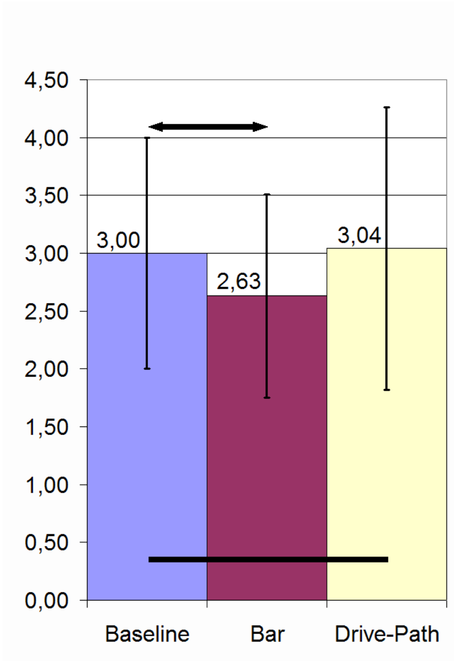


Table 7.14: Overall Driving Quality

scheme interesting for further analysis. The facts, that visual assistance brings a (wrong) feeling of safety and that common design principles for visual aids in time-critical systems enforce presentation schemes to be as little and easy to perceive as possible let the drive-path scheme appear be the most interesting candidate for further extension to a platooning aid. Thus the bar scheme should be preferred to the drive-path scheme.

7.8 Summary for Visual Longitudinal and Lateral Assistance

Concept Summary

This study reported on an approach for implicit driver assistance incorporating new technologies for the generation of AR presentation schemes. Two visual presentation schemes, a bar and a drive-path, to be presented in the windshield (HUD) of a car have been developed. These two schemes are connected to the in-car control devices for the primary task of driving and therefore convert these control devices into 3D input devices. Since visual output offers a means for immediate anticipation of the trajectory of the car, such AR schemes thus enhance a driver's diving performance. No warnings about upcoming dangerous situations are used to prohibit accidents, but a visual system keeping the driver in the loop of the control circuit applies less distracting interaction concepts.

Focus on Bar Scheme

Objective and subjective results show that such visualization does not affect overall workload, yet it does improve lane keeping behavior. The results further support the general design principles that presentation schemes must be as minimal and easy to perceive as possible. Due to the general principle and due to the results of the study, the bar presentation scheme should be selected for further extension in future work.

α-Values	Baseline	Bar	Bar & Path
Baseline		0.503	0.008
Bar			0.210
Bar & Path			
Mean	2.19	2.33	2.74
Std.dev	0.88	1.00	1.35

Table 7.15: Concentration on Task of Driving

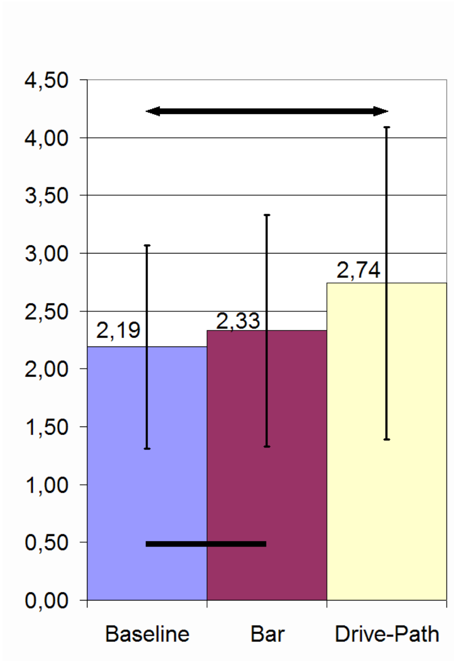


Table 7.16: Concentration on Task of Driving

Three major directions for future investigation can be defined. Future Work

First, colors should be explored as a means to indicate a following distance to inform drivers of safe distances and critical approaches in platooning traffic. Colors for Platooning

Second, further usability tests must integrate analysis of eye movement behavior to determine whether effects of peripheral tunneling are introduced by such visual add-ons. Glance Behavior

Third, incorporation of such visual assistance schemes into a real car is necessary. To this end, a HUD that can display visual content in an area of at least about a A3-sized sheet of paper in correct focal distance is required. This setup will enable long term studies on driver customization and will reveal lots of data about human factors of AR. Transfer to Real Car

8 Guidance of Attention in Dangerous Situations

Direction indication towards imminent dangerous situations under time-critical demands

Invisible Occurrences

In chapter 3 three kinds of interaction between car drivers and ADAS systems were classified. First, *direct indication of information*, second, *indicating an invisible situation* and third, *drawing attention towards an invisible situation*. These aspects are illustrated and classified in section 3.2.2 (page 58ff). The previous chapter investigated concepts for the first kind, *direct indication of information*. AR schemes for car motion status information were designed and tested. According to the two remaining issues of chapter 3, AR can also be applied to reduce the delta between sensor systems and car drivers. This delta exists because sensor systems have a wider range of sensing or another scope of modalities than the human driver has. ADAS systems thus know about a wider area around the car and, in case of a critical occurrence, have to inform the driver about the *existence of an invisible situation* or have to *draw the driver's attention towards the direction of the yet invisible situation*.

Issues in AR

Both tasks are general issues in the field of AR as well. Here the question is, how a user's attention can be directed effectively to a location or direction which is not in the user's field of view. This type of issue is interesting because AR usually enables direct indication of objects through highlighting or direct pointing. Referencing invisible objects therefore is a demand for the applicability of AR in general. One approach that is enabled by AR is enhanced vision by x-ray like systems. For instance, Sielhorst et al [138] developed a system for visualization of occluded data and investigated opportunities for improved perception of the spatial dependencies. Bichlmeier et al [24] also investigated improved depth perception of such AR x-ray systems. In combination with the demand that the object may be outside the field of view of the user, only guiding the attention of the user to the object enables superimposition of the target object with AR. In case of objects outside the field of view, AR can only be applied to use spatial relationships between real and virtual objects and the user to generate an understandable AR presentation for guidance. Such guidance systems have been developed for other applications, such as commissioning [135] and location indication outside of small displays [12]. In contrast to the automotive aspect, application in these fields does not have time-critical demands. The potential benefit of the application of AR keeps the user's frame of reference and does not request him to interpret an exocentric presentation from another perspective. AR schemes can thus reduce response times to the understanding of spatial relations.

Structure of Guidance

For this reason, this chapter investigates the differences between attention guiding schemes in different frames of reference. In the HUD, a symbolic, map-like presentation scheme and a spatial AR scheme are investigated in driving simulator studies on task response time and effects on driving performance. Two experiments have been conducted, the first defining initial version of the presentation schemes and the second, in detail clearing out the ambiguities, the initial study revealed. Both experiments have been published [160, 155] focusing on the studies independent from the full context of integrated assistance systems. This chapter motivates the demand for such assistance, illustrates related work and then reports on both studies. Each study summarizes its concept design the experimental design and discusses the results. The last section of the chapter summarizes the discussion about issues in guidance of attention.

8.1 Motivation

Driver Inattention

Indication of dangerous situations in the near environment of the car again is motivated through accident numbers. Driver inattention is a primary cause for up to 78 % of crashes and 65 % of near-crashes [88]. ADAS systems should help reduce driver inattention. To this end, an ADAS system needs to monitor and track the environment of the car, using the increasing availability of sensors to detect imminent dangerous situations of traffic and other obstacles in the vicinity of the car. The auras of the sensors differ from the aura of the driver (section 3.2.1, page 56ff). The delta between both auras must be compensated through the ADAS system (section 3.2.2, page 58ff). Such sensor data must be provided via suitable output channels to catch a driver's attention and to guide him in that direction.

Matching Auras

A particular problem of imminent dangers is the fact that their occurrence is not necessarily in the driver's field of view, but, e.g., approaches from behind. The visible field of view of the driver is characterized through the concept of the *Sphere of Vision* (section 3.1, page 51ff). The ADAS system has to determine the current visible field of view of the driver, has to build a model of the aura of the driver and has to match this model with the sensor systems aura. If the system determines, that the object is not in the field of view at the moment, direct indication of the dangerous location is not possible. Instead, the ADAS system must communicate to the drivers that they should turn their heads towards the corresponding direction.

2D vs 3D

The question arises, whether 3D Augmented Reality technology can outperform classic 2D assistance systems. Classic approaches for instance can show a map-like overview and thus can show the location of the danger. AR approaches can only give a hint about the location or direction of the imminent danger.

Two Times two Schemes

To compare the effects of 2D versus 3D information presentation, two approaches for guidance schemes were investigated. The first approach used guidance aids in the frame of reference of the driver showing information presented from the point of view of the driver while the second scheme applied a bird's eye perspective presentation schemes. Accordingly, two visualization schemes were designed. The first scheme implements a 3D arrow floating in front of the car, pointing towards the direction of the dangerous situation as a *Compensatory Display*. The bird's eye scheme shows a symbolic car and indicates the location of the dangerous situation with a nearby octagon as a *Compensatory Display*: the presentation is aligned along the facing direction of the driver. Both schemes were investigated in a pilot study. Deficits and ambiguities of the two schemes were discussed and extended to face these issues. In the resulting two visualization schemes, one used an animated bird's eye perspective direction indicator and the other one used an extended animated 3D arrow mounted on a pole. Spatial sound for guidance with another modality was incorporated as well.

Collaborative Work

The experiments were implemented and conducted in a university term project [1] in cooperation with LfE.

8.2 Related Work

Wayfinding and Alerts

The incorporation of further experiences into guidance systems for attention can use different approaches. First, wayfinding issues in virtual and augmented environments have been investigated on various respects. Experiences can give hints about design issues for ADAS systems for guidance of attention. Second, warning systems already try to inform drivers about the existence of an imminent danger and often intend to give a clue about the location or direction of the danger. Related work in both areas of interest is presented in subsequence.

8.2.1 Navigation in Virtual and Real Environments

Similarity to Navigation

Tasks concerning the guidance of attention are related to navigational tasks in the 3D user interfaces domain. Instead of navigational information for the whole unity of car and driver, only information concerning navigation of the attention of teh driver is presented.

3D Navigation

Various research on such tasks and on wayfinding in virtual environments has been conducted. The work of Chittaro and Burigat [41] concerns the design of the visual part of presentation schemes. They examined aids for enhanced navigation in virtual environments by comparing 3D arrow schemes with 2D schemes in the HUD. The visualization consisted of an arrow defined by a cone and a cylinder. A sphere at the back end of the arrow defined the mounting point for rotations. Since more than one arrow could be seen simultaneously, the sphere specified the rotation invariant origin. Experiments in a flight simulator resulted in the observation that a majority of the participants found their destination easiest by use of the 3D navigational arrow. The participants also preferred this kind of scheme.

Finding a Location

Echtler [51] built a solution for finding a location in 3D for welding studs to a car chassis. He mounted a small LCD display on a tracked welding gun. When the user is at a distant location or is holding the welding gun in another direction, a 3D arrow appears in the display and points towards the direction, the user has to move to. When the desired welding spot appears within the field of view, the arrow disappears and a crosshair cursor appears supporting exact placement of the welding gun. The system has been compared to the process used hitherto and significantly accelerated the whole welding process.

Wayfinding

Smith and Hart [141] evaluated various presentation schemes for wayfinding tasks in virtual environments, measuring their cognitive loads. Among other schemes, a 2D graphical compass, and a 3D graphical plan based on a ribbon metaphor were evaluated. The 3D graphical plan was presented as a long ribbon floating some meters above the ground, leading from the start to the destination. The user had to walk underneath the ribbon to get to

[1] Design variants and the study have been realized in the term project of Uli Koch: *Comparative Study on Miscellaneous Augmented Reality Visualization Schemes for Spatial Warnings in Driver Assistance Systems*, http://campar.in.tum.de/Students/SaKoch

the destination. Such a ribbon metaphor could be used to guide a driver. The ribbon starts at the position of the driver, heads straight forward at first, so that the driver can see it and then turns towards the imminent danger. The eyes just have to follow the course of the ribbon and reach the target. Such a ribbon cannot be presented in the upper part of the drivers fields of view, because it could not reach a dangerous location on the ground. Placing the ribbon like a carpet on the ground would cover a certain area of the environment and therefore is not suitable in ADAS systems. From all evaluated schemes, the 2D graphical compass and the 3D graphical plan required the highest mental load. Smith and Hart did not yet evaluate a 3D compass.

AR Compass

Information visualization in AR systems has, since its inception, dealt with the problem of directing a user's attention to a point of interest, e.g. by using a compass metaphor when the user is looking in the wrong direction [45].

Ego- to Exo-centric

Milgram and Kishino [112] give a taxonomy of mixed reality presentation schemes ranging from egocentric to exocentric, suggesting the use of egocentric visualizations for local guidance [11]. Experimental results of Barfield [11] have also consistently shown that local guidance is supported best by egocentric visual information.

Viewpoint Tethering

Wang [166] also compared schemes for navigational tasks. He describes a dependency in exocentric systems between the distance of the viewpoint to the own avatar and global and local control. The larger the distance is, the better global awareness is, but similarly local guidance performance deteriorates. To guarantee good control of the close environment, short distances for presentation schemes are recommended.

8.2.2 Warning Icons and Acoustic Systems

Multi-modal ADAS Systems

Ergonomic aspects of ADAS systems and especially collision warning systems have been evaluated. Experiments on such assistance systems cover visual, as well as acoustic and multi-modal driver feedback.

Collision Warning

Campbell et al. [40] compared various symbols for ADAS systems, which were intended to warn about frontal and lateral collisions, as well as about lane departures. They found that 2D presentations from the side were optimal for frontal warnings and bird's eye presentations were best suited for lateral collisions. Their study only evaluated 2D presentation schemes where all ranked almost equally.

Warning Icons

Green [65] has evaluated various warning icons to indicate upcoming obstacles. He concludes that pure text and orientational 2D arrows give best results for road warning systems.

User Developed Icons

Sayer [132] requested study participants to develop dead-angle warnings for lane-change assistance systems. Afterwards all participants had to rank those symbols. In every case, bird's eye perspectives ranked best.

Meta Surveys

Wickens and Seppelt [136] published a survey on 18 experiments that rate visual and auditory signals for various tasks in an in-car environment. The summary states that generally acoustic warnings should be used, except when the optical warning appears in the foveal field of view of the driver.

Design Guidelines

Lerner [103] offers extensive guidelines for the design of optical, acoustical and tactile warnings. In general, he recommends the use of multi level warning systems: at least one pre-warning, followed by a more immersive one. On the highest level of warnings, redundancy is important to ensure that a warning is definitely realized. This is supported by Bubb [35]. He states that feedback must be given on as many sensory channels as possible.

Guidance with Sound

Gunther [72] explored ways to use sound to support wayfinding in virtual worlds. He states that object detection is supported, but that getting a global overview can be disturbed. Furthermore he points out a problem in distinguishing spatial sounds from positions in front and behind the subject.

8.3 Pilot Study

Initial System

As part of the TUMMIC research project towards creating and evaluating novel visualization and interaction schemes for car drivers, two different visualizations for application in the HUD have been generated and tested in usability studies. An iterative approach was used, testing the two schemes first in a pilot study, and then applying the gained experiences to an extended design resulting in a main user study. The following section describes the initial presentation concept, the dependent hypotheses and the usability study that was conducted to validate the hypotheses.

8.3.1 Presentation Concept

Inside Field of View

Augmentations cannot be placed at their true physical position of the danger, because its origin may reside outside the driver's field of view. They rather have to be positioned within the driver's current field of view (i.e., in the windshield), telling him how to move his head to see the dangerous situation.

Two Schemes

Two visualization schemes have been generated, one using 2D representative presentation to indicate the location relative to the car and one using a 3D perspective, pointing towards the desired direction. The first visualization scheme describes a 2D map-like presentation from an exocentric bird's eye perspective. The second scheme is a 3D arrow floating in the driver's field of view.

Bird's Eye Perspective

The first scheme presents a two-dimensional exocentric view of the car from a bird's eye perspective at a fixed position in front of the windshield (figure 8.1). The point of danger is indicated by an octagon. Several symbols were preevaluated for the location indicator. An octagon provided the best perception. Even if the scheme could be displayed at any position, e.g. in the central information display, is it presented in the HUD. That way, both schemes, the 2D symbolic and the following 3D AR scheme do not have any differences through presentation location.

3D Arrow Compass Metaphor

The second visualization scheme presents a 3D arrow (figure 8.2). Arrow schemes are already used widely in the automotive sector and every new application therefore should be treated with care [156]. The experience with the arrow scheme through the VR and AR communities nevertheless shows elementary advantages for some important issues concerning efficient and fast reactions of such a scheme. Upcoming dangerous situations require immediate reactions. The simple shape and intuitive understanding of the scheme contribute to short reaction times. The 3D arrow is mounted at a fixed length tether in a driver egocentric

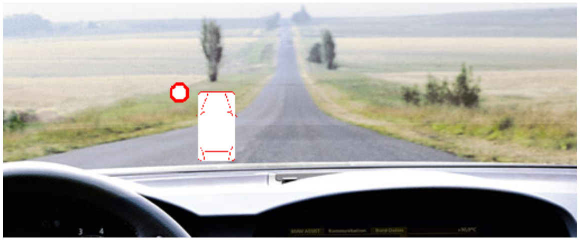


Figure 8.1: Bird's eye view showing the position of imminent danger relative to the car

frame of reference. The 3D arrow seems to be floating in front of the car. Its back end is placed about 3 meters in front of the driver in height of a typical driver's head. The front end of the arrow points in the direction of the imminent danger.

Figure 8.2: 3D arrow in front of the car pointing towards the position of imminent danger

Both schemes are not shown continuously but only become visible in case of an alert. Only on Alert

8.3.2 Hypotheses

The idea of situation referencing via spatial indicators as guidance schemes for attention enables definition of some hypotheses to test in usability studies.

1. *The 3D arrow has shorter response times than the bird's eye scheme.*
2. *The 3D arrow has less effect on lane deviation than the bird's eye scheme.*
3. *The bird's eye scheme has lower target detection errors.*

8.3.3 Experiment

Demographic Data

Twelve individuals, 10 males and 2 females between the ages of 22 and 49 (mean 27.8, standard deviation 13.9), participated in the experiment. All drivers were licensed and had normal or corrected normal vision. Drivers were aware of the nature of the research prior to their participation.

8.3.3.1 Physical Setup

Testing Environment

Both visualization schemes were tested in the initial stationary driving simulator of LfE (see section 5.1.1, page 81). The HUD visualizations were shown by a second appropriately calibrated projector on the same screen as the 3D world scenery.

Alert Targets

To test targeting quality of the presentation schemes, 20 targets were defined around the car in the driving simulator. Different approaches were preevaluated, ranging from real objects over images of objects to plain numbers. Numbers were chosen as they are easily identified, avoiding lengthy object identification. Thus only the time required for interpretation of the presentation scheme contributes to the reaction time. The car therefore was surrounded by 20 evenly spaced, letter-sized sheets of paper. They were arranged around the car in height of the driver's head. The sheets were labeled with numbers between 1 and 20, distributed randomly. Fig. 8.3 shows the paper sheets to the back and right of the driving simulator.

Figure 8.3: Driving Simulator surrounded by Numbered Sheets at Eye Level

8.3.3.2 Experimental Design

Within-subject Design

A within-subject design [30] to test the two visualization schemes was used. Before the experiment the participants had to fill out a demographic questionnaire and were instructed about how to operate the simulator.

Familiarization

The experiment itself consisted of two phases. In the first, participants could familiarize themselves with the overall setup of the driving simulator and the behavior of the simulated car. They were asked to drive down a rural road at usual speed following traffic rules and staying in the lane.

In the second phase, the simulator was augmented with visualizations of imminent danger. The participants were expected to look as quickly as possible in the indicated direction and read out loud the number of the paper sheet that they saw. This procedure was performed twenty times for each of the two visualization schemes. Target Detection Phase

After the experiment participants had to fill out a questionnaire reporting on their experiences with both visualization schemes. In total, participation in the experiment took about an hour. Final Questionnaire

Independent Variables The independent variable of the within-subject experiment was the selected *visualization scheme*. All participants were exposed to both visualization schemes. Six of them started with the 3D arrow, the other six with the bird's eye view. In each case, 20 alert situations were generated for each scheme. The sequence of alert positions was permuted in each session. Testing the Schemes

Dependent Variables Some dependent variables were used to quantify the quality of the visual schemes. Objective Measures

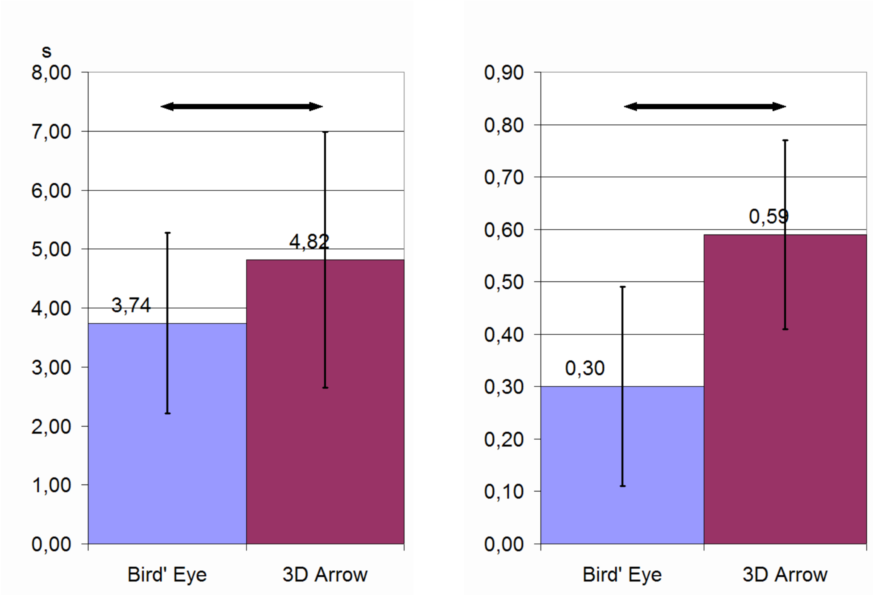
The *response time T* is the time it took a driver to react to a visualized alert, i.e., the time difference between the presentation of an alert in the HUD and the participant's answer by shouting out the number of the corresponding paper sheet. The response time helps to determine the intuitiveness and the cognitive load required by each of the presentations schemes. Response Time

The *error quotient E* is the percentage of wrong answers. The error quotient helps measure which of the two presentation schemes enables the participants to determine the place of danger more reliably. Error Quotient

The average mistake describes how many sheet positions participants were off when they announced sheet labels that did not correspond to the true position of the imminent danger. Because different positions of the sheets along the side of the car result in small angular differences for the 3D arrow in front of the car, the average mistake is weighted by the angular differences between each two neighboring paper sheets and the 3D arrow. This gives the *weighted average mistake M*. This variable is an indication of accuracy. Average Mistake

The *average lane deviation A* measures how well drivers were able to stay on the road while having to determine the direction of imminent danger. It is characterized by the average distance of the car from the center of the lane it is occupying in the simulation, and is an indicator of the amount of distraction imposed on the driver. Lane Deviation

Subjective Questions After the experiment the drivers were asked to fill out a questionnaire to describe their *subjective judgment* on the two visualization schemes. They were asked which kind of presentation they liked more and which one was easier to use. Furthermore, they were asked by which of the two visualization schemes they could determine the paper sheet faster and more precisely. Subjective Impression



(a) Response Time (b) Error Quotient

Figure 8.4: Diagrams showing the Objective Results

8.3.4 Results and Discussion

T-Test

Data was gathered from the twelve subjects, with 20 dangerous situations for each variant, resulting in 480 records, 240 for each visualization scheme. A T-Test for paired samples was used to analyze the data.

8.3.4.1 Objective Measurements

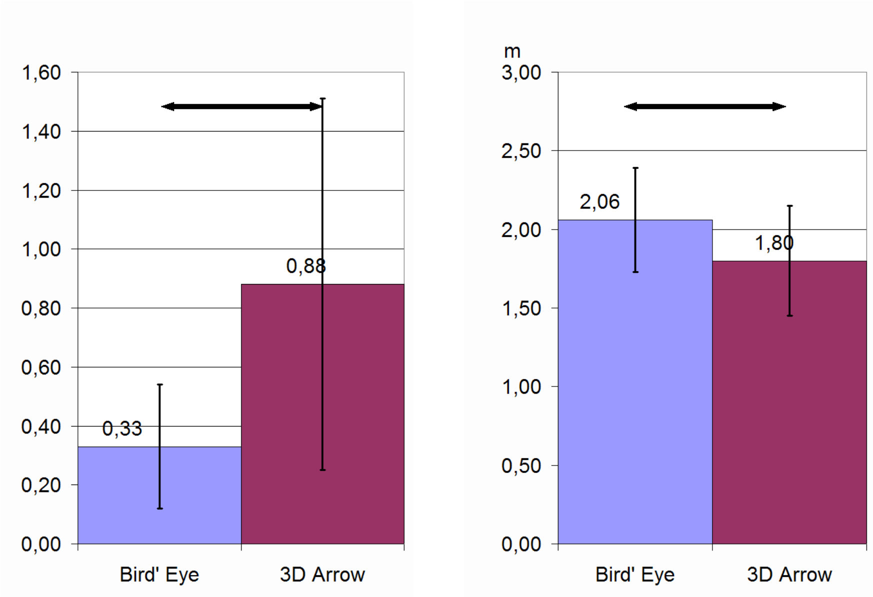
Objective Results

Table 8.3.4.1 and Fig. 8.4, 8.5 present the measurement results for the dependent variables with respect to both visualization schemes.

