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A Head-Mounted Display to Support Remote Operators of Shared Automated Vehicles

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Abstract

Automated driving systems will be severely challenged under the unpredictable conditions of mixed traffic. Consequently, some form of human support remains essential in the foreseeable future. This challenge is particularly true for Shared Automated Vehicles, as these vehicles will likely not include any human driver onboard. When a Shared Automated Vehicle encounters a situation it cannot handle, a remote human operator will be needed to intervene. The remote operator can help the passengers to continue their journey by resuming vehicle operations. This thesis has investigated whether using a Head-Mounted Display in comparison to a computer display improves Situation Knowledge for remote operators of Shared Automated Vehicles. This research adopted a user-centred design approach to develop a Head-Mounted Display and computer display prototype. In one of the first studies on a Shared Automated Vehicle remote control interface, this thesis considered implicit measurements of Situation Knowledge and did not focus on performance indicators. In a user study, twelve participants were given the task to determine the reason why the Shared Automated Vehicle had stopped based on pre-recorded driving scenarios. Strong qualitative evidence indicates that a Head-Mounted Display can provide remote operators with improved Situation Knowledge in comparison to computer displays. To deepen the understanding of the performance and Situation Knowledge for remote operators of Shared Automated Vehicles under various conditions further research is necessary. Future studies can extend knowledge by assessing different scenarios and tasks in a live remote control situation, and develop and evaluate additional interface elements.

Keywords: Situation Knowledge, Head-Mounted Display, Teleoperation Interface, Shared Automated Vehicle, Remote Operator, Human-Computer Interaction

Sammanfattning

Automatisk körning kommer möta stora utmaningar vid införandet i blandad trafik. Någon form av mänskligt stöd kommer att vara viktigt under en överskådlig framtid. Denna utmaning stämmer speciellt för “Delade Automatiserade Fordon” eftersom dessa fordon mest sannolikt inte kommer att innefatta någon mänsklig förare ombord. När ett delat automatiserat fordon möter en situation som den inte kan hantera, kommer en fjärransluten mänsklig operatör behöva ingripa. Genom att återuppta fordonsoperationer, via distans, kan denne hjälpa passagerarna att fortsätta resan. Denna uppsats har undersökt om användning av en huvudmonterad bildskärm i jämförelse med en datorskärm förbättrar lägesuppfattningen/situationsförståelsen hos fjärranslutna operatörer av delade automatiserade fordon. En användarcentrerad designmetod har använts för att utveckla gränssnittet till den huvudmonterad bildskärmen och datorskärmsprototypen. Som en av de första studierna av gränssnitt för fjärrstyrning av delade automatiserade fordon användes implicita mätmetoder för test av operatörernas lägesuppfattning/situationsförståelse istället för resultatindikatorer. I den presenterade användarstudien fick tolv deltagare uppgiften att, i förinspelade körscenarier, identifiera orsaken till att det delade automatiserade fordonet hade stannat. Studien visar på starka kvalitativa bevis på att en huvudmonterad skärm kan ge fjärroperatörer förbättrad lägesuppfattning/situationsförståelse i jämförelse med användandet av traditionella datorskärmar. För att förstå förutsättningarna för fjärrstyrning av delade automatiserade fordon med avseende på prestation och lägesuppfattning/situationsförståelse hos operatörerna vid olika situationer, krävs mer forskning. Specifikt kan framtida studier som testar olika senarior och uppgifter i realtid bidra vara värdefullt och bidra med kunskap kring utformningen av gränssnitt för fjärrstyrning av delade automatiserade fordon.

Preface

This thesis is an original and independent work by the author, M. Bout. The thesis is in partial fulfilment of a double Masters Degree in Human Computer Interaction Design at KTH Royal Institute of Technology, Sweden and the University of Twente, The Netherlands. The research has been facilitated by Research Institutes of Sweden (RISE) Viktoria, Gothenburg and Integrated Transport Research Lab at KTH Royal Institute of Technology, Stockholm. Supervising the project from Integrated Transport Research Lab is Anna Pernestål Brenden and from RISE Viktoria, Maria Klingegård. Academic examiner for the degree project is Konrad Tollmar from the ICT-School department, KTH Royal Institute of Technology. This thesis commenced in the spring of 2017. The work in this thesis has led to the creation and acceptance of a Work-in-Progress paper in the Adjunct Proceedings of the 2017 AutomotiveUI ACM International Conference. The associated work of the paper is located in *Chapters 2, 7 and 8* of this thesis.

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Acronyms

AR Augmented Reality.

HMD Head-Mounted Display.

IQR Interquartile Range.

MED Median.

OOTL Out-Of-The-Loop.

ROV Remotely Operated underwater Vehicle.

SA Situation Awareness.
SAV Shared Automated Vehicle.
SK Situation Knowledge.

VR Virtual Reality.

Chapter 1

Introduction

This thesis details research on an interface for remote operations of a Shared Automated Vehicle (SAV)[1]. This chapter welcomes the reader by introducing the motivations underlying the thesis. The problem is detailed after which the objectives and goals of this thesis are outlined. The chapter concludes with a description of the structure of the thesis.

1.1 Motivation

Developments in technologies supporting automated driving have seen a proliferation in recent years. These technologies are expected to grow and have the potential to drastically reshape the nature of mobility. Developments in automated technologies and anticipated effects are publicised widely, not only in scientific publications but also in popular media outlets. Optimistic forecasts state that fully automated vehicles (SAE level 5 (SAE International, 2013)) are projected to make an appearance on public streets within the next few years, while conservative predictions estimate full automation to only arrive by 2030-2040 (Underwood, 2014; Litman, 2014). Regardless of when these vehicles will arrive, early generations will have a rather simple level of autonomy, adapted only for certain conditions. Traffic with both automated and human operated vehicles (mixed traffic) is characterised by its unpredictable nature. Consequently, automation will be severely challenged in the dynamic conditions of mixed traffic, e.g. obstructions or exceptional traffic situations. Autonomy will therefore not only be a challenge for vehicle automation in the near future but also for the decades to come.

1.1.1 Shared Automated Vehicles

These challenges will have especially implications for SAVs. SAVs are vehicles without a responsible driver onboard and are meant for commercial and public applica-

[1]The term automated vehicle is used to describe these concepts of vehicles for the purposes of this thesis, as it more accurately describes their capabilities in contrast to autonomous.

tions (i.e. not for private use), see *Figure 1.1.* An example of such an application is to provide an automated first/last mile transportation service, as a supplement to mass public transport (Alessandrini and Mercier-Handisyde, 2016). A number of pilot SAV projects have already taken place: Auto Rider[2] in Singapore, WePods[3] at Wageningen University, SOHJOA[4] in Finland and NAVYA[5] in France. By design, SAVs will no longer be equipped with an onboard interface for steering and longitudinal control. At the same time, high service reliability is crucial in their application, and any discrepancy in the reliability of automation will limit the everyday operability of these SAVs (Alessandrini and Mercier-Handisyde, 2016), and thereby also the service reliability. SAVs will encounter situations in which automation functions are limited, and in order to continue operations, human intervention is needed. While in current pilot projects, an onboard steward is often used as a fallback, this solution essentially undermines the premise of fully automated vehicles. An on-demand remote human operator, monitoring a fleet of vehicles and taking control of a vehicle when required, provides a sustainable solution for efficiently combating shortcomings in automation (SAE International, 2013; Corwin et al., 2016). Technical solutions of teleoperations of SAVs have already been demonstrated (Vulgarakis et al., 2017), enabled by developments in 5G mobile network. While Vulgarakis et al. (2017) have shown the technical feasibility of SAV remote control, the details of how such a remote control interface should look like are yet to be defined.

Figure 1.1. An Easymile EZ10 SAV in Sophia Antipolis in March 2016. *Retrieved from Easymile media press kit.* Picture by Easymile. Copied with permission.

[2]http://easymile.com/portfolio/gardens-by-the-bay/ Accessed: 2017-08-03
[3]http://wepods.com Accessed: 2017-07-25
[4]http://sohjoa.fi/in-english Accessed: 2017-07-25
[5]http://navya.tech/2016/06/lancement-de-lexperimentation-sur-voie-publique-en-suisse-2/ Accessed: 2017-07-25

1.2 Problem statement

The brittleness of vehicle automation under the challenges imposed by mixed traffic conditions in urban areas signifies the necessity of human intervention and control (Martens and van den Beukel, 2013; Sivak and Schoettle, 2015; Bilger, 2013; Simonite, 2016; Woods and Cook, 2006). In vehicles with an onboard driver, the driver is the likely choice for takeover. In SAVs such option is simply not available. Teleoperations could be a means through which vehicles can quickly and safely resume operations. Because teleoperations offer high service reliability and operability, it is a preferable choice. However, human intervention in an automated process brings a widely documented challenge in itself; the Out-Of-The-Loop (OOTL) performance problem (Endsley and Kiris, 1995). A challenge that is even more accentuated when the operator is remote as with teleoperations. As Endsley and Kiris (1995) describe, the OOTL performance problem is characterised by a fundamental loss of perception of elements in time and space within a given environment, the comprehension of their status and meaning, now and in the near future. For a remote operator to combat the OOTL performance problem, it is important that they deeply understand and grasp the situation and are able to resolve it, therefore an appropriate level of Situation Knowledge (SK) (Andre, 1998; Banbury et al., 2000) is essential. Research on teleoperations and the OOTL performance problem (Endsley, 2017) in the specific context of SAVs is sparse. The appliance of computer displays in teleoperation systems have been well-researched (Kikuchi et al., 1998; Hainsworth, 2001; Grange et al., 2000; Porat et al., 2016). However, the use of a Head-Mounted Display (HMD) in teleoperations is less investigated (Schmidt et al., 2014; Jankowski and Grabowski, 2015). Studies by Meng et al. (2014); Santos et al. (2009) have shown promising results for using an HMD during navigational tasks. Studies on the use of an HMD by remote operators of SAVs have, to the author's knowledge, not been published. These reasons motivate this work to explore the use of an HMD as a human machine interface between the SAV and remote operator.

1.3 Objectives

The thesis aims to extend the knowledge on the use of an HMD for teleoperations. In doing so, a comparison is made between a computer display and an HMD, in the context of SAV remote control. The results of this thesis aim to contribute to the acceptance and integration of SAVs in society.

It is not the objective of this thesis to develop production ready prototypes for SAV teleoperations. Also, this thesis does not consider live remote control operations of an SAV during the user study. Lastly, this thesis considered implicit measurements of Situation Knowledge and did not focus on performance indicators.

1.3.1 Research questions

To support the research successive to the outlined objectives, the following leading research question is formulated:

1. **Will the use of a Head-Mounted Display, in comparison to computer displays, improve Situation Knowledge during teleoperations of Shared Automated Vehicles?**

   Situation Knowledge encompasses an operator's both implicit and explicit knowledge about an environment and their continuous assessment (but not explicitly conscious) about the information in the environment (Banbury et al., 2000; Andre, 1998). A set of sub-questions are formulated to further investigate the leading research question. In a first phase of analysis the following questions are explored, to develop a better understanding of different components constituting the leading research question.

   a) What is Situation Knowledge for SAV operators and what measurements can be used to measure Situation Knowledge?

   b) What characterises the work of an SAV control room operator and which challenges arise?

   c) What interface elements support an SAV remote operator?

   In a second phase dissimilarities between an HMD and computer display are researched.

   d) What are the key differences for a remote operator between using an HMD or a computer display?

In the third and final phase the leading research questions is studied. A detailed structure of the thesis is described in *Sections 1.4 and 3.1*

1.3.2 Goals

In order to answer the aforementioned research questions the following goals are identified:

1. Describe relevant related work on teleoperations;
2. Identify challenges in vehicle automation and remote takeover;
3. Describe the construct Situation Knowledge;
4. Research needs and requirements for remote operators;
5. Conceptualise HMD interface concepts for teleoperations;
6. Evaluate the interface concepts;

7. Develop an HMD and computer display prototype;

8. Evaluate the prototypes in a user study.

1.4 Outline

In this first chapter the rational for this thesis is motivated and the problem and research questions are described. In *Chapter 2 Theoretical framework* concepts of automation, remote control and SK are detailed. Moreover, the notions of mixed realities and a HMD are explained. *Chapter 3 Methodology* describes the methodology. This thesis has been divided into three parts to indicate different phases of the research process. *Phase 1: Analysis*, encompasses *Chapters 4 Related work* and *5 Design requirements*. Relevant research and applications on teleoperations, control rooms and remote operator interfaces are introduced, after which needs are analysed and requirements are specified. *Phase 2: Conceptualisation*, entails *Chapter 6 Interface concept development*, concepts are presented and evaluated. *Phase 3: User study*, details the prototype development process and user study. In *Chapter 7 Prototype development* two prototypes are detailed. *Chapter 8 Prototype evaluation* discusses the results from the user study with the two prototypes. *Chapter 9 Discussion* presents a discussion on the findings of the thesis and recommendations for future work. Finally, in *Chapter 10 Conclusions* this thesis summarises the process and results.

Chapter 2

Theoretical framework

This chapter introduces theory on automated driving systems and automation failure, moreover, human factors in teleoperations are examined. The concept Situation Knowledge is introduced as a means to evaluate the operators understanding of the vehicle its environment. This chapter continuous with relevant aspects of a Head-Mounted Display in teleoperations.

2.1 Automated driving systems

Automated driving systems enable vehicles to plan and execute driving operations independent of humans. An automated driving system consists of various components. These components have various tasks, such as to plan, track and compare current driving states and finally determine whether an autonomous driving interruption is required (Urano and Taguchi, 2016). Automated vehicles are equipped with sensors used to assess the environment, commonly used technologies include laser-, radar- and camera-based systems. All systems together facilitate vehicle autonomy. A widely used framework (J3016) has been developed by SAE International (2013), a United States based automotive standardisation organisation, to classify levels of automated driving systems. Their taxonomy consists of six levels (level 0-5) and ranges from no automation functions to full vehicle autonomy, see *Figure 2.1*. SAVs are considered vehicles with either level 4 or 5 functions of automation.

