InCarAR: A Design Space Towards 3D Augmented Reality Applications in Vehicles

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ABSTRACT

Advances in vehicle automation and the resulting change of the interior of cars lead to new challenges for user interface concepts. Augmented reality (AR) is a promising solution for the emerging design needs due to its diverse opportunities for user interaction and presenting information. This paper supports the development of novel AR applications. We describe a corresponding use case set consisting of 98 examples from a literature review and two focus groups. Based on these samples we present a design space for in-car AR applications. To demonstrate the benefit thereof, we show a fictional design process including our proposed design space to derive a custom AR system. This work supports designers and engineers by providing a systematic approach for integrating 3D AR interfaces in a vehicle, excluding windshields and windows.

CCS CONCEPTS

• **Human-centered computing → Interaction design theory, concepts and paradigms**.

KEYWORDS

augmented reality, automotive, design space, 3D AR

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1 INTRODUCTION

Today's cars show a trend towards increasing automation. In the near future, drivers are able to turn away from the steering wheel and focus on non-driving related activities [41, 51]. Vehicle design goes beyond safety and navigation to include entertainment and interaction functions [35, 52]. Improved connection quality (e.g., through 5G [5]) creates a possibility to connect multiple vehicles or further entities and thus open up interaction possibilities with remote entities e.g., passengers from other cars. Current advances in 3D-display technology and augmented reality (AR) combined with groundbreaking changes in vehicle automation open unexplored opportunities for cars' interiors. Related work looked into the usage of AR technology to support drivers and augment the outside world with information, e.g., by using a head-up or windshield display. In contrast, in this work we focus on the use of AR in the vehicles interior.

A change in public mobility towards car sharing is likely [41] therefore drivers might need to adapt to new interfaces and different car functions. For example, the time we commute is steadily increasing [27]. It is therefore challenging to provide an intuitive user interface that quickly provides all necessary functions a commuter for example needs. The use of AR technology is promising to support all these needs. Car manufacturers [16, 70] and researchers [10, 12] present concepts to use AR for the design of novel in-car interfaces, e.g., augmented buttons floating in the air. 3D AR applications facilitate transferable personalized and context-situated information interfaces inside of vehicles. Floating 3D objects can be manipulated from different perspectives. Head-mounted displays (HMDs) that display AR objects and support user input, are very likely to shrink in their form factor and might become as small as contact lenses [59]. Due to the high transportability of compact HMDs the need for a fixed physical interface structure might become obsolete. There is no security risk of wearing HMDs inside a vehicle in case of autonomous driving as the driver does not need to pay attention anymore.

The development of in-car AR is an emerging field of research that is gaining increasing attention. Previous work showed that it is beneficial for practitioners and researchers to have a design space at hand to built upon [13, 21, 48]. In contrast to related work presenting design spaces based on years of work on the subject and hundreds of practical examples, we present a design space to a recently emerging field of research. It is important to provide designers and researchers a design space in this early stage of development to give guidelines and support the research and development. Due to the early phase of the development of AR systems in cars, there is a lack of examples for in-car AR systems and experience in designing them. Lacking tools and experience in designing new systems is time consuming, has the risk of not using design dimensions to their full extend and thus missing out on important aspects. Therefore, we propose a design space for 3D AR applications in vehicles.

Our design space supports the concept development of in-car AR systems, serves as a communication tool, enables objective comparison of systems and can be used to formulate standardized requirements descriptions for building prototypes. The scope of this work is mainly focused on SAE level 4 [28]. To derive this design space we conducted a literature review of papers, patents and commercial products. Two focus groups ($N = 3$; $N = 5$) with experts from the AR and automotive domain provide 84 additional novel use cases. Combined with the literature review, 98 matching examples for in-car AR are identified and clustered (Figure 1). By analyzing the use cases for their design dimensions and combining those with existing design spaces and taxonomies, we derive a design space for in-car AR applications. Hence, we contribute to the emerging field of in-car AR by transferring previous insights into a new context and drawing attention to possible differences. To motivate the feasibility we explore the design space by sorting in existing concepts and present a fictional usage scenario.

2 BACKGROUND AND RELATED WORK

The following summarizes work from the field of AR and design spaces in the wider automotive context.

Augmented Reality. Azuma defines AR as any system that combines real and virtual content, is interactive in real time and registered in three dimensions [2]. Visual, audio and tactile feedback is therefore an AR output modality. Devices that create mid-air 3D AR objects include Head-Mounted Displays (HMDs), 3D Tabletops and Holographic projectors. A particular advantage is the high mobility of modern AR HMDs, with integrated natural input possibilities such as speech or gesture (e.g., Hololens[1]). Previous work on floating 3D objects inside cars focuses on communication [36], new input possibilities [57] or dashboard visualization [10]. Practitioners such as car manufacturers presented concepts of mid-air buttons in the car (BMW 2017, [16]). An AR sound curtain is additionally considered in this concept vehicle.

Design Spaces. Previous work provides different forms of design spaces to support the design process. Kern et al. set up a design space for the automotive context [32]. The design space they present is focused on manual driving and the classical dashboard input and output modalities. Current research explores the possibilities of integrating mobile devices in the vehicle [17]. Endsley et al. introduce design heuristics regarding human factors, ergonomics and user experience of AR devices [19]. They establish eight design heuristics, among others "Adaptation to user position and motion" or "Fit with user environment and task". Especially the increased dynamic positioning and attention direction is explored. Müller et al. investigate the required design elements for public displays by exploring the mental models of the user and interaction modalities [48]. Current research and resulting design spaces focus on the challenges emerging from autonomous driving and possibilities of AR technology [21, 51]. The work by Tönnis [63] and Häuslschmid et al. [21] investigate head-up and windshield displays and their design dimensions. We applied a similar approach to our work with a focus on mid-air 3D AR applications inside the car. In contrast to Häuslschmid et al., we aim at a design space for a field that is just emerging, with a limited number of existing concepts, prototypes and consumer products. From the related work we derive the questions about what are the future use cases of in-car AR, how they can be integrated in the car and what are categories that define a design space of in-car AR applications.