Measured variable	Mean		Std deviation		Significance
	Bird	Arrow	Bird	Arrow	
Response Time T [s]	3.74	4.82	1.53	2.17	0.02
Error Quotient E	0.3	0.59	0.19	0.18	0
Average Mistake M	0.33	0.88	0.21	0.63	0.006
Lane Deviation A [m]	2.06	1.80	0.33	0.35	0.016

Complicated Perception

Reaction Time The participants' reaction time T was significantly faster for the bird's eye presentation. The participants could directly get a feeling for the orientation of the alert by looking at the bird's eye view. So they could quickly name the corresponding number. The monoscopic 2D projection of the 3D arrow might be the reason for this result. The schemes were rendered on the projection plane in front of the car rather than in a stereoscopic display, thus complicating perception of the 3D shape of the arrow.



(a) Average Mistake (b) Lane Deviation

Figure 8.5: Diagrams showing the Objective Results

Error Quotient and Average Mistake The error quotient E and the average mistake M indicate a significant superiority of the bird's eye view. The direction of the arrow is not as precisely determinable on the HUD as the octagon in the bird's eye view. Due to the different viewing angles the positional resolution of the bird's eye view is higher than that of the 3D arrow. Different positions of imminent danger along the side of the car result in small angular differences for the 3D arrow when seen from the driver's perspective. Fig. 8.6 shows this effect in a sketch. There is further indication that drivers mentally translated the arrow from the position in front of the car to their own eye position inside the car thereby looking too far backwards. Fig. 8.7 illustrates this aspect.

Complicated Direction Interpretation

Lane Deviation The average lane deviation A indicates the average distance to the center of the lane. It showed significantly worse results for the bird's eye view than for the 3D arrow. This may be due to the larger mental effort required of the drivers in the bird's eye presentation in order transform from their own viewing frame into the bird's frame and then back to the frame of the car to find the correct sheet.

Less Mental Transformation

8.3.4.2 Subjective Answers

The questions in the questionnaire allowed personal estimations between 1 (best) and 6 (worst) in German school marks. The results of the subjective answers are shown in table 8.3.4.2 and in Fig. 8.8, 8.9.

German Grading System

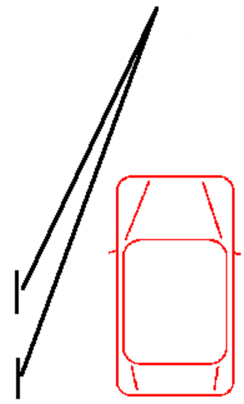


Figure 8.6: A sketch for a sharp angle in the rear side area of the car by use of the pointer device

Measured variable	Mean		Std deviation		Significance
	Bird	Arrow	Bird	Arrow	
Preference	2.00	4.00	0.45	1.10	0.00
Ease of use	1.75	3.83	0.45	1.11	0.00
Speed	2.00	4.00	0.85	1.54	0.04
Precision	1.83	4.00	0.72	1.28	0.00

Bad Impression of 3D Arrow

The table indicates that for all measured variables, participants fare significantly better with the bird's eye view than with the AR-based 3D arrow. The 3D arrow gave a negative impression due to its current flat presentation on a projection screen, as discussed above. Thus the results are probably strongly influenced by inadequate display technology and not an inherent function of the visualization scheme itself.

8.3.5 Summary of Pilot Study

Bird's Eye View Outperforms

Investigating the significant results of the objective measures, the bird's eye scheme outperforms the 3D arrow in response time, error quotient and mean error. The 3D arrow scheme only gives better results for the lane deviation.

Hypotheses

Comparing these results to the defined hypotheses, the following validations can be considered. Hypothesis 1, stating shorter response times for the 3D arrow scheme, must be rejected. Hypothesis 2, stating less effect of the 3D arrow scheme on lane deviation, is validated. Hypothesis 3, assuming lower target detection errors for the bird's eye scheme, can also be accepted as true.

Further Investigation

Although egocentric visualization aides have proven superior to exocentric schemes for local guidance tasks in other scenarios, the pilot study could not uphold this finding. Yet, it would be premature to draw conclusions from these findings since the driving simulator may not have been presenting all relevant aspects realistically enough.

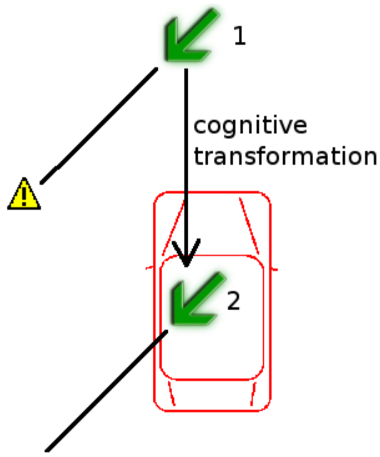


Figure 8.7: Sketch for the cognitive transformation of the pointing scheme. Arrow 1 shows the real position and arrow 2 the transformed one

Further Development

Improvements on the driving simulator, specifically the HUD, will reveal what impact is generated by the inclusion of more realistic presentation technology. Furthermore, different appearance patterns of the arrow to help drivers determine the correct orientation more easily can increase the results of the 3D arrow relative to the bird's eye scheme. To finally clarify the ambiguity stemming from the cognitive transformation that was noticed by some participants, a mount for the 3D arrow requires investigation.

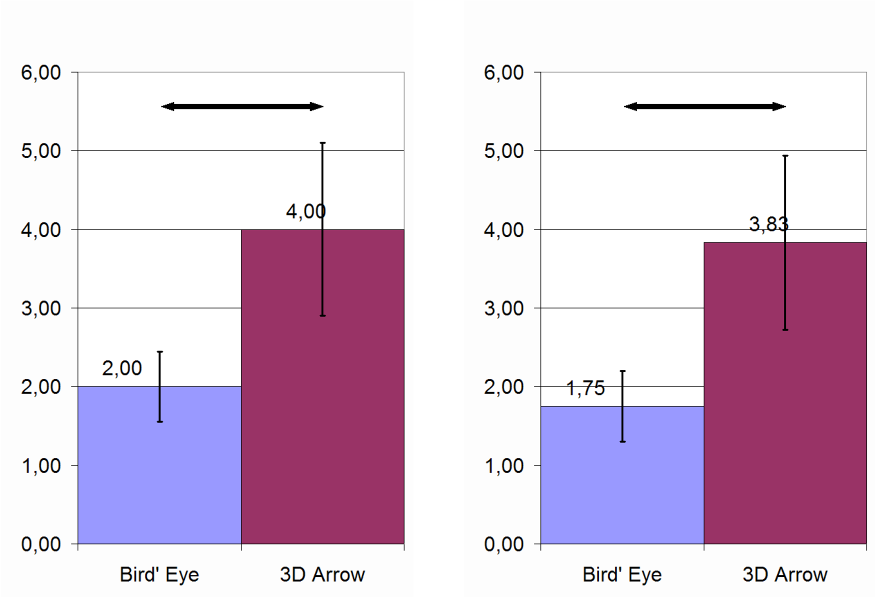
8.4 Main Study

Revealed Issues

The initial experiment was conducted in a driving simulator which did not have a real Head-up Display. Instead, HUD-like augmentations were shown on the same flat projection wall as the landscape of the simulated environment. In case of the perspectively rendered 3D arrow, its planar projection and its basic shape, a cone and a cylinder, made it difficult for drivers to perceive the orientation of the arrow. In some cases, the experiment revealed a mental translation of the floating arrow from its original location 3 m in front backwards to the position of the driver's head. Except for its virtual appearance about 3 m in front of the driver's head, it had no further fixation to the simulator car, complicating the estimation of the exact position of the arrow. Therefore, it was very difficult for drivers to obtain a good mental picture of the place of the imminent danger towards which the arrow was pointing. As a result, drivers looked too far backwards and generated higher errors in determining the correct direction than with the bird's eye map.

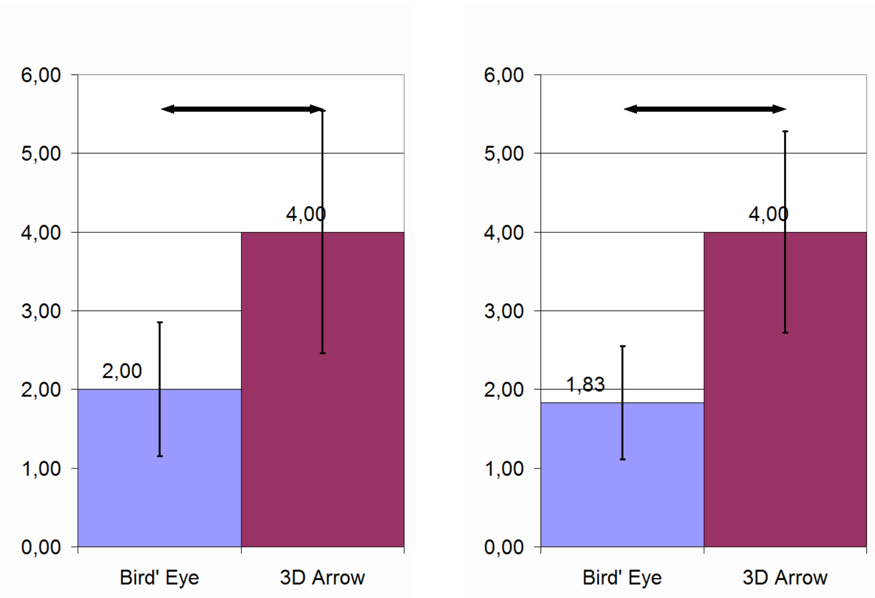
Clarification

To clarify these ambiguities and imprecise designs, several extensions were made to the concept and a new study was conducted. To increase comparability between both presentation schemes, the indication principle was made unique. In the main study only direction indication was used, because AR schemes can operate only on this principle. Thus the bird's eye scheme was modified to meet these constraints. The 3D arrow scheme was extended to enhance spatial perception and direction indication. Animations were added to the pre-



(a) Preference (b) Ease of use

Figure 8.8: Diagrams showing the Subjective Results



(a) Speed (b) Precision

Figure 8.9: Diagrams showing the Subjective Results

sentation schemes to enhance the impression of urgentness and, in case of the 3D arrow, to enhance the spatial perception. To also investigate the effects of spatial sound on the indication of directions, the study was conducted with and without spatially encoded acoustic presentation schemes. Finally, a real large scale HUD was built to place the focal plane of the HUD spatially decoupled from the projection wall.

Main Study Structure

The following sections report on the extended presentation concept and the extension of the acoustic modality. The sections then describe the construction of the HUD and the experiment. The section of the main study closes with a summarizing discussion of the results.

8.4.1 Presentation Concept

Direction Indication

The extended visual presentation concept with two visualization schemes, the birds eye view and the 3D arrow, based both schemes on the compass metaphor. Incorporating the indication of the direction in both visualization schemes maintains comparability for the evaluation and the correct analysis. Otherwise it would not be possible to attribute certain influences exactly to the effects on objectively measured variables.

Visual and Acoustic Issues

The first following section illustrates the visual part of the presentation concept, while the subsequent section investigates acoustic issues.

8.4.1.1 Visual Presentation Concept

Intuitivity and Simplicity

Generally intuitivity and simplicity are important for the design of visualization schemes. Visualization schemes must not be overloaded with details, but use an easy design and they must be easy to understand [103].

Animation

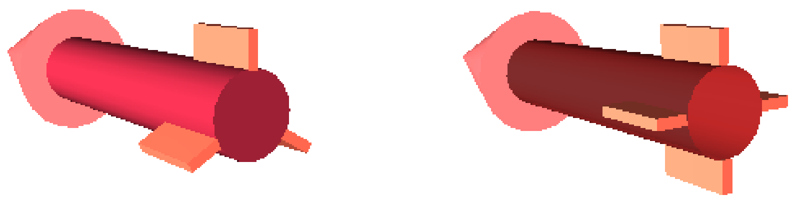
Both visualization schemes are animated to appear urgent. Animated icons are perceived better and therefore are more suitable for immediate alerts because they attract the direct attention of the driver [99].

Attaching Fins

3D Arrow Warning Scheme The first visualization scheme extends the 3D arrow floating in front of the driver's head which points towards the direction of the danger. The direction of a simple 3D arrow made out of a cone and a cylinder is difficult to interpret in its direction, when it is pointing directly forward or backward. Attaching fins at the rear-side of the arrow resolves this ambiguity. After creating mock-ups with three and four equally distributed fins, the three-finned approach was selected. For the three finned approach (see figure 8.10(a)), two fins (which are visible in every rotational state of the 3D arrow) always aim into different directions from the arrow pole and at least one is not aligned along the line of sight. Therefore perceptibility of the direction is increased. For the four finned approach (see figure 8.10(b)), each two opposite fins are aligned along the same axis and only convey the spatial alignment of this axis. Fig. 8.10 shows both types of 3D arrows and illustrates the alignment of the fins.

Mounting on a Pole

A further problem in identifying the exact direction is given through the floating of the 3D arrow. The location of the floating arrow in front of the driver is at the distance of the front bumper. The exact placement is unknown to the driver. Some test participants therefore



(a) A 3D arrow with three fins - each fin is oriented in another direction

(b) A 3D arrow with four fins - two opposite fins are aligned along the same spatial axis

Figure 8.10: Different Variants of Fins on a 3D Arrow

translated the arrow to the position of their own head. Fig. 8.7 above showed this in a sketch. As a result, the imminent danger is searched for in a too far backward orientation. To avoid any ambiguity about the exact location, where the 3D arrow is, a vertical pole was attached to the arrow. From the driver's perspective this pole seems to be mounted at the front of the car. The focal distance of the virtual image in the HUD was placed at the same distance placing the virtual image of the HUD at exactly the virtual distance of the presentation scheme.

Centered Mounting

AR visualizations must not cover large areas in the windshield, because obstacles in upcoming traffic could be occluded. A minimal volume for indicating various directions of the arrow is reached by rotating the arrow around its midpoint rather than its back end (as in first study). The arrow is mounted accordingly on the pole. Fig. 8.11 shows the 3D arrow from the driver's point of view.

Enhanced Spatial Perception

For enhanced attentional capture and increased spatial perception of the direction of the arrow, a short animated rotation was implemented. The 3D arrow appears in front of the driver, fixed to the pole. Initially it is pointing in a direction that is $45\,^\circ$ off from the direction of imminent danger, oriented forward. The arrow then starts rotating horizontally by $45\,^\circ$ into the direction of the imminent danger. This animation takes $0.25\,s$. The rotation around the horizontal axis has been chosen, because it is the most familiar rotation for ground traffic. All other rotations, would include vertical rotations and therefore require more spatial interpretation.

Keeping Comparability

Bird's Eye Perspective Warning Scheme A bird's eye perspective is capable of displaying locations close to a car. To suppress the effect of incomparability of different visualization approaches, as a location indication would manifest w.r.t. to a directional indication, the compass metaphor was applied for the design as well. Thus, the second presentation scheme uses a bird's eye sketch of the car with a 2D arrow pointing into the direction of the upcoming danger.

Avoiding Ambiguity

The arrow has been placed in front of the car silhouette and overlaps slightly with the car to avoid the impression that the arrow might be pointing towards the front of the car – which might be conceivable as a malfunctioning front light. For the same reason the silhouette is shown in green, avoiding the impression that existing damages on the car are being

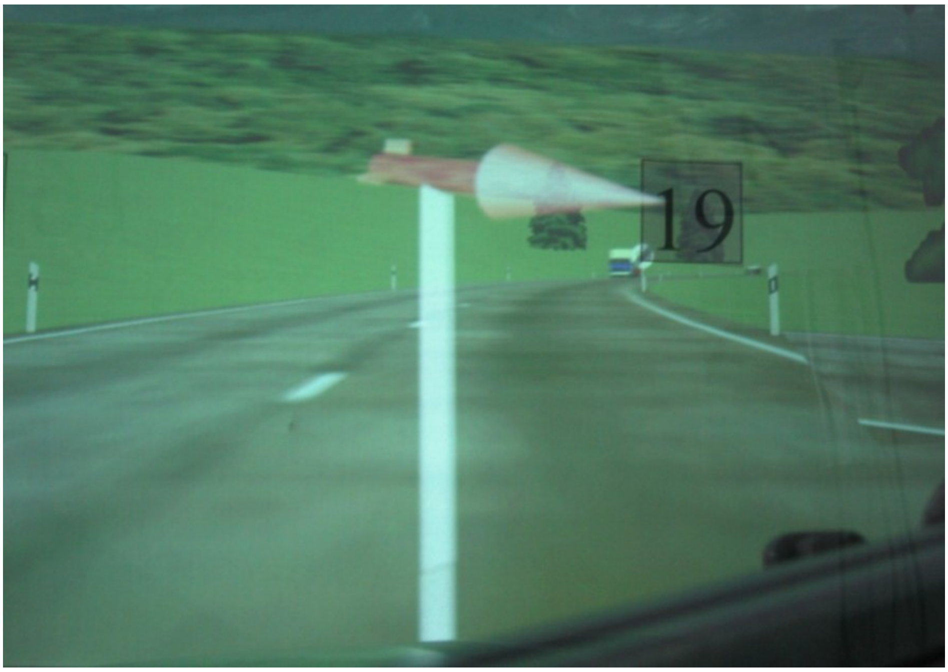


Figure 8.11: The 3D Arrow pointing to the back Right

indicated. The arrow has been placed in front of the driver's position rather than along the central axis of the car. In principle, the bird's eye presentation scheme is almost a projected visualization of the 3D arrow scheme, seen from above. All these design decisions attribute to the generation of a spatial relationship between the arrow and the car, without indexing the car itself. Fig. 8.12 illustrates the appearance of the bird's eye perspective from the driver's point of view in the HUD.

Capturing Attention

While the warning scheme is active, it is blinking at a rate of four Hertz, following the recommendation of Lerner [102] to get the driver's attention.

8.4.1.2 Guidance Using the Acoustic Channel

Multi-modal Approach

The auditory channel offers a means for providing additional directionally encoded information. A multi-modal extension with 3D encoded sound supports acoustic guidance. It has been well established that is useful to announce critical information on as many sensory channels as possible [35, 103]. For warnings which require fast reactions, abstract sounds are preferred to the use of speech indicators [99]. 3D encoded warning sounds are well suited to control the attention of car drivers and to give them further hints regarding the position and direction of an imminent danger.

Location or Direction

It is not clear whether a warning signal is a location identifier or a directional indicator. If sound specified a location, the presentation concept would not be affected, but the experiment could not be executed because two independent variables would influence each other. It would remain unclear, whether the indication of direction of the visual presentation scheme was supported by sound or whether the location indicating property of sound

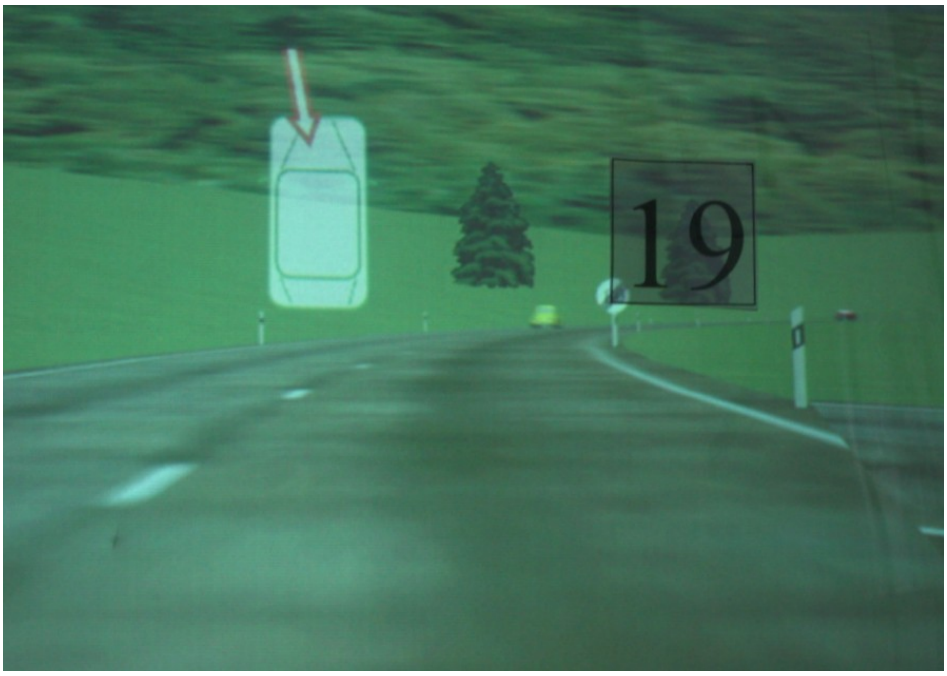


Figure 8.12: The Bird's Eye Perspective pointing behind the Car to the right

increased the perception. To keep the experiment objectively measurable, this ambiguity of sound has to be discussed. In general, sounds are always hybrids of location and direction indication. On the one hand, a sound originates from a certain direction and therefore indicates this specific direction. For familiar sounds, distance becomes indirectly specified through loudness and frequency of tones. Furthermore sounds are reflected by objects in the environment. Such secondary sounds enable 3D location estimation for the listener. Although a warning sound is not an explicit direction indicator, its use as a directional warning scheme can be considered valid when secondary sound reflections are suppressed.

Spatial Localization

The auditory channel provides two mechanisms for spatial localization [27]. First, for frequencies below 1500 Hertz, localization works through the perception of the differential delay between the left and the right ear. The brain analyzes phase differences of the waves reaching the ear and infers the corresponding direction of the sound. The wave length of the sound has to be longer than the distance of both ears, which causes the restriction to frequencies below 1500 Hz. The second locating mechanism uses perception of intensity for frequencies above 1500 Hz. Shadowing and attenuation effects of the head generate different levels of the waves in the ears, from which the brain estimates the corresponding direction. Only wave lengths that are shorter than the width of the head are attenuated. Frequencies near 1500 Hz are difficult to locate, because both location mechanisms reach physical limits.

Frequencies Attributing to Directions

Another phenomenon of sound is that certain frequency levels are attributed to certain directions [101, 27]. Frequencies around 300 Hz and 3000 Hz seem to be in front, while frequencies around 1000 Hz seem to come from the rear. Fig. 8.13 shows these dependencies in a graph.

Sound Design

Therefore a warning sound composed of eight harmonic frequencies, 600, 1000, 1400, 1800,

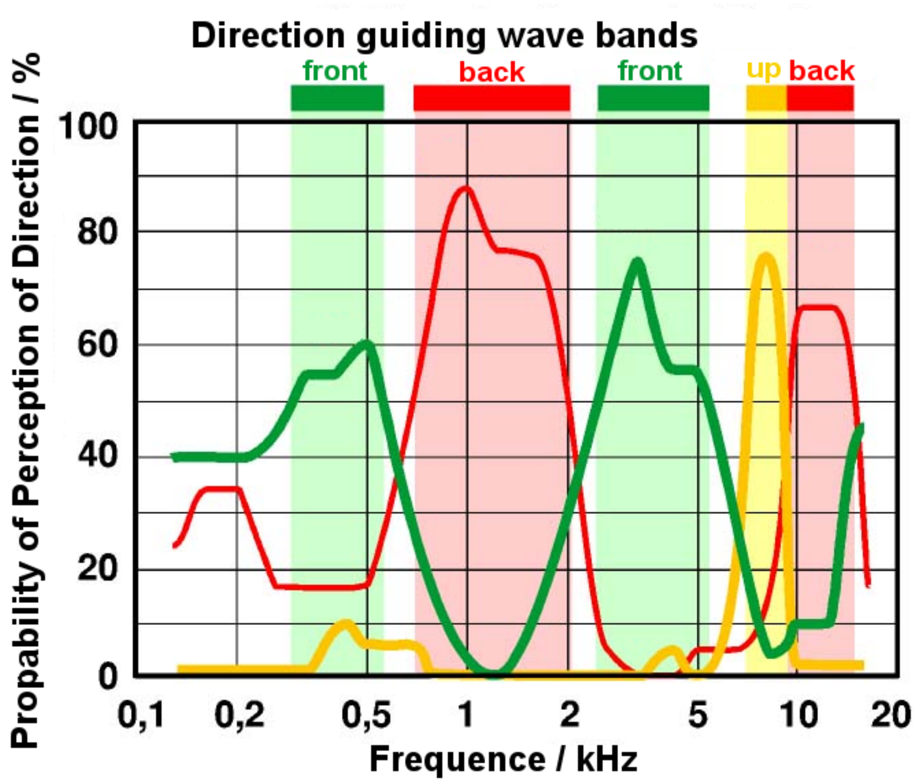


Figure 8.13: Relationship between acoustic frequency and human understanding of relative direction; adapted from [26]

2200, 2400, 2800, 3200 Hz [67] was designed. The frequencies above 2200 Hz were intensified to satisfy the requirement for high urgency. The use of frequencies below and above 1500 Hz enables both locating mechanisms. This mixture also compensates for unconscious association with certain directions.

The sound has been modeled with a periodicity of 4 Hz [102], to be synchronized with the blinking of the visual warning scheme. Synchronicity

8.4.2 Hypotheses

The extensions to the visual presentation schemes and the incorporation of spatial sound enable definitions of hypotheses for the main study:

1. *The 3D arrow has shorter response times than the bird's eye scheme.*
2. *The 3D arrow has less effect on lane deviation than the bird's eye scheme.*
3. *Both schemes have no difference in target detection errors.*
4. *Acoustic schemes increase reaction time*

5. *Acoustic schemes reduce target detection errors*

8.4.3 Experiment

Demographic Values

The experiment was executed with 24 participants none of which had participated in a similar study. 14 participants were male, 10 participants were female. The average age was 39.2, the standard deviation 13.3, and the largest group was between the age of 46 and 55 years. The youngest participant was 20 years old, the oldest 60 years. The subjects were paid 15 Euro for their participation.