2.1.1 Automation

Automated driving systems are part of a larger trend of automation. This thesis adopts the definition of *Automation*, as defined by Parasuraman and Riley (1997), "the execution by a machine agent (usually a computer) of a function that was previously carried out by a human". Underlying the process of automation is a demand for optimisation; such as cost reduction, increased efficiency and reliability (Parasuraman and Riley, 1997). When driving operations are shifted away from humans towards vehicle systems, humans are relieved from the cognitive and physical tasks of

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
Human driver **monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system **("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 2.1. Taxonomy and levels of automation by SAE International. *Retrieved from: http://self-balance-unicycle.com/wp-content/uploads/2015/12/Table-summarizing-automation-levels-for-road-vehicles.jpg.* Copyright (2014) SAE International.

driving. In line lays the task for the designer or engineer to limit human intervention as much as possible, under the belief that human error and inefficiency is limiting performance (Bainbridge, 1983). However, as Bainbridge (1983); Parasuraman and Riley (1997) suggest this effort gives rise to two paradoxical issues. Errors by design give rise to new, unexpected problems and human oversight remains required for tasks which fail to be automated or are unforeseen. That automation limitation or automation failure are critical aspects in vehicle automation, is supported by the indisputable dangers of placing humans in moving vehicles with significant mass and speeds. Automation limitations or failure may be answered through two types of responses; someone may be required to oversee automation processes or be asked to intervene manually. Remote control operations will be a vital part ensuring the operations and uptime of SAVs.

2.1.2 Severity of automation failure

In understanding automation failure and the process of a remote takeover of an automated vehicle, it is important to examine and classify the cause. Recent studies by (Eriksson and Stanton, 2014; Strand et al., 2014) have discussed causes for human intervention and classified the severity of such events into; critical and non-critical. In non-critical situations, which will be most frequent, the vehicle is leaving its *Operational Design Domain* (experiencing automation limitations) in a normal traffic situation (SAE International, 2013; Nilsson, 2014). In a study by Strand et al. (2014) a critical driving situation is exemplified through a severe malfunctioning of the automation. In this example, a partial or full deceleration failure is a reason for a human take over. This study considers the case of non-critical situations in which SAVs will leave their normal *Operational Design Domain* and are able to come to a safe stop independently. In such situations, when the SAV cannot continue independently, a remote operator is required. The remote operator is not required to take over in the event of a critical failure. This thesis assumes it is unreasonable to expect a remote operator to assess a situation and act appropriately, given the extremely short response-times of only seconds.

2.2 Human factors in teleoperation

Humans can shift their attention away from tasks which are taken over by automation processes. However, when automation reaches limitations or encounters failures, a human is often asked to step in. Consequently, human factors are reintroduced to the formerly automated process. A number of issues arise when humans intervene in an automated process. Research by Bainbridge (1983); Sheridan (2002) suggests that humans tend to perform poorly in monitoring an automated process. Moreover, Parasuraman et al. (1994); May (1993) point out that operators tend to be poor at monitoring automated functions when they are performing other manual tasks at the same time. These findings underline the necessity for operators to maintain higher levels of cognitive engagement on tracking automated functions.

The trust of the operator and reliance on automation seem to correlate to the reliability of the automated process. Reliable automation positively influences the level of trust (Lee and Moray, 1992), while (May, 1993) suggests that inconsistent reliability should not engender trust. Consequently, if during modes of teleoperation the operator experiences discrepancies in system performance, this may negatively affect their trust in the system. Moreover, in a study by Endsley (2017) it is found that the degree of a systems' autonomy and its reliability correlate negatively to the capability of an operator to take over when needed. When the level of automation authority over system functions increases, the humans' knowledge and skills should meet or exceed the level of the system. This effect requires a proportionally high level of feedback such that the operator can effectively monitor the behaviour and intentions of the automated driving system (Parasuraman and Riley, 1997). As for the automated system; "The more removed the operator is from the process, the more this feedback must compensate for this lack of involvement; it must overcome the operator's complacency and demand attention, and it must overcome the operator's potential lack of awareness once that attention is gained." (Parasuraman and Riley, 1997, p.248). Other studies have also found that an operator is less likely to succeed in a takeover when situational awareness is reduced due to automation (Kaber et al., 1999; Kaber and Endsley, 1997; Stanton and Young, 2005; Young and Stanton, 2002). These concerns are formulated in the *automation conundrum* (Endsley, 2017), stating that with increased automated system functions and reliability, the chances of an operator monitoring the operation being conscious of critical information and able to take-over when requested is reduced. Consequently, the probability of remote takeover failure due to an OOTL performance problem will increase (Endsley, 2017).

2.3 Spatial awareness

A lack of awareness is considered an absence of the knowledge and mental model of an object or environment by a (remote) operator. The construct Situation Awareness (SA) (Endsley, 1988) is commonly used to describe this phenomena. Early research by Wiener and Curry (1980) has already suggested that automation, in aviation, causes loss of situation awareness for pilots. Moreover, Riley et al. (2004) present further evidence that SA correlates to the performance of an operator during teleoperation. In early research by de Waard et al. (1999) findings indicate that a loss of SA for drivers faced with automation failure also influences their performance. A number of theories of SA exist (Salmon et al., 2008), and have been developed in line with advancing research. Endsley and Kiris (1995) their three-level model of SA is widely used for applications in different domains (Salmon et al., 2008). In a recent publication, Endsley (2017) extends SA supporting theorem, stating; that reduced SA for an operator overseeing automation, is characterised by three key mechanisms: operator engagement, change of information presentation following automation and operator trust and alertness Endsley (2017).

2.3.1 Situation knowledge

In this thesis, the focus is on the change of information presentation as a component of SA. SA has been criticised for being exclusively focused on measuring *awareness* which is explicitly conscious and articulable (Banbury et al., 2000). Explicit knowledge and understanding as a result of a cognitive process. However, *implicit knowledge*, such as memories, intuition and feelings, is considered be an important factor driving our behaviour (Banbury et al., 2000). In an effort to combat existing critics, an adaption of the construct SA is used, namely SK. SK encompasses an operator's both implicit and explicit knowledge about an environment and their continuous assessment (but not explicitly conscious) about the information in the environment. SK is not a direct measure of performance or effective decision making, it constitutes a person's dynamic and internal model of the information environment, and drives their subsequent responses and behaviours (Banbury et al., 2000; Andre, 1998).

2.4 Head-Mounted Displays

An HMD is essentially a display mounted on the observer's head. The fundamental principle underlying an HMD is that the observer is presented with images that change perspective according to the head-movements of the observer (Sutherland, 1968). This principle creates the illusion that the observer is directly looking at the scene presented in the images. The described concept constitutes what in more recent literature has been referred to as feelings of immersion or presence (Sherman and Craig, 2003). Various other studies have found evidence that support a positive correlation between the use of an HMD and immersion (Pausch et al., 1997; Witmer and Singer, 1998; Slater et al., 1996). This thesis assumes that the feeling of presence is directly related to the implicit Situation Knowledge of an operator.

HMDs and the concepts of Virtual Reality (VR) (Steuer, 1992; Burdea and Coiffet, 2003) and Augmented Reality (AR) (Sherman and Craig, 2003) have been tightly bound together, and are often used with similar meanings. However, for the purpose of this thesis a distinction is made between an HMD, VR and AR. Whereas VR considers everything visible to the observer to to be computer simulated, augmented reality alters recordings of the physical world with computer simulated graphics. VR and AR classify as different levels of mixed reality technologies, an HMD is regarded as an instrument for displaying VR and AR.

2.4.1 Images

An HMD needs to be complemented with images. For the purpose of using an HMD during teleoperations, this is a recording of the environment around the vehicle. To capture the surroundings of the SAV, a camera can be used. To utilise the full potential of an HMD, a camera which can capture and record 360-degree stereoscopic video is required. A 360-degree recording dictates that images are recorded in a full sphere around the camera. Whether a camera has a mono- or stereoscopic lens-setup determines the depth of vision or 3D-character (Singer et al., 1995). A stereo-lens camera produces two recordings of the same scene. When these recordings are combined, the resulting images contain depth. Stereoscopic images are said to affect the observer's feeling of immersion positively (Sutherland, 1968).

The angle of view of a camera lens defines the extend of the angle of which a scene is imaged. The maximum angle is 180 degrees vertical and horizontal. However, single-lens cameras usually capture significantly less to prevent image distortion. The human visual system observes an angle of view of around 140 (horizontal) by 80 (vertical) degrees (Kollin, 1993). A camera less considered to be 'normal' is said to be similar to the angle of view of the human visual system (Tidwell, 1995). Conventional teleoperation setups generally consist of computer displays which use images captured with a 'normal' camera lens. The field of view describes the angle of a projected scene. The use of an HMD enables for a direct accessibility of a 360-degree angle-of-view with a field of view between 40 and 90 degrees. Finally, operators observe not through the frame of a computer screen but directly without any distinct borders. In *Table 2.1* a comparison between accessing 360x360 degree video through a computer display and HMD setup is provided.

	Computer display	HMD (stereoscopic)
Depth of view	Flat	Depth
Angle of view (V/H)	Usually 140x80	360x360
Head movement	None	Natural
Intuitiveness	Artificial	Realistic

Table 2.1. A comparison between an HMD and computer display based on accessing a 360 degree video.

2.4.2 Cybersickness

The emergence of HMDs has not been without concerns. For some people, the use of this technology inhibits a malady, LaViola (2000), referred to as cybersickness. The feeling of immersion when using an HMD has been found to positively correlate with experiencing sickness (Yang et al., 2012). Under this condition, people exhibit symptoms often associated with motion sickness. Symptoms are among the following; headache, nausea, vomiting, eye strain and disorientation (Lampton et al., 1994). These symptoms can occur during but often after using HMDs, and can range from a couple of hours to for some even days. LaViola (2000) discusses three key concepts which are considered to be causing cybersickness. Sickness caused by *Vection*, when an observer perceives self-motion while they are actually in a static position, is referred to as the *Sensory Conflict Theory.* The *Poison Theory* states that the stimuli provided in a virtual environment may confuse a human to the extent that the body believes it has inserted some poison and a vomit-reflex is triggered. Finally, the *Postural Instability Theory* details that humans naturally intend to preserve postural stability. When the postural stability is abruptly affected through external influence, such as virtual reality it causes motion sickness. The *Sensory Conflict Theory* may play a role within the application of teleoperations, as the remote operator perceives movement while in a static position.

Chapter 3

Methodology

This chapter discusses the methodology applied in the thesis. The research and data collection methods are detailed, and the research strategy is presented. This thesis is an exploratory study, with the objective to create new understanding on the use of an HMD for teleoperations of SAVs. Furthermore, the challenges that arise in teleoperations of SAVs are identified, and a methodology to evaluate solutions to these challenges is presented. The SK of the operator is evaluated, in particular how the aspect of immersion affects the operators understanding. Finally, an HMD and computer display prototype are developed as a tool for researching differences in Situation Knowledge.

3.1 Research approach

3.1.1 Research strategy

In order encompass the objectives as outlined in *Section 1.3 Objectives*, the thesis is set to follow a research strategy. The work of Håkansson (2013) is adopted to outline the research strategy. A research methodology contains a research strategy which composed out of a series of goals and methods, which all together structure and drive the work towards reliable results. Qualitative research is about studying a phenomenon to reach conditional theories or contribute to the development of artefacts and inventions (Håkansson, 2013). It has the ability to explore a terrain through understanding and behaviours and may serve as a basis for further quantitative analysis (Helfat, 2007). A research strategy adhering to a qualitative research can be applied to a data set limited in scale, requiring a consistent choice of methods (Håkansson, 2013). This thesis sets out to answer the research questions detailed in *Section 1.3.1 Research questions.* An artefact, an HMD interface for teleoperations of SAVs, is developed and compared with a baseline (computer display), employing a qualitative research approach.

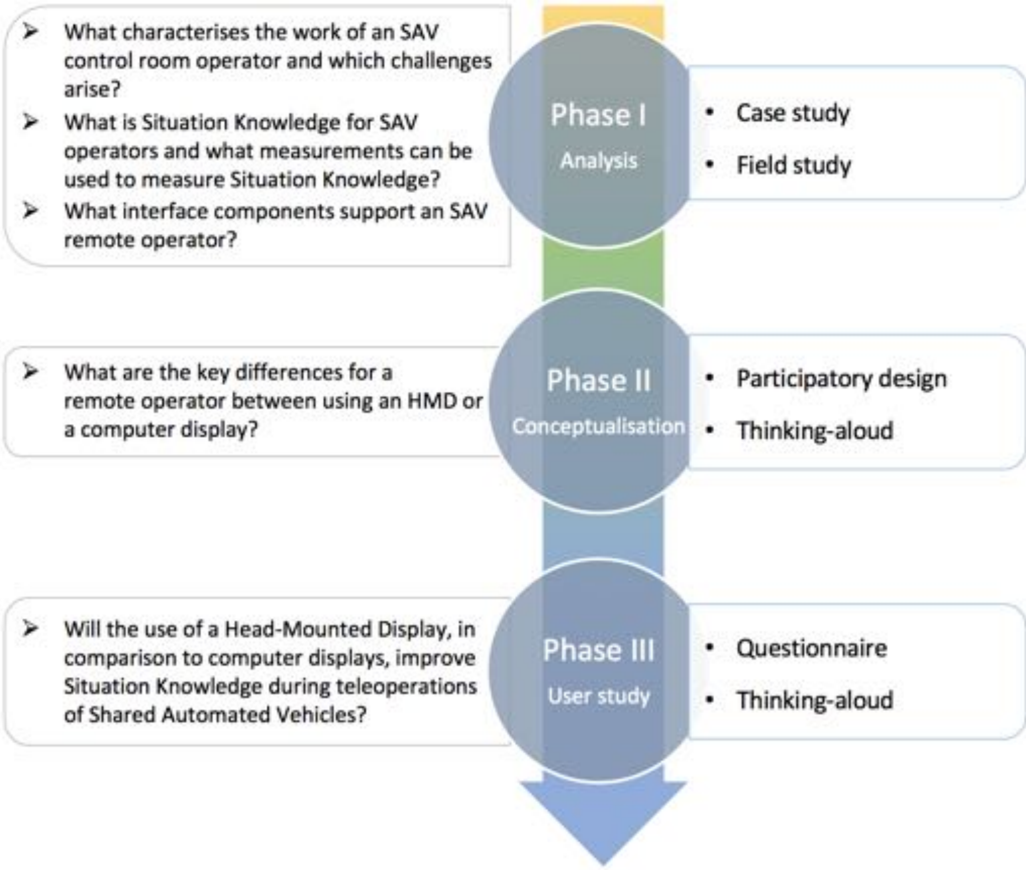

Figure 3.1. Illustration of the research design framework. For each phase the research questions and corresponding evaluation methods are depicted. Illustration by author.