3 METHODOLOGY

To define the categories describing the design space for in-car AR we followed four steps:

1 Literature Review – Related Work

We reviewed related work on related design spaces and design categories for the development of user interfaces, namely public displays [48], head-up displays [21, 32] and windshield displays [21].

[1]https://en.wikipedia.org/wiki/Microsoft_HoloLens, last access: June 2019

2 Literature Review – In-car AR use cases

To verify existing, remove unnecessary and add important categories found in step 1, the literature review focused on existing in-car AR applications (Section *Literature Review*).

3 Focus Groups – In-car AR use cases

We identified examples for in-car AR usage by conducting focus groups with experts from the field of AR and autonomous driving (Section *Focus Groups*). This way, we avoid missing application cases that are not yet published or developed, e.g., due to technical limitations. In the focus groups the novel use cases were sorted into the use case set of step 2 while critically reflecting upon them (Section *Resulting Use Case Set*).

4 Building the design space

Based on the resulting use case set (Figure 1) the authors started to go through the dimensions of related design spaces collected in step 1. When going through these dimensions and discussing the applications, missing dimensions or unsuitable categories and characteristics became obvious. Some design categories were removed, enhanced, split or extended. To get a better impression of this process, we show in Figure 3 use cases, which are exemplarily fitted into the final design space (Figure 2).

4 CREATION OF THE DESIGN SPACE

This section describes the systematic procedure for developing the design space. We describe the individual work steps of the methodology in detail.

Literature Review

We conducted a literature review using the following search terms: *hologram*, *holographic display*, *3D representation* and *S3D* and combined them with the terms: *augmented reality*, *AR* and *automotive*. We specifically investigated literature regarding in-car usage hence, applications within the car. To that end, we searched on the following platforms: Google Scholar [2], Springer Link [3], ACM DL [4] and IEEE Xplore DL [5].

Focus Groups

We organized a first ($N = 3$) and second ($N = 5$) focus group to find possible new categories for the use case set that resulted from the literature review. In our focus groups, we had one female and seven male participants between the ages 25-35. Four were AR experts, two autonomous driving experts and two professionals working in both domains. In the first focus group, use cases were generated by a Brainwriting session [66]. To prepare for the writing, participants were introduced to the topic and several examples from related work were presented and discussed. They were told to focus on highly automated vehicles from Level 3 to Level 5. Additionally, we specifically told them to just think of use cases that do not need windows or dashboards. After finishing the writing, resulting ideas were sorted by the participants into the existing subcategories – e.g., Subcategory *View Point* in category *Safety* (see Figure 1) – of the use case set of Haeuslschmid et al. [21]. The first focus group came up mainly with ideas in the category *Entertainment and Communication*. To create a richer set of possible use cases, the initial question in the second focus group was: *"What is important for you during a journey in the car during the start (navigation), the driving on the highway/city (safety and entertainment) until the end (looking for a parking lot)?"*. Additionally the following scenario was outlined: *"Imagine you live in the year 2040. You are a designer for car interiors. Your new task is to design the next car's interior with focus on floating 3D AR interfaces. You have the following information: vehicle status, car2car information, information of the surroundings, infrastructure information and passenger information."* We then asked the participants to brain-write ideas for AR systems that address a particular user group in the vehicle. They should imagine a *"driver"* that is conducting a take over request. Then to think of the *"attentive co-pilot"* that also pays attention to the road and helps the driver. Finally they wrote concepts for a *"passive passenger"* in the vehicle. The other categories were not explained to not bias the participants towards the existing use case set. The examples from the brain-writing were discussed and similar ideas were put in relation to each other by the group. After the focus group two of the authors compared the created clusters with the existing use case set. Further the authors sorted the resulting ideas in the subcategories of the use case set independently, again to find possible gaps. The focus groups lasted about 120 minutes each.

Building the design space

We identified 14 use cases for our problem space through the literature review. The focus groups resulted in 84 novel use cases for floating 3D in-car AR applications and can be identified in Figure 1 as they do not have a reference to literature. AR applications are dominantly imaginable in the category *Entertainment and Communication* with 43 examples. The use cases were clustered into five categories. The use cases identified by the literature review were in the category safety (e.g. an AR warning [40], a 3D AR avatar [23] or a 3D representation of the highway to prepare a take-over request [68]), vehicle monitoring [40, 54], entertainment and communication such as a 3D AR video calling

[2]https://scholar.google.com/, last access: September 2018
[3]https://link.springer.com/, last access: September 2018
[4]https://dl.acm.org/, last access: September 2018
[5]https://ieeexplore.ieee.org/Xplore/home.jsp, last access: September 2018