8.4.3.1 Physical Setup

Test Environment

The presentation schemes were implemented and set up in the test environment in the initial version of the fixed-base driving simulator (see section 5.1.1, page 81). To generate the spatial sound, the corner speakers of a Dolby 5.1 sound system were installed in a modified dashboard and on top of the backrest of the backseats.

Targets

As in the initial study, the car was surrounded by 20 evenly spaced, letter-sized sheets of paper with a new distribution of the numbers.

Separating HUD and Scenery

The approach of the first study to project HUD visualizations onto the same projection wall as the landscape scenery complicated spatial perception of the alignment of the shape. The 2D image of the 3D object was projected onto the same projection wall as the 3D world scenery. The participants had to mentally reconstruct the 3D shape from the 2D image. This worked acceptably well for objects that were associated with other objects, such as another car, whose external shape is familiar in the context of roads and the overall environment. Additional objects like the initial 3D arrow without fixed attachment to the car were more difficult to interpret since they should not be associated with the physical projection wall.

Spatial Decoupling

Spatial decoupling of HUD presentations and virtual scenery is the way out of this issue. Placing virtual objects, where no associable real object such as the projection wall exists, increases volumetric perception of the virtual 3D objects. To achieve this the same approach as car manufacturers do with their HUDs was used, see section 2.3.3 on page 35 for details.

HUD Construction

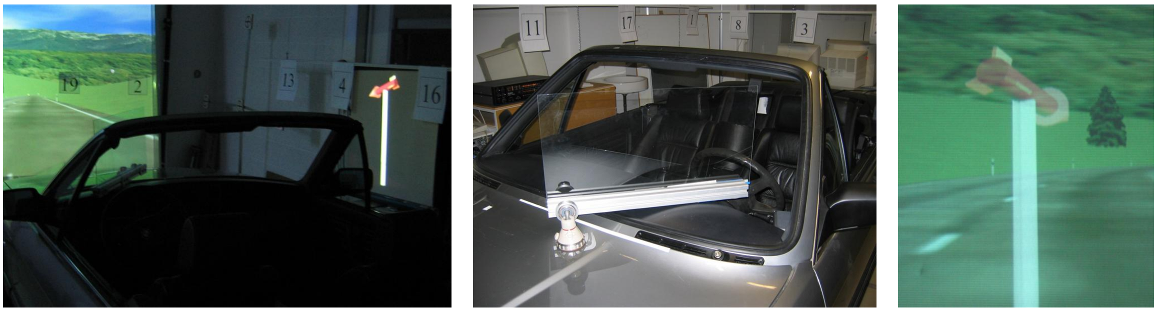
The setup requires a larger field of view than available HUDs provide. Consequently we built a specifically designed HUD. A second projection wall besides the right side of the car was placed where it was almost covered by the right A-pillar from the driver's point of view (see figure 8.14(a)). A flat glass plane in front of the driver acted as a combiner (see figure 8.14(b)) and mirrors the augmented objects into the real environment. All distances between the second, smaller projection wall, the combiner and the driver's eyes summarized result in a focal image plane at about 2 m in front of the driver, creating the impression that the arrow is mounted at the front bumper (see figure 8.14(c)).

Equal Distances

This depth is exactly the depth, at which the 3D arrow appears to be mounted to the front bumper. To intensify the 3D depth perception the imaginable alignment to another object is generated. Additionally, 3D perception is enhanced by size relationships to the well known car and on the other hand, the superimposed 3D arrow is decoupled in depth from the projection wall in 3 m distance.

Appropriate Calibration

The second projector and the rendering system for the HUD screen was appropriately



(a) Emergence of the HUD-Image (b) HUD-Combiner (c) Superimposed Scenery

Figure 8.14: Construction of the Head-Up Display

calibrated to be combined with the projector of the driving simulation that shows the superimposed scenery from the general driver's head position in the car.

8.4.3.2 Experimental Design

Familiarization Phase

After filling out a demographic questionnaire, the participants had a test drive of about 10 minutes to familiarize themselves with the handling of the stationary driving simulator. Afterwards they were sequentially confronted with each of the warning schemes pointing forward, sidewards and backward, so that they got a first impression of the presentation schemes.

Testing Phase

In the next step the objective measurements were performed. A within-subjects design [30] was applied for the experiment. All 24 participants were exposed to all four presentation schemes: bird's eye perspective and 3D arrow, both without and with 3D sound. Groups of six participants each started with a different presentation scheme. The follow up schemes also were permuted for each group accordingly. In each case, 20 alert situations were generated for each scheme. The sequence of alert positions was permuted in each session.

For each of the four presentation schemes, the subjects drove for about 15 minutes on a course within a rural landscape. The experimenter activated each of the 20 different directional indicators in randomly permuted order. The subjects then had to react to the presented alert by turning their heads in the perceived direction of imminent danger and reading out loud the number of the closest paper sheet. The time from activating an alert to task completion by the subject was recorded.

Final Questionnaire

After the objective measurements the participants had to fill out a subjective questionnaire.

Four Variants

Independent Variables The selected presentation scheme was the independent variable in the within-subjects design. The presentation schemes were: the bird's eye perspective and the 3D arrow, both without and with 3D sound.

Motion Effects

Objective Dependent Variables During the tests, *speed* and *lane deviation* of the car were recorded in a protocol file at a frequency of 30 Hz. Speed changes and the lane deviation are indicators of how much drivers are distracted by the presentation schemes of the alerts, since their interpretation adds a secondary cognitive load on drivers – in addition to the primary driving task.

Response Time

The protocol recorded additional discrete tokens of the points in time when a presentation scheme was activated and when the identification of a paper sheet was accomplished. The time differences describe the *response time*. This variable is the most important objective measurement, because in case of a dangerous situation, the driver's reaction time is more important for avoiding a time critical accident than any minor mistake in keeping the lane or keeping speed.

Targeting Errors

The experimenter wrote down the spoken-out number of each paper sheet in a written protocol for each participant, together with the correct number, i.e. the number that was used for generating the alert. From this data, the *average mistake* and the *error quotient* were computed. The average mistake specifies by how many paper sheets an answer was off in comparison to the correct paper sheet. The error quotient counts the number of wrong answers relative to all exposures. Both variables are indicators for the spatial accuracy of the presentation schemes.

Subjective Grading

Subjective Questions The final questionnaire covered the subjective impression, the participants had during and about the experiment. The subjects had to answer the following four questions, grading them according to German schools grades from 1 (best) to 6 (worst):

- How much did you like a certain variant?
- How well could you deal with it?
- How quickly could you nominate the corresponding paper sheet?
- How exactly could you identify the paper sheet?

These four self-appraisals had to be filled out for all four presentation schemes.

The session ended with a final question aimed at ranking how much participants were pleased with the four presentation schemes with respect to each other.

8.4.4 Results and Discussion

Results Presentation

The following section reports on computed results. The results are reported as described in section 2.4.4, page 48. The text discussing the results also shows minimum and maximum values.

8.4.4.1 Objective Measurements

Analysis

Objective measurements were gathered from 24 subjects for four times 20 dangerous situations, resulting in 1920 records, 480 for each visualization scheme. Significances were computed for all measurements, given as α-values. The significance niveau is $\alpha = 0.83\,\% =$

0.0083. A one way analysis of variance with Bonferroni-correction [29] was used for analysis. The Bonferroni-correction adjusts the significance niveau to the possible number of combination of pairs. The four variants of the experiment allow six combinations, therefore dividing a general significance niveau of 0.05 by a value of 6 which results in $\alpha = 0.0083$.

Response Time The response time indicates how long the subject needed from the first appearance of a presentation scheme until they nominated a paper sheet. The aggregated results for the reaction time can be seen in table 8.1 and in Fig. 8.15. The 3D arrow presentation scheme with sound achieved the best results with a mean of 2.66 s (std.dev 0.66 s), followed by the same variant without sound (mean 2.93 s, std.dev 0.94 s). The next best reactions with a mean of 3.32 s (std.dev 0.93 s) was the bird's eye presentation scheme with sound. The slowest variant was the bird's eye presentation scheme without sound (mean 3.77 s, std.dev 1.46 s). The differences are significant, except for the pairs that only differ in having sound or not.

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.001	0.049	0.006
	Bird's eye			0.000	0.068
with sound	3D arrow				0.000
	Bird's eye				
Mean [s]		2.93	3.77	2.66	3.32
Std.dev [s]		0.94	1.46	0.66	0.93

Table 8.1: Response Time

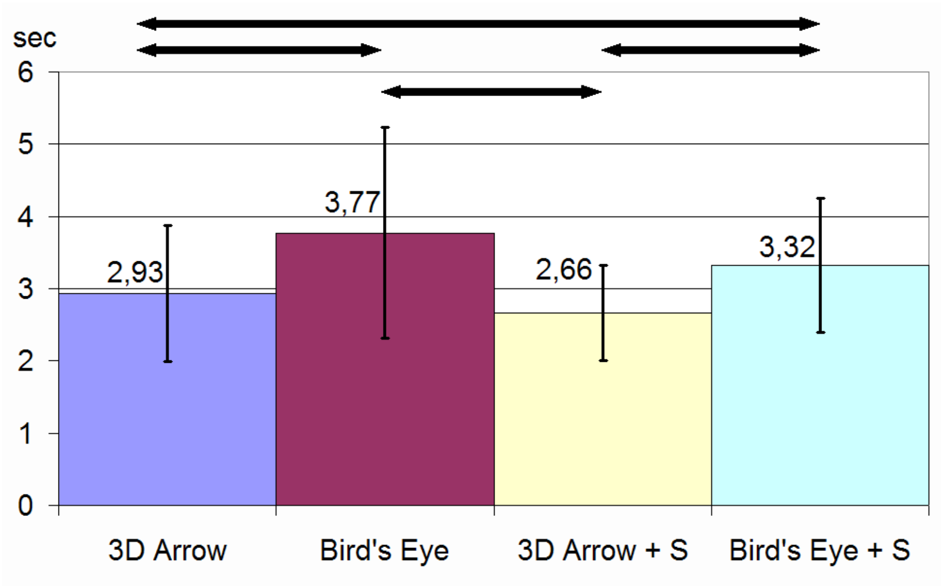


Figure 8.15: Response Time

The longest reaction time was 7.89 s in the bird's eye perspective presentation scheme. The shortest reaction time was 1.65 s under the 3D arrow with sound.

For the response time, the 3D arrow scheme is superior to the bird's eye scheme and each time the variant with sound is superior to that without sound. Thus sound serves its purpose to increase attentional capture. Especially the number of very slow reaction times is reduced dramatically by use of acoustic signals.

The 3D perception time of the arrow is reduced by decoupling it from the projection wall. Thus a monoscopic Augmented Reality presentation like the 3D arrow, that is placed in free space in front of the driver is easier to perceive in its 3D shape than one that is projected onto a projection wall. This fact must be taken into account for further driving simulator experiments.

Average Mistake The average mistake indicates how many paper sheets a participant's answer was off from the correct paper sheet. The average mistake for the 3D arrow is minimally lower than the average error for the 3D arrow scheme with sound (0.71 to 0.73, with std.dev 0.34 without sound to 0.32 with sound). Both birds eye schemes yielded worse results than the 3D arrows. The variant with sound proved to be the slightly better one (0.83, std.dev 0.33). The worst result were computed from the pure bird's eye presentation (0.94, std.dev 0.68). None of the results is significant. The detailed collection of the results can be found in table B.9, see section B.2.1, page 254 in the appendix.

Transformation into the bird's eye perspective and back into the egocentric perspective seems to increase angular errors. Future ADAS systems should thus strive for keeping subjects within their own frame of reference. Furthermore the use of a pole to fix the 3D arrow on a certain position prohibits the potential mental translation of the driver's position in the car. The results show that sound generally does not increase accuracy, but in case of the bird's eye scheme, sound can reduce large mistakes in interpreting directions.

Error Quotient The error quotient shows how often the participants failed to name the indicated paper sheet. Again, the 3D arrow without sound yielded the best results with an error quotient of 0.48 (std.dev 0.13), closely followed by the same variant with sound (error quotient 0.52, std.dev 0.14). Both bird's eye presentation schemes (with and without sound) achieved almost identical values of 0.58 for the error quotient (std.dev 0.14).

There are no significances in the paired error quotient comparison, as table B.10 shows in the appendix. Details can be found in section B.2.2, page 255.

The pure 3D arrow presentation scheme is the only one with a majority of correctly identified paper sheets. Here again, the use of the same frame of reference for the indication of the direction proves to be more useful than the exocentric perspective. Furthermore 3D perception is highly increased by placing the warning icons, especially the 3D arrow, onto a separate spatially decoupled display.

Mean Lane Departure Lane departures can occur in both lateral directions. To illustrate this, we use negative values for departures to the left and positive values for departures to the right side. These values indicate a departure from the perfect trajectory in the own lane.

The results are not significant and thus moved to the appendix, section B.2.3 on page 255 shows details in table B.11.

It is remarkable, that 19 from 24 participants (76 %) using the bird's eye presentation without sound left the perfect trajectory to the left, departing towards the opposite lane. All other variants had more evenly distributed values.

As in the previous experiment, lane deviation is lower for the 3D arrow. Executing the task of getting spatial orientation is easier in the driver's personal frame of reference.

Standard Deviation of Lane Departure We also computed the standard deviation of the lane departure values. The base values were taken out of the interval, a presentation scheme was activated until the number of the paper sheet was spoken out.

Table B.12 shows that the α-Values are too high for significances. The table moved to the appendix and can be found in section B.2.4, page 255.

The largest variation was 1.14 m on the test drive with the bird's eye presentation scheme with sound. The straightest road course with a variation of only 0.04 m was produced under the 3D arrow with sound.

As for the total lane departure, the standard deviation during detection of the paper sheet is minimized by use of the 3D arrow.

Speed Variation Speed variations indicate problems in dealing with a presentation scheme. No value is significant here, as table B.13 shows in section B.2.5 on page 256 in the appendix.

8.4.4.2 Subjective Measurements

The personal opinions were given according to the German school grade system, ranging from 1 (best) to 6 (worst).

How much did you like a certain variant? For the question *How much did you like a certain variant?*, the 3D arrow without sound reached the first position with a mark of 2.71 and a standard deviation of 1.20. It is followed by the bird's eye perspective with a rank of 2.92 (std.dev 1.14). The third place is reached by the 3D arrow with sound (3.04, std.dev 1.15). The bird's eye perspective with sound came to the forth place with a mark of 3.17 (std.dev 1.43). All results for this question are not significant (see table B.14 in appendix section B.2.6, page 256) because they exceed the significance niveau of 0.0083.

Most participants did not like the sound, they said the sound was annoying. This was due to the experimental nature of the study, where the participants were exposed to the sounds very often. As this sound will only occur in critical situations, annoyance due to repetition should be no problem.

How well could you deal with it? The question *How well could you deal with it?* brought the 3D arrow with sound to place number one with a mark of 2.67, standard deviation 1.27. It is followed by the same 3D arrow, but without sound (2.87, std.dev 0.99). With a larger offset, the bird's eye perspective follows with a mark of 3.29 (std.dev 1.23). The fourth place goes to the bird's eye perspective without sound (3.33, std.dev 1.17). No result is significant (see table B.15, section B.2.7, page 257).

Here the presentation schemes that use the 3D arrow are better than the bird's eye schemes. In all cases the variant with sound performed better than the corresponding one without sound.

How quickly could you nominate the corresponding paper sheet? The question *How quickly could you nominate the corresponding paper sheet?* resulted in the 3D arrow with sound on rank position number one with a mark of 2.50 (std.dev 1.18). The 3D arrow without sound yielded the second best result (2.79, std.dev 1.14). Place three in the ranking of this question is taken by the bird's eye presentation scheme with sound and a mark of 3.21 (std.dev 1.14). It is followed by the same scheme without sound and a mark of 3.63 with a std.dev of 1.01. Only one comparison is significant: the pair given by the bird's eye presentation and the 3D arrow presentation with sound, see table B.16(see section B.2.8, page 257 in appendix) for details.

The 3D arrow presentation ranked better than the bird's eye ones and every time the variants with sound were ranked better than the ones without.

How exactly could you identify the paper sheet? The fourth question from the questionnaire was: *How exactly could you identify the paper sheet?* The participants claimed that the identification of the respective paper sheet was most simple when an 3D arrow with sound indicated the direction. Here they ranked it to 2.70 (std.dev 0.95) in average. The 3D arrow without sound was the second best-ranked presentation scheme (2.83, std.dev 0.87). This is followed by the bird's eye perspective with an average mark of 3.17 (std.dev 0.87). α-Values never are significant - see table B.17 (section B.2.9, page 258 in appendix).

Ranking of Presentation Schemes Finally, the participants had to rank the presentation concepts directly. They had to specify an order, listing which presentation scheme they thought was best, second best, second worst and worst. The 3D arrow with sound (2.13, std.dev 1.15) received the best placement, followed by the pure 3D arrow averaged to 2.33 (std.dev 1.09). On position three, the bird's eye presentation scheme with sound was placed with 2.67 (std.dev 0.96), while the bird's eye presentation without sound earned the fourth rank with 2.88 (std.dev 1.19). Table B.18 shows that the α-values are above the critical threshold of 0,0083, therefore the results are not significant. The table can be found in the appendix in section B.2.10, page 258.

Summary of Subjective Results Summarizing all subjective measurements, the subjective order of the participants preferences states as follows:

1. 3D arrow with sound

2. pure 3D arrow
3. bird's eye presentation with sound
4. pure bird's eye presentation

The 3D arrow presentation is generally preferred, similarly the variant with sound.

8.4.5 Summary of Main Study

The main study enabled definition of a wider set of hypotheses. The results of the experiment allow the validation whether the hypotheses can be accepted or rejected.

Hypotheses

In contrast to the pilot study, hypothesis 1, assuming that the 3D arrow has shorter response times than the bird's eye scheme, now can be accepted as correct. Hypothesis 2, stating that the 3D arrow has less effect on lane deviation than the bird's eye scheme, in contrast to the pilot study now must be discarded. Hypothesis 3, that both schemes have no difference in target detection errors, is accepted because the analysis indicated no difference. Hypothesis 4, stating that acoustic schemes increase reaction time, can not be accepted, because the equal variants with and without spatial sound do not show a significant difference. Hypothesis 5, assuming that acoustic schemes reduce target detection errors, is discarded because the results do not indicate significant differences.

The approach to use AR in cars to assist in the driving task offers several possibilities. This leads to an important new field of research , analyzing the use of AR-based presentation metaphors in situations where users have to divide their attention between several spatially-based tasks. While managing the car and spatial relationships in the environment, the driver might not observe an imminent danger. Guiding a driver's attention in the own frame of reference is superior to a presentation in another frame of reference. Primarily detection times are significantly reduced, while other factors such as speed and lane deviation are better than in an exocentric warning scheme. In time critical situations, the reaction time is the most important factor for safety, so this is the most relevant achievement. Reducing the reaction time by concurrently reducing driver distraction is the main goal to achieve when testing spatial alerting systems. Furthermore, multi-modal warning presentations which use sound in combination with a visual scheme prove to be another improvement towards fast attention capture and towards minimization of misinterpretations of visual presentations.

Equal Frame of Reference

The findings are based on two major extensions to the pilot study. First, the use of a monoscopic HUD to present visual information that is registered in 3D. Second, increased perceptibility of the position and orientation of the 3D arrow.

Two Main Causes

The HUD which has been integrated into the driving simulator presents a monoscopic projection of the 3D arrow. Surely a stereoscopic HUD would further increase 3D perception significantly, but currently there seems to be no acceptable possibility to introduce such a setup in a real car. Instead, this approach realises an extended field of view.

Technological Demand

Another problem was identified in the design of the 3D arrow. Generally it is recommended to use a shape as basic as possible, but spatial perception requires some more details to enhance perception of spatial orientation. Extending the 3D arrow with fins as well as a short animation enhanced the perception of the orientation. Cognitive translations can be

Relative Mounting

avoided by attaching the arrow to a pole that virtually connects the 3D arrow to the car. In the experiment, the pole was very thick. Future evaluations should decrease the thickness of the pole, so that less of the driver's view is blocked.

Superior 3D Arrow

In contrast to the previous experiment, the main study can recommend the 3D arrow for use as a warning indicator specifying the direction of an imminent danger. Reaction times are significantly shorter and other objective measurements are comparable.

8.5 Summary for Guidance of Attention

Summary

Guidance of attention is a serious subject for time-critical environments, such as the automotive sector, where even a very short time intervals can determine about a serious accident. A general concept has been defined and investigated in a pilot study and the subsequent main study. Here, experiences in design and setup were incorporated and the results were refined. The results of both experiments thus can only be compared to a certain degree. This comparison can identify possibilities for future investigation of the concept of guidance of attention. Thus, both experiments are compared and in afterwards, future directions for investigation are illustrated.

8.5.1 Comparison between both Experiments

Improved Testability

Even though comparison between the pilot and the main experiment is only valid to a limited degree, this section relates the two experiments to each other. Limitations to a perfect comparison are the different participants with different age and the use of a constructed HUD for presentation of the optical presentation schemes in the second experiment. In addition, the pilot experiment did not take the difference of indicating a direction or a location into account. Only the driving simulator, the landscape and the test procedure were kept unchanged. These factors influence the independent variables of the studies and do not allow an analysis of individual reasons for the effects.

Overall Ranking

Five values of the objective measurements can be compared to the previous experiment. The most crucial value is the response time, the time people need to react on a certain trigger. All other measurable values, lane deviation, speed variation, error quotient and average mistake are less relevant and only indicate the driver's distraction. Comparing the reaction time between both experiments, the 3D arrow presentation with sound of the main experiment ranks best, followed by the same variant without sound. The next best ranked scheme is the bird's eye presentation with sound, followed by the variant without sound, both from the main experiment. The bird's eye variant from the previous experiment reached the second last place with almost the same reaction time as the bird's eye scheme of the main study. The worst reaction time was measured for the 3D arrow of the previous experiment. With respect to lane deviation, the 3D arrow of the main experiment ranked best. For all other measurements, speed variation, error quotient and average mistake, the bird's eye presentation of the previous experiment held its superiority, surely because it indicated the direct location of the imminent danger. But all three results are within the interval spanned by the two types of the previous experiment, shrinking down the distance between the different variants.

Subjective Ranking

There are four subjective questions in the previous experiment, asking which presentation scheme was *liked best*, could *dealt with best*, could *fastest name* and *exactly name the paper sheet*. In all four cases, the bird's eye view of the previous experiment resulted best with marks around a value of 2 (1 is best, 6 is worst), followed by both current experiments 3D arrow presentation schemes with and without sound with marks around 2.8. The next best are the bird's eye presentation schemes of the current experiment with marks in the area of 3.2. The worst results were attributed to the 3D arrow of the previous experiment, pointing to a mark of 4.

Non-Comparability

This comparison should be read with caution, because the previous experiment did not clearly deal with the topic of pure directional indication. The pilot study used direct location indication (bird's eye scheme), which is easier to deal with. Such a scheme is impossible to realize for the case of a egocentric presentation, when the target is not in the field of view of the driver.

Conclusions

The problem of direct or indirect location indication remains a problem which ADAS systems must compensate. If an ADAS system has to cover all possible locations with one presentation schem, egocentric information visualization has to fall back to direction indication. Such egocentric presentation, at least for the moment, seems to be an interesting alternative.

8.5.2 Future Direction of Investigation

Tethered Viewpoint

It has yet to be examined to what extent a tethered viewpoint, showing a 3D car and the relative direction from a lifted backward position could be used as a presentation scheme for informing a driver about certain dangers.

Glance-fixed Mounting

Further experiments should evaluate the effects of mounting the warning presentation scheme glance-fixed, so that it always remains near the driver's viewing direction. Drivers could then follow the 3D arrow until they look directly at the imminent danger. When the desired direction has been reached, the 3D arrow will point away from the driver, directly towards the critical location. The hypothesis is, that the results will provide further indications towards the superior usability of the 3D arrow. Such glance-mounted approaches will face the issue that the mounting on a pole, as introduced for the main study will no longer be possible.

Ambiguous Arrows

Further investigation of attentional guidance systems should consider integration issues into human-centered systems. The arrow scheme is already a widely used presentation scheme in the automotive sector and should not be used too often. Design considerations should classify frequency of application and types of mounting. Navigational arrows appear on the street and on road signs, they are thus location-fixed. Automotive navigation systems introduced symbolic navigation arrows. Such arrows somehow are car-fixed in their presentation. Any navigational arrows in general appear at crossings or forks. Arrows applied for warning and alerting systems in contrast can appear in any situation. Further investigation of the elementary behavior of such situations can facilitate the generation of an integrated presentation concept without ambiguities.

9 Towards Mobile Setups

Implementation of the *Sphere of Vision* and fundamentals for correctly registered information presentation in automotive setups

Aligned HUD

Some aspects of AR concerning usability criteria have been investigated in the previous chapters. Different concepts for ambient visualization of the physical behavior of the own car and for guidance issues of driver attention have been investigated. Experimental results indicate the potential of AR through transformation-free information presentation leading to reduced response times with no effect on or increased driving performance. Specifically the two studies investigating the guidance scheme for a car driver's attention in chapter 8 (page 160) with different approaches for visualization revealed the strong dependency to suitable presentation technology. Accurate alignment of the presented information is a strong factor contributing to the efficiency of AR presentation schemes. HUD systems therefore require mechanisms to appropriately render AR schemes parallax- and distortion-free at any distance. Contact-analog presentation working on the combiner principle therefore requires to know about the position of the viewer relative to the display to render the scheme correctly aligned in the right perspective.