3.1.2 Research design

This section describes the framework and intermediary stages of the thesis. A graphical representation of the research design framework, adapted upon the work of (Maguire and Bevan, 2002), is depicted in *Figure 3.1.* The chosen design framework is well fitted for the development of an artefact (Maguire and Bevan, 2002). Three phases are identified. *Phase I: Analysis* entails the process of information acquisition and analysis. *Chapters 4 Related work* and *5 Design requirements* inhibit key notions for shaping the study, interface design and experiments. A set of interface requirements are formulated and serve as a basis for the next phase. *Phase I: Analysis* corresponds to goals 1-4 as identified in *Section 1.3.2 Goals*. Within *Phase II: Conceptualisation*, the creative process of generating and developing concepts takes place. As Maguire and Bevan (2002) describe, in this phase requirements are translated and possible concepts are ideated. A participatory design study is conducted and the deliverable of this phase includes a set of interface concepts for teleoperations of SAVs, corresponding to goals 5 and 6. In *Phase III: User study*, a concept is developed further into an HMD and computer display prototype. A user study is performed with a small number of subjects. *Phase III: User study* fulfils goals 7 and 8.

3.2 Research methods

A philosophical assumption is essential to a research strategy and constitutes assumptions about a valid research and appropriate research methods (Håkansson, 2013). An *interpretative* philosophical assumption is chosen, which works well with opinions and experiences and is well fitted for developing artefacts (Håkansson, 2013; Salkind and Rainwater, 2006). Through *Interpretivism*, phenomena are explored in an inductive manner, to reveal people their interpretation of the phenomenon. This thesis employs an *Inductive research approach*, in which qualitative research methods are chosen on their ability to achieve the research objectives. Non-experimental and empirical research methods are being used iteratively. This iterative component is described in the Design Thinking methodology (Zimmerman et al., 2007). Zimmerman et al. (2007) describe a process in which non-experimental research leads to a set of findings which are ideated iteratively, resulting in varying perspectives on solving a problem. The chosen methodology is well suited for researching people their behaviours and opinions of functions and interfaces. Empirical research, deriving understanding from experiences and observations (Håkansson, 2013), is practised to understand the use of an HMD for teleoperations.

3.3 Data collection methods

In this qualitative research the methods of Case Study, Field study, Participatory Design, Thinking-aloud and Questionnaire are used.

3.3.1 Case study

Within a case study analysis the researcher looks for specific aspects, in the context of the research question(s), in existing cases. Case studies are considered fruitful for creating a qualitative data set and inducing propositions from observations in a real-life context (Håkansson, 2013). The Case study method is criticised for being subjective to the personal perspective of the researcher. In defence, (Pyett, 2003) argues that research and development in their essence are driven by subjectivity. Case study analysis has been applied in this thesis to investigate the theory and experiences following from related work on teleoperations. The selection of cases follows from the stipulated research questions and goals (see, *Section 1.3*).

3.3.2 Field study

In a field study the phenomena researched are observed in their normal situation. The field study in this thesis compromises the methods of semi-structured and contextual interview. Interviews can uncover deeper notions underlying the behaviours or experiences surrounding the research problem (Håkansson, 2013). Semi-structured interviews are a fitting method for initial data collection on the study of an artefact. Semi-structured interviews are constructed around a set of key-questions which enclose the specific area of interest. Meanwhile, allowing both the interviewer and interviewee to touch upon closely-related topics, in order to deepen the understanding of the issue (Gill et al., 2008). The indisputable advantage of this method is its ability to uncover new information that turns out to be unexpectedly valuable to the researcher but was not anticipated (Gill et al., 2008).

When the field of research has been further explored, and key notions of interest are identified, more tailored interview methods can be used. The contextual interview is well suited to investigate the motive to why users do what they do, how they do it and the challenges and highlights in their current approach (Holtzblatt and Jones, 1995). Contextual interviews take place in the framework of the notion studied. An interviewee is queried while in the context of performing the studied tasks or notion at hand, their answers are enriched and are based on close experiences and not taken from memory. Both interview methods are employed in *Section 5.1 Field study analysis*, to create a comprehensive report on operator needs, responsibilities, use cases and tasks.

3.3.3 Participatory design

Participatory design is a method which involves asking potential users (usually non-designers) to take part in numerous co-design activities (Sanders et al., 2010). The participatory design method comprises a wide range of tools and techniques. Practices within participatory design research have been divided into three basic stages; Stage 1: the initial exploration of work, Stage 2: Discovery process and Stage 3: Prototyping, (Spinuzzi, 2005). In this work Stage 3: Prototyping, is considered. Future scenarios are explored, and the generation of ideas and concepts takes place (Sanders et al., 2010). To facilitate the participatory design study a decision is made for the tools and techniques and their mode of application. This thesis focuses on enactment and envisioning, by placing participants in the position of a remote operator overseeing an SAV. In this task-based evaluation, participants are asked to describe the actions they believe are necessary to reach a by the researcher predefined goal. The evaluation concludes with participants answering a small set of open questions motivating their considerations.

3.3.4 Thinking-aloud

Thinking aloud is a method of data elicitation which revolves around participants verbalising whatever comes to their mind, while they are engaged in a given task

(Jääskeläinen, 2010). The written transcripts of these audiotaped sessions are referred to as think-aloud protocols. Thinking-aloud as a method in cognitive psychology was first defined in a study by (Ericsson and Simon, 1980). The method comprises extracting rich and in-depth information from a small set of subjects (Fonteyn et al., 1993). Ericsson and Simon (1980) made a distinction between two modes of verbal reporting; concurrent and retrospective. Within concurrent verbal reporting the subject is asked to express their thoughts while performing a task, in contrary, retrospective reporting involves the researcher asking the participants to recall what they experienced and was on their mind. Thinking-aloud is suited to retrieve underlying thought processes and notions, which would likely not be exposed through interviews or questionnaires. This thesis applies the method of retrospective verbal reporting during the user study, to elicit underlying thoughts and feelings resulting from the interaction with the developed artefacts.

3.3.5 Questionnaires

A questionnaire can consist of quantifying or qualifying questions. Questionnaires composed of closed questions, result in quantifiable data, while, open and reviewing questions result in qualifying data (Håkansson, 2013). The evaluation questionnaire constructed in this thesis consists of both open and closed questions, aiming to acquire a broad understanding of the operator's SK. Specific questionnaires for measuring spatial or situation awareness already exist. Situation Awareness for SHAPE (SASHA) is a questionnaire best fit for screening the appliance of an artefact. To gather additional information on how a new system might change a controllers understanding, other methods should be used (Dehn, 2008). Research by Franz et al. (2015) indicate that the method Situation Awareness Global Assessment Technique (SAGAT), a comprehensive conduct developed by Endsley (1990), cannot fully cover all information available to a driver. Other techniques such as SALIANT, SPAM and SAVANT were also reviewed but found to be incompatible with this research regarding methodology and goals. The Situation Awareness Rating Technique (SART) questionnaire (Taylor, 1989) is widely used and has been applied in various domains such as automotive (Davis et al., 2008), the method fits within the scope of the study.

The questionnaire in this study comprises a set of 10 open questions and 16 closed statements. The closed statements are answered on a 7-point Likert-scale (1: Completely disagree and 7: Completely agree). The statements in the questionnaire are adopted upon, research by Lagstrom and Lundgren (2015) and the SART questionnaire. SART questions focus on articulable understanding, explicit SK. To measure implicit SK, selective questions from both the SART and Lagstrom and Lundgren (2015) questionnaire are adapted to repeatedly question on measures of immersion and an operator's perceived capabilities.

3.4 Data analysis methods

Data analysis is an essential part of the research strategy and consists of methods used to analyse the collected information. Through the processes of reviewing, transforming and abstracting the information, decision-making and reaching conclusions are supported. To analyse the collected information, this thesis applies the methods of Pattern-matching, Median (MED) and Interquartile Range (IQR) and Thematic Analysis.

3.4.1 Pattern-matching

According to Yin (1994) case studies can be analysed by means of three analytic methods; pattern-matching, time series analysis and explanation building. Explanation building is conceived as a type of pattern-matching, and according to Trochim (1989) a very successful technique for case analysis. In this thesis, cases are analysed through building explanations; constructing a set of links about how or why some phenomena happened, this process is usually iterative (Miles and Huberman, 1994).

3.4.2 Thematic Analysis

Thematic analysis is a method used to identify, analyse and document themes within a set of information (Braun and Clarke, 2006). A theme is considered to express a notion about the data and important to the research question. The meaning of the notion is often patterned throughout the set of information. Thematic analysis can also be used to expand the understanding of a notion and highlight related experiences of people (Braun and Clarke, 2006). A thematic analysis consists of a number of stages (Aronson, 1995), first the data is collected. The next step is to code the data, this involves looking for reoccurring statements in the data-set related to the research question. Boyatzis (1998) has identified two types of coding; semantic and latent. Semantic coding attempts to disclose the explicit and obvious meaning of the data, while, latent coding aims to expose underlying intents and assumptions. Semantic coding is well fit to reveal clustered experiences or opinions, such as for the purpose of this thesis. The final step is to categorise and bring together themes and compose a complete picture of the notions related to the research question.

3.4.3 Median and Interquartile Range

To review and derive results following from the 7-point Likert-scale questions, a measurement of dispersion can be used (Patten, 2017; Lang and Secic, 1997). The Median and IQR are considered measures of dispersion or variability, and are well fitted for measuring central tendencies on a data set with a small sample size. The variability captures the range in which participants differ from one another. The Median and IQR provide an indication of how the data is dispersed over the continuum (Lang and Secic, 1997). This thesis aims to compare the variance of experiences between an HMD and a computer display.

Part I

Analysis

Chapter 4

Related work

The chapter on related work describes research and implemented application of teleoperation and remote control. Four facets, relevant to the leading research question, are identified; vehicle teleoperations with an HMD, implemented remote presence solutions, teleoperation interface design and SA in teleoperations. Each of the cases discussed links to one or more of the four facets.

4.1 Head-mounted displays for teleoperation

In this passage, an analysis of the results and challenges found in studies by Schmidt et al. (2014); Candeloro et al. (2015) using an HMD for teleoperations of mobile robots is discussed. The work on Teleoperation of robots for plant inspection (Schmidt et al., 2014) involves a comparison study and Candeloro et al. (2015) explore HMDs as a tool for a Remotely Operated underwater Vehicle (ROV).

4.1.1 Teleoperation of robots for plant inspection

In research by Schmidt et al. (2014) a study is performed to investigate usability aspects in teleoperations of mobile robots for plant inspection. The focus of the study is on the effects of using an HMD and different input devices for tasks in a remote control situation. Two systems are developed; one desktop computer based graphical interface for planning and monitoring operations and an HMD interface for an intervention through remote control. Two aspects specific to teleoperations with an HMD are investigated; the task and control efficiency as well as symptoms of cybersickness. In an experiment with an identification task, in which a head-slaved (the camera turns according to the head movement) and joystick-based control of a camera was investigated, the head-slaved interface with the HMD proved to be superior. A correlation was found between the total time an HMD is used and feelings of cybersickness. However, participants rated the effects acceptable for periods of time not exceeding 20 minutes. Schmidt et al. (2014) conclude that to accelerate efficiency, additional assistance systems for teleoperations are needed on top of the tested setups. This thesis adopts the findings that, the time spent using an HMD correlates to feelings of cybersickness and recommendations on additional assistance systems.

4.1.2 HMDs as a tool for teleoperations of ROVs

Candeloro et al. (2015) explore the use of HMDs for ROVs, with the objective to increase the telepresence experience and situation awareness. A setup is developed which enables control of the motion of the ROV through a head-slaved HMD. The aim of the study is to determine whether a joystick based control can be replaced by an HMD head-slaved control for industrial ROVs. The study uses an Oculus Rift DK2 HMD in combination with a setup of two cameras providing stereo vision connected to computers for processing. The experiments in the study have been performed on a full scale and in an unstructured environment. Experimental results are indecisive, using an HMD for straight directional control seemed to give rise to issues of smoothness. Sideways tilted head-movements gave positive results, and the completion of half circles around an underwater object were successful. The study concludes that an HMD has the potential to be valuable for offshore operations, and that augmented reality could be implemented to improve SK.

4.2 Interfaces and situation awareness in teleoperation

This section discusses two cases; interfaces for teleoperation and the relation between the interface and spatial awareness. Furthermore, related work on technologies for awareness and monitoring in the context of control room operations are outlined.

4.2.1 Usability evaluation of VR interfaces

The development of virtual reality interfaces for HMD devices is a relatively new field; consequently, usability aspects are to be studied and evaluated. Jankowski and Grabowski (2015) present a usability evaluation of three remote control interfaces. The primary VR interface is based on an HMD stereo vision system and data gloves. The other two systems consist of stereoscopic and monoscopic LCD computer displays and a joystick. A user study was performed in which participants were asked to perform tasks with a small mobile robot through one of the interfaces. The concept of spatial presence was measured through a questionnaire. Differences in the spatial situation model and spatial presence were observed in favour of stereo vision. The study found that the level of spatial presence was perceived highest while using the VR interface. The level of spatial presence could be attributed to the use of stereo vision and the possibility of natural control of the mobile robot arm through the data gloves. Moreover, the VR interface was perceived as most intuitive and comfortable. The interface provided the user with a sense of depth, and it increased their efficiency in completing the tasks. Stereoscopic images and the use of hand-based controllers are taken as recommendations for this thesis.