Safety		
Vision Extension	Extension of the driver's view by displaying occluded objects	Using 3D AR to visualize occluded objects on the road (D,C) Visualization of approximate traffic situation (D,C) Visualization of Countdown until dangerous situation (D)
Vision Enhancement	Enhancement of the driver's vision in bad viewing or lighting conditions	Visualization of surrounding to aid with decision making in uncertain situations (D,C)
View Point	Display of the views of virtual or real cameras; often replacing mirrors	Camera image of accompanying drone in vehicle (D, C)
Spatial Awareness	Improvement of the driver's understanding of the space around the car	Enlarge vehicle interior with virtual objects to see dangers further on (D) Comparison between vehicles 3D sensor model and reality by overlaying camera pictures to enhance situation awareness and give recommendation for action (D) 3D AR avatar that reacts on the environment [23] 3D representation of the highway to prepare take-over request [68]
Monitoring Surroundings	Safety-relevant information about the environment	Birds-eye view of possible dangerous situation to inform about dangers and limitations and give information about route and alternatives (D) Adaptive virtual map with dynamic objects of surroundings and information about other drivers on the road (risk and aggressiveness) (D)
Driver Monitoring	Driver performance and physical state observation	Inform passenger about status(attentiveness, tiredness, aggressiveness) of driver with a 3D overlay over the driver (C)
Breakdown	They help the driver in breakdown situations	Help of virtual assistant of breakdown service (D,C,P) Block doors with virtual signs to prevent passengers from leaving through wrong door (D,C,P) 3D tutorial what to do (D,C,P)
Specific Support Systems	Systems directed at a specific party, support several tasks or provide various information	3D Highlight to focus gaze of driver on situation that requires his/her attention (D) Giving action recommendations (D) Show how where hands and feet should be to steer vehicle (D) Visualization of trajectory planning and showing alternative routes in possible situation (D) Guiding of drivers attention on highly priorized external factors (D) Co-driver guides attention of the driver on specific situation by manipulating virtual arrow (C) Visualization of intention of other drivers when they are crossing my way (D) Using an avatar of other drivers to communicate with them (D, C) AR Warning [40]
Navigation		
Path Finding	Support in finding the way to the target	Digital representation ("digital twin") of highway to visualize real-time route information (D,C)
Car-Following	Support when following a car	Compass that points towards car to follow (D,P) Visualization of distance and status of other vehicle (D)
Traffic & Street Signs	Display of traffic signs currently applying; street signs and names	Representation of current speed limit sign (D)
Points of Interest	Additional on-route information to find people, shops or services	Visualizing map with parking spaces (D,C) Visualization of POI along the road in map (D,C,P) Preview of route highlights in AR (D,C,P)
Public Transport	Support for commuters who switch to public transportation	3D Model of car park/train station with visualization of walking routes (D,C,P) Visualization of time of arrival of train by displaying train model in different locations depending on time of arrival (D, C,P)
Path Planning	Support in planning the route and adjusting the route while driving when external influences force a route change	Activity planning on interactive map that notify all passengers of their tasks (C, P) Support to plan route when several passengers need to pick up by using avatars in interactive map that can be dragged & dropped (C, P)
Convenience		
Wellbeing Aid	Aids to prevent motion sickness	Abstract 3D Forms and pictures to visualize vehicle kinematics (P) Inform passenger visually about routes ahead to prepare him/her for the next section of the ride (P)
Load	Everything that is related to loading the car.	Luggage Tetris to visualize best packing strategy (P)
Interface Enhancement	Alternative interfaces	Interface elements in 3D (D,C,P) 3D highlight of individual interface elements and own touch zones (D,C,P) 3D AR Dashboard [8][9][10][16][57][70] Multimodal Feedback with AR [57]

Entertainment & Communication		
Commercials	Commercials for products or services, e.g. restaurants or promotions of stores	Display products to support buying decision and to draw attention to offers of products (P)
Economy & Costs	Economical driving and costs display	Show optimal trajectory in 3D world (D)
Work & Tasks	Information about general tasks, activities or (office) work tasks	Display route/map to visualize topography (P) Calendar with interactive elements (P) Visualize weather like clouds/ current weather in vehicle (P) Virtual keyboard (P)
Driver Mood & Status	Observation of the driver's status to promote a specific mood or physical state	Display basic requirements of single persons as a bubble over head (stress, fatigue, …) (P)
Education	The driver can gain knowledge or learn a specific behavior	After Take over: Show Status of traffic situation/vehicle before take over (D,C) Highlights within car of interaction elements that are needed (D, C, P) 360° view of the last 30 seconds to recapitulate past traffic situation (D, C, P) Sightseeing objects and information about them are displayed that one is driving past (D, C, P) Certain movements of the body are augmented to train the body (C, P)
Gaming	Game play alone or together with others	Board games in AR (P) Cooperative AR games with other passengers (P) Extended world, the horizon of the visualization extends over the boundaries of the car (P) Virtual play partner for kids (P)
Multimedia & Web	General information; music or video player; access to the Internet or news; specific for passenger entertainment and waiting times	Entertainment interface (D, C, P) Locked interface wherever he is turned to to manipulate entertainment depending on the view direction (P) 3D world to look at (P) Extended interface cooperating with laptop, so that contents can be dragged and dropped. (P) 3D movie (P) Floating text (P) 3D AR Video Calling [36]
Arts & Photography	Picture or arts presentation, applications that enable drawing and taking photos	In Air Drawing (P) Taking Pictures of situations outside and sharing them with others in the car (P) Taking picture of environment as 3D picture (P)
Atmosphere	Creation of a different atmosphere in the car by displaying different surroundings or ambient lights	Blend out dangers outside (P) Relaxation/reduction of information like counting sheep (P) Personal spaces during ride sharing (P) 3D curtain to block out distraction from other passengers (D;C) Visual Overlay of other vehicle passengers (P) Relaxing abstract forms that adapt to the car movement (P) AR sound curtain [16]
Observation	Observation of a person, normally relatives, or an object and its state	virtual huts/routes in the mountain (P) other chosen vehicles relative to destination (D, C) Prediction and visualization of vehicle trajectory (D,C)
Social Interaction	Social interaction with other parties than drivers	Teleport friends in vehicle (P) Easier conversation with back seat, like showing kids virtually where snacks are; (P) Virtual personal assistant (P) Telephone partner in AR (P)
Driver 2 Driver Communication	Communication with other drivers	3D avatars (car, person) to communicate with other vehicles/people on the road (P) Shared interface during convoy driving to plan trip/ choose music (P)
Internet of Things	Access to or control of things	Smart Home: model of house and easy interaction, see status of connected devices/house (P)
Health	Encourage and support healthy behavior in the car	AR trainer shows movements to follow (P) Virtual Sport: Sailing or Golf that adapt the movement of the car for interaction.(P)
Vehicle Monitoring		
Vehicle Status	Information about vehicle parts and the momentary status of the engine	3D Model of vehicle with status information and eventually statistics of vehicle functions (D,C, P) Miniature 3D Model of vehicle with luminated defective parts (D,C,P) AR owner manual [54] AR vehicle status [40]
Supervision	Support in supervising the vision of the vehicle's sensors; most of them aim to increase trust	Visualize breakdown of sensors in virtual digital twin of vehicle sensors (D,C,P)
Fuel & Battery	Information about the current fuel or battery status	Status information of fuel/battery in sight (D,C,P)
Maintenance	Information of the overall status of the vehicle	3D Avatar of vehicle with a character that indicates that everything is ok (D,C,P)