Design Phase

Also during early laboratory system development, issues for the inspection of AR schemes arise. A new ADAS system concept may require presentation areas, where no HUD is available. The unavailability of displays either can apply for HUDs, when the display area of the available version is too small or for development teams, where only one can investigate an AR presentation at a time from the driver seat of a car. Then, specialized display systems must bridge the gap between collaborative experience of the AR schemes and the insufficient display technology. An implementation of the *Sphere of Vision* (see section 3.1, page 51) can bridge this gap between ADAS concept and HUD development. A portable TFT can visualize the AR schemes from every point of view to multiple persons at a time. Such a system allows for ergonomic testing of presentation schemes before large scale Head-Up Displays are available for real in-car environments. Thus an accelerated technology transfer is obtained, since parallel research on technology and human factors is enabled.

Sensor Development and Fusion

For the development of such multi-sensor systems, the foundation of ADAS systems, it is necessary to visualize representations of all levels of such data, starting with raw data from each single sensor up to fused data and interpreted contextual data. Such visualization is necessary for debugging purposes during the development process of perception systems. They will also become invaluable when cars with increasing sensor functionality are introduced into market and sensor (re)calibration becomes part of the daily production and maintenance routine since the correct operation of the sensors has to be evaluated or maintained on a regular basis. Visualization of sensor data also can bridge the gap between researchers in sensors and in HMI presentation concepts, thus leading to new ways of collaboration.

Common Issue

All three previous listed dependencies to AR ADAS systems have in common, that a combined tracking and software system must compute the actual viewpoint for correctly aligned perspective rendering of AR. Tracking data is required to know about the driver's head position which is a central variable in the computation of a correctly aligned image on the display, whether it is the screen in the HUD or a portable TFT.

Implementation of *Sphere of Vision*

My last contribution in context of this thesis is presented in this chapter. The chapter focuses on the implementation of the concept of the *Sphere of Vision* (see section 3.1, page 51). The *SensorVis* system [159] for experience of AR schemes and collaboration is developed to present any kind of spatial data superimposed to the real environment on a portable TFT. The system also supports an HMD for personalized experience and allows, if modified minimally, for usage in HUDs, when available in future. The internal setup for all kinds of displays, whether a portable TFT, a HMD or a HUD, is almost similar w.r.t. their spatial relationships.

Structure of Chapter

The chapter is structured as follows. The chapter reports on the presentation setup of the system that successfully displays live sensor data from a car equipped with a laser scanner. The system first has been developed in a laboratory to visualize recorded sensor data. Presentation takes place in a Head-Mounted Display (HMD), on a back-projection workbench and on a portable TFT. As a next step, the *SensorVis* system has been ported to a test vehicle. In a car, real sensory data can be presented directly where and while it is perceived. The HMD allows for a personal experience, while the TFT enables collaborative experience of the visualization schemes. The chapter reports on experiences with calibration of such setups, system internal data flows and tracking issues in the test vehicle. The data flow in the *SensorVis* system has been developed to meet the requirements of the mentioned presentation devices as well as the requirements of correctly registered HUDs. Tracking technology, excluded off the context of the thesis, has been incorporated as of-the-shelf components and only experiences in accuracy and stability are mentioned.

9.1 Related Work

Window into the World

Besides Feiner's window into the virtual and augmented world [55] as foundation for visualization systems for delimited areas of superimposed content, some applications in the automotive sector used virtual overlays for experiencing enhanced sceneries.

Superimposed Sceneries

Bock et al. [28] equipped a sedan with an optical see-through HMD for a vehicle in the loop application. While driving in a real world environment simulated traffic is displayed to the driver. Based on this simulation data advanced driver assistance systems can be evaluated economically and without endangering the test vehicle or other road users. A similar concept is sketched by Regenbrecht et al. [125] who developed a driver safety training system with overlaid virtual content. Both, the trainee and the trainer wear head-mounted displays with video see-through capabilities which are tracked by a combination of fiducial and inertial systems. In a carefully controlled environment, the trainee learns to cope with adverse road and weather conditions and simulated accident situations rarely found in everyday life.

Navigation Information

Another Augmented Reality (AR) application within an automotive environment is navigation. Narzt et al. [117] for example present advanced navigation information to the driver by superimposing the recommended route or a virtual guiding vehicle with the image of a fixed camera.

9.2 Hardware Setup

Demand for Tracking

To present the sensor data correctly aligned, a tracking system was required. A system similar to the laboratory system has been integrated into a test vehicle. This tracker delivers orientation and position data of the visualization devices to the rendering system. The system also could track a user's head, if a tracking-target were attached.

9.2.1 Lab Setup

Pre-recorded Scenes

The first system has been carried out in the laboratory, enabling to put the focus on tracking issues in a convenient development environment. The perception sensor data provided by pre-recorded scenes is rendered in a down-scaled form to both portable visualization devices (HMD and portable TFT) and to a back projection workbench. The table provides an overview of the scenery, whereas the HMD and the portable TFT offer an in-detail visualization of arbitrary sections of the scene. Fig. 9.1 shows the components of the laboratory setup and their interconnectivity.

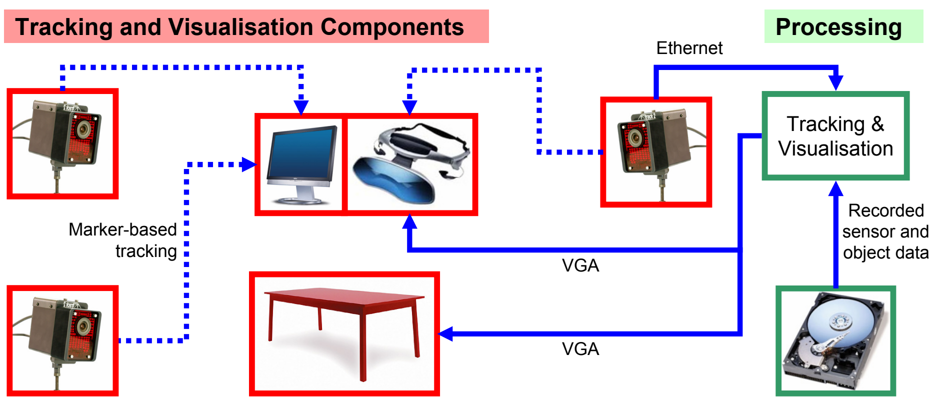


Figure 9.1: Overview of Hardware Components of the Lab Setup

9.2.2 In-Car Setup

Sensors for Live Scenery

A test vehicle has been equipped with a multi-sensor perception system for road user detection. In the following this system is called *iFuse*. For a more detailed description see [104, 165]. The system consists of a laser scanner utilized for object localization and an automotive video camera used for object classification (see Fig. 9.2). Furthermore, two infrared tracking cameras (ART smARTrack) mounted on a rigid carrier have been installed at the rear seat behind the driver surveying the area of the co-driver (see Fig. 9.10 for more details). Any distraction of the driver or the co-driver can be avoided by this mounting position. Most of the communication paths are based on 100 Mbit ethernet links. A schematic overview of the setup is shown in Fig. 9.3.

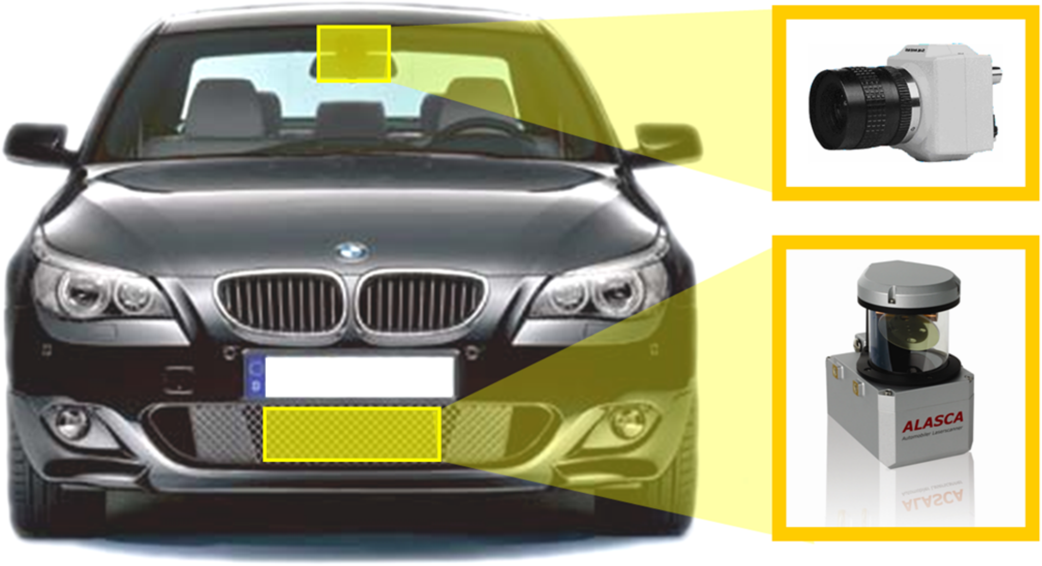


Figure 9.2: Mounting points of the two perception sensors. The automotive video camera is located behind the windshield and the laser scanner beneath the license plate

9.2.3 Visualization Devices

The visualizations are shown in a monocular Head-mounted Display (HMD), on a portable video see-through TFT or on a back-projection workbench. The HMD allows for a individual experience, while the TFT and the table enable collaborative experience.

HMD A Sony Glasstron PLM-S700 has been used for the personalized experience of AR. Although it is equipped with two displays capable of a 800x600 resolution, this HMD is limited to monocular vision. Six optical markers have been attached at the upper front part of the HMD to ensure robust and precise tracking of the position and orientation (see Fig. 9.14(a)).

Portable Video See-Through-TFT I built a video see-though display by mounting a FireWire camera (resolution 1024x768 at 30Hz) at the middle of the back side of a common 19” TFT display (see Fig. 9.14(b)). Five optical markers at the top of the display allow for robust tracking.

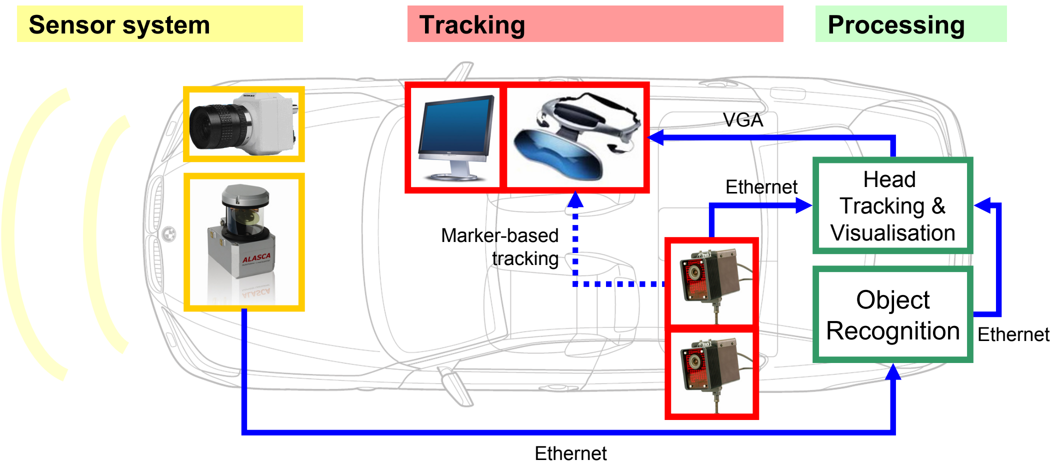


Figure 9.3: Overview of the hardware components, the communication channels and the rough respective installation locations in the test vehicle

Back-projection Workbench For collaborative work and discussion with many people a workbench [50] was incorporated in the *SensorVis* system. A mirror mounted beneath the tabletop reflects the image of a projector so that it is shown on the workbench. Using back-projection, visualization is not disturbed or occluded by interacting participants.

9.3 Software Aspects

The real world vehicle surroundings and the sensor configuration are reflected by a virtual environment, modeled as a hierarchical scene-graph structure [25], ensuring centralized data access and efficient spatial dependency processing. A vector-quaternion-scalar (VQS) [126] representation has been chosen to achieve coordinate system transformations between the entities of the scene-graph.

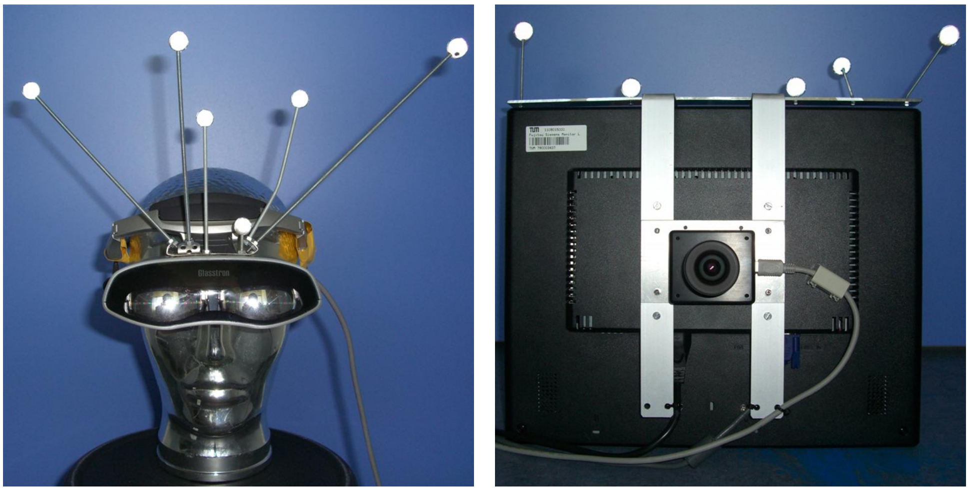
9.3.1 Spatial Relationship Graph

Relative Spatial Dependencies

Each rendering system works on continuous data streams relating 3D positions and orientations (poses) of various sensors, objects and display devices to one another. Fig. 9.5 illustrates these relations in a spatial relationship graph (SRG) [123]. Relationships that are of special relevance for the lab and car experience systems are the edges with labels A through L.

iFuse System

The left part of the SRG describes the internal setup of the *iFuse* system, consisting of the a laser scanner and a camera in the car. Their pose is described relative to the center of the front bumper. Both sensors measure their environment. Fig. 9.6(d) shows the results rendered as 3D objects relative to the sensors by the *iFuse* renderer [104, 165]. In the SRG, the *iFuse* node represents the virtual viewpoint according to which the scene is rendered. In



(a) HMD (Sony Glasstron PLM-S700) used for visualization worn by an artificial head

(b) Backside of the 19″ TFT video see-through display with an attached FireWire camera at the center

Figure 9.4: Utilized visualization devices with attached optical markers

the bare *iFuse* system, the viewpoint can be controlled via mouse input – as typical for VR scenes.

Tracking of Displays

The center part of the SRG shows the tracking setup that is required to determine the mobile pose of the TFT and the HMD in the car or in the lab. Tracking is provided by an outside-in optical tracker from ART. Depending on whether the system is set up in the car or in the lab, the origin of the tracker is related either to the car or to the lab (edges A, B). It tracks optical markers on both display devices (edges C, D). The user's viewing position is provided relative to the TFT or HMD (edges F, G). The viewing positions control the virtual viewpoint of the *iFuse* renderer (edges I, J). If the system is set up in the lab, the presentation is scaled down by a factor of 10 (edge L).

Laboratory Extension

The right part of the SRG represents the pose of the projection table within the lab (edge E) and the placement of a bird's eye viewpoint relative to the table (edge H). This viewpoint controls how the *iFuse* system renders the sensor data on the table (edge K).

9.3.2 Calibration of Sensor and Tracking Coordinate Frames

Initialization of Tracking

The origin of the ART tracking system is set automatically when the tracking system is initialized and calibrated. The system coordinator has to place a special calibration object (a large, L-shaped optical marker) at a position in the scene where it is well visible by all cameras of the tracking system. The pose of this marker defines the pose of the tracking coordinate system.

Tracking in the Lab

For the lab setup, the L-shaped marker is placed on the projection table. That way, the sensor data of the *iFuse* system is automatically aligned with the tracker, the lab and the table. These nodes in the SRG represent the same pose, and the edges B and E are unit matrices.

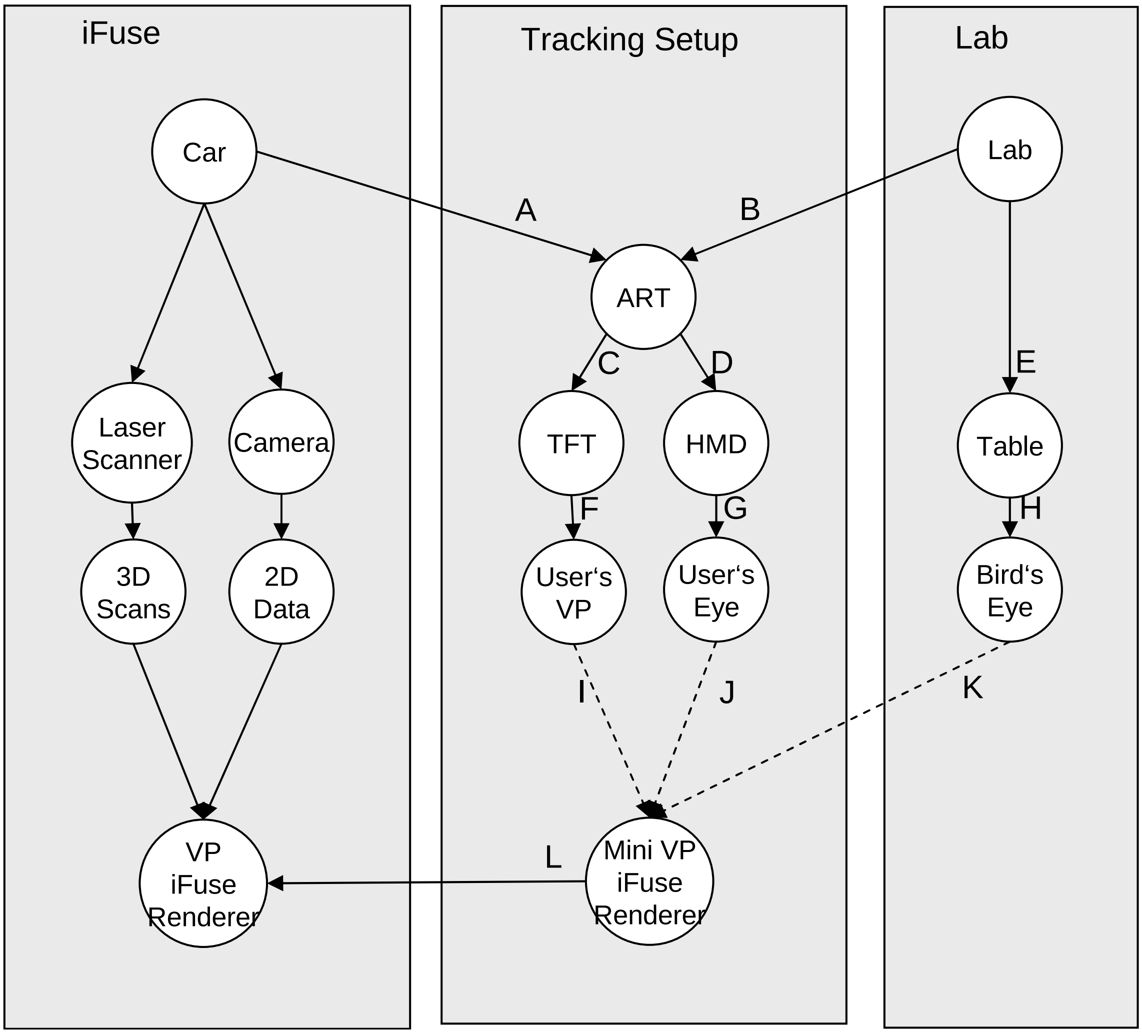


Figure 9.5: The Spatial Relationship Graph of the Presentation System

Tracking in the Car

The origin of the car coordinate frame lies in the center of the front bumper plate. The L-shaped marker can not be placed on the bumper plate since that area is not within the visible range of the tracker. Thus a transformation between the origin of the car and the origin of the ART tracker (edge A) had to be computed. The origin of the tracker coordinate system is located where the L-shaped tracking initializer was placed. The origin of the sensor coordinate frame is placed in the middle of the front bumper. Registration of the tracker relative to the bumper is reached by computing its absolute orientation [77]. To provide the matching points, the required number of points on the car surface must be touched with a tracked pointing device. The same points relative to the *iFuse* reference frame are measured by mounting the test vehicle on a measurement base plate. A large scale measuring sensor can measure the transformation between the origin of the sensor system and the target points in the test vehicle. This setup is part of a well-established routine for registering various sensors for *iFuse*. A GUI to manually read parameters of the absolute orientation calibration, that exhibited minor errors, was implemented as extension. This way, minor errors that occurred during the manual procedure of selecting matching calibration points can be fixed without requiring to mount the test vehicle on the base plate again.

9.3.3 Calibration and Tracking of Visualization Devices

Position of Viewpoint

After the general data flow in the system is specified and the sensor and tracking system coordinate frames are related to each other, the visualization devices need to be registered to the *SensorVis* system.

Device Poses The poses of the TFT and the HMD (edges C, D) are provided in realtime by the ART tracking system. The projection table is placed at a fixed position in the lab (edge E). It could easily be equipped with an optical marker like the TFT and the HMD, such that it can be wheeled to different positions. However, this has not been necessary for the current setup.

User Viewpoints To show *iFuse* visualizations on the TFT, HMD, the projection table or on any further device, such as a HUD, the viewpoint of the user needs to be described relative to these display devices (edges F, G, H). Since the tracking system places the origin of tracked markers at a position within the target that cannot be easily determined in a real setup, calibration routines are needed to relate the marker poses to a specified point of each display, such as the center of the display.

Looking with the Display

For the TFT (edge F), a static transformation describes the offset from the pose of the marker to a fixed viewpoint at the center of the display (edge F). To this end, a pointing device (similar to the one used for the absolute orientation algorithm) was used to mark all four corners of the presentation area and compute the center. For the lab setup, the viewpoint then was moved along the optical axis 40 cm in front of the TFT since, if a person holds the display right in front of his eyes, the average distance of the display is about 40 cm to the user's head. Thus if he looks perpendicularly at the display surface, a field of view that is correctly aligned to the real world is covered. If the display is seen from an oblique angle, e.g., when viewed by a second person, the augmented video picture does not perfectly match up with reality. Not a full window into the world is implemented here, instead, the users look with the display. The idea of looking with a display is easily understandable as it reflects working a normal camera. The resulting transformation F is written to a configuration file. This file is parsed by the *iFuse* system on startup and the transformation matrix is placed in the data flow of the rendering system.

Head-mounted Display

For the HMD (edge G), the Single Point Active Alignment Method (SPAAM from [162]) is applied. This method requires a user to align a cross-hair on the 2D screen of the HMD with several points in the 3D space. The algorithm computes a projection matrix for a perfectly aligned view and also incorporates the transformation of the marker-target to the viewpoint. After the HMD calibration, the resulting projection matrix is written to the *iFuse* configuration file. In contrast to the startup of the system in HMD mode, not only the transformation is set, but the projection matrix including the transformation replaces the standard projection of the rendering system.

Static Viewpoint

For the projection table (edge H), we set the viewpoint to a fixed position above the surface.

9.4 Presentation Schemes

Any Kind of Scheme

The initial system visualizes raw sensor data as well as perception data in realtime. Such perception data can reach from simple bounding-boxes as in the given setup to any kind of AR presentation scheme. In the see-through HMD case only the laser scanner data and the perception data is rendered (cf. figure 9.7). In case of the portable TFT, the laser scanner data is rendered on top of the video images of the automotive camera (cf. figure 9.11).

(a) Snapshot from the automotive video camera (b) Depth color-coded laser scanner data projected on top of the automotive video image (c) Detected and classified objects projected into the automotive video image (d) Virtual view of our test vehicle and the detected object data

Figure 9.6: A snapshot from a city-scene recorded with our test vehicle. The depicted presentation schemes are at the moment used with our offline perception system development toolkit

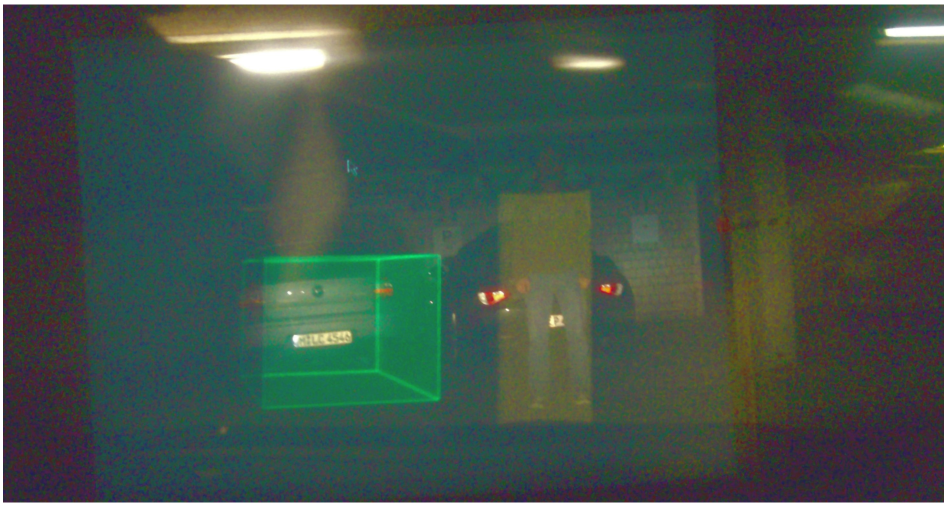
Laser Scanner Data

The laser scanner has a horizontal opening angle of 160 degrees with four vertically spanned layers with an inter-layer distance of 0.8 degrees and a horizontal single-scan sampling of 0.5 degrees. The lowest layer points forward in exactly horizontal direction. Layer one and two are taken at angles of 0.8 degrees and 1.6 degrees, respectively. The topmost (fourth) layer aims 2.4 degrees upward. The total sampling rate is $10\,Hz$. Thus the *SensorVis* system visualizes $(160 \div 0.5 \cdot 4 \cdot 10) = 12800$ distance measurements per second. The video signal is in NTSC format with 29.97 interlaced frames of video per second. To avoid flickering of the laser scanner data due to the reduced sampling rate of the scanner compared to the TFT-mounted camera, data from old scans is repainted in a fading-out manner until new scan data arrives. Each individual measurement from the laser scanner is drawn as solid rectangle, depicting the intersecting plane of the laser beam at the given distance. The rectangles are color-coded with respect to their distance (see Fig. 9.6(b) and 9.6(d)) to preserve the depth perception with both the monocular HMD and the portable TFT.