4.2.2 Virtual Environment Teleoperations Interface

In a study by Hine et al. (1995) an operator interface, Virtual Environment Teleoperations Interface (VEVI), for planetary exploration is described. The study investigates the use of virtual environments to allow an operator to plan and review high-level based commands of a remote vehicle system and quickly understand the current and past system status. Key challenges in the scope of their research are the time delay caused by the distance between the operator and the vehicle as well as the bandwidth limitations. The use of fixed camera views is greatly reducing situation awareness in comparison to human operators, as humans have a very wide field of view and allow for smooth scanning. The interface consists of 3-Dimensional renders and 2-Dimensional displays linked to user/sensor input devices. The 3-dimensional render is essentially a simulation of the vehicle along with the available and known information on the environment. The 3-dimensional model on the 2-dimensional displays is used for controlling and manipulating the remote vehicle. The digital control panels consist of buttons and status indicators ordered in categories. Planning input takes place using buttons and keyboard strokes, a graphical representation of the current state of the vehicle as well as the intended state forthcoming from input commands is presented. The researchers conclude that the use of the VEVI interface, based on virtual environments, has improved situation awareness for operators. Communicating a significant amount of information about the vehicle in its surroundings is recommended to facilitate situation awareness.

4.2.3 Technologies for everyday awareness and monitoring in control rooms

In a study by Luff et al. (2000) a review is presented of technologies in support of awareness and monitoring of the complex environment of London subway stations. Their study investigates how supervisors monitor the various spaces including their dynamic conditions. The supervisors have a broad set of responsibilities ranging from managing operations to detecting and managing critical incidents. A wide range of communication and information technologies is at their disposal. The communication technologies are among radio, announcement and phone systems. The supervisor's most notable technology at hand is a set of camera displays. The supervisor may operate panning and static cameras. The remote environments that these operators need to survey poses significant challenges, e.g. blind spots. Supervisors do not solely rely on directly observing disturbance, but, may also infer 'trouble' from the behaviour of passengers. Moreover, the experience or 'intuition' of the supervisors may predict scenes in which trouble can occur. As a consequence supervisors may configure their technologies in such a way to best meet their demands for a particular area. Such configuration can for instance include a specific camera arrangement. These findings indicate that technology in support of awareness is activity dependent. The operation of these supporting technologies is acquired through a collection of experience and knowledge of the supervisors. Analysis of these findings may support the design of control rooms for awareness and monitoring of SAV environments.

4.3 Teleoperation solutions

This section discusses two complete solutions of remote presence in a control situation. Saab digital air traffic solutions is an implemented and functional solution and Seamless autonomous mobility by Nissan is a functional proof-of-concept of an integrated solution for teleoperations of automated vehicles.

4.3.1 Saab Digital Air Traffic Solutions

Saab Digital Air Traffic Solutions is a remote air traffic control tower product (SAAB, 2017a). It consists of a setup (SAAB, 2017b) of sensors at an airport, connected through a redundancy approved network, to a remote centre where air traffic controllers take place. The setup at the airfield consists of a set of cameras providing a 360-degree panorama field of view, with additional pan-tilt zoom-cameras. The latency between the airport and remote control centre is under a second. The remote control centre is similar to a regular air traffic control tower. However, the windows are replaced with computer displays or a setup of projectors. Information is overlaid, e.g. aircraft call-sign or warnings over the images that remote controllers receive. By using 360-degree panorama images of the airfield, remote controllers are expected to have similar situation awareness as their colleagues in actual air traffic control towers.

4.3.2 Seamless Autonomous Mobility

Seamless Autonomous Mobility (NISSAN, 2017), proposed by Nissan, is a backup driving system for driver-less automated vehicles (Sierhuis, 2017). The system architecture consists of a graphical user interface on a computer display with high-level command-based remote control functions. Cameras in and around the vehicle provide live video-feeds to a remote operator. An essential part of this interface is a birds-eye view component which allows for way-point planning of the vehicle. Additionally, satellite-based images complemented with sensor output creates a dynamic situation sketch of the environment around the vehicle. The process of teleoperation is initiated through a request by the vehicle, after which a human is required to inspect the situation of the vehicle. A path-based planning strategy can be used to control the vehicle (Golson, 2017). The concepts of a birds-eye-view and the ability to use way-point planning are adopted in the development of the prototype interfaces in this thesis.

Chapter 5

Design requirements

This chapter on design requirements concludes *Phase 1: Analysis*. The chapter details requirements for creating an SAV teleoperation interface concept and prototype, as defined in *Section 1.3 Objectives*. Findings from expert interviews on teleoperation systems are presented after which use cases and operator needs are listed. The last part of this chapter details a specification of design requirements.

5.1 Field study analysis

In this section important findings from interviews with professionals in the major areas of this study are discussed. These key areas include control room operations, SAV operations and engineers within the fields of control room design and automated vehicles. An interview was conducted with an engineer from Scania AB working on the design of control rooms for automated vehicles, to identify design considerations for control rooms of automated vehicles. Engineers within the WePod project[1] were questioned on their experience of operating an SAV within a test environment. A remote operator working at the Parkshuttle[2] was interviewed about their experience with teleoperating SAVs. Finally, an interview with an air traffic controller was conducted to understand their experiences with working in control rooms. In each section the main findings are discussed.

5.1.1 Scania AB control centre

An interview took place at Scania AB with a designer to explore design considerations for control rooms of automated vehicles. Scania AB has been, during the spring of 2017, in the development of a control centre system for automated vehicles. This control centre for monitoring and control operations is specifically tailored towards mining and industry and has a production-output focus. Therefore information indicators in the interface are among fuel-consumption, energy efficiency and resource

[1] http://wepods.com Accessed: 2017-07-22

[2] https://www.connexxion.nl/reizen/1190/parkshuttle/238 Accessed: 2017-07-22

flow. Vehicle sensor information is streamed to the control room; such information may consist of: e.g. a video feed linked to map data. Vehicles are expected to be capable of communications with infrastructure as well as problem-solving through inter-fleet communications. The interviewee repeatedly underlined the necessity of a remote operator considering the operations of a whole fleet of vehicles and to visualise this in the interface through Key Performance Indicators.

5.1.2 WePod

Interviews were conducted with a WePod project manager and engineer to reveal challenges and lessons from SAV operations in traffic. The WePod project is a SAV research project based in Wageningen, The Netherlands. Researchers investigate the use of an Easymile EZ10 vehicle (see, *Figure 1.1*) in mixed traffic. In this project, a steward is onboard of the vehicle at all time to assure safety and restart the vehicle systems upon failure. The type of SAV in the WePod project is meant to drive autonomously and to carry-on passengers as an addition to public transport. The vehicle has by default no onboard human steering interface, also, the vehicle is not equipped with a graphical user interface for remote control of the vehicle. Manual control of the vehicle is realised by adding a controller pad inside the vehicle or via a command based network interface. Cameras facing-forward, rear and inside are installed on the vehicle to observe the vehicle and other road users in traffic. The vehicles are programmed to, in the case of safety-critical situations, come to a safe stop. From the interviews, it was found that weather conditions negatively influence autonomy functions. Researchers envision a teleoperation system to be part of the complete operational process of SAVs. An operator would be alerted through a notification. It was argued that because of safety regulations and network limitations a command-based remote control structure is the preferred choice for SAVs. Also, the security of the network connection of the supervisory system is of great importance to the SAV's operational safety and reliability, and a consideration to the public opinion.

5.1.3 The Parkshuttle line

An interview with a Parkshuttle operator took place to investigate the work and experiences as a remote operator of automated vehicles. The Parkshuttle is a public transport line in the city of Rotterdam, connecting a metro-station with a nearby business park. A total of six SAVs can be operated on a dedicated road with two lanes. These vehicles drive back and forth between two end-nodes and may carry up to 12 passengers each. The vehicles are assigned one scenario out of a set of predefined scenarios. Each scenario dictates how the vehicle should drive a route. By using artificial landmarks in the infrastructure, passive magnets, and counting wheel revelations, the vehicles are able to navigate along the dedicated track. A laser-based sensor system can detect obstacles and will upon an obstacle detection initiate an emergency vehicle stop. Operational experience has taught that human supervision and intervention is needed and a vital part of everyday operations. A remote operator is appointed to supervise the operations of the system. There is a continuous active role for the operator during operations, as difficulties may arise at any point.

To facilitate the tasks of the operator, a broad set of tools and information is at their disposal. The interface used by the operator has the following key components: a Windows based operating system, with various applications distributed over two computer displays. A video-component presents a set of cameras-feeds along the serviced-track. Another component of the application shows a birds-eye, front and inside view from any selected vehicle. Status updates and statistics are textually listed, indicating the current task, scenario and status of the vehicle. Key procedures of remote control include; analysing the situation by means of visual confirmation, stopping, holding and continuing the vehicles. Moreover, new scenarios can be assigned, e.g. go to the garage. The interviewee expressed a desire for remote manual control, to optimise operations in case of small incidents. The Parkshuttle case has highlighted important tasks for an operator and demonstrated the importance of visual information during teleoperations.

5.1.4 Arlanda Airport

An interview took place at Arlanda airport air traffic control in Stockholm, with the goal of gathering information on controllers working in an air traffic control tower. The following findings underline important notions in the workflow of a controller at Arlanda. The training of controllers is focused on the principles of their work. The type of interfaces and specific procedures may vary significantly from airport to airport. The shift of a controller may take up to a maximum of one hour, after which the controller has to take a break. One of the key tasks of a ground controller is to be aware of the current positions of vehicles as well as in relation to other vehicles and aircrafts in the surroundings. A ground radar system helps controllers to digitally observe ground traffic on the airport. Another consideration for the ground controller is vehicle dependent behaviour, different types of vehicles behave differently depending on their task and mode of operation. Moreover, controllers are tasked with scenario anticipation to be able to predict how the position of vehicles will be laid out in the near future.

There is some degree of freedom in how a controller manages the process and which instruments they can use. Also, the interviewee indicates that controllers tend to personalise the layout of their workspace and prefer and use different setups of the interface. However, this degree of freedom is very situation dependent. At Arlanda air traffic control there are currently at least three computer screens per controller with each different input devices. The interviewee expressed their desire to minimise the number of screens and input devices. A lot of information is available to the controller at once, the interviewee indicates that it is important for interfaces to create a balance between showing either too much or too little information. In this context the position of the information relative to the screen size and other information is important. Nonetheless, the controller would want to be able to access all information easily. In some rare cases, the ground radar and other systems may give faulty measurements. To assure safety, controllers rely heavily on their sight by using for instance binoculars to verify system information. These findings have relevance for the design of interfaces for control rooms of SAVs regarding situation assessment and anticipation.

5.2 User needs identification

This section discusses key stakeholders, anticipated use cases and corresponding tasks in SAV teleoperations. A persona of the operator is presented along with scenarios remote operators are prone to encounter during teleoperations. This section concludes with a set of tasks analogous to remote control of SAVs. The objective is to understand the various dimensions of a teleoperation interface for an SAV remote operator.

5.2.1 Stakeholders

The list of stakeholders below are people who either have an interest in or are directly affected by teleoperations of SAVs. Operators are the primary users considered in this thesis. To create a broader outlook, other stakeholders are also described.

- **Operators**, are at the heart of teleoperations and this thesis. Their role and tasks are crucial for the operations of SAVs. It is the task for the operator to monitor and take control when required. Operators are trained on and skilled in traffic scenario analysis and capable of adequate decision making. Operators are familiar with operating vehicles and have a thorough understanding of the capabilities, limitations and dimensions of the SAV. The operators are familiar with the processes in a control room and are trained on using an HMD. Essentially, in most of the cases, the remote operator is asked to override system (safety) limitations, transferring a great deal of responsibility from the system to the remote operator.
- **The passengers** of an SAV are also an important stakeholder. However, their role is limited concerning tasks; it is the passenger's responsibility to act responsibly in the case that SAV operations hold. The comfort of the passengers is an important aspect for remote operators during teleoperations.
- **Other road users** (humans), their role is important to consider in mixed traffic, as people may react unexpectedly to driving SAVs. Other road users are also impacted by SAV teleoperations, as SAVs under remote control may drive differently compared to what people are familiar with.

Authorities and public transport companies are also stakeholders, although they are not 'users' interacting with SAVs. Authorities their interest is to create secure and safe operations of SAVs for the public. Legislation for, as well as the inspection of, SAVs are among the responsibilities of authorities. Public transport companies which will operate SAVs have an interest in the accessibility and uptime of the service offered by SAVs. These companies will be attentive to the development and actualisation of SAVs and remote control systems.

5.2.2 Use cases

The aim of this section is to explore use case scenarios when an SAV is leaving its operational domain, and a need for teleoperation arises. These scenarios are largely envisioned upon the perspective of an SAV operating in mixed traffic (Nilsson, 2014; SAE International, 2013). The scenarios listed involve any form of the SAV leaving its designed operational domain. Such event can be caused by a system exceeding design limitations, system malfunctioning or any other unforeseen event. Such an occasion can be a direct or indirect threat to normal system operations or even the well-being of the passengers. The scenarios listed are supported by interviews and findings as part of the case and field study analysis.

1. Vehicle obstruction, in these scenarios the vehicle is unable to continue normal operations due to obstructions on the road;
   a) External road user, another road user has blocked normal operations,
   b) Pedestrians, pedestrians are blocking normal operations, e.g. a crossing,
   c) Incident, a traffic incident is obstructing normal operations,
   d) Ghost objects, a non-existent object is detected preventing the vehicle from advancing.
2. Infrastructural/traffic limitations;
   a) Road crossing, an intensive road crossing is limiting normal operations,
   b) Police officer, a police officer may need to direct traffic,
   c) One-lane crossings, one-lane crossings require a human to mediate interaction between the SAV and another vehicle,
   d) Aggressive driver behaviour, aggressive drivers may needlessly trigger safety systems of the SAV.
3. Exit obstruction, passengers of the vehicle are unable to exit the vehicle.
4. Malfunctioning/sabotage, operations are stopped because system components are not working properly.
5. Leaving pre-programmed route, when the vehicle has to leave the physical operational domain.

6. Weather conditions, extraordinary weather conditions limit the operational domain.

7. Manual reboot, a manual reboot of the system is required.

8. Conflicting system responses, conflicting system responses may cause the vehicle to require human intervention.

Limitations and failure of SAV systems may occur in different domains. Hence, the list of use cases is by no means comprehensive but is supposed to provide a thorough understanding of the various complex situations SAVs may encounter.