Figure 1: The use case set for in-car AR applications. Use-cases are sorted in categories (colors). Each category features entries accompanied by a short title, description and examples from either related work or focus groups. The results from the focus group are labeled with the primary user group (D = Driver, P = Passenger, C = Co-Driver).

interface [36] or a sound curtain [16] and in convenience, as alternative interfaces to the dashboard [8–10, 16, 57, 70]. The category *Navigation*, includes path finding, planning and public transport. We identified the need for a category regarding *Convenience*. A similar category is also described in the work of Brandt [7] in which it is linked to the category Entertainment and Communication. The focus of the category "Convenience" in Brandt's paper is on telecommunication and radio. For a clearer separation of the use cases, we decided to separate the categories into *Convenience* and *Entertainment and Communication*. The new subcategories in the category *Convenience* are: Well-being Aid, Load and Interface Enhancement. It also describes alternative interfaces to the dashboard [8–10, 16, 57, 70]. Exemplary use cases are related to level out bodily effects of the ride, storage of objects in the car or providing alternative interfaces on surfaces. *Entertainment and Communication* relates to leisure activities in the car. *Vehicle Monitoring* combines the vehicle's status, its supervision, maintenance and fuel or battery status [40, 54]. The methodological approach of sorting the use cases in the design space is clarified in Figure 3. The colored lines indicate the design categories that are used or should be considered in designing the example application. The visualization can be used to not forget about certain design alternatives during the creative process.

Defining The Targeted User Groups. The user group benefiting most of this design space are drivers of SAE Level 4 [28] vehicles or higher, attentive co-drivers and passive passengers. Drivers of SAE Level 0-3 vehicles need to observe the road and should not be distracted by floating 3D in-car AR applications [22, 25]. *Drivers of SAE Level 4* vehicles may benefit from in-car AR before the situation of a take over request occurs and while driving manually. *Attentive Co-drivers* support the driver in navigational, safety and dashboard control tasks within their range of control. *Passive Passengers* is the umbrella term for the driver who is driving autonomously, the co-driver who does not pay attention to the road and other passengers.

5 DESIGN SPACE

This section presents the outcome of our methodological approach described in the previous section (Figure 2). In the following, we describe the dimensions (e.g., *User*), categories (e.g., *User Mode*) and their characteristics (e.g., *Single User*).

User

We identified three user groups which are defined in the section above (*Defining The Targeted User Groups*).

User Mode. The user mode contains *Single User* and *Multi User* as the systems can either be used alone or in cooperation with others.

Observer. Users observing the system are part of our identified user groups: the *Driver*, *Attentive Co-driver* and *Passive Passenger* of a vehicle. Additionally, observers are only in this role if they are focused (either with their gaze or mind) on the application.

Actor. An actor is defined as a user manipulating the interface [21]. All observers might be actors. Additionally, a remote actor can interact with the interface. For example, a service transmitting information to maintain the car or a non-present colleague cooperating via a shared interface with actors inside the vehicle.

Context

The *context* of use is defined as the nature of the users, tasks and equipment. Furthermore, it includes the physical, social and cultural environment in which a product is used [20, 60].

Application Purpose. The *Application Purpose* contains the characteristics *Safety*, *Navigation*, *Vehicle Monitoring*, *Entertainment, Communication and Work* and *Convenience*. These characteristics are defined by Brandt et al. [7]. *Work* was added to the category *Entertainment and Communication* because of the possible importance of this category in autonomous driving. We added one category since we believe productive (office) work will become a relevant aspect of highly automated driving [14, 39, 55, 58]. *Navigation* includes information about the trip or path and in contrast to previous definitions, we include route planning as well.

Information Context. This dimension describes factors influencing the situation in the car. *Environment* includes e.g., the size of the available space inside a vehicle, the amount of seats and their orientation or people who are present. *Vehicle* considers the vehicle and its purpose, e.g., information about the engine or the car type. *Personal* includes all information about a person, such as position, age or physiological data. *Time* describes the time of the day, date and season.

Driving Mode. The driving modes are based on Häuslschmid et al. [21] and include *Driving*, *Waiting* and *Parking*.