Deduced Perception Data

The perception system of *iFuse* detects and tracks vehicles and pedestrians in the data from the laser scanner and the automotive video camera. The recognition results are visualized as bounding boxes and bounding cylinders which enclose the respective object. The colors of the virtual objects encode the object type (green bounding boxes for vehicles and yellow cylinders for pedestrians, see Fig. 9.6(c)).

(a) The image shows sensor data from the automotive laser scanner. The persons' legs and the curbstone can be seen superimposed with sensor data.



(b) The image has been taken in a basement garage and shows the detection results of the perception system (pedestrian: yellow box, vehicle: green box)

Figure 9.7: Two handmade photographs taken through the HMD. Both are not perfectly aligned (=calibrated), because no mount for the camera and the HMD was available.

9.5 Issues during System Deployment

Lab and Automotive Issues

The system was primarily developed in a laboratory and tested with an offline version of *iFuse*. This off-line version is capable of replaying sensor data recorded earlier. When the tracked HMD and TFT were integrated, the *SensorVis* system was transferred into the automotive environment. For both environments, we had to cast a number of trade-offs, to be described and discussed next.

9.5.1 Lab Setup

Extensions to iFuse

To visualize prerecorded sensor data in a virtual laboratory environment, some extensions to the original *iFuse* system had to be made.

Scaled Presentation To have a suitable test environment, the original sensor data had to be scaled such that all presentations virtually fitted in the laboratory. For the see-through HMD, users would have been irritated if they had perceived the real walls of the laboratory to be closer than parts of the virtual traffic scene. Furthermore, it is easier to examine a scaled environmental scene from different vantage points around or inside the test vehicle. Users can walk around the scaled car and can even dive into the car to get a view from the driver's perspective. The entire scenery was scaled by a factor of 10.

Location-Fixed Car Sensor data is delivered relative to the car coordinate frame. In principle, the car is moving relative to the real world. However, it does not make sense to account for such motion in the laboratory-based visualization since the car would then quickly leave the lab setup on its test rides. Instead, the coordinate system of the (moving) car was fixed to the origin of the tracking coordinate system in the lab (edges B and E in figure 9.5), and the visualizations are shown relative to the car coordinate system. As a consequence, the road, as well as world-fixed objects can be seen as mobile objects floating by the car in reverse direction. The car is standing still in the laboratory, while the sensor data appears to move toward it, passing by and leaving the sensed area.

Absolute Placement The laboratory constitutes a fully virtual environment. No real object such as the real test vehicle or obstacles is present. For a better understanding of the virtual setup, a user has to know where to perceive the virtual scenery in the lab. To ease scene discovery and joint discussions among researchers, a stationary visualization of the sensor data from a bird's eye view on the back-projection workbench was visualized. The origin of the presentation on the table is aligned with the origin of the tracking system, enabling all users to get an impression of what is going on in the virtual world (see Fig. 9.8). Users holding the TFT or wearing the HMD can get another perspectively rendered view of the same scenery.

9.5.2 In-Car Environment

Issues of In-car Tracking

To deploy the system in the test vehicle, the major issue was to find a suitable mounting point

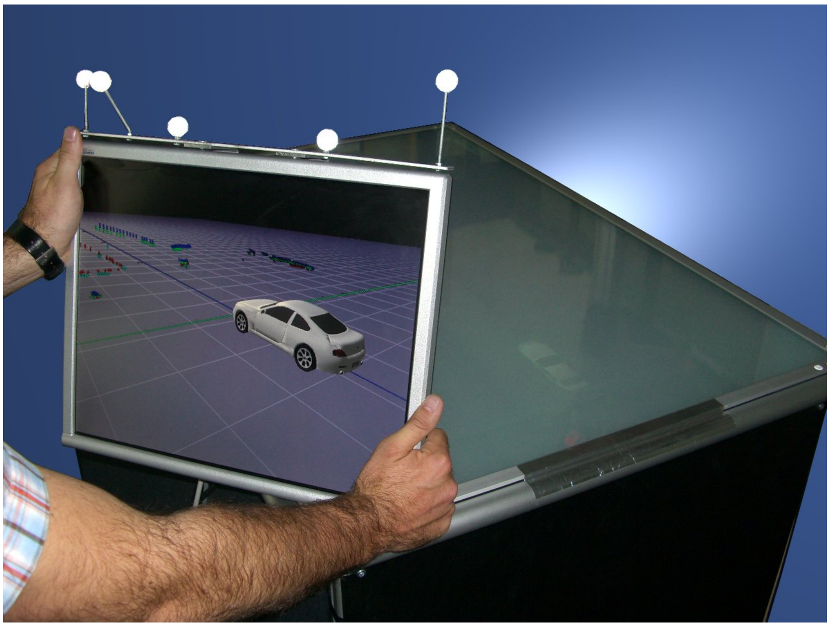


Figure 9.8: The portable TFT held into the tracking volume at the laboratory visualizes the virtual test vehicle and the perceived laser scanner data. The same scene is rendered from a birds-eye view on the back-projection workbench below

for the tracking system. Certain concerns were related to tracking, others to presentation issues and a sufficient throughput of the system:

- Non-occluded tracking volume to track the visualization devices.
- Stable vibration-free tracking of the visualization devices.
- Minimal perturbation of in-car systems to infrared tracking cameras.
- Brightness and contrast of visualization devices
- Superimposing reality.
- Minimal time difference between environment perception, in-car tracking and rendering.

In-Car Tracking The cameras in the car environment must be able to track the following region: the two presentation variants for the *iFuse* system consume an area from up to 40 cm in vertical, 80 cm in horizontal and 60 cm in depth from a seated person. A wide angled tracking camera must be used to supervise this volume. To receive valuable position and orientation data for all degrees of freedom, the orientation of each camera to one another should have a certain angle, not facing along the same axis and should have a certain distance in between [14]. Tracking Volume

The ART smARTrack cameras provide such tracking quality – aside from the fact that their Tracking Accuracy size is not really suitable for in-car use. Both cameras are mounted on a carrier in a suitable distance (about $50\,cm$). Their focal axes cross in a distance of $160\,cm$ to the middle of the carrier and the tracking volume starts in a distance of about $30\,cm$, where the borders of the field of view cross almost perpendicularly. With this fixed setup, the resolution of the cameras for a standard target ranges from $0.25\,mm$ to $0.5\,mm$ depending on the distance to the cameras (about $50 - 100\,cm$) and axis relative to the lines of sight of the cameras [15].

Placement of Cameras

The carrier bar had to be mounted such that both cameras can track movements of the HMD and of the TFT. First thoughts of placing the cameras in front of the co-driver, above the right part of the dashboard failed due to the required minimum distance of the tracking volume. Moving the cameras further away, to the drivers side also failed because the car still has to be maneuverable without any handicap.

Tracking from Back-seat

Thus the cameras had to be moved behind the front seats. The attempt to mount the cameras directly behind the co-driver's head-rest prohibited tracking the visualization devices, because the user's head often occluded the line of sight of one or both cameras. From the three remaining options to mount the cameras near the seat behind the driver or on the back-shelf, the two horizontal approaches failed. Placing the camera bar horizontal on the back-shelf failed, because the co-driver's head-rest occluded too much of the tracking volume. Also the placement directly behind the driver, the bar turned about 45 degree to the right, facing toward the tracking volume did not prove suitable, because here, both head-rests occluded some parts of the tracking volume.

Vertical Placement

Finally, the approach to place the bar vertically above the right knee of a left backside passenger enabled a large enough view of the required tracking volume. The photo in figure 9.9(a) illustrates the extent of the freely visible tracking volume.

Visible Areas

When a visualization device is brought into this volume, a passenger has taken seat. To illustrate what the tracking cameras record: Fig. 9.11 shows the TFT as it can be held in the tracking volume. Both cameras can recognize the markers. Fig. 9.9(b) shows the HMD as it can be worn. Especially the upper tracking camera sees all marker balls. Yet, the lower one also has a good vantage point.

Occlusion Issues

The volume that can get occluded is characterized by the following coincides: first, the driver's right elbow, when moved backwards or the co-driver's left arm can occlude parts of the lower volume. Second, when a tracked object (TFT or HMD) is moved or turned far to the right side, the co-driver's left arm or left shoulder can occlude the markers on the TFT, while the head still can occlude the marker-balls of the TFT.

Troublesome Light Sources

After a suitable location was found for the camera carrier, it had to be ensured, that no (infrared) light source from the interior of the car impaired the spot detection algorithm of the tracking system. Detection checks of the tracking system showed that a transponder of the car mounted near the driver's back-mirror placed a unintended spot in the video image. Right next to this spot, depending on its adjustment, the back-mirror reflected the infrared pulses of the tracking system, generating a second dead spot.

Vibration-free Mounting

A final issue in incorporating the tracking system into the car concerned finding a stable, vibration-free mounting of the tracking system. The two-camera system is rigid in itself. It correctly maintains the calibration between the two cameras themselves. To ensure that the origin of the full tracking system does not alter due to vibrations of the driving car, a stable connection between the car and the tracking system had to be built. A construction, applying

(a) Snapshot of the two tracking cameras from behind and the covered tracking volume

(b) The HMD worn in the tracking volume. The tracking cameras (back right) can see the markers

Figure 9.9: The Tracking Cameras and the Tracking Volume inside the Test Vehicle

the two hand-rests near the roof of the car above the rear car doors (cf. figure 9.10(b)) and the mount point of a child seat at the lower end of the backrest gave enough stability against longitudinal (front-to-back) and vertical (top-down) vibrations. Lateral movements (left-to-right) were reduced by an additional aluminum profile in the passenger's footwell. The complete construction is depicted in Fig. 9.10.

Stable Tracking

With all these issues solved, a working tracking system was mounted successfully in the car.

Perception in different Lighting Conditions

Presentation Issues While driving on the road, various lighting conditions can occur. From almost full darkness on rural roads during night, brightness can range to full sunlight and reflection spots from other objects, especially from the windshields of other cars in certain daytime conditions. The human eye is capable of adjusting its iris, the retina cells and their processing to such conditions. If a visualization device does not produce an image bright enough to be comparable with outside lighting, the perception of the AR presentation schemes is reduced. Under large changes in brightness, focal adaption between different brightness levels takes longer. Perception of a standard TFT display can thus be more exhausting for the user. Furthermore, a direct overlay on an optical display can have such a low brightness, that it is no longer visible in bright daylight conditions. Fortunately our car had slightly toned windows, so that incoming light is reduced in the in-car environment.

TFT Brightness

For the TFT, the camera mounted on its backside had a lens with adjustable iris. In addition, the software driver automatically adjusted the brightness of the image. Hence, overlaid sensor data always appeared in a good perceivable relationship. The TFT had a screen diag-

(a) Overview of Mount for the Tracking System

(b) Left side Handhold Mount for Tracking System

Figure 9.10: Construction of Mount for the Tracking System

onal of 48 cm and a brightness of 300 $\frac{cd}{m^2}$. Presenting the generated image to several people was judged satisfactory on a sunny summer day with hardly any clouds. Fig. 9.13 and figure 9.11 show photos of the TFT while presenting a scenery on that day. In contrast to the digital camera used to take these pictures, the differences in brightness are handled easily by the eyes of a human being.

HMD Brightness

For the HMD, the real environment is directly augmented with virtual objects. Here brightness of the HMD (Sony Glasstron) is a more critical issue. A scenery viewed in full daylight is too bright to still perceive any augmentation. For normal sunny daylight with no direct solar radiation (cf. figure 9.7), a respectable amount of the superimposed scenery remains perceivable for the user.

System Performance An immediate system response is crucial for augmented reality systems. Therefore we put some effort into achieving realtime performance. The system response times are composed of the timings from the tracking system, the TFT-mounted camera, the perception system, the rendering and the communication paths. The communication times are negligible. The scene rendering has been implemented in OpenGL and is accelerated by a 3D graphic adapter, resulting in a processing time of about $20\,ms$. The laser scanner frequency is $10\,Hz$ which results in a worst case processing time of $100\,ms$. Altogether the processing time sums to about $100\,ms$ in average.

Visualization on the Road Once all issues of installation and presentation were addressed, the system was ready to be tested.

Figure 9.11: The TFT held into the tracking volume while driving. One can see the laser-scanner augmentation on the vehicles and the guardrail

General Problems

First tests on a parking lot quickly revealed, that the construction of the TFT introduced several problems: first, the rather large TFT did not fit easily into a sedan. Moving and turning were possible, but the user had to be careful, not to disturb the driver's area around the gearstick. Furthermore, the TFT was heavy and thus uncomfortable to hold for a longer time. Third, due to its size, the TFT display had to be held very close to the ceiling of the car. In such position, the marker-balls were tracked well. Yet, the user had to ensure, that the markers on top of the display were not deformed. Handling the TFT was possible, but more complicated than necessary. The fourth observation concerns the mounting point of the digital camera on the backside of the display. It was mounted on the opposite of the center of the screen, to give an intuitive understanding to the user, that he is observing the scene from inside TFT. Due to the layout of car interior, the height between the dashboard and the roof allowed for the camera only to look over the dashboard, when the TFT was held so high, that it almost touched the ceiling. In that case, about two thirds of the environment shown on the TFT was outside area, while the remaining part showed the dashboard.

Quality of Tracking

These first tests also gave feedback about the quality of the marker-tree construction. The setup of the TFT display required that all markers be attached along the upper edge of the display. Otherwise, single marker-balls would have had too large a distance to the TFT, complicating handling even more. The same applies to the HMD. All marker-balls are attached on top of HMD to improve its trackability. The marker-balls on the HMD define a wide, but not that deep and high volume. So, for both displays, rotations like nodding (i.e.: pitch) produce the high tracking imprecision. Thus the largest misalignments in rendering attribute to

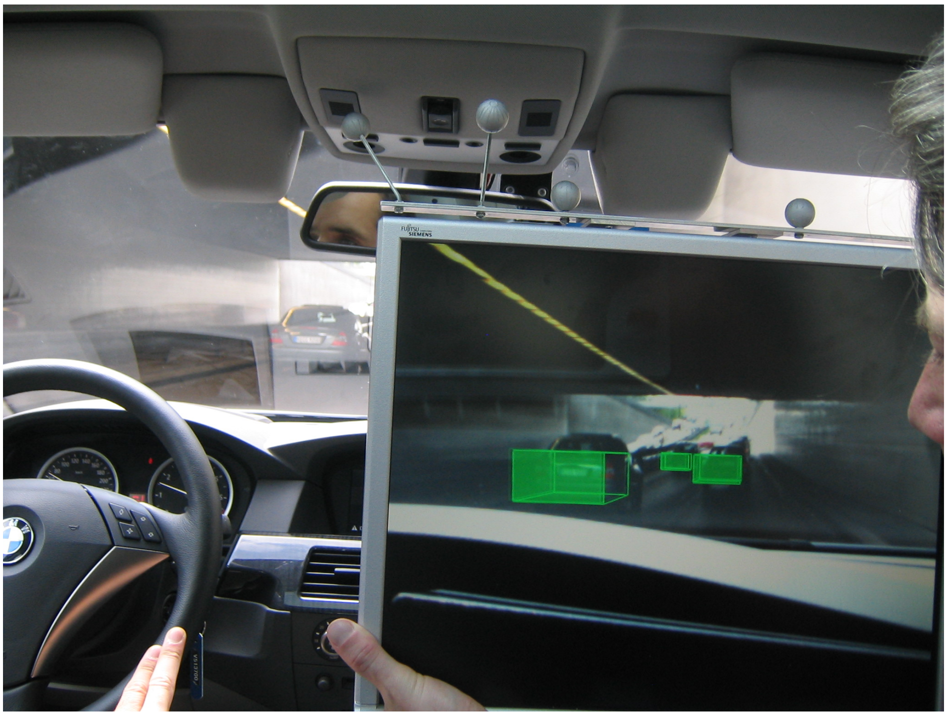


Figure 9.12: The TFT held into the tracking volume while driving. One can see the green augmentation of the detected vehicles

vertical (non)conformity.

Field of View

The depth based alignment between the real environment and the superimposed sensor data in the TFT was good when we used a camera model with a fixed focal length to initialize the corresponding projection matrix in the rendering system. For the HMD, the projection matrix was generated by the SPAAM algorithm - a tricky task to achieve in a car since the algorithm requires the alignment of a calibration device with a crosshair, and both the calibration device and the HMD must be tracked accurately. The extremely limited space to calibrate the HMD in the car are the reason, why the frustum of the HMD tends to be slightly too wide - as can be observed for objects at large distances.

Problems while Driving

After the first tests in the parking lot, the *SensorVis* system was tested under driving conditions on the road. Here the stability of the mount of the tracking system was tested. The vibration of the car, when driving on normal concrete streets generated perceivable jitter. Augmented objects, sensor data and boxed objects reached misalignments of 0.5 cm to 1 cm in average when driving over a bump. To determine the effect of the not quite perfectly rigid mounting, we mounted a marker-target in a fixed position at the maximum distance (1.02 m) to the tracking cameras. This target, being light in comparison to the cameras should not swing very much, even if the car drives over a bump. Then, tracking data was recorded while standing and while driving. Recorded tracking data was analyzed and results showed that, for a standing car position, tracking precision varied below a value of 0.1 mm and orientation below a value of 0.2 degrees. When driving with the car, positional changes reached

Figure 9.13: Snapshot of the See-Through TFT. One can see the superimposed sensor data on the garbage container and the Vespa scooter

about 4 mm in all three axes. Rotational changes remained below 1 degree. The increased positional imprecision contributes to up to 0.6 degree in altered orientation. Thus the cumulated error of the vibrating tracking system can sum up to 3 cm for a maximum amplitude in both position and orientation. In general, on even concrete, calculated with 68 % of the maximum amplitude, the error is about 1 cm.

Sources of Misalignments

In summary, misalignments can be attributed to four major factors. First, they are caused by tracking errors due to suboptimal marker-target design, as described above. Second, system lag can sum to 100 ms, causing significant misalignments for a moving car. A third cause of misalignments are blinding spots from bright outside objects and in-car light sources. Fourth, a non-rigid mounting of the smARTrack camera carrier disturbs the tracking data.

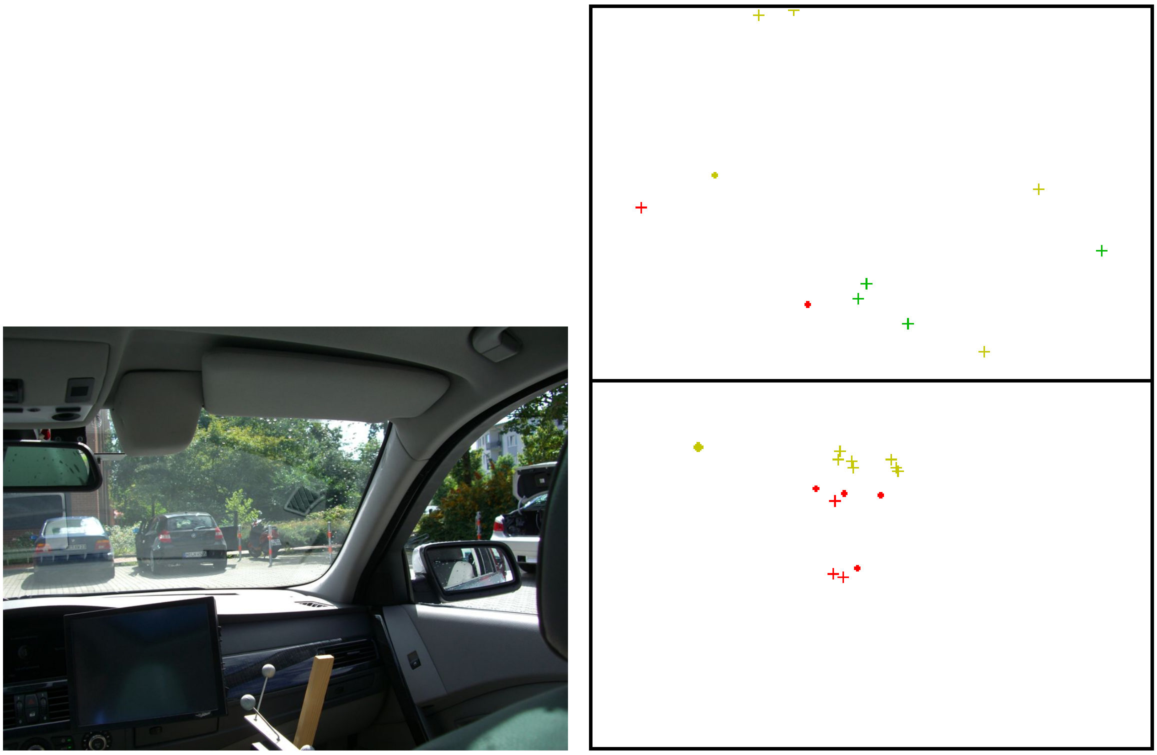
Fan-like Laser Scans

Another issue during the test drives, pertaining to the rendered data from laser scanner was determined. When driving through, e.g., a tunnel, sensor data was perceived from the walls, too. Looking at the graphical representation gave the impression of a miscalibrated frustum. This effect vanished when the setup of the laser scanner was recaptured. The lowest layer of the scanner aims horizontally forward, while every layer above aims another 0.8 degrees more upwards. Therefore the graphical representation can appear as not scaling down fast enough with increasing distance.

Signal-Noise Ratio of Infrared Tracking Automotive environments are no usual environment for infrared trackers. Natural sunlight, reflection spots and lighting rays can flood in through the windows. In-car bulbs and infrared interfaces like central locking systems generate noise that reduces tracking quality. Static spots like most of in-car light sources can easily be neglected by disabling tracking in the corresponding camera images. Thus tracking the brightest spots, which then are the marker-spheres again, is enabled again. For car-external light sources, the situation is different. As the car can move through the environment, light-source locations can change and no blind spots can be placed in the camera images. Adjusting the infrared flash intensity can increase the signal to noise ratio. Users have to stand occurring inconsistencies brought up by occurring wrong spots.

Tracking in different Lighting Conditions

We tested tracking in different environments under various lighting conditions, from bright sunlight to just in-car lighting during night. In the first tests we realized, that we have to adjust the camera flash intensity to the upper end so that the reflection of the marker-spheres are stronger than unintended lighting. Then, surprisingly, tracking worked well under most conditions. Fig. 9.14 shows a scene taken on a bright sunny day and the screenshot of the tracking software showing the tracked points. One can estimate the location of the three spheres of the marker target (green crosses) in the lower part of the upper tracking software screenshot. The other spots are false positives, but are colored in red and yellow, indicating not-as-good hits. This figure is a good example to illustrate the good overall tracking.



(a) A photography taken from the center of the smARTrack bar: Sunny day and a reflecting windshield

(b) The two smARTrack images. The upper part shows the upper camera and the lower part shows the lower camera

Figure 9.14: Two images showing the centered view out of the windshield and the tracked points, the tracking software receives from the cameras – both pictures were taken at the same point in time

Extreme light conditions still bring in high noise and thus tracking fails, when, e.g., the sun is directly in front of the cameras. The slightly darkened glasses surely facilitate tracking, but can not cope with the strength of natural light. Tracking Failures

9.6 Summary for Technical Presentation Systems

SensorVis, a presentation system for spatial sensor data has been developed and reported about in this chapter. In contrast to any HUD system which is static mounted to the car and thus can only enable AR in a certain area of the driver's view, the *SensorVis* system enables AR overlays in the whole surrounding of the user. The *Sphere of Vision* as stated in chapter 3 (page 50ff) got its implementation through this system. The tracking system for the displays has been mounted inside the car, but also can be placed besides a standing car. Without the constraints of the narrow driver cockpit, the displays can be used in every direction to place AR overlays for car drivers. In a standing car no specialized mounting is necessary because the car is not moving and does not generate any tremor to the tracking system. The *SensorVis* system in a standing still setup can be used to examine sensor functionality or to experience AR schemes in a driving simulator without touching any simulator software system. Implementation of the *Sphere of Vision*

The idea for such presentation of sensor data is motivated by the need to debug sensor and perception data in real setting and by the need of user interface designers to get a better understanding of what sensor measurements can principally be provided to novel driver assistance applications. The *SensorVis* system is not intended to as the final presentation system for in-vehicle driver assistance systems. Instead, the *SensorVis* system can serve during the development and testing phase of sensors and AR schemes. Experiences made during system development can strongly facilitate the development of contact-analog HUD systems with correctly registered and aligned AR presentation schemes. The spatial relationships and the corresponding spatial transformations can completely be reused for future contact-analog HUDs, they only require extension of a tracking facility for the driver's head. The subsequent section discuss all capabilities of the *SensorVis* system in detail. Broad Impact System

9.6.1 Checking Sensor Functionality

Both setups, the laboratory setup and the car setup can be used for a visual check, whether a sensor works properly. Operabiltiy of Sensors

The laboratory setup can be used for visualization of sensor data, which for instance, had been recorded directly after assembly of each sensor. Experts can compare object recognition schemes by looking at recognized objects from different perspectives in a downscaled setup. Multiple Perspectives

The car setup allows for direct inspection of the perception system. While our system has been developed for in-car use, the tracking system surely could also be mounted around a (stationary) car such that an inspector can walk around it and investigate the quality of sensor calibration and of sensor operation in a much larger space. Live Inspection

New prototypes of sensors, analysis strategies and object detection methods could now be more easily experienced, evaluated and discussed by the sensors community. Easy Experience

9.6.2 Designing Visual Driver Assistance Systems

Parallelization of Development

In addition to the inspection of the functionality of sensors, car embedded visualization of presentation schemes can support development of upcoming visual driver assistance systems. Although large scale HUDs are not available yet, research in usability and applicability of such embedded presentation schemes is enabled by our presentation system (e.g., as used by [161]). Furthermore, new warning schemes for road hazard warnings or traffic dependent navigation can easily be developed and experienced.