5.2.3 Task analysis

In this section actions and cognitive tasks as part of the remote control process are detailed. The list is devised based on findings from the case and field study analysis. An operator is required to take over when an SAV is leaving its operational domain and has come to an independent stop. *An operator is tasked with*:

- assessing the vehicle's condition;
- assessing the vehicle's environment;
- creating a mental model of the situation;
- providing a solution to the problematic situation;
- executing the actions as part of the solution;
- manual/command/path-based steering and longitudinal control;
- maintaining an understanding that their actions may compromise system-safety limitations;
- communicating with the passengers;
- communicating with other road users;
- monitoring vehicle and system performance.

The list of tasks is by no means complete, but should provide a profound understanding of the various tasks of a remote operator. The tasks and actions listed are part of the entire process of SAV teleoperations. This process is likely to adhere to a set of stages. Similar stages have been described for control room operators of process industry (Nazir et al., 2012). The first stage for an operator is to use the information available to create a mental model of the situation. In the second step the SK helps the operator to understand factors of key influence in the situation. In the last stage of teleoperations the remote operator should plan their following actions and anticipate the effect of these actions. These actions are similar but not limited to those of any vehicle driver. Two types of remote control are identified; manual steering and high-level planning (Nguyen et al., 2001), whereas high-level planning may consist of command- (*5.1.2 WePod*) or path- (*4.3.2 Nissan*) based teleoperations. Command-based remote control entails an operator assigning pre-defined scenarios to the vehicle. Path-based remote control enables an operator to draw a path which the vehicle should drive.

5.3 Requirements specification

In the stage of requirements specification, the requirements identified in the analysis are translated into design specifications. The requirements specified in this section serve as a basis for the development of the HMD and computer display prototype. A list of requirements for a real product is supposed to be more extensive than detailed here. *Usability* and *User requirements* form the basis for the system design specifications.

5.3.1 Usability requirements

Usability requirements are considered non-functional system requirements. Usability requirements stipulate, in global terms, what a user can expect from the system regarding e.g. reliability, understandability and supportiveness (Maguire and Bevan, 2002). A more extensive list of types of usability requirements can be found in Maguire and Bevan (2002, p.141). The following usability requirements are stipulated in support of the prototype development:

1. The system should be easy to understand for the operator;
2. The system should support the operator to complete their tasks efficiently;
3. The system should support the operator to complete their tasks effectively;
4. The system should be flexible in use; components should be adjustable;
5. The system should limit symptoms of cybersickness.

5.3.2 User requirements

User requirements are considered functional system requirements. User requirements capture the user's needs, expectations and desires for the development of the system. The requirements define in a systematical manner what the system should do; a functionality (Maguire and Bevan, 2002). An overview of user requirements identified and prioritised according to the scope of this thesis is listed in *Table 5.1*. In the table '...' should be read as *'An operator has to be able to'*. The purpose of the user requirements is to support the development of an HMD and evaluation of remote operator's Situation Knowledge (*1.3 Objectives*).

ID	User requirement	Justification
UR1	... assess the vehicle's condition,	4.2.2 Virtual Environment Teleoperations Interface
UR2	... assess the vehicle's environment,	5.1.3 The Parkshuttle line
UR3	... assess the vehicle relative to its environment and other road users,	5.1.2 WePod
UR4	... perceive depth in the images,	4.2.1 Usability evaluation of VR interfaces
UR5	... manually assess steering and longitudinal control,	5.1.3 The Parkshuttle line
UR6	... use path-based moving operations,	5.1.3 The Parkshuttle line
UR7	... monitor vehicle and system performance,	5.1.4 Arlanda Airport
UR8	... adjust the graphical user interface,	5.1.4 Arlanda Airport
UR9	... use a single interface for all interactions,	5.1.4 Arlanda Airport

Table 5.1. A specification of User requirements.

5.3.3 Conclusions from Phase I

This section details the specification of the design requirements from user and usability requirements as mentioned earlier. The design requirements specification presents a set of prerequisites for Phase II: Conceptualisation. The specifications listed in *Table 5.2 A specification of Design requirements* are mapped with the user and usability requirements. User requirements are indicated to with the id 'UR' and usability requirements are mentioned with the id 'XR'.

ID	To accommodate the requirement the system should:
UR1	Present textual and graphical information on the vehicles condition,
UR2	Feature a 360-degree view around the vehicle,
UR3	Visually depict the object detection information,
UR4	Use a stereo vision supported interface,
UR5	Provide an interface option to engage in manual control,
UR6	Provide an interface option to engage in path-based control,
UR7	Update and inform the operator of vehicle status information,
UR8	Support the operator moving or hiding the graphical user interface,
UR9	Support the operator in controlling the interface through a single-input device,
XR1	Have a uniform design and be understandable with an explanation of less than 5 minutes,
XR2	Limit the number of interactions an operator should engage in,
XR3	Balance the amount of information communicated,
XR4	Support UR8,
XR5	Should not be used in excesses of over 20 minutes.

Table 5.2. A specification of Design requirements.

Part II

Conceptualisation

Chapter 6

Interface concept development

This chapter describes the concept generation and participatory design study as part of *Phase II: Conceptualisation*. The aim is to develop concepts based on the analysis as described in the previous chapters. Also, to evaluate the experiences of control room professionals working on tasks of teleoperations with the developed interface concepts.

6.1 Concept generation

Based on the design requirements specification (see *Table 5.2*) a process of ideation is initiated. The process of idea and concept formation is cyclical and relies upon the creativity of the designer. The participatory design study uses a set of low-fidelity concepts; therefore the aim is to develop concepts in the form of paper mock-ups. An important consideration is to unify the visual information of both the HMD and computer display interface, to limit the influences on SK caused by differences in interface information and interaction.

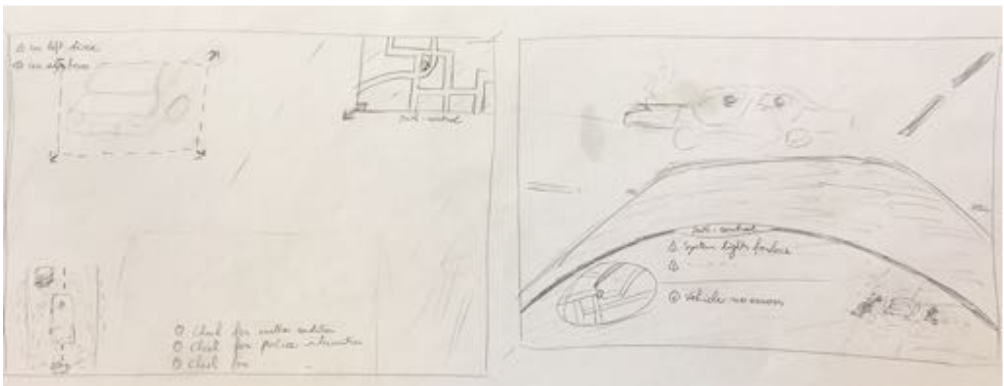

Figure 6.1. Interface sketches by the author during the process of concept development. Picture by author.

A number of sketches on paper are made, each of these sketches inhibit various styles of structuring the interface and its components. Two of the sketches made are depicted in *Figure 6.1*. From left to right, in the first sketch, the interface components are spread around the viewport (the viewport is the area visible to the operator). In the second sketch, the interface components are aligned on a tilted plateau at the bottom of the viewport facing the operator.

Figure 6.2 depicts an abstract illustration of how a complete SAV teleoperation system could look like. A remote operator can be working from any place in the world while using an multimodal interface with an HMD. Via a network connection the operator can control the SAV driving in a remote location.

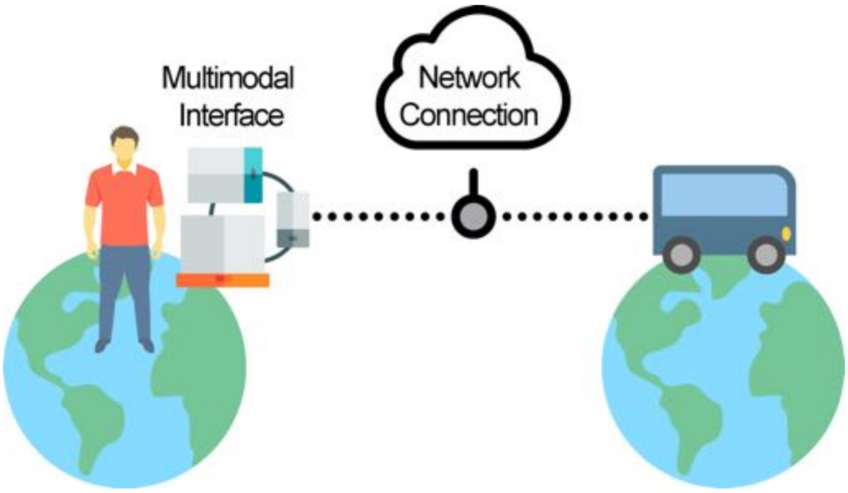

Figure 6.2. Illustration of a complete SAV teleoperation system. Image courtesies of Freepik, Vectors Market and Gregor Cresnar. Illustration by author.

6.2 Interface concepts

Three concepts, see *Figures 6.3, 6.4 and 6.5* are developed through reviewing and iterating over aforementioned sketches. These concepts are visualised using Adobe Photoshop image-editing software. A picture of an actual traffic situation is taken after which it is overlaid with various interface elements. Concepts diversify through the layout of the interface elements. The underlying assumption is that the position of the interface elements may affect visibility and intuitiveness. Considering *UR2* the position of the camera is chosen to be on top of the vehicle. Each concept has a general information section which outlines vehicle information and complies with *UR1, UR7, XR3*. Each interface graphically depicts the objects the vehicle detects around (*UR3*). Also, each interface shows a map with the route of the vehicle, adhering to *UR7*. Unaccounted requirements specified in *Table 5.2* could not be visualised using a two-dimensional mock-up but were considered during the participatory design study. For example, *UR4: Use a stereo vision supported interface* could not be shown, but was explained prior to the evaluation with the help of a paper metaphor (*Figure 6.6*).

Figure 6.3. Interface concept 1 with the interface elements positioned along the bottom. Illustration by author.

Interface concept 1 (*Figure 6.3*) depicts a 2-dimensional outlook of the perspective of a remote operator. At the top of the viewport, a warning message appears. An enlarged image of the road-construction sign is shown. On the bottom of the viewport, from left to right, a map with the current position and heading of the vehicle is shown, an interface bar element displays information about the current speed, remote operators tasks and battery of the vehicle. On the right side, a 3-dimensional image depicts how the vehicle perceives its environment.

Figure 6.4. Interface concept 2 with the interface elements positioned on both top and bottom. Illustration by author.

Figure 6.5. Interface concept 3 with the interface elements positioned similar to an observed control room. Illustration by author.

Each concept contains the same amount of information. However, the position of the interface elements is different for each concept. In concept 3 (*Figure 6.5*) the interface elements are aligned at the bottom of the viewport, similar to how the interfaces were organised in the detailed Arlanda field study case. Concept 2 (*Figure 6.4*) depicts the interface components at the top of the viewport, under the belief that any element at the bottom could obstruct the operator's view. Concept 1 (*Figure 6.3*) depicts the interface elements along the bottom of the viewport, opening up a view in the upper part of the viewport.

6.3 Participatory design study

The objectives of the participatory design study are to; determine possible issues with the concepts, whether concepts support operators and the overall experience of using the interfaces. The participatory design study is conducted with a small number of subjects (n=3), all males and their age ranging between 38 and 51. All of the subjects indicated that they had a basic understanding of the concept of an SAV, two subjects indicated they had experience with remote control operations. Subjects were selected on the basis of their experience with control rooms. To diversify the feedback, the experience was detailed to designers of and operators in control rooms.

6.3.1 Study design

This section describes a summary of the protocol used in the participatory design study. The participatory design sessions are conducted individually. A full overview of the protocol used during the session can be found in *Appendix A Participatory design protocol*.

1. The subject is introduced to key aspects of the research, this includes the type of SAV (see *Figure 1.1*) and motivation for teleoperations. Also, a small LEGO car surrounded by a paper panorama (see *Figure 6.6*) is used to introduce the concept of how an HMD could be used for teleoperations.

2. The subject is primed by a short story which portrays their tasks and objectives as a remote operator.

3. The participatory design study includes the following three tasks; assess whether there is an intervention due to emergency services, create an understanding of the situation around the vehicle and explain how to remote control the vehicle. For every task, the subject is asked to go through the steps of describing the task and identifying the actions required to complete the task. Lastly, the subjects are asked to pick a concept best suited to complete the task and motivate their choice.

4. After the subject has completed all the steps for all of the three tasks, they are interviewed according to a set of six open questions (see *Appendix A Participatory design protocol*).

Figure 6.6. A small LEGO car with a LEGO figure sitting on top, a metaphor for the perspective from an HMD interface. Picture by author.

6.3.2 Results

Subjects were overall enthusiastic about the potential the interface concepts presented to them in their role as a remote operator. A common thread was the belief that through using the interface it would be possible to quickly observe the situation around the vehicle and perceive depth; *".. looking around would be the easiest way to get information."* (Subject 1). Subjects illustrated their feeling of connection with the situation by highlighting that it would be similar to sitting in a normal car and looking around. It was found that the subjects were positive about control via both manual steering and path-planning. However, steering was preferred when sensor reliability was in dispute; *"I would probably want to drive and feel how the vehicle (SAV) moves forward"* (Subject 2). Subjects indicated that their choice of control would be task and scenario dependent.

The subjects mentioned some considerations which could improve their experience. The possibility to change the layout of the interface elements along the viewport and to only display interface information which is relevant to the current task of the operator. An explicit consideration mentioned is that the map interface element should clearly indicate where the vehicle is heading (Subject 1). Subject 2 remarked that when designing for an HMD interface, interface elements should not be attached to the viewport, but to points in the perceived world. Moreover, subjects expressed a desire that they would want the interface to highlight key objects and people in the scene.