Level of Automation. We focus on SAE Level 4 [28] of automation. Hence the level of automation can be *Manual*, *Semi-automated* and *Autonomous*.

Privacy. The privacy settings of an application can be *Public* (e.g., sports results), *Personal* (available for family or business insiders) and *Private* (only accessible for a single person) as proposed by Häuslschmid et al. [21].

Travel Time. We added this category to distinguish between *short*, *medium* or *long* duration of a drive. Depending on the travel time different side effects might occur. Especially long

Dimension	Category						
User	**User Mode**	Single User	Multi User				
	Observer	Driver (SAE Level 4)	Attentive Co-Driver	Passive Passenger			
	Actor	Driver (SAE Level 4)	Attentive Co-Driver	Passenger	Remote Actor		
Context	**Application Purpose**	Safety	Navigation	Vehicle Monitoring	Entertainment, Communication and Work	Convenience	
	Information Context	Environment	Vehicle	Personal	Time		
	Driving Mode	Driving	Waiting	Parking			
	Level of Automation	Manual	Semi-automated	Autonomous			
	Privacy	Public	Personal	Private			
	Travel Time	Short duration	Medium duration	Long duration			
Visualization	**Level of Augmentation**	Reality ←	Augmented Reality	→ Virtual Reality			
	Registration	Unregistered	2D registered	3D registered			
	Placement Strategy	None	Binary	Linear	Exponential/Higher Order		
	Field of View Position	Foveal	Central	Peripheral/Ambient			
	Presentation	Symbolic ↔ Naturalistic					
	Graphic Design Factors	Color	Transparency	Size	Motion	Depth	
Interaction	**Input Modality**	Touch & Control	Gestures	Gaze	Speech	Behavior	Physiological
	Multimodal Feedback	Haptic/Tactile	Auditory	Olfactory	Sense of Balance	Temperature	
Technology	**Image Generation**	Glasses-Based Displays	Head-Worn Displays	Autostereoscopic 3D Displays	Hand-Held Displays		
	Size	Full Space	Full Dimension	Static Area	Situated	Dynamic	
	Depth	2D	Pseudo-3D	3D			
	Display Factors	Color Depth	Resolution	Contrast	Brightness	Transparency	

Figure 2: Design Space for in-car AR.

rides require planning breaks or considering energy loading stations.

Visualization

In this dimension we describe relevant categories related to the visual presentation and perception of in-car AR.

Level of Augmentation. In contrast to previous design spaces we do not include discrete categories such as AR and virtual reality (VR). We base the definition of the *Level of Augmentation* on Milgram's Mixed-Reality Continuum [46]. The Mixed-Reality Continuum is an axis with real world content on the one end and exclusively virtual content on the other end. The idea of the continuum is that an AR system can be anywhere along the axis. A designer can use this continuum to decide for the degree of virtual content presented to the user. Furthermore, Mann's Mediated Reality continuum [44] adds the idea of filtering to Milgrams concept [46]. Examples for filtering are visually slowing down time [42].

Registration. Unregistered visuals are placed unrelated to an physical object within the car. *2D registration* is defined as being registered to an object, but not meeting its depth. *3D registration* means a positioning of elements with regards to a physical objects position and its depth. Different to previous definition [21], we do not include gaze-dependency in this category. We argue that the definition of AR registration describes a positioning of virtual objects relative to the physical world. In case of a visualization that follows the gaze, the *2D or 3D registration* changes based on the focus of the gaze. Therefore the gaze-dependency is a result of a change in the *3D registration* based on the users *input* via *gaze*.

Placement Strategy. Previous work lacks in a description of the change between two points of registration, therefore we add the new category *Placement Strategy*. The placement strategy describes animations, needed to change positions of an AR object or the registration state, e.g. from 2D to 3D registration. We came up with categories based on work by Lauber et al. [38]: *None* (the former visualization stays untouched, a new one appears), *Binary* (e.g. disappearing on one spot and emerging at a new one), *Linear* (e.g. following the head movement) and *Exponential/ Higher Order* (e.g., inertia on an element when turning the head, it follows slowly, then catches up).

Field of View Position. Häuslschmid et al. [21] propose the characteristics *Foveal*, *Central* and *Peripheral/Ambient* which we are using.

Presentation. The Presentation of augmented reality objects can be *symbolic* (abstract) or have a *naturalistic* (real-world) appearance. There are no discrete distinctions between the characteristics but a smooth transition with infinite states in between.

Graphic Design Factors. In addition to the definition of Häuslschmid et al. [21], we add *depth* as characteristic to the category *Graphic Design Factors*. Many of the examples found in the focus groups rely on having objects in different depths available. Zooming, panning, moving and interacting with objects benefit from providing a depth dimension.

Interaction

Interaction with 3D AR applications can be designed by altering the following categories.

Input Modality. Inputs can be triggered in an implicit or explicit manner. Implicit actions describe a reaction of the system without a conscious decision of the user, whereas explicit inputs include only informed actions of the user. *Touch & Control*, *Gestures* and *Speech* are normally used for explicit input. *Gaze* can be used for explicit input but might also be executed without any intentions. *Behavior* and *Physiological* are mostly used to define implicit input. *Behavior* describes facial expressions, eye movements, body position and posture of the driver [48]. To avoid implicit *Gestures*, they should differ from natural movements and thus be learned. However, gestures can reflect movements used in natural interactions, such as unscrewing a bottle by turning the hand [53].