Collaboration

The laboratory setup enables fully joint examination of such presentation schemes. The visualization on the table enables all participants of a research group to get an overview of a proposed scheme, while the direct neighbors of the person holding the TFT can examine the presentation scheme from a certain point of view. A fully personalized view can be obtained in the HMD, where the user can choose an arbitrary perspective.

Automotive Conditions

The car setup enables in-place examination of such driver assistance schemes. Perception based driver assistance systems that have been declared valuable for evaluation can be integrated directly into the car setup and thus become AR presentation schemes. Test subjects can experience these augmentations in real traffic.

9.6.3 Building Contact-analog Head-Up Displays

Foundation for Contact-analog HUDs

The *SensorVis* system, except for the presentation devices serves as foundation for contact-analog HUDs. The implementation incorporates almost all spatial transformations which are necessary for correctly registered and aligned overlay of AR schemes. To present spatial information accordingly, the display component of the HUD, now car-fixed, must be registered correctly to the car coordinate frame and the position of the viewer must be tracked so that the relative position of the viewer to the display can be computed. Here again, the concept of the window into the world [55] becomes apparent. Instead of tracking the display, the presentation system needs to know about the position of the head of the driver. Such tracking issues can be disregarded under the condition that the focal plane is in a large distance [20, 21]. Misalignments of distant information are not perceivable because the parallax error between the computer generated image and the real environment only generates perceivable effects in near distance.

Tracking Technology

Tracking systems applied for HUDs must become smaller than the one used for the visualization system in this chapter. Here a benefit will be the smaller volume that needs to be covered by the tracking system. Instead of tracking the volume the head covers with the HMD and the volume, the LCD display requires, only the volume of the driver's head requires to be monitored. First approaches still can use marker-trees while later systems should use natural features to track the user's head position.

Sensor Data

For environmental sensors, no change in the system is required. The issue of mapping each sensors coordinate frame to the car coordinate frame is fully incorporated in the *SensorVis* system. Thus, any sensor delivering data for superimposition of objects can be incorporated in the system without extension to the algorithms.

Display Brightness

Brightness of displays is an issue that can be solved with specialized displays such as the type of backlight already used in conventional HUDs.

9.6.4 Future Work

There are a number of open issues that need to be solved in the future. Most of them have been identified after the system was set up and tested. New Issues

Extensions to the System The usability of the portable TFT and the HMD for in vehicle applications could be further increased: additional markers would enhance tracking performance. For the TFT, the markers are currently placed on top of the display, to be visible all the time. Those markers are nearly linearly aligned along the horizontal axis. Rotations around the horizontal axis thus cannot be tracked with high precision. At least one additional marker, placed more toward the lower end of the TFT, can fix this issue. For the HMD, the long marker-sticks on top of the HMD make it difficult for large persons to move their head freely, because those sticks can hit the roof. Using OLED technology will enable more flexible, lightweight and thus more ergonomic displays. Moreover, further testing should evaluate the potential of video see-through, high contrast or stereo vision HMDs regarding user acceptance and usability. Moving the video see-through camera to the top of the TFT would increase the variety of viewpoints that show image data that is not partially occluded by the dashboard of the vehicle. This in turn requires changes of the TFT calibration algorithm.

Bridging the Gap to HMI Further research is needed to evaluate the suitability of the presented setup and visualization schemes regarding the design and assessment of advanced driver assistance systems for both HMI and application developers.

External View on the *Sphere of Vision* The current *SensorVis* system allows only inspection of AR schemes in the *Sphere of Vision*. The *Sphere of Vision* itself, from an outside point of view can not be examined. Thus, visible or occluded parts of the sphere and the driver's field of view can not be visualized. The system should be extended to meet these demands. Reflective examination of the constraints described by the *Sphere of Vision* then can help HMI developers to find undetermined limitations of ADAS systems.

Distortion of Optical Elements of HUD When porting to HUDs, future work has to face issues of image distortion. Lenses used for stretching of the focal plane to larger distances generate a radial distortion of the image. The further an AR scheme is to the outer border of a display, the more it is distorted. When, in addition, the windshield is used as combiner, it acts like an aspherical lens, leading to an irregular distortion of the computer generated image. Lenses distort the image in all three dimensions. The image is distorted in a way that, for instance, a chess board no longer looks like having sets of perpendicular crossing lines, it seems as if it has the shape of a cushion or a barrel. Also the focal distance is affected and different areas of the image have different distances to the viewer. While the focal distance is of less concern in the larger presentation distances of HUDs, the 2D image distortion must be compensated. A HUD system intending to enable contact-analog presentation must face such 2D lens distortion issues in combination with the relative position of the viewer to the windshield and the setup of the other lenses to correct the 2D image distortion.

10 Conclusion

Summary, outcome, lessons learned and future work

Structure of Conclusion

This chapter concludes my thesis. First a summary of the conducted work is given. The summary collects all contributions made to facilitate the future introduction of AR in automotive environments. Specifically the AR concept, the tools, tool-sets and working environments I built and the ADAS concepts and their investigation are discussed. Subsequently some lessons I learned during my four years of research are reported. The final sections then collect future issues to be investigated to finally enable AR in cars.

10.1 Summary

Promising Idea

The application of AR for ADAS systems appears promising for a new generation of safety and comfort systems. Embedding relevant information into the real world has a definite effect on glance behavior. If this effect only reduces off-road glance time and does not have increasing effects on cognitive workload, AR ADAS systems can support safety.

New Paradigms

At the very beginning of my work in this field of research, I discovered that fundamental work is necessary before I could begin with the investigation of usability effects. Similar to many other new paradigms, direct incorporation into the application domain first required a broad overview about the dependencies and effects on the situated environment. Fundamentals of human factors, ergonomics, physics and computer science had to be collected and brought together. Through this collection, *dependencies of AR on their automotive application* could be classified. In conjunction, the concept of the *Sphere of Vision* was developed. It enables examination of available spaces for AR content.

Concomitant Issues

On the way to test the applicability of AR for automotive car driver assistance, several further issues that needed to be investigated were observed. These issues forced to conduct investigation and I succeeded in developing of working environments, tools and tool-sets to enable suitable and efficient development cycles for testing automotive AR systems. Driving simulators were extended with a system based on an *architecture for a rapid prototyping environment* that facilitates such short implement-test-modify roundtrip cycles. To meet the dependency of ADAS systems on natural behavior of traffic a tool for the *creation of traffic scenarios through human induced behavior* was developed. To open the way for later incorporation of such systems into an integrated human-centered system, the SCORE system was developed. SCORE is a tool-set for *independent and integrated analysis of spatial dependencies*. ADAS system concepts often require visualization at locations where no display is available. To face this issue, I developed an inspection and examination system for a wide range in visual content. The implementation of the so called *SensorVis* system is based on the concept of the *Sphere of Vision*. Besides facilitating AR concept development, the *Sphere of Vision* is a means for *testing of sensor functionality, maintenance and sensor fusion*. It can bring together developers of sensors and human-computer interaction systems through visualization of any kind of data during analysis phases of spatial dependencies. As a side-effect of the development of the *sensor data visualization system SensorVis*, issues of correct alignment of AR on see-through displays were solved by a *data flow network*. Spatial relationships of sensors, displays and viewers are correctly transformed and care for correctly aligned AR overlay.

Experiences in Usability

With some of the systems that have been developed, specifically with the rapid prototyping environment and the spatial context reasoning system, several ADAS systems were developed. These systems range from active accelerator pedals over screen-fixed symbolic HUD assistance to full AR assistance systems. Especially two of these systems, which are reported in this thesis, are of main interest for AR ADAS systems. The system for *ambient visualization of the physical motion of the own car* and the system for *guidance system for a car driver's attention* were developed and examined to collect experiences for different types of application of AR which were stated in the previous definition of the AR concept.

Structure of Summary

The subsequent sections summarize and discuss my contributions under the terms of *constraints, concepts and guidelines*. They recapitulate the *working environments, tools and tool-sets* developed and extract the experiences made during the *usability studies*.

10.1.1 Constraints, Concepts and Guidelines

AR Concept

I investigated constraints concerning human factors, ergonomics, physics and communicative aspects together with AR technology. The investigation revealed that thus far, nobody has collected all issues which AR systems must meet to compensate any kind of obvious negative effects. My *first contribution* therefore covers the integration of all different influences into one general concept for AR.

The *Sphere of Vision*

I started with the conceptual model of the so called *Sphere of Vision*. This model brings together the demand of AR presentation schemes and technical constraints. Demands on AR presentation schemes are specified with respect to the task to execute, the form factors of the presentation scheme and the placement of the scheme. Technical issues arise in relationship to HUD displays and form factors of the car. HUD displays only allow presentation at a certain focal distance and can only cover a certain field of view, where certain parts of the presentable area might be occluded through, e.g., the A-pillar. The *Sphere of Vision* allows keeping track of these constraints while an AR scheme is under development.

Interactive Communicative Dependencies

Subsequent to the definition of the *Sphere of Vision*, communication models were investigated. I ported the concept of *aura*, *focus* and *nimbus* to the automotive domain and defined an interactive communication model for information exchange between automotive instances. With this definition, awareness for the different range of human capabilities and sensors is generated. This difference defines a *delta in knowledge between the driver and ADAS systems*. User interfaces of ADAS systems must compensate that delta to enable the driver to know about the further knowledge of the ADAS system. Three types of application of AR could be derived from this concept. AR ADAS systems can *directly indicate a situation or an object*, they can *indicate something that is occluded in the field of view* of the driver and AR can be used to *guide the driver's attention towards a situation outside the field of view*.

Focal Depth

The subsequent combination of the *Sphere of Vision* and the interaction model then requires a revision of technical issues. To achieve optimal glance behavior, not only location-related AR overlays are necessary, but AR presentation must also be placed in the correct focal distance so that the human eye does not have to perform focal accommodation.

Collection of Guidelines

All investigations together with the initial collection of fundamentals lead to my first contribution which is summarized in chapter 3 (page 50ff) and concludes with a set of *guidelines for interactive AR concepts*.

10.1.2 Working Environments, Tools and Tool-Sets

Several Systems

The *second contribution* provides a wide set of working environments and supplementary tools. These tools and systems on the one hand aim at *efficient development cycles* for AR ADAS systems and on reduced differences between simulated and real environments through *introduction of test subjects in the development process of traffic scenarios*. On the other hand, these tools, from a technical point of view, support human-centered systems through a *systematically decoupled analysis and reasoning system for spatial dependencies*. The last tool-set provides a system that accompanies a development process from initial approaches to the final deployment in future cars. The *implementation of the concept of the Sphere of Vision* in the *SensorVis* system either serves as an examination and experience tool for early AR concepts or for sensor maintenance and also serves as fundamental baseline for a 3D rendering system that ensures correctly transformed 3D perspectives in HUDs. The following paragraphs report on the systems separately.

New Requirements

Rapid Prototyping Environment During concept development for AR driver assistance systems I analyzed several driving simulator systems. In general, driving simulators do not allow full access to the components necessary for AR overlays and do not necessarily serve well for short development cycles.

Incorporation of AR Schemes

Access to the rendering engine of driving simulators often is encapsulated so that only predefined 3D models can be incorporated and only reduced sets of behavior can be applied to the 3D models. Appearance and motion behavior of ADAS systems in general quickly require more specialized design factors.

Roundtrip Cycles

To effectively develop AR systems, short roundtrip cycles are necessary. Iterative design and development processes require the simulator system to be started often to experience the modifications made to the ADAS system. Several computers often require manual startup of all simulator system components.

Rapid Prototyping Environment

Besides other issues, these are the two major issues that lead to the development of a *rapid prototyping environment* for ADAS systems. Chapter 5 (page 80) reports on the architecture and implementation. Based on a *component-based architecture* with capabilities for *remote startup* of components, the rapid prototyping environment was used to develop a wide range of ADAS systems. Primarily the usability studies which are reported in this thesis have been developed with this system as well as ADAS systems applying active accelerators, other in- and output devices or screens [96]. Details on the different ADAS systems and studies are reported in the chapters.

Test Subject driven Creation of Traffic Scenarios ADAS systems have a strong dependency on outside events. Sophisticated ADAS systems must react in a similar manner as car drivers do. Such systems otherwise cause an annoying or unconfident feeling for the driver. Even minor changes in trajectories or other occurrences lead to completely different behaviors. Reproducibility of such minor changes is a difficult issue, whether on the road or in simulated environments. On roads, exact timing can not be guaranteed. In simulated environments, behavior in general follows strictly programmed rules. To *generate traffic scenarios* for simulated systems, I developed a system incorporating a tracked miniature car on a table-top surface combined with a driving simulator environment. The system either enables direct *comparison of human behavior* through repeated generation of traffic scenarios with multiple test subjects or allows for reuse of such traffic scenarios in the testing phase of ADAS systems. The first part of chapter 6 (section 6.1, page 111ff) reports on this system and how to work with it to create rather complex traffic scenarios. Thus a system for the generation of spatial context is at disposal for future development.

Reproducing Traffic Scenarios

Understanding Spatial Context In contrast to the creation of spatial context do ADAS systems have to analyze sensor data to provide meaningful support to the driver. To ensure that multiple systems deduce the same results from the sensed data, the reasoning functionality should be decoupled from the user interface of the ADAS systems. The *federation and reasoning system for spatial sensor data* was designed and implemented. The architecture follows the principles of a component-based architecture and incorporates distributed systems so that sensors mounted in the environment as well as car to car communication can provide additional information for a car-mounted reasoning system. The system, which is based on ontologies provides low-level interfaces for sensors and high-level interfaces for ADAS systems. The SCORE system, in the second part of chapter 6 (section 6.2, page 125ff) provides a centralized reasoning system per car and can serve any number of ADAS systems.

Analyzing Traffic Behavior

AR Visualization System A tool accompanying the design process of AR schemes is the AR visualization system *SensorVis* that has been developed for the experience of AR and sensor data. With a portable LCD display or with a HMD, users or groups of users and developers can *investigate a wide range of visualization data*. The system enables presentation and inspection of *raw sensor data* as well as investigation of the *visual components of ADAS system concepts*. The *SensorVis* system can be used in simulator environments as well as in or next to real cars. The system reflects the concept of the *Sphere of Vision*. Chapter 9 (page 188ff) reports on its implementation and its adjunct issues.

Implementation of the *Sphere of Vision*

Besides facilitating AR concept development, the system can be used for *testing of sensor functionality*, for *sensor maintenance and recalibration* and for the *inspection of sensor fusion algorithms*.

Testing Sensors

The *SensorVis* system also serves as a *bridge between developers of sensors and developers of the user interfacing side of ADAS systems*. Visualizing of any kind of data, in the one direction ADAS system developers can indicate areas that require more sensing and in the other direction sensor developers can visualize new capabilities of sensors.

Bridge between Expertises

10.1.3 Experiences on Usability

My *third contribution* focuses on experiences as the results of usability studies exploring the use of AR concepts for ADAS systems. The conceptual chapters defined three areas where AR can serve for increased information transfer (section 3.2.2, page 58f). AR ADAS systems can *directly indicate a situation or an object*, they can *indicate something that is occluded in the field of view*, or AR can be used to *guide the driver's attention towards a situation outside the field of view*. To investigate the effects of AR, two ADAS systems have been developed covering these three aspects.

Aura of Motion

Ambient Visualization of the Physical Motionof the Own Car A direct indication of a situation is specified as the visualization of the physical behavior of the own car. Using a *braking bar scheme* and an extended *drive-path scheme*, a car driver can get an enhanced perception of the movement of the own car. Corresponding to the collection of automotive auras in section 3.2.1 (page 56f), both schemes can be interpreted as an aura of physical motion. This aura visualized in the HUD reduces the potential risk that a car driver underestimates lane departures or safety distances.

Pilot Study

The concept of ambient visualization of such information and the corresponding study is reported in chapter 7 (page 142). The study should be taken as pilot study, because no further study has been conducted evaluating platooning traffic. Subsequent studies need to be conducted, testing the scheme on narrow road sections and with leading cars. Yet, the pilot study generated two major findings. First, lane keeping behavior is improved and second, workload is not affected by the presentation scheme. Besides the mentioned external situations to be examined it remains to include measurements of glance behavior into the studies.

Referencing Invisible Dangers

Guidance System for a Car Driver's Attention The second concept evaluated in user studies investigated *referencing objects that are not visible*, either because they are occluded or because they are not in the field of view of the driver. Chapter 8 (page 160) defines and evaluates a concept where a 3D compass metaphor was examined with respect to its potential for guiding a car driver's attention towards such an invisible dangerous situation.

Mutual Problem Elimination

The comparison to a bird's eye map yielded a *significantly shorter reaction time* for the 3D arrow even with or without spatially encoded sound. Encoding of direction via the acoustic channel helped clearing out ambiguities in special cases where the direction of the arrow could be interpreted wrongly (pointing straight forward or backward). The main study shows that such a concept has *promising potential* for future ADAS systems. As classified in section 2.1.5 (page 17), where different levels of automation are collected, such a concept can be used in a warning stage (mutual control cooperation mode) to inform a car driver about the existence of an imminent danger. This way, the driver has an extra chance to eliminate the danger before a system in the fully automatic cooperation mode takes over control.

Preliminary Studies

Even if two studies have been conducted on such a concept, these studies should also be taken as preliminary. Subsequent studies should investigate guidance systems with glance fixed mounting of the directional indicators. This kind of mounting guarantees that the AR scheme always stays in the driver's field of view. A further classification of sectors of accumulated dangerous directions could support further specialized concepts.

10.1.4 Towards Mobile Setups

Preparing Contact-analog HUDs

The *fourth contribution* developed the *SensorVis* system for visualization of sensor data and AR schemes. As a side-effect the *implementation controlling the spatial transformations between the sensors, the displays and the AR schemes* can completely be *ported to a car with a large scale contact-analog HUD*. The issues of correct alignment of AR on see-through displays are encapsulated in a spatial relationship graph that can be adapted easily to meet the fact that not the display is moving, but rather the user's head. When such a HUD is available, registration of new sensors and AR ADAS schemes will be a simple configuration step.

10.2 Outcome and Lessons Learned

The Vision

When I first came into contact with ADAS systems and AR, I thought of implementing such technology in a real car. I wanted to quickly equip this car with a newly developed large scale HUD. Investing some months into registration for correctly aligned AR should be sufficient to have an acceptable working system. Thus, after a year, I would surely be able to start testing AR under real circumstances.

Legal Constraints

Instead, I realized that legal issues thwarted me. Visual overlays are not allowed in Germany. The HUDs available on the market are an exception, because their image appears very low in the windshield and occludes only a small area directly in front of the car. Furthermore, the risk of serious accidents prohibited direct application of AR in cars.

Going to Driving Simulators

The fact that a benefit of any kind of ADAS system (and any IVIS system over all) must be proven, before it can be brought to a car on the road, lead to driving simulator environments. Here pilot investigations of AR concepts can be realized without risking any harm to test subjects (except for simulator sickness issues).

New Simulator related Issues

Even in simulators AR generates new demands on the infrastructure. I therefore changed the focus and investigated the working environment of ADAS system research. Here thankful new issues appeared. An environment that facilitates AR concept development and investigation was required. The contribution provides a broad set of architectures and implementations. These systems range from rapid prototyping environments, which facilitate the development and design process of in-car systems, to specific components serving as managers for independent subissues. Such subissues, for instance, are the concurrent non-overlapping layout of presentation schemes and managers for different output modalities.

In-house Development vs. Outsourcing

Especially the first one and a half year required a lot of effort in enhancing the driving simulator system and the rapid prototyping environment. The fact, that a new driving simulator was built, was necessary to satisfy the need for high quality computer graphics and up to date standards. Even if it appeared as throwing everything away, that has been implemented in the first part of my work, this system change was one of the best evidences for the underlying architecture of the initial system. The architecture I developed for the rapid prototyping environment was very similar to the system layout of the new high quality system. The fact that still components of the initial system are running with the new system accounts for quality and fitting to the demands of such an environment.

Sensor System Issues

Having a system capable of efficient development procedures, the focus could move to adjacent issues of ADAS systems. The strong dependency of ADAS systems on the outer environment of the car revealed a further demand for systems that bridge the gap between reality and simulated environments. Two issues that both affect the use of sensor data for ADAS systems required applied solutions. First, the requirement for traffic scenarios that comprise human behavior and second, independent and cross-system consistent analysis of sensor data. For each issue a solution was developed.

Table-top Integration into Driving Simulators

The table-top miniature toy car environment which I developed and integrated into a driving simulator enables creation of traffic scenarios by test subjects themselves. The system extends traditional driving simulator environments by an interactive extra display with dynamically adjustable points of view. Even if this system has not yet been fully evaluated, its potential for new development principles is already given through further research towards zones of minimal maneuverability (in German: Zonen Minimaler Manövrierbarkeit). Here the system is used for collaborative bird's eye inspection of traffic together with overlays of the maneuverable region of each car.

Consistent Analysis of Sensor Data

The second development decouples ADAS systems internally. Multiple ADAS systems can access a common repository that manages the spatial context of the car and can query for spatially related information. The common infrastructure for spatial reasoning guarantees that all algorithms generate equal results for similar queries. The novel concept to apply ontologies and the evidence, that performance reaches sufficient rates and low lag now enables new architectures for a wide range of ADAS systems. With the SCORE system, developers now can focus either on reasoning above sensor data or on the user interface.

Eventually Usability Testing

With some systems at hand, specifically the rapid prototyping environment and the SCORE system, the initial idea to investigate the effects of AR on human performance could start. Especially in cooperation with the LfE, various in-car systems were developed. While many of these systems had no direct influence on my research on AR, the thankful cooperation let me provide my experience in computer systems to reach both of our goals in a team. The two usability studies reported in this work incorporated AR. Both studies, the study concerning ambient visualization of the braking distance and the drive-path, and the study concerning directional guidance for imminent dangers, revealed a potential for the application of AR in automotive systems for driver assistance. In addition, the usability studies showed that, similar to each new technology which is to be applied in a new environment, guidelines and principles require redesign and extension. New technologies provide a wide range of application, but only a small number of systems finally can bring a benefit. The multi-touch controllers introduced in the late 90 s can be compared to the application of AR. First, the controllers provided eight directions to push, they could be turned and pressed. With gained experience, the number of pushing directions was reduced to four. With the new upcoming version, still four directions are possible to push, but in general only two are applied. Coming back to AR in ADAS systems, the usability studies I contribute can only show that AR can prove useful for automotive driver assistance, but will require further investigation and concept design in future.

Guidelines and Principles

Research towards a general concept for AR in automotive environments supports determination and classification of AR interfaces. The *Sphere of Vision* provides a powerful principle of investigation for spaces that can be used for AR. The definition of auras around different entities in traffic generates awareness for the perceptive and cognitive delta between car drivers and sensor systems. The combination of the *Sphere of Vision* and the definition of auras together with physical dependencies of display systems in HUDs leads to the collection of guidelines for either the development process of ADAS systems and the constraints, AR ADAS systems must achieve to guarantee positive effects.

Seeing Real Overlays

The last system developed in the context of my thesis had a different approach than the previous systems. In the *SensorVis* project, technical issues were investigated to provide a system that can visualize perceptive sensor data correctly aligned. This project, very interesting for putting AR systems in the context of real cars, solves problems of registration and correct alignment of visual data. This project defined a suitable end to the work the thesis covers. The *SensorVis* system is the implementation of the early concept of the *Sphere of Vision*. To really see data of sensors was a really satisfying experience for me. It showed, that it is possible to install tracking systems in cars and that visual presentation schemes can be correctly aligned to the real scenery.

Topics Covered in Thesis

As mentioned in the beginning of this section, similar to the realization that AR can not be applied in cars directly, I felt a great pleasure when really seeing the result of the visual overlay system. Such visualization surely is no ADAS system, but the system supports the development process of ADAS systems. As summarized in section 9 (page 188ff), such a system facilitates various processes and tasks, all concerning environmental sensors, tracking, overlay registration and collaboration. To this end, it is on time to summarize the contributions in a mapping to development processes of ADAS systems in different aspects. Fig. 10.1 shows these professions and the corresponding tasks over a time-line. The green marked areas indicate the areas covered in this thesis and illustrate for which aspect of ADAS system development processes contributions are available.