Findings indicate that each subject had their unique motivation for choosing their preferred interface layout. Key aspects mentioned were; to prevent obstruction of view by interface components and to group the graphical information in an area of the viewport. Two out of three subjects indicated they found *Interface concept 3* (*Figure 6.5*) best suited to complete all the tasks part of the participatory design study.

6.3.3 Conclusions from Phase II

The participatory design study has underlined a need to differentiate between steering and path-based remote control. This differentiation depends on the vehicle's condition and situation. The experiences of the subjects demonstrate that the developed concepts provide a solid basis for an HMD teleoperations interface. The concepts facilitate an easy way of looking around and perceiving information. Important considerations for the realisation of the HMD interface prototype are identified. The layout of the interface elements is a matter of personal preference and personalisation should be supported. *Interface concept 3* is chosen as a basis for further development, because the interface elements are attached to an object in the perceived world.

Part III

User Study

Chapter 7

Prototype development

Phase III: User Study encompasses the prototype development and a task-based evaluation with an HMD and computer display interface prototype. This chapter describes the implementation of these two teleoperation prototypes. The prototypes detailed in this thesis do not use real data from an SAV.

7.1 Prototype design

The HMD and computer display prototype adopt the requirements listed in *Table 5.2 A specification of Design requirements* and are inspired upon interface Concept 3 (*Figure 6.5*). The game engine software Unity3D[1] is used to design and program the interfaces. The software supports both 2-dimensional and 3-dimensional environments and can show content on an HMD and a computer display. Although both prototypes have the same interface elements, the alignment of the elements and the method of control is different for each interface. The interface elements are dummy components, in other words, the information shown is not derived from sensor data of a vehicle but predefined. In the prototypes, the operator takes the perspective from on top of an SAV.

7.2 HMD prototype implementation

The HMD prototype consists of a number of components as detailed in *Figure 7.1*. The VIVE[2] Head-Mounted Display by HTC is chosen as a platform for the HMD prototype. The VIVE is a well renown HMD and can track the head movement of a user and the relative movement of the headset in a confined space, such as a room. The HMD has a display with a total resolution of 2160×1200 pixels, 1080×1200 per eye (ibid.). A VIVE setup consists of a headset with a display, two controllers and a set of two base stations. To be able to run programs on the VIVE without delay, the headset needs to be connected to a laptop with a VR-ready graphics card.

[1] https://unity3d.com Accessed: 2017-07-27

[2] https://www.vive.com/eu/product/ Accessed: 2017-07-27

Figure 7.1. Illustration of the different components constituting the HMD and computer display prototypes. *Images are retrieved from the MSI and HTC presskit.* Illustration by author.

The Unity3D software uses the plugin *SteamVR*[3] to communicate with the VIVE and to deliver images to the HMD. The Unity3D software uses a framework of scenes and game-components. A developer can create scenes in which various types of game-components can interact with each other. In the scenes created for the prototype, a Unity3d 'camera' game-component is linked to the HMD to reflect the direction of where an operator is looking. The camera game-component is placed inside a spherical game-component. On the inside of this spherical game-component images can be projected. The *VR Eye Shaders*[4] Unity3D plugin is applied on the spherical game-component. Through this plugin different images can be projected to the left and right eye when using an HMD; as a result, the observer perceives depth in the 2-dimensional images. A 3-dimensional model of an SAV is positioned under the camera game-component, to enhance the illusion of a realistic SAV teleoperation scenario.

The HMD prototype, see *Figure 7.2*, has its interface segments by default aligned under an angle facing the operator. The operator can move the interface segments up and down, as well as position the segments in sight of the direction they are looking, by using one of the VIVE controllers. The VIVE controller can be used to point and click on interactive interface components such as the buttons for steering and drawing. The structure and contents of the interface segments are:

- The rectangular segment on the left represents a map with objects that the vehicle detects in the surrounding,
- The rectangular segment on the right represents a map with the current position and heading of the vehicle,

[3]http://u3d.as/cjo Accessed: 2017-07-28
[4]http://u3d.as/P7r Accessed: 2017-07-28

- The segment at the bottom shows; malfunctioning components of an SAV, a battery indicator, a warning message, current speed, a task for the operator and the two options of manual or drawing for remote control.

Figure 7.2. A 2-dimensional screen capture of the HMD interface where an operator is teleoperating an SAV. Picture by author.

7.3 Computer display prototype implementation

The computer display prototype (see *Figure 7.3*) operates with similar interface segments like that of the HMD prototype. However, it uses a mouse and keyboard as input devices (see *Figure 7.1*). The computer display has a resolution of 1920x1080 pixels. The prototype setup consists of a laptop with a computer mouse and Unity3D software. By moving the computer mouse, the operator can turn the camera game-component, and look around the vehicle. The spacebar on the keyboard can be used to hide or show all of the interface segments. The computer display prototype applies the same software setup as described in *Section 7.2 HMD prototype implementation.* The interface segments are aligned on the bottom of the viewport; the object detection component is in the left corner and in the right corner a map with a current position and direction is depicted.

Figure 7.3. A screen capture of the computer display interface where an operator is teleoperating an SAV. Picture by author.

Chapter 8

Prototype evaluation

This chapter concludes *Phase III: User study* by evaluating the prototypes and examining the leading research question fundamental to this thesis. The chapter describes the framework of the user study and the outcomes of the evaluation.

8.1 Experiment design

This section outlines the framework of the user study experiment.

8.1.1 Objectives

To examine the leading research question, the following objectives are derived and formulated for the purpose of the evaluation:

- Evaluate the participant's confidence and Situation Knowledge during teleoperation;
- Evaluate the perceived performance of both prototypes for use in teleoperation;
- Evaluate whether an HMD provides an improved user experience in comparison with a computer display.

8.1.2 Equipment

The following materials and equipment were used during the user study:

- The HMD prototype (as described in *Section 7.2*),
- The computer display prototype (as described in *Section 7.3*),
- A Vuze stereoscopic 360 degree video camera[1],

[1] http://vuze.camera Accessed: 2017-07-28

- An Integrated Transport Research Lab Research Concept Vehicle (*Figure 8.1*),
- A smartphone to audio record the evaluation.

Figure 8.1. The Research Concept Vehicle in the Integrated Transport Research Lab. Picture by author.

8.1.3 Participants

To compensate for the lack of SAV operators, two substitute user groups were selected; a group of experts and non-experts. The group of experts had previous experience in working in traffic control rooms or the design of control rooms. The group of non-experts consists of individuals affiliated with KTH Royal Institute of Technology, but with no background in teleoperations or control rooms. An experimental setup with both types of these groups ensures a diverse data set and increased knowledge about SK during SAV teleoperations. Also, future SAV operators will be beginners and the HMD interface will need to work well for people without prior experience in using such interface. In total 12 people participated (10 male, 2 female). Six of the participants were between 20-29 years old, four of the participants were between 30-39 years old, and 2 participants were older than 40. Drivers have experience in evaluating and understanding driving scenarios, consequently only participants with a drivers license were selected for the user study.

8.1.4 Test procedure

The user study consisted of a number of scenarios in which the participant took the role of a remote operator of SAVs. The experiment was preceded by a pilot study with student peers to evaluate and optimise the test procedure. For each scenario participants were asked to determine the reason why the SAV had stopped. The following three scenarios were chosen, because they could be easily simulated and fit within the scope of the outlined use cases (see *Section 5.2.2*).

- **Scenario A: Construction site**. In this scenario, the SAV is driving on the road, but a construction site blocks its lane.
- **Scenario B: Obstructed sensors**. In this scenario, the SAV is driving towards a T-shaped road crossing where it stops. Cars are parked in the vicinity of the SAV and are blocking line of sight for approaching traffic.
- **Scenario C: Missing lane markings**. In this scenario, the SAV enters a domain where pedestrians have priority; therefore it needs to stop, after which operations cannot continue because the lane markings are missing.

The scenarios have been recorded using the Vuze camera. The Vuze camera was mounted on top of the Research Concept Vehicle and driven across the campus of KTH Royal Institute of Technology. The videos were downsampled and imported into the prototypes using the Unity3D software. The experiments took place at the Integrated Transport Research Lab in a closed room and were conducted individually. The participant is seated in a rotating chair as depicted in *Figure 8.2*. An audio-recording consent form was filled in prior to the experiment. The whole evaluation was recorded with an audio recording application on a smartphone.

Figure 8.2. A photo depicting a participant using the HMD prototype during the user study. Picture by author.

The experiment commenced by the test leader (the author) informing the participant about the topic of the research, after which the structure of the experiment is outlined. To create the opportunity for the participant to speak freely about their experiences, the participant is asked to imagine that it is their first day working as a remote operator of SAVs. In every scenario, the participant is shown a 1-minute video playback prior to the moment the vehicle stopped, after which a warning message appears in the interface. For a remaining 2 minutes, the participant can explore the scene and determine the cause. If after a total of 3 minutes the participant has not found a cause, the scenario is ended. Six participants started with the HMD prototype and the other six with the computer display prototype to combat learning effects (see *Figure 8.3*).

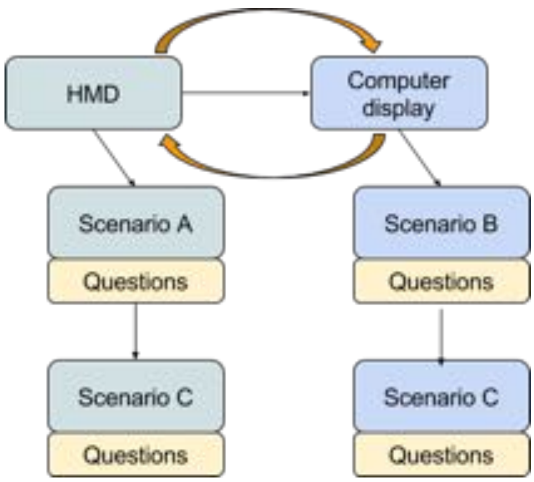

Figure 8.3. Illustration of the sequence of scenarios in the user study. Illustration by author.

After each scenario, the test leader read aloud the 7-point Likert scale questions from the questionnaire (see *Appendix B Evaluation questionnaire*). Every participant completed in total four scenarios and answered all corresponding questions. For each of the scenario-related questions, the question was asked by the test leader, answered by the participant and filled in by the test leader. The six scenario-unrelated 7-point Likert scale questions from the questionnaire were read and filled in by the participant.

The experiment concluded with the test leader asking and reading aloud four open-ended questions. These open-ended questions inquire for the participant's first feeling and thoughts about the interfaces.

- Now that the experiment has finished, what are your first thoughts?
- Which of these two interfaces worked best for you and why?
- Did you feel comfortable using the HMD prototype?

- Is there something that we could change that would make the prototype better for you?

8.1.5 Data analysis

To analyse the 7-point Likert scale questions, the Median and Interquartile Range (see, *Section 3.4.3*) were considered. The data on the 7-point Likert scale questions was plotted using a Box-and-Whisker plot. Both the open-ended questions and the transcriptions of the audio recordings were analysed using a Thematic Analysis (see *Section 3.4.2*).

8.2 Results

Scenario A and *Scenario B* were training scenarios to familiarise the participant with the interface. The *Scenarios A* and *B*-related questions were therefore not considered for a direct comparison between the HMD and computer display prototype. Only the questions after *Scenario C* were considered for a direct comparison. However, the scenario-unrelated questions captured the aggregated experiences of the participants over all scenarios.

8.2.1 Scenario-related questions

A clustered Box-and-Whisker plot depicted in *Figure 8.4* shows the results from *Scenario C*-related questions, in which the participant operated either the HMD prototype or computer display prototype.

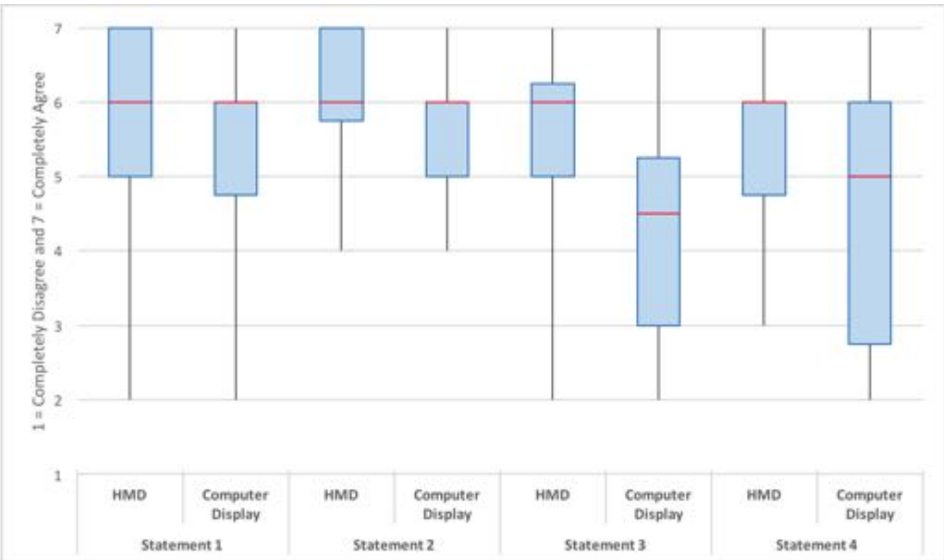

Figure 8.4. Clustered Box-and-Whisker plot with Median and IQR from **Scenario C-related** 7-point Likert scale questions.

The vertical axis indicates the agreement (1 = Completely Disagree and 7 = Completely Agree) with the statements 1-4. The labels with statement numbers on the horizontal axis refer to the following statements:

1. It was easy to identify the reason why the SAV had stopped;
2. I had a very good understanding of the traffic and situation around the vehicle;
3. I felt strongly connected to the vehicle in the scenario;
4. I would feel really confident operating the vehicle.

The Fisher's exact test on the medians of the results from *Statements 1 to 4* indicate, with a 95% confidence, that the central tendencies between using an HMD and computer display prototype are similar. The results show that participants were in agreement that it was equally easy to identify the reason why the vehicle stopped using both interfaces. Also, from the results, it can be observed that an HMD and computer display provide a similar understanding of the traffic and situation around the vehicle. A small variance is observed in *Statement 1 and 2* for respectively both interfaces. A larger variance can be observed for the computer display prototype in *Statement 3 and 4* (with IQR=2.25 resp. IQR=3.25). These findings indicate that a stronger disagreement can be observed, whether participants felt strongly connected to the SAV and would feel confident operating the vehicle while using a computer display. In comparison, results from *Statement 3 and 4* when using the HMD prototype show stronger agreement (resp. IQR=1.25, IQR=1.25); the answers are clustered around the median.