Multimodal Feedback. In this category we include *Haptic/Tactile*, *Auditory*, *Olfactory*, *Sense of Balance* and *Temperature*. The use of *tactile* feedback is well established in the domain of smartphones and could be transferred to in-car AR objects. The *sense of balance* can be activated via movements of the car chassis. For example, to support virtual sports experiences such as sailing (use-case "sailing" in Figure 1). *Temperature* has been used as a feedback modality [69]. It could indicate points of interests on a map (e.g., feeling warm spots indicating restaurants on a map).

Technology

The technology used to create 3D images in a car is based on an effect achieved by showing two slightly different images for each eye [43]. We refer to Billinghurst et al. [4] for more detailed information of AR technology.

Image Generation. Based on previous work [8, 64, 65], we identified four suitable classification categories for in-car AR display technologies: *Glasses-Based*, *Head-Worn*, *Autostereoscopic 3D* and *Hand-Held Displays*.

Current *glasses-based* commercial products e.g., the "3D Vision 2 Wireless Glasses" by NVIDIA [6], combine a display with glasses worn by the user. The glasses separate the two stereoscopic pictures for the left and right eye respectively and often implement active shutter systems [6, 43]. Other glasses use interference filters [31, 43] or polarization [43], to produce the 3D effect. Current technology, such as the Microsoft HoloLens [7] or Vuzix Blade [8] enable a field of view of about 30°×17.5° (HoloLens). Designers need to understand if their chosen technology is able to comply with their field of view requirements. *Head-worn Displays* include two optical micro displays to produce a 3D experience [24, 50, 56]. Benefits are independency of the user's position and head-tracking possibilities. They can support the full spectrum of the *level of augmentation* [29, 61, 62]. *Autostereoscopic 3D Displays* show 3D images without additional devices [18, 24, 43, 64]. Well-perceivable 3D-visual effects created by such systems are restricted to a specific point of view. Additionally, they can suffer from distortion, lead to fatigue or display flipping images [1, 30, 37, 45]. Broy et al. [11] implemented a stereoscopic 3D interface in the dashboard of a car and showed that it enhances the presentation of spatial information (e.g., navigational cues) compared to 2D presentations. *Hand-Held Displays* are a useful tool for implementing optical see-through applications to augment reality [47, 67].

Size. The AR content can make use of the *Full Space* of the vehicle interior. Alternatively, it could cover a *Full Dimension* in one of the three spatial axes limited by the vehicles interior dimensions. AR objects could also fill any geometric *Static Area*, e.g., floating circularly inside the interior. Additional AR features could be placed contextually *Situated*. Hence, information regarding the status of the car could overlay parts of a physical instrument cluster. Furthermore, the image size could actively adapt to the displayed content by using a *Dynamic* range.

Depth. Images for in-car AR features could render *2D* views e.g., for a digital speedometer, a web browser floating inside the vehicle or the top-view of a map. *Pseudo-3D* imitates depth with perspective *2D* images in a way that objects do not appear flat but rather cubical (e.g.,[33]). Real *3D* images show a spatial illustration which has visual information in three dimensions analog to real world objects [3, 15, 26, 49]. Thus, these representations contain an explicit value for depth perception. Kulshreshth et al. present active *3D* stereoscopic rendering techniques adapting to the displayed content [34].

[6]https://www.nvidia.com/object/product-geforce-3d-vision2-wireless-glasses-us.html, last access: July 2019
[7]https://www.microsoft.com/en-us/hololens, last access: July 2019
[8]https://www.vuzix.com/products/blade-smart-glasses, last access: July 2019