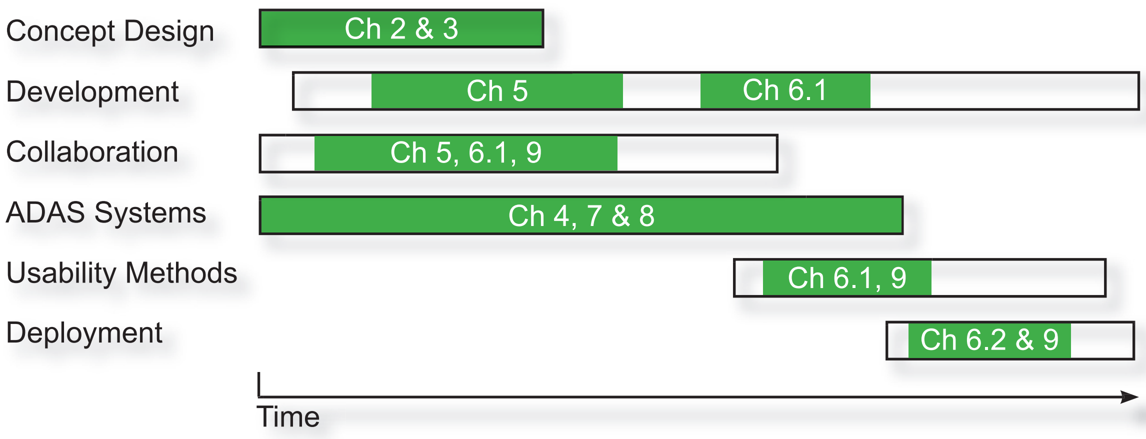


Figure 10.1: Aspects of the Development Process of ADAS System and Contributions of this Thesis

Relative Alignment

Dimensions in this sketch do and can not reflect real dimensions. The figure is more like a sketch showing in which areas my contributions can be seen and used. The time axis defines a relative placement, at which point in time the tools and systems can be incorporated in other projects.

Placement over Time

Concept design processes can apply the content of chapter 2 and chapter 3 continuously. Development processes usually start shortly after the concept design phase. Development processes for ADAS systems can take expertise from chapter 5 to build rapid prototyping environments at early stages. Later in the development process, influences of section 6.1 can be incorporated to generate hybrid development environments with table-top systems. Collaboration is supported again through the architecture of the rapid prototyping environment (chapter 5) and through the visual investigation system in chapter 9. The related work investigated in chapter 4 and the two ADAS systems developed in chapters 7 and 8 are only listed for reasons of completeness, to show that there has not been a deployment to a real car. Usability testing phases start with the end of system development. No direct measurement systems have been developed, but systems that can be used for any kind of investigation and expert discussion. The table-top system from chapter 6.1 and the AR visualization system *SensorVis* from chapter 9 are a notion for concept investigation. For the final deployment of systems to a live environment, chapters 6 and 9 are of interest. Here the analysis system for spatial context and the system for AR alignment are of interest.

10.3 Future Work

Three Directions

Automotive AR leaves a wide range for future work. Even if Fig. 10.1 seemingly covers the white boxes with green fields to a large degree, several areas can be investigated in future. My work identified four areas of major concern for investigation. Similar to the structure of this thesis, the sections of the future work are structured. Future issues start with concept investigation, are followed by developing tools and systems. In subsequence, inspection issues of usability and in the end technical issues of deployment are illustrated.

10.3.1 Classification of Traffic Situations for Mapping of AR Concepts

Incorporating Accident Causes

Concepts for the application of AR still require investigation. Existing analyzes of reasons and types of accidents can be used as a foundation for a classification of AR to dependent situations. The definition for application areas of AR in section 3.2.2 thus can be extended to more specific situations.

Incorporating Traffic Conditions

An analysis of traffic conditions provides a further field for investigation. Highways generate other demands than rural or urban roads. Especially in cities, where traffic density is much higher than anywhere else and the structure of the roads is more complex than in rural environments, many new demands become existent. Investigation of such environments under the paradigm of AR can reveal further classification for the use of AR in ADAS systems. Two major issues are to be investigated here: effects of occlusion and the effect of the delta in knowledge between driver and sensor systems.

Effects of Occlusion

First, occlusion on the one hand is an important factor contributing to monocular depth perception. AR on the other hand can reverse depth cues and can display AR schemes visually in front of objects that normally would occlude the scheme. It has to be determined whether such inversion improves performance or not. Especially in dense traffic, where an AR scheme could be fully covered, such presentation could improve perception. Cognitive workload then could become a negative effect, because the user could be irritated by the incorrect presentation. A further issue pertains to the investigation of the focal depth. Should the AR scheme in front of the object be placed at its correct focal distance behind the object or should the focal depth be reduced, so that the object appears at least at the received focal depth?

Effect of the Delta in Knowledge

The second major issue to investigate concerns the delta between an ADAS system and the driver. The common rule is that an ADAS system has to compensate that delta so that the driver has the same situational awareness as the ADAS system. It could be valuable in certain critical situations, not to show the actual situation, but to use other principles. This shall be explained with an example. Instead of indicating a dangerous location (e.g. a set of lost nails on the road) and thus telling the driver to brake or go around that location, the ADAS system could perform a different action. Such an action could be, that the system places another object (e.g. construction site) at the location of the danger. Alternative approaches could fade out the road markings and place new markings that lead the driver around the location or could use a completely different course. This example has been chosen very visionary to generate awareness for the potential of AR.

Incorporating Implicit Knowledge

Another requirement for investigation is visualization of ambient information. Explicit AR schemes have the potential to inform about a wide range of situations. Steadily presented information must not be obtrusive and therefore has to use ambient presentation. The question is, whether AR can incorporate ambient information to encourage certain actions of drivers through implicit knowledge. Here again an example might illustrate this. An ADAS system detects a location where accidents occur very often. The ADAS system determines that the driver, who is approaching very fast, might have exactly that accident. The ADAS system could superimpose a wet road, convincing the driver to slow down. This is a very rough example that only intends to show the possibilities of the AR paradigm.

About the Examples

It is not intended to realize the two given examples as they are written here. As mentioned, they are used only to explain the potential and the possibilities of AR.

10.3.2 Analysis of Anticipation Behavior

Principles of Anticipation

The table-top environment (section 6.1, page 111ff) allows for efficient creation of traffic scenarios with individual human behavior. Traffic scenarios can be created, stored and various parameters can be modified. Other test subjects can be exhibited to specific traffic situations under various conditions. Such scenarios enable analysis of principles of anticipation. To determine, which factors have influence on reactions of car drivers facilitates the development of ADAS systems. ADAS systems must compensate the delta between their knowledge and the knowledge of the driver. Algorithms and principles of ADAS systems therefore have to rebuild the mental model of car drivers and have to adapt on their behavior.

Wider Range of Parameterization

To enable such analysis, the creation system for traffic scenarios must be extended to allow for variation of a wider range of parameters. Different types of vehicles can already be incorporated and exchanged. Trajectories can be combined in every way. Parameters concerning turn signals, environmental conditions and appearance of other drivers are missing. Facilities for such parameterization must be incorporated. Then, the system itself must be validated in user studies. Studies concerning the validity of the system have to show, whether any usability aspects of the system have to be extended and what further parameters are necessary to incorporate.

10.3.3 Contact-analog Support for Situational Awareness

Two further AR ADAS systems

The second area of future work aims at ADAS systems concepts and investigation.

Continuation with Existing Concepts

Two concepts for new ADAS systems have been defined in the context of this thesis. Pilot studies have been conducted and showed that AR has an effect on the situational awareness and on driving capabilities. Further investigation of both concepts is necessary to come to ADAS systems that could be installed in real test cars.

Longitudinal and Lateral Assistance

The concept for awareness of the own motion behavior of the own car should be extended to meet requirements for platooning traffic. In platooning traffic, safe distances to a leading car are shorter than the braking distance. Investigation has to find suitable ways to communicate this difference in distance to the driver. Further investigation has to examine the effects of the AR schemes on glance behavior. Such examination must be conducted in long term studies to experience learning effects.

Guidance of Attention

The concept for guidance of attention using a 3D arrow requires also future investigation. At the moment, the scheme is relatively large and in the center of view of a forward looking driver. Investigation has to find the optimal size and location for such an AR scheme. Further investigation should examine glance-mounted approaches for the AR scheme. Such time-critical situations, as an imminent upcoming danger, require immediate information transfer wherever the driver is looking at the moment. A visual guidance scheme therefore must focus on the foveal visual aura, or at least at the parafoveal visual aura. Other examination should not only investigate fully exocentric or egocentric approaches for information presentation, but also information presentation in the continuum between both types of presentation. Tethered egocentric viewpoints could possible improve situational awareness.

Two further AR ADAS systems

I decided to mention two specific further systems to recommend for future investigation. The first system focuses at situational awareness at crossings and the second uses AR for a contact-analog navigation system.

Situational Awareness at Crossings

The idea to increase situational awareness at crossings already is under a first investigation in cooperation with the LfE. This initial investigation will reveal, whether egocentric bird's eye perspectives, tethered or fully egocentric frames of reference better support this kind of awareness. Subsequent studies then have to investigate different presentation concepts for the not necessarily time-critical situation at crossings.

Contact-analog Navigation Systems

Navigation systems are hybrid in-car systems. On the one hand they are not necessarily ADAS systems, because they primarily increase comfort. On the other hand a certain benefit for safety in reached, because the navigation task is supported and drivers do not need to read maps while driving. Placing navigational arrows on the road can be a next step towards reduced off-road glance times and ambiguity free information presentation. Complex crossings can be superimposed with explicit information about which route to follow. The concept of a contact-analog navigation system raises several questions to investigate. Besides the general question about the shape of the scheme has to be determined, at which distance a presentation scheme is perceivable. A hybrid concept, at large distances giving symbolic information and at nearer distances showing the contact-analog waypoint information then could be developed. In addition, the issue of occlusion needs to be investigated because, especially in cities, other cars might occlude the AR schemes completely.

10.3.4 Distortion-free Presentation in Contact-analog HUDS

Software driven Image Distortion Correction

The final and most technical area for future work aims on display technology. The current approach to generate a rectangular image for the HUDs available on the market uses special aspheric lenses to straighten the image distorted by the windshield. Such lenses are expensive to compute and to build. For contact-analog HUDs, such lenses must exactly fit to the windshield. If the windshield breaks and a new one is built in, a new aspheric lens must also be built in. Computer vision and 3D computer graphics could enable software driven image correction for such displays. The distortion of the windshield could be measured and an inversely distorted texture could be generated that, perceived through the windshield lets the image appear correctly. Such a system requires generating the inverse distortion according to the actual position of the viewer and thus requires applied head-tracking. In addition, such distortion correction works only sufficient, when the computation of the corrected image is fast enough. If the computation of the inverse image is too slow, swimming effects between the superimposed image and reality are generated. Such swimming effects have a very negative effect and are much more demanding for the human eye and understanding. Research must investigate these issues to provide a high-performance system that correctly aligns visual presentation schemes. Thus, distortion-free and correctly aligned visual overlay of AR is enabled.

Parallax-free Depth-corrected Video Overlay

Such overlays are necessary for superimposition of AR schemes and vision enhancement systems. Vision enhancement systems use camera images to enhance a car driver's perception. Such cameras can not be mounted at the position of the car driver. Images recorded with such cameras have a parallax error. To use such camera images for superimposition of the field of view of the driver, parallax correction mechanisms are necessary. Information about the focal distance is required to warp the images according to the egocentric frame of reference of the driver. The camera image can be analyzed for relevant information and the warped image then can be superimposed in the HUD of the car driver. Research has to develop a suitable fundament for such off-axis camera systems.

10.4 Last Words

Encouraging Investigation

This work investigated the development process of AR ADAS systems and provides a set of tools to support such processes. Efficient development cycles are necessary to encourage investigation of AR in ADAS systems. With the systems described in this thesis, variants and alternatives of AR schemes can easily be evaluated and discussed in collaborative teams. Subsequent demands can easier be visualized and communicated to researchers in other domains.

Future Demands

Research in innovative user interfaces is enabled with the tools and systems I developed. Direct use of the development environments and application of supplementary tools showed their suitability and enabled investigation of different AR concepts for automotive assistance systems. Such systems will have an increasing demand in future to enhance safety aspects and to differentiate philosophies of car manufacturers and their products.

A Questionnaires

Subjective questionnaires used in the usability studies

The subsequent questionnaires are printed in their original versions in German, because the studies have been conducted in German and any translation could distort the phrasing.

A.1 Demographic Questionnaire of Study for Ambient Physics Visualization

Demografischer Fragebogen

1 Angaben zur Person

Alter:			
Beruf:			
Geschlecht:	❒ Männlich	❒ Weiblich	
Händigkeit:	❒ Linkshänder	❒ Rechtshänder	❒ Beides
Brille:	❒ keine	❒ zum Autofahren	❒ zum Lesen
Farbenblindheit:	❒ nein	❒ wenn ja, welche Art: ______________	
Wie viele Personen leben in Ihrem Haushalt?			
Wie viele Autos befinden sich in Ihrem Haushalt?			

Haben Sie bisher schon an einem Fahrversuch teilgenommen?
❒ Ja, in einem Simulator
❒ Ja, in einem Versuchsfahrzeug
❒ Ja, beides (Simulator und Versuchsfahrzeug)
❒ Nein, noch nie

DEMOGRAFISCHER FRAGEBOGEN

2 Angaben zur Fahrerfahrung

Seit wann besitzen Sie Ihren Führerschein?	

Welche Fahrerlaubnisklassen besitzen Sie?	
❐ PKW	❐ LKW
❐ Motorrad	❐ Sonstige:

Wie viele km fahren Sie in etwa pro Jahr?	
❐ Weniger als 5.000	❐ 5.000 –10.000
❐ 10.000 – 20.000	❐ mehr als 20.000

Ich fahre derzeit:	
❐ Immer den gleichen PKW	❐ Verschiedene PKW
Welche Marke/Fabrikat? ______________________________	

Wie oft fahren Sie derzeit mit dem Auto?			
❐ 1x wöchentlich	❐ 1-3x wöchentlich	❐ 3-5x wöchentlich	❐ fast täglich

Wo fahren Sie am häufigsten?		
❐ Stadtverkehr	❐ Landstraße	❐ Autobahn

Was fahren Sie öfter?	
❐ Kurzstrecke (bis 10 km)	❐ Langstrecke

Haben Sie Erfahrung mit einem Automatikgetriebe?	
❐ Ja	❐ Nein

3

3 Angaben zur Fahrertypeinschätzung

Im Vergleich zu anderen Autofahrern würde ich mich folgendermaßen einschätzen:		
Sehr erfahren	❒ ❒ ❒ ❒ ❒ ❒	Sehr unerfahren

Ich würde meinen Fahrstil beschreiben als:		
Sportlich/dynamisch	❒ ❒ ❒ ❒ ❒ ❒	Ruhig/ausgeglichen

Bei hoher Verkehrsdichte verhalte ich mich:		
Eher offensiv	❒ ❒ ❒ ❒ ❒ ❒	Eher defensiv

Meine Kontrolle über das Fahrzeug schätze ich wie folgt ein:		
Ich beherrsche mein Fahrzeug in jeder Situation	❒ ❒ ❒ ❒ ❒ ❒	In manchen Situationen habe ich Schwierigkeiten

Mit einem fremden Fahrzeug zurechtzukommen …		
fällt mir leicht	❒ ❒ ❒ ❒ ❒ ❒	bereitet mir Schwierigkeiten

Ich bin an technischen Dingen um das Auto …		
sehr interessiert und informiert	❒ ❒ ❒ ❒ ❒ ❒	nicht interessiert

Autofahren bedeutet für mich:		
Spaß	❒ ❒ ❒ ❒ ❒ ❒	ein notwendiges Übel

Beim Autofahren …		
bleibe ich meistens entspannt und locker	❒ ❒ ❒ ❒ ❒ ❒	fühle ich mich oft gestresst

DEMOGRAFISCHER FRAGEBOGEN

Im Alltag achte ich auf eine Sprit sparende Fahrweise …		
überhaupt nicht	❒ ❒ ❒ ❒ ❒ ❒	sehr stark

Geschwindigkeitsbeschränkungen halte ich strikt ein:		
überhaupt nicht	❒ ❒ ❒ ❒ ❒ ❒	immer

Ich kann mich für Technik … begeistern		
überhaupt nicht	❒ ❒ ❒ ❒ ❒ ❒	immer

Ich probiere gerne neue technische Geräte aus		
trifft zu	❒ ❒ ❒ ❒ ❒ ❒	trifft nicht zu

Ich spiele Computerspiele …		
überhaupt nicht	❒ ❒ ❒ ❒ ❒ ❒	sehr oft

5

4 Erfahrung mit technischen Systemen

Welche Erfahrungen haben Sie mit folgenden Systemen?

	Keine Erfahrungen	Schon mal gesehen	Ausprobiert	Nutze ich manchmal	Nutze ich oft	Nutze ich sehr oft
Tempomat	❐	❐	❐	❐	❐	❐
Aktive Geschwindigkeitsregelung (ACC; elektronische Abstands- und Geschwindigkeitsregelung)	❐	❐	❐	❐	❐	❐
Navigationssystem	❐	❐	❐	❐	❐	❐
Zentrale Bedieneinheit in der Mittelkonsole (z.B. iDrive, MMI, COMAND)	❐	❐	❐	❐	❐	❐
Head-Up-Display	❐	❐	❐	❐	❐	❐
PDC (Park Distance Controll; elektronische Einparkhilfe)	❐	❐	❐	❐	❐	❐

5 Aktuelle Gefühlslage

Ich fühle mich im Moment:		
Entspannt	❐ ❐ ❐ ❐ ❐ ❐	Gestresst
Erholt	❐ ❐ ❐ ❐ ❐ ❐	Müde
Locker	❐ ❐ ❐ ❐ ❐ ❐	Nervös
Gesund	❐ ❐ ❐ ❐ ❐ ❐	Krank

A.2 Final Questionnaire of Study for Ambient Physics Visualization

Fragebogen zum Fahren mit optischer Assistenzfunktion

Versuchsperson:	
Datum:	

FRAGEBOGEN ZUR OPTISCHEN ASSISTENZ

Im Folgenden werden Ihnen Fragen zum Fahren mit optischer Assistenzfunktion gestellt!

Fragen zur Belastung/ Beanspruchung:

1. Mentale (geistige) Belastung		
In welchem Maße stellte das Fahren geistige Anforderungen, also denken, entscheiden, beobachten?		
Das Fahren ist leicht und verzeiht Fehler. Insgesamt eine recht einfache Aufgabe.	gering hoch	Das Fahren ist komplex und erfordert hohe Genauigkeit. Insgesamt eine sehr schwierige Aufgabe.

2. Physische (körperliche) Belastung		
Wie viel körperliche Aktivität, also drücken, bewegen ist erforderlich?		
Das Fahren ist leicht, dabei geht es langsam zu. Man kommt beim Fahren mit wenig Bewegungsaufwand und Kraft aus.	gering hoch	Das Fahren ist anstrengend, dabei geht es hektisch zu. Es erfordert viel Bewegungsaufwand und Kraft.

3. Zeitliche Anforderung		
Welchen Zeitdruck empfinden Sie aufgrund der Geschwindigkeitsanforderungen, die das Fahren stellt?		
Das Fahren ist leicht und verzeiht Fehler. Insgesamt eine recht einfache Aufgabe.	gering hoch	Das Fahren ist komplex und erfordert hohe Genauigkeit. Insgesamt eine sehr schwierige Aufgabe.
4. Aufgabenerfüllung		
Wie zufrieden sind Sie mit dem Grad an Aufgabenerfüllung, also Spur-,		

2

FRAGEBOGEN ZUR OPTISCHEN ASSISTENZ

Geschwindigkeits-, und Abstandshaltung zusammen?		
Ich bin mit der Aufgabenerfüllung sehr zufrieden (perfekt erfüllt).	gering hoch	Ich bin mit der Aufgabenerfüllung sehr unzufrieden (bei der Erfüllung versagt).

5. Anstrengung		
Wie sehr mussten Sie sich beim Fahren insgesamt anstrengen (geistig und körperlich)?		
Das Fahren erfordert überhaupt keine Anstrengung.	gering hoch	Das Fahren erfordert sehr hohe Anstrengung.

6. Stress		
In welchem Maße fühlten Sie sich beim Fahren gestresst?		
Das Fahren stresste mich überhaupt nicht.	gering hoch	Das Fahren stresste mich sehr.

FRAGEBOGEN ZUR OPTISCHEN ASSISTENZ

Fragen zur Fahrperformance:

Spurhaltung:		
Bitte bewerten Sie, wie gut Sie in der Lage waren die Spur zu halten:		
sehr gut	❒ ❒ ❒ ❒ ❒ ❒	sehr schlecht

Geschwindigkeitshaltung:		
Bitte bewerten Sie, wie gut Sie in der Lage waren die erlaubte Geschwindigkeit zu halten:		
sehr gut	❒ ❒ ❒ ❒ ❒ ❒	sehr schlecht

Abstandshaltung:		
Bitte bewerten Sie, wie gut Sie in der Lage waren den Abstand zum vorausfahrenden Fahrzeug zu halten:		
sehr gut	❒ ❒ ❒ ❒ ❒ ❒	sehr schlecht

Konzentration:		
Bitte bewerten Sie, wie gut Sie in der Lage waren sich auf das Fahren zu konzentrieren:		
sehr gut	❒ ❒ ❒ ❒ ❒ ❒	sehr schlecht

Gesamturteil zur Erfüllung der Geschwindigkeits-, Abstands-, und Spurhaltung:		
Bitte bewerten Sie, wie gut Sie in der Lage waren die Geschwindigkeits-, Abstands-, und Spurhaltung zu bewältigen:		
sehr gut	❒ ❒ ❒ ❒ ❒ ❒	sehr schlecht

Sicherheitsgefühl:		
Bitte bewerten Sie, wie Ihr Sicherheitsgefühl beim Fahren war:		
sehr gut	❒ ❒ ❒ ❒ ❒ ❒	sehr schlecht

4

Entspannung:		
Bitte bewerten Sie, wie entspannt Sie bei der Fahrt waren:		
sehr entspannt	❐ ❐ ❐ ❐ ❐ ❐	Überhaupt nicht entspannt

Fragen zum Gefallen der Systeme:

Gesamteindruck:		
Bitte bewerten Sie, wie gut Ihnen insgesamt diese Variante gefallen hat:		
sehr gut	❐ ❐ ❐ ❐ ❐ ❐	sehr schlecht

Realisierung im Fahrzeug:		
Bitte bewerten Sie, wie gerne Sie diese Fahrvariante in Ihrem PKW verwirklicht hätten, angenommen es kostet keinen Aufpreis:		
sehr gerne	❐ ❐ ❐ ❐ ❐ ❐	Überhaupt nicht

A.3 Demographic Questionnaire of Studies for Guidance of Attention

Technische Universität München

Lehrstuhl für Ergonomie, Fachgebiet Augmented Reality

Fragebogen zur Persona

Lehrstuhl für Ergonomie
Technische Universität München

1 Angaben zur Person

Alter:						
Beruf:						
Geschlecht:	❐	Männlich	❐	Weiblich		
Händigkeit:	❐	Linkshänder	❐	Rechtshänder	❐	Beides
Brille:	❐	keine	❐	zum Autofahren	❐	zum Lesen
Höchster Ausbildungs-abschluss	❐	Promotion	❐	Hochschulabschluss		
	❐	Fachhochschulabschluss	❐	Abitur		
	❐	Mittlere Reife	❐	Hauptschulabschluss		
Wie viele Personen leben in Ihrem Haushalt?						
Wie viele Autos befinden sich in Ihrem Haushalt?						

Haben Sie bisher schon an einem Fahrversuch teilgenommen?
❐ Ja, in einem Simulator
❐ Ja, in einem Versuchsfahrzeug
❐ Ja, beides (Simulator und Versuchsfahrzeug)
❐ Nein, noch nie

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ERFAHRUNG MIT TECHNISCHEN SYSTEMEN

2 Angaben zur Fahrerfahrung

Seit wann besitzen Sie Ihren Führerschein?	19___

Welche Fahrerlaubnisklassen besitzen Sie?	
❒ PKW	❒ LKW
❒ Motorrad	❒ Sonstige:

Wieviele km fahren Sie in etwa pro Jahr?	
❒ Weniger als 5.000	❒ 5.000 –10.000
❒ 10.000 – 20.000	❒ mehr als 20.000

Ich fahre derzeit:	
❒ Immer den gleichen PKW	❒ Verschiedene PKW
Welche Marke/Fabrikat? ___________________________________	

Wie oft fahren Sie derzeit mit dem Auto?		
❒ Täglich	❒ Ab und zu	❒ Sehr selten

Haben Sie Erfahrung mit einem Automatikgetriebe?	
❒ Ja	❒ Nein

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ERFAHRUNG MIT TECHNISCHEN SYSTEMEN

3 Angaben zum Fahrbefinden

Im Vergleich zu anderen Autofahrern würde ich mich folgendermaßen einschätzen:		
Sehr erfahren	❒ ❒ ❒ ❒ ❒ ❒	Sehr unerfahren

Ich würde meinen Fahrstil beschreiben als:		
Ruhig/ausgeglichen	❒ ❒ ❒ ❒ ❒ ❒	Sportlich/dynamisch

Bei hoher Verkehrsdichte verhalte ich mich:		
Eher defensiv	❒ ❒ ❒ ❒ ❒ ❒	Eher offensiv

Meine Kontrolle über das Fahrzeug schätze ich wie folgt ein:		
Ich beherrsche mein Fahrzeug in jeder Situation	❒ ❒ ❒ ❒ ❒ ❒	In manchen Situationen habe ich Schwierigkeiten

Mit einem fremden Fahrzeug zurechtzukommen …		
fällt mir leicht	❒ ❒ ❒ ❒ ❒ ❒	bereitet mir Schwierigkeiten

Ich bin an technischen Dingen um das Auto …		
sehr interessiert und informiert	❒ ❒ ❒ ❒ ❒ ❒	nicht interessiert

Autofahren bedeutet für mich:		
Spaß	❒ ❒ ❒ ❒ ❒ ❒	Ein notwendiges Übel

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Erfahrung mit technischen Systemen

Bitte kreuzen Sie an, inwieweit folgende Aussagen auf Sie zutreffen:

Welche Erfahrungen haben Sie mit folgenden Systemen?