8.2.2 Scenario-unrelated questions

The Box-and-Whisker plot in *Figure 8.5* depicts the results from the six *scenario-unrelated* questions, after having completed all four scenarios. The vertical axis indicates the agreement (1 = Completely Disagree and 7 = Completely Agree). The labels on the horizontal axis refer to the following statements:

- I I prefer to use the computer display prototype instead of the HMD prototype;
- II The HMD prototype made it easier for me to interpret the traffic situation;
- III The HMD prototype provided me with more information about the traffic situation;
- IV The HMD prototype gives me more visibility around the vehicle;
- V Using the HMD prototype makes it easier to predict how the traffic situation will develop;
- VI Future control rooms of autonomous vehicles should use an HMD prototype.

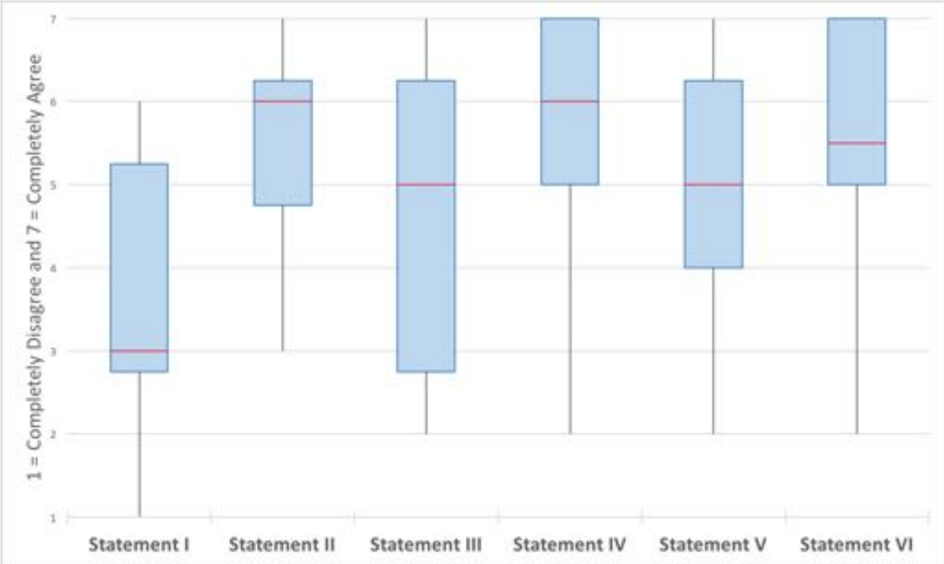

Figure 8.5. Box-and-Whisker plot with Median and IQR from **Scenario-unrelated** 7-point Likert scale questions.

Results from *Statement I* (MED=3, IQR=2.5) indicate that the participants did not have a distinct preference for using either the HMD or computer display prototype. However, the results from *Statements II and IV* are not in line with this finding; they show that an HMD was more beneficial than the computer display regarding interpretation of the traffic situation and visibility. More specifically, in *Statement II*, the participants agreed that the HMD prototype made it easier to interpret the traffic situation (MED=6, IQR=1.5). Similarly, in *Statement IV*, the participants stated that the HMD gave them more visibility around the SAV (MED=6, IQR=2). Findings from *Statement III* are indecisive, results do not show that the participant's answer are strongly clustered (MED=5, IQR=3.5). Hence, it cannot be concluded that the HMD prototype or computer display provided them with more information about the traffic situation. Results from *Statement V* indicate that the participants found that using the HMD prototype does not make it significantly easier to predict how a traffic situation will develop (MED=5, IQR=2.25). All of the participants expressed agreement with the statement that future control rooms should use an HMD prototype (MED=5.5, IQR=2).

A comparison between the experts and non-experts for all scenario-unrelated statements is shown in *Table 8.1*. The experts are in a stronger agreement with *Statements II, V and VI* than the non-experts. That is, the experts agreed more strongly than the non-experts that the HMD made it easier for them to both interpret (*Statement II*, MED=6) and predict the traffic situation (*Statement V*, MED=6) than the computer display. Also, the experts were more decisive that the future control rooms should use an HMD rather than a computer display (*Statement VI*, MED=6.5). With regard to the *scenario C-related* questions, no significant differences between expert and non-expert participants were observed.

	Experts	Non-experts
Statement I	2.5	4
Statement II	6	5.5
Statement III	4	5
Statement IV	5.5	6
Statement V	6	4.5
Statement VI	6.5	5

Table 8.1. A comparison of the median results between experts and non-experts based on **scenario-unrelated** questions.

8.2.3 Thematic analysis

Based on the objectives outlined at the start of the evaluation a categorisation is made between findings about confidence and awareness, implicit performance and the user experience of using an HMD. Thematic analysis of the transcribed audio recordings revealed a number of topics with regard to confidence and awareness.

- Three participants stated that when using the HMD prototype they were more looking around and taking in what is happening. When using a computer display, the participants found themselves looking more at the interface in comparison with the HMD prototype.

- Four participants expressed that when using an HMD they feel and understand better what is going on. For five participants it felt more 'natural/intuitive' to use an HMD. A majority, seven participants, stated that by using the HMD they felt like they were more in the situation and 'with the vehicle'.

- Two participants indicated they would feel weird if they would have to take control using a computer display because they experienced to be distant from the vehicle. Moreover, two participants also expressed that they would feel more confident and safe to operate a vehicle when using the HMD because the computer display did not give a satisfactory overview and awareness of surroundings. One participant mentioned *"If I were to command the vehicle, I would use the Head-Mounted Display because it would enable me to look aside more quickly"*.

- Four participants mentioned that the HMD would not be necessary for all situations. For example, the computer display would work better in situations when the operator wants to get a quick overview of the situation. However, the HMD would be preferable in more complex situations where traffic is quickly changing or the operator needs to watch and drive the SAV.

The following aspects detail key user experiences when using the HMD prototype:

- Two participants found the first use of the HMD overwhelming. Also two participants mentioned that they were uncomfortable at first when using the HMD. Three participants felt more 'shaky/dizzy' while using the HMD in contrast to using the computer display.
- Also, three Participants indicated they are able to easily look around by turning their head when using an HMD.
- For driving tasks, three participants mentioned that they would like to have a simple and straightforward big button to continue automated operations. Alternatively, three other participants mentioned that they would like to steer the SAV by drawing a path on the ground ahead of the SAV.

Qualitative evidence of significant variances in performance between the HMD and computer display could not be found. No differences were recorded between the HMD and computer display concerning the number of times participants were able to observe the appearing warning message upon the moment the vehicle came to a stop.

8.3 Conclusions from the user study

The user study has revealed the following key findings:

- Findings from the questionnaire with the scenario-related questions, indicate that no significant differences between the use of an HMD prototype and computer display are perceived by the participants. However, the participant's answers were more homogeneous regarding the HMD in comparison to the computer display.
- Results from the thematic analysis indicate that participants feel and understand better what is going on in the remote situation when using the HMD. These findings are supported by statements of increased engagement in the remote situation and proximity to the SAV. Answers from the questionnaire reinforce these claims, as the HMD prototype made it easier for participants to understand the traffic situation and it gave them more visibility around the vehicle.
- Results from Likert-scale questions do not indicate that the participants felt that the HMD provided them with more information about the traffic situation nor that the HMD makes it easier to predict how a traffic situation would develop. However, the thematic analysis shows that participants prefer to use an HMD interface compared to the computer display for remote control, feeling increased confidence and safety.

- The analysis of the open-ended questions shows that all of the twelve participants mentioned distinct advantages in their experience when using the HMD prototype for teleoperations. An HMD interface would not be necessary for all teleoperation situations. However, participants strongly agreed that future control rooms should make use of an HMD prototype.
- Experts are more positive than non-experts that the HMD makes it easier to interpret and predict a traffic situation. Also experts agree strongly that future control rooms should use an HMD.

Chapter 9

Discussion

This chapter outlines a discussion regarding the results, process, methods and limitations. A discussion on aspects of ethics relevant to the contents of this thesis is presented. The chapter concludes with recommendations for future work.

9.1 Results

The central theme of this work has been Situation Knowledge for SAV remote operators. The study has found that increased visibility, understanding and feelings of presence are effects associated with an operator using an HMD in teleoperations. Results also indicate that feelings of confidence and safety towards driving operations increase when using an HMD for remote control.

9.1.1 Findings

Regarding research question 1.a, the study found that SK for SAV remote operators constitutes a thorough understanding, both conscious and intuitive, of the environment now and in the future. Concerning research question 1.b, the study revealed various aspects and challenges of existing control room operations that also find relevance for SAV remote operators. Regarding research question 1.c, it was found that a map of the environment, status information and a visualisation of the perceived environment are interface elements supporting an SAV remote operator. With regard to question 1.d, the findings from the participatory design study indicated that experts perceived an HMD interface to provide an effortless method of looking around and greatly valued the ability to perceive depth.

Concerning the leading research question, qualitative results from the user study provided strong evidence that the use of an HMD positively influences the SK of remote operators. These findings were supported by the results from the Likert scale questions, in which participants expressed that using the HMD prototype gave them more visibility and made it easier for them to understand the traffic situation. Results from the scenario-dependent questions, giving an implicit comparison between the HMD and computer display prototype did not reveal any significant differences. However, the results from scenario-independent questions indicated that the HMD does provide better visibility and traffic situation understanding. No differences between the prototypes were found with regard to the amount of information communicated. As both prototypes used similar interface elements and video these results can be explained. If different interface elements or different designs had been used results could have been different, either negatively or positively influencing the operator's experience with the HMD.

9.1.2 Findings in context

In studies by Schmidt et al. (2014); Jankowski and Grabowski (2015) similar findings have been reported. It is found that the use of an HMD in combination with a VR-environment increase the operator's sense of depth in space in comparison to a computer display (Jankowski and Grabowski, 2015). This study has also found that the use of an HMD results in increased visibility for a remote operator. Schmidt et al. (2014) have found that an HMD is a preferred instrument for visualisation during teleoperations for mobile robots. The results from this study are in line with the findings by Schmidt et al. (2014). Studies by Pausch et al. (1997); Witmer and Singer (1998); Slater et al. (1996) have also reported evidence that the use of an HMD for teleoperations increases feelings of immersion and presence.

From this study, it can be concluded that when a remote operator uses an HMD their experience more closely resembles the experience and knowledge of an in-vehicle driver. These findings support the efforts under the belief that a remote operator will have satisfactory SK when the presentation of information is similar to that of an in-vehicle driver. However, it can also be argued that this model is not the best-suited method for obtaining higher levels of SK. Rather, it could be the case that information of the environment and situation presented through higher levels of abstraction, will bring about a better mental model and consequently improved SK. In addition, Luff et al. (2000) argues that an operator's awareness might not be supported by simply extending the access to the remote spaces in which activities take place. However, supporting operator's awareness might be tied to focused support for particular organisational or collaborative demands and activities. The research into teleoperation systems and activities for SAVs could be an opportunity to explore new and optimise current models of SAV teleoperation.

9.2 Process and limitations

This thesis has in accordance with the framework outlined in *3.1.2 Research design* completed three phases. In *Phase I: Analysis* research, interviews and applications of teleoperation and remote control were described, after which prototype design requirements were specified. Ideally, additional interviews in other domains (e.g. explosive ordnance disposal and ROV) could have deepened the knowledge about procedures and goals for remote operators and remote control systems. Due to time constraints, this could not be achieved within the scope of this thesis.

In *Phase II: Conceptualisation* the acquired information was adopted and translated into a set of HMD interface concepts. The concepts were evaluated in a participatory design study with three experts. In a more comprehensive study, the participatory design method could have been extended to later stages in which a prototype is jointly developed. An advantage of this latter approach is the ongoing interaction between the designer and user to shape the artefact (Spinuzzi, 2005). However, the availability of the experts in this study was constrained.

Phase III: User study describes the development of an HMD and computer display prototype and the user evaluation that followed. During the process of prototype development, the focus has been to test and evaluate the SK for remote operators of SAVs. In order for the system to be applied by industry, it would require considerable further exploration of design and system requirements. Lastly, in a best case scenario the user evaluation would have taken place with a group of established remote operators of SAVs. Their experience on SK would have been of irreplaceable value. However, no such group of users currently exists.

9.3 Methods and limitations

In *Phase I: Analysis* the methods of case study, semi-structured and contextual interviews were successfully applied to identify and analyse aspects of SAV remote control. The data collected revealed important design notions for control rooms, teleoperations interfaces and operator needs. The method of observational research could have complemented the data set and disclosed additional information. However, within the limited scope of this study case study and interviews were prioritised because of their directness.

The participatory design method was used in *Phase II: Conceptualisation* to collect feedback from experts on interface concepts. The feedback from experts provided evidence for the usefulness of an HMD. The number of expert participants was small (n=3), accessibility to additional people with knowledge of control rooms and remote control was limited. During the participatory design study, an explanation of the concepts was provided to clarify the elements of the interfaces. As a result of introducing features and meanings, the understanding and interpretation of the participants were influenced. As a result participants, their scope of thinking and terminology was subject to biases. However, the limitations of the concepts necessitated the use of an introductory explanation.