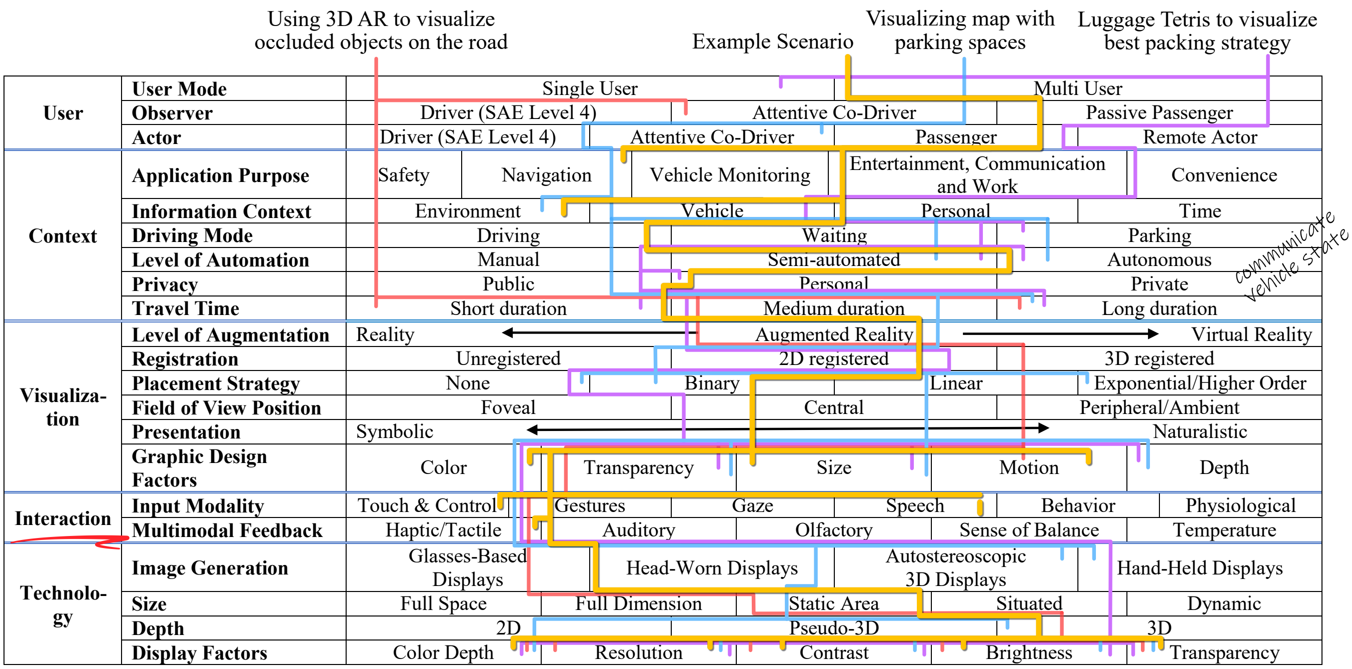

Figure 3: The lines visualize the possibility to sort in and compare exemplary use cases from the use case set (Figure 1). Lines crossing a field vertically indicate that it belongs to the use case. In yellow, underlaid with a shadow, the line for the implication example (Section 'Example Scenario') is shown.

Display Factors. The attributes *Color depth*, *Resolution*, *Contrast*, *Brightness* and *Transparency* are crucial attributes for a well perceivable illustration. The source of the image has to meet specific requirements to present a satisfying in-car user experience. Changing light conditions (day / night) and rapidly passing-by shadows are potential aspects of everyday drives and need to be considered in the design process.

Differentiation from other design spaces

We refer to our suggested classification system as design space, although we introduce more than two dimensions and no x- or y-axis to locate content. We consider our work as a tool to enhance future developments of in-car AR, therefore it is more than a taxonomy. Also, it is not hierarchic structured. Hence, our work extends the usual appearance of a design space and could be perceived as a meta-design space with influences of common taxonomies. Our proposed design space builds upon previous work from the automotive domain and therefore has some overlapping factors [21, 32, 48]. However, we did not find similar work focusing on in-car AR. In contrast to the previous work there are manifold additional opportunities for positioning, interaction, use cases and users. With our design space we add the novel categories *travel time* and *placement strategy*. We have also significantly redefined the categories *level of augmentation*, *registration*, *graphic design factors*, *multimodal feedback*, *observer*, *actor* and *image generation* to meet the needs of in-car AR. To distinguish our design space further from others, we discuss the particular differences below:

Positioning. The position of the interaction element plays a significant role for its use case. Augmented objects on the windshield force the user to actively turn towards a window. 3D AR objects can be boundlessly adapted to the user's field of view and orientation in three spatial dimensions. Therefore, our suggested design space expands beyond multiple positioning options and includes placement strategies.

Interaction. Floating 3D objects are manipulated with different gestures than 2D interfaces [53]. Direct touch interaction is not recommendable for windshields applications as it would obstruct with the vision[21]. Public displays need to count on attracting the passers-by attention and need a different interaction design [48]. In-car AR demands a consideration of interaction strategies, which is reflected in this design space.

Use Cases and Users. The use case set of 3D in-car AR and windshield displays both include a majority of entertainment and communication applications. However, use cases for 3D in-car AR applications are not limited to a position (e.g., windshield) and can address all passengers of a vehicle without occlusion. Especially, if the vehicle design changes in the future, the windshield might not be a point of interest anymore. For example, all seats could face each other. Use cases for in-car AR include every possible user inside of a vehicle and furthermore, could be used to digitally augment passengers or even replace empty space with people who are not present.

6 USAGE OF THE DESIGN SPACE

In the following section we suggest a way how to use the Design Space and motivate its validity. We intend the design space to be a tool during the creative design process that (1) helps to keep all dimensions in mind, (2) provokes an objective and thorough discussion of each design category, (3) supports identification of critical design categories. In the following example we will refer to these numbers, wherever the story addresses one of the prerequisites. We present a fictional scenario that showcases the ability of the design space to achieve these goals. As input we introduce personas and a user story. The aim of the fictional example is to develop a new concept for a system that enables joint planning of the drop-off point at the destination.

Personas and Use Case

We introduce two personas that are different in their background and abilities, still they are very likely to work together in a UX design process.

Laura is a 29-year-old UX designer that just graduated from university. She has some background in the automotive domain from lectures at university and is a specialist in the application of UX methods and user-centered design. However, she does not yet have a proper overview on technological trends and user needs when designing in-vehicle applications.

Peter is a 45-year-old computer scientist with 15 years of experience in developing for the automotive domain. He is responsible for the implementation of technology for the human machine interface in the car. Throughout his working experience he gained some knowledge about UX design, however his main interest is in making things work. *Use Case* Due to the current success of AR technology and the ongoing progress in the development of automated vehicles Laura and Peter are asked to think about how these two domains can complement each other. On a higher management level it was decided to work on concepts that explore collaborative route planning. When several persons drive together in a vehicle, the route is defined early on. If spontaneous alterations in the route occur due to the needs of the passengers, for example due to a sudden changed meeting point, the drop off location changes as well.