	Keine Erfahrungen	Schon mal gesehen	Ausprobiert	Nutze ich manchmal	Nutze ich oft	Nutze ich regelmäßig
Tempomat	❒	❒	❒	❒	❒	❒
I-Drive (Zentrale Bedieneinheit in der Mittelkonsole)	❒	❒	❒	❒	❒	❒
Navigationssystem	❒	❒	❒	❒	❒	❒
Head-Up-Display	❒	❒	❒	❒	❒	❒
Aktive Geschwindigkeitsregelung (ACC; elektronische Abstand- und Geschwindigkeitsregelung)	❒	❒	❒	❒	❒	❒
PDC (Park Distance Control; elektronische Einparkhilfe)	❒	❒	❒	❒	❒	❒

4 Aktuelle Gefühlslage

Ich fühle mich im Moment:		
Entspannt	❒ ❒ ❒ ❒ ❒ ❒	Gestresst
Erholt	❒ ❒ ❒ ❒ ❒ ❒	Müde
Locker	❒ ❒ ❒ ❒ ❒ ❒	Nervös
Gesund	❒ ❒ ❒ ❒ ❒ ❒	Krank

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Für die Auswertung reserviert, bitte frei lassen:	
Versuchsperson:	

A.4 Final Questionnaire of Pilot Study for Guidance of Attention

Technische Universität München

Lehrstuhl für Ergonomie, Fachgebiet Augmented Reality

Abschlussfragebogen

Lehrstuhl für Ergonomie
Technische Universität München

Abschlussfragen

Sehr geehrte Versuchsperson

Zunächst einmal vielen Dank, dass Sie an unserem Versuch teilgenommen haben.

Abschließend haben wir noch ein paar kurze Fragen, in deren Rahmen Sie die unterschiedlichen Systemvarianten beurteilen können.

Die folgenden Fragen beziehen sich auf die beiden Darstellungsvarianten, die Sie im eben durchgeführten Versuch erlebt haben. Nachstehend sind die beiden unterschiedlichen Ausführungen noch einmal dargstellt. Die direkte Darstellung bedeutet, dass Sie den Warnhinweis über den 3D-Pfeil bekommen haben. Die symbolisierte Anzeige heißt, Sie bekommen die Szene symbolisiert von oben dargestellt.

Direkte Darstellung

Symbolisierte Anzeige

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Technische Universität München

Bitte kreuzen Sie an wie gut Ihnen die beiden Varianten jeweils gefallen haben. Vergeben Sie dazu bitte Noten im Schulnotensystem. Die „1“ steht für „hat mir sehr gut gefallen“, die „6“ steht für „hat mir überhaupt nicht gefallen“.

Direkte Darstellung	1	2	3	4	5	6
Symbolisierte Anzeige	1	2	3	4	5	6

Bitte kreuzen Sie an, wie gut Sie meinen, dass Sie mit der jeweiligen Variante zurechtgekommen sind. Vergeben Sie dazu bitte Noten im Schulnotensystem. Die „1“ steht für „ich bin mit der Variante sehr gut zurechtgekommen“, die „6“ steht für „jch bin mit der Variante überhaupt nicht zurechtgekommen“.

Direkte Darstellung	1	2	3	4	5	6
Symbolisierte Anzeige	1	2	3	4	5	6

Bitte kreuzen Sie an, mit welcher Variante Sie meinen, dass Sie schneller die geforderte Zahl nennen konnten. Vergeben Sie dazu bitte Noten im Schulnotensystem. Die „1“ steht für „ich konnte die Zahl sehr schnell nennen“, die „6“ steht für „jch konnte die Zahl sehr langsam nennen“.

Direkte Darstellung	1	2	3	4	5	6
Symbolisierte Anzeige	1	2	3	4	5	6

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Bitte kreuzen Sie an, mit welcher Variante Sie meinen, dass Sie genauer die geforderte Zahl nennen konnten. Vergeben Sie dazu bitte Noten im Schulnotensystem. Die „1“ steht für „ich konnte die geforderte Zahl sehr genau bestimmen“, die „6“ steht für „ich konnte die geforderte Zahl sehr ungenau bestimmen“.

	1	2	3	4	5	6
Direkte Darstellung						
	1	2	3	4	5	6
Symbolisierte Anzeige						

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A.5 Final Questionnaire of Main Study for Guidance of Attention

Technische Universität München

Lehrstuhl für Ergonomie, Fachgebiet Augmented Reality

Abschlussfragebogen

Lehrstuhl für Ergonomie
Technische Universität München

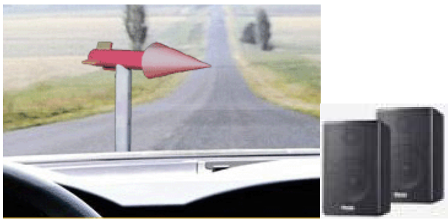
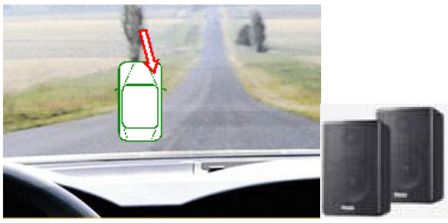
Abschlussfragen

Sehr geehrte Versuchsperson,

zunächst einmal vielen Dank, dass Sie an unserem Versuch teilgenommen haben.

Abschließend haben wir noch ein paar kurze Fragen, in deren Rahmen Sie die unterschiedlichen Systemvarianten beurteilen können.

Die folgenden Fragen beziehen sich auf die vier Varianten, die Sie im eben durchgeführten Versuch erlebt haben. Die direkte Darstellung bedeutet, dass Sie den Warnhinweis über den 3D-Pfeil bekommen haben. Die symbolisierte Anzeige bezieht sich auf die symbolisierte Darstellung der Szene von oben. Beide Anzeigevarianten gibt es als rein optische Warnhinweise und zusätzlich als Variante mit Ton. Nachstehend sind die vier sich somit ergebenden unterschiedlichen Ausführungen noch einmal dargestellt.

 Direkte Darstellung	 Direkte Darstellung mit Ton
 Symbolisierte Anzeige	 Symbolisierte Anzeige mit Ton

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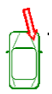
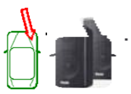
Bitte kreuzen Sie an, wie gut Ihnen die vier Varianten jeweils gefallen haben. Vergeben Sie dazu bitte Noten im Schulnotensystem. Die „1“ steht für „hat mir sehr gut gefallen“, die „6“ steht für „hat mir überhaupt nicht gefallen“.

 Direkte Darstellung	1	2	3	4	5	6
 Direkte Darstellung mit Ton	1	2	3	4	5	6
 Symbolisierte Anzeige	1	2	3	4	5	6
 Symbolisierte Anzeige mit Ton	1	2	3	4	5	6

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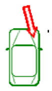
Bitte kreuzen Sie an, wie gut Sie meinen, dass Sie mit der jeweiligen Variante zurechtgekommen sind. Vergeben Sie dazu bitte Noten im Schulnotensystem. Die „1" steht für „ich bin mit der Variante sehr gut zurechtgekommen", die „6" steht für „ich bin mit der Variante überhaupt nicht zurechtgekommen".

 Direkte Darstellung	1	2	3	4	5	6
 Direkte Darstellung mit Ton	1	2	3	4	5	6
 Symbolisierte Anzeige	1	2	3	4	5	6
 Symbolisierte Anzeige mit Ton	1	2	3	4	5	6

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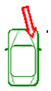
Bitte kreuzen Sie bei jeder Variante an, wie schnell Sie Ihrer Meinung nach die geforderte Zahl nennen konnten. Vergeben Sie dazu bitte Noten im Schulnotensystem. Die „1“ steht für „ich konnte die Zahl sehr schnell nennen“, die „6“ steht für „ich konnte die Zahl sehr langsam nennen“.

 Direkte Darstellung	1	2	3	4	5	6
 Direkte Darstellung mit Ton	1	2	3	4	5	6
 Symbolisierte Anzeige	1	2	3	4	5	6
 Symbolisierte Anzeige mit Ton	1	2	3	4	5	6

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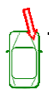
Bitte kreuzen Sie bei jeder Variante an, wie genau Sie Ihrer Meinung nach die geforderte Zahl nennen konnten. Vergeben Sie dazu bitte Noten im Schulnotensystem. Die „1“ steht für „ich konnte die geforderte Zahl sehr genau bestimmen“, die „6“ steht für „ich konnte die geforderte Zahl sehr ungenau bestimmen“.

 Direkte Darstellung	1	2	3	4	5	6
 Direkte Darstellung mit Ton	1	2	3	4	5	6
 Symbolisierte Anzeige	1	2	3	4	5	6
 Symbolisierte Anzeige mit Ton	1	2	3	4	5	6

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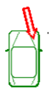
Bitte geben Sie schließlich eine Rangfolge der vier verschiedenen Kombinationen an, indem Sie die Nummern von „1“ bis „4“ zuweisen. Tragen Sie in das Kästchen neben dem System, das Ihnen am besten gefallen hat, eine „1“ ein, eine „2“ neben dem zweitbesten System, usw., bis hin zur „4“ für das Ihrer Meinung nach schlechteste System.

 Direkte Darstellung	Nummer: ☐
 Direkte Darstellung mit Ton	Nummer: ☐
 Symbolisierte Anzeige	Nummer: ☐
 Symbolisierte Anzeige mit Ton	Nummer: ☐

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B Detailed Results of User Studies

Brief summary of non-significant results of usability studies

Some user studies were conducted in the context of this thesis. To keep the chapters short, only significant differences were reported in the chapters. Measures not revealing any significant difference were only indicated briefly. For completeness, the non-significant results are listed here.

B.1 Non-Significant Results of the Drive-Path Study

The experiments concerning the braking bar and drive-path presentation scheme in chapter 7 (page 142ff) did not reveal any differences for several measures. A brief explanation, including minimum and maximum values, mean values, standard deviation and α-errors are presented in subsequence.

B.1.1 Time of Speeding Violation

A further indicator for speed behavior is the analysis of real speeding violations. To define a general limit, a threshold, $10\,km/h$ above the allowed speed for a road section was defined. For all road sections with constant speed, the time periods were we cumulated, were people exceeded the allowed speed plus the given percentage values. Results show, that test subjects exceeded the allowed speed for a longer time, the more visual assistance they had. On the baseline drive, they went more than $10\,km/h$ faster for $22.87\,\%$, with the bar presentation scheme, for $24.26\,\%$ of the total time on the four section types. With the drive-path assistance scheme, they were over the limit for $26.95\,\%$ of the time. Table B.1 shows, that none of the results is significant.

α-Values	Baseline	Bar	Bar & Path
Baseline		0.625	0.214
Bar			0.292
Bar & Path			
Mean [%]	22.87	24.26	26.95
Std.dev [%]	21.58	23.75	23.59

Table B.1: Time of Speeding Violations

B.1.2 Time to Line Crossing

The lateral acceleration measurements were used to compute the Time to Line Crossing (TLC), an indicator for lane keeping behavior. The TLC has been computed following Pomerleau [120]. All resulting mean values ranged between $11.20\,s$ and $11.56\,s$ and had no significant impact on their pair-wise comparison.

α-Values	Baseline	Bar	Bar & Path
Baseline		0.108	0.108
Bar			0.680
Bar & Path			
Mean [s]	11.20	11.56	11.49
Std.dev [s]	1.45	1.67	1.48

Table B.2: Time to Line Crossing

B.1.3 15. Percentile of Time to Line Crossing

Another indicator for lane keeping behavior is the 15. percentile of the TLC. Sorting all measured TLC values in ascending order and taking the value at the 15 % limit gives the 15. percentile [61].

Table B.3 shows slightly longer periods in time ($6.71\,s$) to cross a lane marking for the bar presentation scheme. This result comes close to significance in comparison to driving without any visual assistance ($6.34\,s$).

α-Values	Baseline	Bar	Bar & Path
Baseline		0.078	0.138
Bar			0.510
Bar & Path			
Mean [s]	6.34	6.71	6.59
Std.dev [s]	1.25	1.46	1.35

Table B.3: 15. Percentile of Time to Line Crossing

B.1.4 Pleasure

Pleasure of in-car systems is, besides driving performance, a very important factor in the automotive domain. If people do not like a system, they will not use it. The final questionnaire asked the test participants, how much they liked both assistance schemes. They ranked the bar scheme (2.37) higher than the drive-path scheme (2.56). The results are given in the German school grading system, ranging from 1 (best) to 6 (worst). Table B.4 shows that the comparison is not significant.

	Bar	Bar & Path
Mean	2.37	2.56
Std.dev	0.93	1.34
α-Value	0.355	

Table B.4: Pleasure

B.1.5 Wish for Realization

Asking the participants, which system they would like to see in real cars, the analysis preferred the bar presentation scheme with a grade of 2.37 over the drive-path with a grade of 2.56. The results are given in the German school grading system, ranging from 1 (best) to 6 (worst). Table B.5 shows all values related to the wish for realization.

	Bar	Bar & Path
Mean	2.37	2.56
Std.dev	0.93	1.34
α-Value	0.130	

Table B.5: Wish for Realization

B.1.6 Relaxation

Another question concerned the topic, whether test subjects could execute the test drive in a relaxed manner. Participants were more strained the higher the added visual content in the windshield was. The results are given in the German school grading system, ranging from 1 (best) to 6 (worst). Without any assistance, they gave a 2.56, with the bar presentation scheme, they gave a grade of 2.59 and for the drive-path they gave an average mark of 2.70. Table B.6 reveals no significances for any pair of measures.

α-Values	Baseline	Bar	Bar & Path
Baseline		0.823	0.556
Bar			0.676
Bar & Path			
Mean	2.56	2.59	2.70
Std.dev	1.28	1.19	1.41

Table B.6: Relaxation

B.1.7 Ability to Stay within a Lane

Asking the participants about their opinion, with which of the three alternatives they could maintain their lateral course better, they preferred the bar presentation scheme and graded it as 2.56. In comparison to no assistance, the bar scheme nearly reached significance with an $\alpha-$value of 0.059. The results are given in the German school grading system, ranging from 1 (best) to 6 (worst). This result does not completely match to the objective measurements, where lane deviation decreased with increase of visual assistance. The step from no assistance to the bar scheme aligns with the objective results. But the subjective decrease of the lane keeping performance from the bar scheme to the drive-path scheme is in contradiction with the objective results. Table B.7 shows mean and standard deviation values as well as the significance values.

α-Values	Baseline	Bar	Bar & Path
Baseline		0.059	0.879
Bar			0.152
Bar & Path			
Mean	2.89	2.56	2.93
Std.dev	0.89	0.85	1.27

Table B.7: Ability to Maintain Lane

B.1.8 Feeling of Safety

The results are given in the German school grading system, ranging from 1 (best) to 6 (worst). Drivers felt safest when driving with the visual bar scheme (2.37), followed by normal driving with no assistance (2.41). Driving with the drive-path presentation scheme did not make the participants feel as safe in both other cases and resulted in a grade of 2.56. Table B.8 shows that none of these results is significant.

α-Values	Baseline	Bar	Bar & Path
Baseline		0.839	0.596
Bar			0.466
Bar & Path			
Mean	2.41	2.37	2.56
Std.dev	1.08	0.93	1.34

Table B.8: Feeling of Safety

B.2 Non-Significant Results of Attentional Guidance Main Study

The experiments concerning the main study for the presentation schemes to guide a car driver's attention towards imminent dangers in chapter 8 (page 160ff) did not reveal any differences for several measures. Brief illustrations with mean values, standard deviation and α-errors are presented in the following sections.

B.2.1 Average Mistake

The largest average mistake occurred in the pure bird's eye scheme with a value of 3.8. The lowest average mistake was 0.2 measured in the 3D arrow experiment without sound.

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.113	0.709	0.129
	Bird's eye			0.184	0.183
with sound	3D arrow				0.396
	Bird's eye				
Mean []		0.71	0.94	0.73	0.83
Std.dev []		0.34	0.68	0.32	0.33

Table B.9: Average Mistake

B.2.2 Error Quotient

The maximum error quotient with a value of 0.85 occurred in the pure bird's eye presentation, while the minimum value of 0.20 again was generated from the pure 3D arrow without sound.

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.019	0.223	0.013
	Bird's eye			0.124	0.810
with sound	3D arrow				0.098
	Bird's eye				
Mean []		0.48	0.58	0.52	0.58
Std.dev []		0.13	0.14	0.14	0.14

Table B.10: Error Quotient

B.2.3 Mean Lane Departure

The 3D arrow with sound has the smallest mean value (-0.02 m, std.dev 0.27 m). It is followed by the 3D arrow scheme with sound which has a mean value of -0.04 m (std.dev 0.26 m). The third best presentation scheme is the bird's eye perspective with sound (mean value -0.07 m, std.dev 0.22 m). The worst presentation scheme is the bird's eye presentation without sound with a average lane deviation of -0.13 m (std.dev 0.21 m).

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.023	0.767	0.297
	Bird's eye			0.031	0.094
with sound	3D arrow				0.156
	Bird's eye				
Mean [m]		-0.04	-0.13	-0.02	-0.07
Std.dev [m]		0.26	0.21	0.27	0.22

Table B.11: Mean Lane Departure

B.2.4 Standard Deviation of Lane Departure

The pure 3D arrow presentation gave the best results for the standard deviation of the lane departure with a value of 0.17 meters (std.dev 0.06). The 3D arrow scheme with sound is minimally worse with a value of 0.18 m (std.dev 0.17 m). Both bird's eye presentations almost got the same lane departure values, with a standard deviation of the lane departure of

0.20 m, but the standard deviation of the variant with sound is greater (std.dev 0.21 m), as the meter value of the variant without sound (std.dev 0.08 m).

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.081	0.819	0.403
	Bird's eye			0.488	0.991
with sound	3D arrow				0.141
	Bird's eye				
Mean [m]		0.17	0.20	0.18	0.20
Std.dev [m]		0.06	0.08	0.17	0.21

Table B.12: Standard Deviation of Lane Departure

B.2.5 Speed Variation

The least speed variations were generated by the sound supported 3D arrow presentation scheme with a value of -0.61 km/h (std.dev 1.62 km/h). The variant without sound gave a value of -0.69 km/h (std.dev 1.76 km/h). The bird's eye perspective with sound reaches the third position with a value of -0.81 km/h but has a high standard deviation of 3.04 km/h. The worst results are generated by the pure bird's eye perspective (-1.11 km/h, std.dev 1.90 km/h).

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.210	0.622	0.799
	Bird's eye			0.092	0.538
with sound	3D arrow				0.629
	Bird's eye				
Mean [km/h]		-0.69	-1.11	-0.61	-0.81
Std.dev [km/h]		1.76	1.90	1.62	3.04

Table B.13: Speed Variation

B.2.6 How much did you like a certain Variant?

The results are given in the German school grading system, ranging from 1 (best) to 6 (worst).

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.564	0.188	0.293
	Bird's eye			0.781	0.388
with sound	3D arrow				0.722
	Bird's eye				
Mean []		2.71	2.92	3.04	3.17
Std.dev []		1.20	1.14	1.15	1.43

Table B.14: Question: *How much did you like a certain variant?*

B.2.7 How well could you deal with it?

The results are given in the German school grading system, ranging from 1 (best) to 6 (worst).

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.141	0.364	0.233
	Bird's eye			0.088	0.857
with sound	3D arrow				0.044
	Bird's eye				
Mean []		2.87	3.33	2.67	3.29
Std.dev []		0.99	1.17	1.27	1.23

Table B.15: Question: *How well could you deal with it?*

B.2.8 How quickly could you nominate the corresponding Paper Sheet?

The results are given in the German school grading system, ranging from 1 (best) to 6 (worst).

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.010	0.032	0.195
	Bird's eye			0.002	0.015
with sound	3D arrow				0.026
	Bird's eye				
Mean []		2.79	3.63	2.50	3.21
Std.dev []		1.14	1.01	1.18	1.14

Table B.16: Question: *How quickly could you nominate the corresponding paper sheet?*

B.2.9 How exactly could you identify the Paper Sheet?

The results are given in the German school grading system, ranging from 1 (best) to 6 (worst).

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.027	0.185	0.224
	Bird's eye			0.014	0.056
with sound	3D arrow				0.094
	Bird's eye				
Mean []		2.83	3.42	2.70	3.17
Std.dev []		0.87	0.88	0.95	0.87

Table B.17: Question: *How exactly could you identify the paper sheet?*

B.2.10 Ranking of Presentation Schemes

The test subjects had to rank all schemes according to each other. Thus positions 1 (top-ranked) to 4 (worst-ranked) were used for calculation.

α-Values		no sound		with sound	
		3D arrow	Bird's eye	3D arrow	Bird's eye
no sound	3D arrow		0.163	0.504	0.421
	Bird's eye			0.122	0.468
with sound	3D arrow				0.120
	Bird's eye				
Mean []		2.33	2.88	2.13	2.67
Std.dev []		1.09	1.19	1.15	0.96

Table B.18: Question to rank the presentation schemes w.r.t. pleasure

C Glossary

Abbreviations and acronyms

AAM. Alliance of Automobile Manufacturers. Trade group of automobile manufacturers originated as *American Automobile Manufacturers Association* in the United States, but replaced to AAM in January 13, 1999; now represents international manufacturers. Charter members included Ford Motor Company and the General Motors Corporation of the United States; BMW A.G., Volkswagen A.G. and DaimlerChrysler A.G. of Germany; A.B. Volvo of Sweden, and the Mazda Motor Corporation, the Nissan Motor Company and the Toyota Motor Corporation of Japan.

ACC. Adaptive/Active Cruise Control. An active $\rightarrow ADAS$ system that maintains the own car's speed in dependence to the speed of a leading car.

ADAS. Advanced Driver Assistance System. In-car system that actively or passively takes care of safety aspects by informing or warning the driver about dangerous occurrences or by active intervention into the car's motion control.

AR. Augmented Reality. Extends the real world by interactive virtual objects.

C2C. Car to Car. Used in general in the term C2C communication and refers to issues of dynamic networking and data exchange between several cars.

CAVE. Cave Automatic Virtual Environment. Immersive virtual reality environment where projectors are directed to three, four, five or six of the walls of a room-sized cube, generating a fully virtual scenery around the user.

CID. Central Information Display. A display mounted in the middle of the dashborad in modern cars. IVIS systems use this display for visual output.

DiKaBlis. Digitales Kabelloses BlickerfassungsSystem. A digital wireless glance behavior recording and semi-automatic analysis system developed at the chair for ergonomics of the mechanical engineering faculty of the Technische Universität München.

dof. Degrees of Freedom. Amount of directions and orientations, a objects can move. An unbound object can move in three dimensions along all euclidic axes and can turn around all three axes, thus having 6 dof.

DWARF. Distributed Wearable Augmented Reality Framework. Dynamic ad-hoc network infrastructure especially developed for mobile AR application. Developed at FAR.

FAR. Fachgebiet Augmented Reality. Research group at TUM (Head: Prof. G. Klinker, Ph.D.). Associated to the Chair of Computer Aided Medical Procedures & Augmented Reality (Head: Prof. N. Navab)

HUD. Head-Up Display. Semi-immersive display in the windshield of a car. The technology originates from aviation.

IoC. Inversion of Control. A software development pattern based on the principle of loose coupling which is used when tight coupling of the components endangers system functionality. Initialization and reference handling of components is decoupled.

IV. Inventor. A 3D rendering engine derived from VRML.

IVIS. In-Vehicle Information System. In-car system providing comfort, luxury information and entertainment interfaces to the driver and passengers.

LCD. Liquid Crystal Display. A thin, flat display device made up of any number of color or monochrome pixels arrayed in front of a light source or reflector.

LED. Light-Emitting Diode. Semiconductor diode that emits incoherent narrow-spectrum light when electrically biased.

LfE. Lehrstuhl für Ergonomie. Chair for Ergonomics at the faculty of mechanical Engineering, Technische Universität München. Head: Prof. H. Bubb.

OLED. Organic Light-Emitting Diode. Light-emitting diode (LED) whose emissive electroluminescent layer is composed of a film of organic compounds. A significant benefit of OLED displays over traditional liquid crystal displays (LCDs) is that OLEDs do not require a backlight to function.

PDT. Peripheral Detection Task. A quasi standard to measure the rate of peripheral detection. Some LEDs are placed in different angular values to the straight forward horizontal line of sight. Test subjects have to push a certain button, when a LED flashes.

Pose. 6 dof data indicating an object's position and orientation. Usually a 3D vector defines the euclidic position while a 4D vector defines the orientation with a quaternion. Poses per definition define relative coordinate systems of spatial relationships, but are treated as absolute placements relative to a world coordinate system.

SCORE. Spatial Context Ontology Reasoning Environment. A framework applying ontologies to spatial interdependencies. Provides a query mechanism for ADAS systems and thus states an underlying infrastructure for a wide range of information and warning systems.

TICS. Transport Information and Control Systems. Reference model architectures defined by the International Organization for Standardization (ISO/TR 14813-6:2000).

TUM. Technische Universität München. Technical University in Munich.

TTC. Time To Collision. A value computed by ADAS systems to generate warnings about upcoming critical situations to the driver. Other systems use later thresholds to mitigate accidents.

VE. Virtual Environment. Immersive computer generated environment placing the human user completely into a virtual world. VEs in general are CAVEs or driving simulators.

VRML. Virtual Reality Modeling Language. A standard file format for representing 3D interactive vector graphics, designed particularly with the World Wide Web in mind.

WIM. World in Miniature. Concept to incorporate a virtual model of the environment into the user's field of view. Bird's eye maps are systems that implement this concept.

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