In *Phase III: User study* an HMD and computer display prototype were developed, after which the prototypes were evaluated using the methods of questionnaire and thinking-aloud. The focus of this thesis has been on implicit measurements of SK, performance indicators of SK were not considered within the scope of this thesis. A within-group designed experiment was chosen to evaluate the prototype. In a within-subject design experiment, participants compare both prototypes themselves, given that the leading research question dictates a comparison between two interfaces. Moreover, in the preferred setup participants are not asked to imagine using one of the interfaces. Finally, a within-subject design study has fair statistical power for studies concerning small samples sizes (Charness et al., 2012). The user study has been conducted with 12 participants, the number of subjects in the user test is significant given it is a qualitative evaluation and the limited scope of potential users (Nielsen and Landauer, 1993). However, a larger sample could make for more statistical significant differences. Actual teleoperations of an SAV were not feasible due to technical, practical and regulatory limitations. For these reasons, the choice was made to use pre-recorded scenarios for the user study. The focus of the work has been on the visual modality; no audio or haptic feedback was provided during the evaluation. It was found that because *Scenario C* was repeated in the experiment, participants showed signs of recognition after the first encounter. This familiarity could have influenced their answers. However, as the scenarios were counter-balanced an equal amount of participants encountered *Scenario C* first using the HMD prototype as those using the computer display. The participant's their answers might also have been influenced by a social desirability bias (Grimm, 2010), in which the answers are influenced by social desirability, such as in this thesis a bias towards the proposed HMD prototype. Finally, the entire experiment took on average around 45 minutes and consisted of only four scenarios to prevent participant's fatigue and exhaustion.

9.4 Ethical considerations

Goodall (2014); Gerdes and Thornton (2016); Lin (2016) highlight that ethics are an essential aspect to the adoption of automated vehicles and will have profound consequences on how we, humans, will interact and rely on automated driving systems. The safety of the passengers of the vehicles as well as other road users are subjected to automated driving systems and in the case of remote control, the operator. Especially considering that vital computer systems will always remain of interest for those with malicious intents and no computer system will able to provide 100% security. Liability in SAV teleoperations is another urgent concern. The question whom and under which circumstances is responsible for the vehicle. Underlying these topics is the important aspect of network reliability, teleoperations depend heavily on a reliable network connection. Advancing research and developments in both academics and by automotive industries, call for a public discussion about the consequences of the introduction of automation systems. The effects of the emergence of automated driving and shared mobility will extend to many levels beyond the automotive industry; among technology companies, telecom-providers and governments (Corwin et al., 2015; Pankratz et al., 2017; Lang et al., 2016). Safety is and should be a primary concern for the adoption of teleoperation systems. It has not been the aim of this study to investigate potential security solutions, but in this section to hint the reader for real and important ethical considerations to the desirability and application of a remote control architecture for automated vehicles.

9.5 Recommendations and future work

An important limitation of this study is that no direct remote control operations were performed. To deepen the knowledge on SK for SAV teleoperations further research is necessary on remote control in simulated as well as real traffic. This study also recommends to investigate how an HMD affects SK under different tasks and scenarios, to determine whether improved SK is HMD or task dependent. To further investigate what components constitute an effective and representative SK model, the method Goal Directed Task Analysis (Wright et al., 2004) may be used to identify task goals, related decisions and requirements for an effective SK model. However, no defined remote operator tasks and goals exist at this time. SAV teleoperation simulations can provide a means to deepen the knowledge. Moreover, such studies should seek to incorporate measures of task performance under the use of an HMD. Jankowski and Grabowski (2015) has suggested that a positive correlation exists between task efficiency and the use of an HMD.

Future research should aim to test with a larger sample of participants, both experts and non-experts. A larger sample could support statistical significant differences between an HMD and computer display for an operator their connection to and confidence of operating an SAV. Moreover, as preliminary findings indicate a difference in tendencies between experts and non-experts, a larger sample could provide stronger support in favour of an HMD.

With regard to the prototype interface, a technical setup needs to be developed which allows for satisfactory response and control. Interviewees have suggested that the data transmission between the vehicle and control room should have a latency below 100ms. Audio and haptic feedback components were not within the scope of the prototype but were mentioned to be valuable for a remote operator. Findings from this thesis have also indicated that two types of control, high-level planning or manual steering, should be investigated. The type of remote control is likely to be dependent on the specific use cases, operation regulations and working environment of the operator. Future work could investigate which type of remote control performs better under what conditions.

The user evaluation has revealed a number of recommendations with regard to the interface and prototype. Participants reported aspects they would like to see differently. These recommendations would, according to the participants, improve their experience of using the interface.

- An introduction to using an HMD or training session should be provided.
- Sound should be added to the remote control interface.
- Additional information overlaid on the video would aid the participants in their task.

- Specifications of the HMD could be improved, such as resolution.
- Participants would like to see more information on the vehicle status, such as the number of passengers.

Finally, to advance the adoption of Shared Automated Vehicles and teleoperation systems legislation and standardisation are considered to be enabling factors. It recommended that in future projects authorities and industries are invited to become closely involved.

Chapter 10

Conclusions

This thesis has investigated whether using an Head-Mounted Display improves Situation Knowledge in comparison to a computer display for remote operators of Shared Automated Vehicles. This study is a first of its kind on SAV teleoperations and has made a first step towards identifying needs and solutions.

Findings strongly indicate that SAVs will, in the foreseeable future, face limitations and failures which in turn will require human intervention and remote control. Literature and case study analysis have confirmed the OOTL performance problem and loss of SK during teleoperations. A set of tasks and use-cases which remote operators could be faced with are identified. An assortment of prototype requirements are specified and translated into three low-fidelity interface concepts. From these concepts an exemplary HMD interface for SAV teleoperations has been developed. This work has found supportive evidence that using an HMD for SAV teleoperation provides a remote operator with superior advantages in comparison to a computer display. Findings from the prototype evaluations indicate that increased visibility, understanding and feelings of presence are effects associated with a remote operator using an HMD during teleoperations. These effects give an SAV remote operator a firm basis to combat their loss of perception and comprehension of elements in time and space as part of the OOTL performance problem. The study has also found that participants said that the use of an HMD would make them feel more confident and safe in comparison to a computer display. No statistically significant differences were observed based on a direct comparison between the HMD and computer display prototype. Results from the questionnaire indicate that the majority of subjects strongly supported the use of an HMD in future control rooms for teleoperations of SAVs. These conclusion underlines the relevance to consider the use of HMDs in the development of SAV teleoperation interfaces. The value regarding safety and reliability created by an HMD in SAV teleoperations can significantly foster the adoption of shared and automated mobility. However, any remote operator, regardless of their Situation Knowledge should remain attendant to and careful for the safety and well-being of the passengers and significant other road users.

Concluding; the major contributions of this thesis are: a) knowledge about what constitutes the tasks and responsibilities of SAV remote operators, b) an HMD prototype interface for SAV teleoperations, and c) qualitative evidence that an HMD can provide remote operators with improved SK. Future studies can extend knowledge by assessing different scenarios and tasks in a live remote control situation, and develop and evaluate additional interface elements.

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Appendix A

Participatory design protocol

Participatory design protocol

Participatory design tools and techniques by (Sanders et al., 2010)

Objectives:
- Determine issues with existing concepts
- Determine whether concepts support operator goals
- Evaluate experience of using interfaces

User population. The user population are people who have experience in control rooms, overseeing processes or administering remote activity. Users have experience with identifying remote contextual information, deriving this from apparatus.

Tasks for evaluation. The following tasks are considered for evaluation as they are representative for the work of remote SAV operator.

- An operator is asked to assess intervention due to emergency services,
- An operator is asked to create an understanding of the situation,
- An operator is asked to move the vehicle, how would you go about doing so.

Interface definition. The interface is defined to be a graphical mockup image of the interface. This is chosen because a fairly great level of detail is required as participants are assumably unfamiliar with the interface components. The interface is a non-functional interface.

PD planning

Below an overview of parts of the participatory evaluation and a time estimate.

Event	Time
A. Research introduction	5 min
B. Experiment introduction	5 min
C. Task-based evaluation	20 min
D. Questionnaire	5 min

A. Research introduction

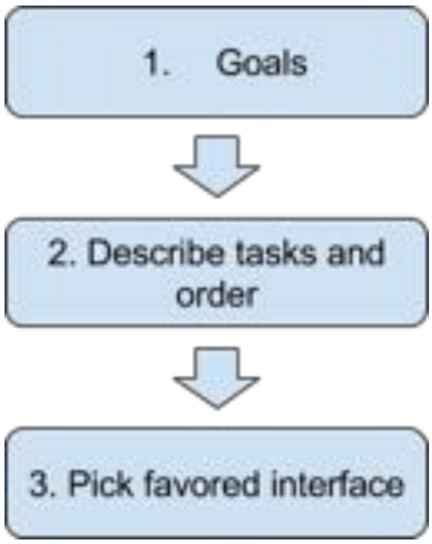
Introduce the topic of the study. "With the introduction of autonomous vehicle technologies we can start to think differently about mobility in cities. An example is shared autonomous vehicles, these shuttles are similar to small busses and take passengers through the city. They do have some distinct differences; first they may not drive on a bus-line, but from any place to the desired destination. Secondly, the most important difference is that in these shuttles no driver or driving apparatus is present. Finally, what I am researching is how a human can take over these shuttles remotely in case this is required." Explain that in this stage their input is very much appreciated and helpful for acquiring additional insight on the task performance within the concepts. Introduce phenomena of augmented reality according to metaphor of lego car. Explain glasses with screens. Highlight their participation is completely voluntarily and it will be treated anonymously.

B. Experiment introduction

Explain that the session today will consist of two parts; a task-based test in which they are asked to work with the concept according to a set of predefined goals. And a second part in which they can reflect on their experiences of using the concepts. Introduce the camera and ask participants if they are okay with being recorded. The participants are now asked to sign the consent form and fill in the participant background questionnaire while the researcher sets up the camera.

C. Task-based evaluation

The task-based happens individually, with the researcher and one test-participant. The three printed concepts are outlined in front of the participant. The participant is primed using the following scenario: "Imagine you are in a control center, you take the role of an operator. The control center is overseeing operations for a fleet of self-driving shuttle vehicles running in the city of Stockholm. Your are tasked to solve problems occurring with these vehicles on the road. You get a notification of a vehicle indicating it needs an operator to examine the vehicle. As this point you are tasked with controlling the vehicle, you can choose to go for manual steering control or drawing a path in the interface." The following methodology is applied to applied to the tasks under **Tasks for evaluation.**



Problem-solving process. The model used for the problem-solving process is based upon the work of (Polson and Lewis, 1990) concerning the cognitive walkthrough. What follows is a description of the process:

1. Participants are provided with a goal
2. Participants are asked to describe the tasks and order they affiliate
3. Participants are asked to pick the favoured interface for this task. Moreover they are asked to explain in detail why they choose the concept and what their considerations were.

D. Questionnaire

The following questions are asked after C. Task-based evaluation.

- Take the interface concept you find best suited for the objectives.
- Did you find it easy to locate the information what you are looking for?
- Did you find it easy to identify possible risky situations?
- What is for you the greatest difference between 2-dimensional and augmented reality?
- Would the system in any way change the way you are used to work?
- From your experience would you want to change something in the interface?

Recording

The whole experiment is video and audio recorded. During the process a think-a-loud protocol is used to gather data. The camera is pointed on the concepts laying on the table such that potential pointers can be recorded. Audio is recorded along with the video.

References

Sanders, E. B.-N., Brandt, E., and Binder, T. (2010). A framework for organizing the tools and techniques of participatory design. Proceedings of the 11th Biennial Participatory Design Conference on - PDC ’10, page 195.

Appendix B

Evaluation questionnaire

Questionnaire *Participant:* *S/P* *Age:*

Scenario A.VR: ____________ control

- What caused the SAV to stop? How did you come to this thought?

  ……………………………………………………………………………………………

  ……………………………………………………………………………………………

- It was easy to identify the reason why the SAV had stopped?

Completely disagree	○	○	○	○	○	○	○	Completely agree

Scenario B.2D: ____________ control

- What caused the SAV to stop? How did you come to this thought?

  ……………………………………………………………………………………………

  ……………………………………………………………………………………………

- It was easy to identify the reason why the SAV had stopped?

Completely disagree	○	○	○	○	○	○	○	Completely agree

Scenario C.VR: ____________ control

- What caused the SAV to stop? How did you come to this thought?

  ……………………………………………………………………………………………

  ……………………………………………………………………………………………

- It was easy to identify the reason why the SAV had stopped?

Completely disagree	○	○	○	○	○	○	○	Completely agree

- I had a very good understanding of the traffic and situation around the vehicle.

Completely disagree	○	○	○	○	○	○	○	Completely agree

- I felt strongly connected to the vehicle in the scenario.

Completely disagree	○	○	○	○	○	○	○	Completely agree

- I would feel really confident operating the vehicle.

Completely disagree	○	○	○	○	○	○	○	Completely agree

- Was there a truck parked behind the vehicle?

  ……………………………………………………………………………………………

Scenario C.2D: ____________ control

- What caused the SAV to stop? How did you come to this thought?

  ……………………………………………………………………………………………

  ……………………………………………………………………………………………

- It was easy to identify the reason why the SAV had stopped?

Completely disagree	○	○	○	○	○	○	○	Completely agree

- I had a very good understanding of the traffic and situation around the vehicle.

Completely disagree	○	○	○	○	○	○	○	Completely agree

- I felt strongly connected to the vehicle in the scenario.

Completely disagree	○	○	○	○	○	○	○	Completely agree

- I would feel really confident operating the vehicle.

Completely disagree	○	○	○	○	○	○	○	Completely agree

- Did you observe someone who was about to cross the street upon the moment the vehicle stopped?

  ……………………………………………………………………………………………

Questionnaire

1. I prefer to use the computer screen interface instead of the headset interface.

Completely disagree	○ 1	○ 2	○ 3	○ 4	○ 5	○ 6	○ 7	Completely agree

2. The headset interface made it easier for me to interpret the traffic situation.

Completely disagree	○ 1	○ 2	○ 3	○ 4	○ 5	○ 6	○ 7	Completely agree

3. The headset interface provided me with more information about the traffic situation.

Completely disagree	○ 1	○ 2	○ 3	○ 4	○ 5	○ 6	○ 7	Completely agree

4. The headset interface gives me more visibility around the vehicle.

Completely disagree	○ 1	○ 2	○ 3	○ 4	○ 5	○ 6	○ 7	Completely agree

5. Using the headset interface makes it easier to predict how the traffic situation will develop.

Completely disagree	○ 1	○ 2	○ 3	○ 4	○ 5	○ 6	○ 7	Completely agree

6. Future control rooms of autonomous vehicles should use a headset interface.

Completely disagree	○ 1	○ 2	○ 3	○ 4	○ 5	○ 6	○ 7	Completely agree

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