Example Scenario

Peter feels overwhelmed by the problem. Although, he knows a lot about the traditional driver centered interface design, he does not know yet how to approach in-car AR solutions. Laura got to know the design space for in-car AR (Figure 2) in her studies and introduces it to Peter. Peter has a look at it and finds a number of familiar words and categories drawing his interest. They agree to focus on the *multi user* aspect of the problem due to the prerequisites of their management. The request is to built something for a *passive passenger* as an *observer* and *actor*. To stay aware of the characteristics, they mark it in the printed out design space, which makes it visible to everybody (final result: Figure 3, yellow). Next they discuss the application purpose to be partly *navigation* and *communication* between the collaborators. Peter knows that navigational tasks can benefit from switching view points, e.g., from a birds view to a perspective view, as not everybody is able to read a 2D map. Peter then starts with a lecture about interaction design for a 2D map. Laura, agreeing with the idea of changing the viewpoint, interrupts Peter. She reminds him to stick to the higher level of the previously decided *multi user* aspects (1). They decide that the tool is used while *driving* in the *autonomous* car. They make a note on the side of the design space to keep in mind the communication of the vehicle state to passengers, as there is no *driver* performing this action. In the category *privacy*, they get stuck in their discussion. Peter argues that *privacy* is never an issue as people in the car know each other and are willing to share information. Laura highlights that they do not really know yet about the usage of the car. What if the users are sitting in an autonomous taxi that they share with strangers, a *public* context. Peter and Laura agree that this is a critical, not yet decided design factor and needs clarification (3). As they are short on time, they decide to design for a group of friends going to a festival willing to share *personal* data. Two friends want to go to the tent area first while the other two want to go directly to the concert. To take full advantage of 3D AR, Laura suggests that festival organizers could already provide a 3D map of the campsite. By exploring the amenities and the distance to the concerts, discussion between the friends can be improved. The *travel time* will be *short*, requiring a quick and easy system setup and strong decision support. To make it fast and easy to use, it should be part of the cars infrastructure to prevent connectivity problems and a setup of external devices. To speed up the decision making process, Peter is thinking about an application that has the *personal* preferences of the single user. The system also knows the time to arrive at the destination and the input of one user that requests a change towards a specific drop off location. Based on this information the system will provide three alternatives for planning the route and parking, which reduces the negotiation time. After having decided the structural boundaries for the system, they proceed with designing the implementation by starting with decisions on the *visualization*. *Augmented reality* would be ideal, as the passengers can still see each other and discuss on a common map. *Virtual reality*, Peter explains, could provide advanced spatial knowledge about the destination, but would hinder interaction as it covers the wearer's face (2). A *2D registration* is ideal to position a map *centrally*. A shared display influences interior design decisions because it requires users to be able to rotate towards each other. To ensure that everybody is able to see the display the system might need information about the *environment* and add a tick to *information context* (1).

A *placement strategy* might be used to blend between the 2D representation of a map and a 3D point of view image to support spatial knowledge for the desired destination. The *presentation* style should have two levels as it is common from other navigational tools. To make a clear distinction they plan to change from a symbolic visualization to more a naturalistic one in a *binary* way. All *graphic design factors* should be optimized for best viewing conditions in the diverse automotive everyday context. In particular, motion and color could be used to support the group awareness about who requested a change and the three alternative destinations the system suggests.

They decide for *touch* and *gestures* as *input modality* and use well known interaction metaphors. Laura had sorted in other concepts for in-car AR experiences beforehand (Figure 3). Hence she suggests to distinguish the input modality from competitors, by adding *behavioral* input (2). For example, as the time frame for the decision is short, the system could detect the single users attention by tracking gaze or head orientation. Peter doubts the practical usefulness of this input modality and suggests to collect more information on this design category. They speculate that *haptic* feedback will be used to support single users interaction with the display. In contrast, *auditory* sound can be used to communicate system states through space that are important to everyone. However, they postpone the detailed work on the interaction and underline it red in the design space (Figure 3) (3).

To support spatial awareness at the destination, they want to have the possibility to present *3D* images. Peter says that *autostereoscopic 3D displays* are feasible however, they are limited in the number of possible users (2). Therefore they should focus on the integration of *head-worn displays* within a *static area* of the car. The *display factors*, he says are not of major importance for a possible prototype.

Laura is happy with their progress, as it provides a focused description of the system specifications. In a further step she will process the results and create some storyboards showcasing possible design solutions, within the decided characteristics of the system (Figure 3, yellow).

7 DISCUSSION AND LIMITATIONS

Although research on in-car AR is very limited, previous work on automotive interface design gives us a strong foundation to base our work on. Thereby, we were enabled to transfer and expand insights from other design spaces into an AR-centered design space. We took great care in creating a use case set covering a large field of applications. To this end, we conducted our focus groups with experts from the field. Our design space can be used as a source of inspiration and to discover gaps of ideas in the current development. Although some use cases can be implemented on other devices, we want to encourage new interactions with new technologies. However, some design dimensions might not be complete yet. In the course of time, new ideas develop during the practical use of these systems, which lead to applications that may not yet be known to us. For example, bodily effects such as motion sickness in context of AR are still under research. We do not restrain the creation of ideas by reporting current technological limitations, but foster the curiosity to search for the latest trends. Our design space is an initial step towards supporting the ideation for novel prototypes. However, we are aware that it might need to be expanded in the future. Therefore, we invite researchers to extend our proposed design space. Due to the limited related work, our design space is mainly based on examples derived from focus groups. As this is exceptional to set up a design space our methodology extends the concept of a design space. We encourage researchers to come up with similar examples to create a clear discrimination between our design space based on non-existing examples and design spaces based on literature. This will lead to an improved understanding of the problem space and sharpen the design space definition.

8 CONCLUSION

In this paper we provide a design space that helps people from all professional backgrounds to develop, analyze and report in-car AR applications. We derive the design space from a comprehensive literature review and 84 novel AR application cases from focus groups. Our results are based on previous knowledge reported in taxonomies and design spaces from the design of car interiors and AR systems. We discuss similarities and differences between our use-case set and previous work on user interfaces, HUDs and windshield displays and we identify the design parameters that we expect to be of primary importance for in-car AR applications. Using a fictional application example, we show the advantages of our design space when used in a real world design process. Ultimately, we want to support the discussion and research about future system design for mobile work, entertainment, social interaction or education for in-car AR.

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