

# Artificial Intelligence Enhanced Extended Reality as Part of Ship Commissioning

UNIVERSITY OF TURKU  
Department of Computing  
Master of Science (Tech) Thesis  
Robotics and Autonomous Systems  
February 2025  
Joni Rajamäki

Supervisors:  
Teijo Lehtonen  
Tomi Westerlund

UNIVERSITY OF TURKU  
Department of Computing

JONI RAJAMÄKI: Artificial Intelligence Enhanced Extended Reality as Part of Ship  
Commissioning

Master of Science (Tech) Thesis, 67 p.  
Robotics and Autonomous Systems  
February 2025

---

Ship commissioning refers to the process of testing and validating the systems on-board a vessel and leads up to the handing over of the ship to the customer. A shipbuilding project consists of vast amounts of contractors, subcontractors and suppliers, and the commissioning of ships is reliant on engineers navigating documentation and manuals from each of these parties. It is estimated that a single hour of sea trials costs a shipyard as much as 32 000 euros. As such, every minute spent unnecessarily shifting through documentation is needlessly expensive.

Extended reality technologies present a new paradigm of human computer interaction, and can be utilized to present data in revolutionary ways. Industrial extended reality solutions have traditionally leaned towards using optical see through devices, rather than video passthrough capable ones, due to video passthrough technology being lacking until recently. Modern video passthrough has seen significant improvements over the last years, and should be considered as a candidate for industrial extended reality solutions.

Artificial intelligence is another technology, which has seen breakthroughs in the recent times. Artificial intelligence can be utilized to compound large sets of information, such as technical documentation related to ship commissioning, and distinguish the relevant parts.

This work aims to evaluate the viability of artificial intelligence enhanced extended reality solutions as industrial tools for ship commissioning. In order to evaluate these technologies, a proof of concept is developed, and then tested via user testing. The test users are linked with the shipbuilding industry as either shipbuilding professionals or as researchers. Analysis of the testing revealed, that the recent advancements in both artificial intelligence and extended reality show promising potential for applications in shipbuilding and ship commissioning. The performance of the extended reality platform and the quality of the artificial intelligence enhancements reached the expectations for an industrial tool for ship commissioning.

Keywords: Artificial Intelligence, Augmented Reality, Extended Reality, Shipbuilding, Ship Commissioning

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Virtual Sea Trial . . . . .	2
1.2	Research Questions . . . . .	2
1.3	Thesis Structure . . . . .	3
<b>2</b>	<b>Commissioning</b>	<b>5</b>
2.1	Overview of Ship Commissioning . . . . .	5
2.2	Challenges Arising During Commissioning . . . . .	6
<b>3</b>	<b>Extended Reality</b>	<b>7</b>
3.1	Overview of Extended Reality . . . . .	7
3.1.1	Need, Development and Adoption . . . . .	7
3.1.2	Extended Reality Platforms and Interactions . . . . .	10
3.2	Extended Reality in an Industrial Settings . . . . .	14
3.2.1	Development of Industrial Extended Reality . . . . .	14
3.2.2	Extended Reality as Part of Ship Commissioning . . . . .	15
<b>4</b>	<b>Artificial Intelligence</b>	<b>17</b>
4.1	Artificial Intelligence Overview . . . . .	17
4.2	Artificial Intelligence in Extended Reality . . . . .	18
4.3	Artificial Intelligence in the Context of Commissioning . . . . .	19

<b>5</b>	<b>Proof of Concept</b>	<b>21</b>
5.1	Problem Statement . . . . .	21
5.2	Requirement Analysis . . . . .	22
5.2.1	Stakeholder Analysis . . . . .	22
5.2.2	Functional Requirements . . . . .	23
5.3	System Design . . . . .	25
5.3.1	Hardware Choice . . . . .	25
5.3.2	System Architecture . . . . .	28
5.3.3	Software Implementation . . . . .	32
5.4	User Experience Design . . . . .	36
5.4.1	Defining Principles . . . . .	37
5.4.2	Applied Design Principles . . . . .	38
<b>6</b>	<b>Testing and Results</b>	<b>44</b>
6.1	Testing Methodology . . . . .	44
6.2	Testing Observations . . . . .	45
6.3	Questionnaire Design . . . . .	46
6.4	Questionnaire Results . . . . .	48
<b>7</b>	<b>Analysis, Discussion and Future Work</b>	<b>55</b>
7.1	Proof of Concept Analysis . . . . .	55
7.1.1	Testing Results . . . . .	55
7.1.2	Discussion . . . . .	57
7.2	Future Work . . . . .	61
<b>8</b>	<b>Conclusions</b>	<b>63</b>
	<b>References</b>	<b>68</b>

# List of Figures

3.1	Virtuality-Reality Continuum . . . . .	9
5.1	Solution Workflow . . . . .	29
5.2	Solution Dataflow . . . . .	30
5.3	Oscilloscope Digital Model . . . . .	32
5.4	Vive HMD Digital Model . . . . .	33
5.5	Oscilloscope Digital Dials . . . . .	34
5.6	Fading Digital Models . . . . .	35
5.7	Menu In Augmented Reality . . . . .	39
5.8	Highlighted Options In An AR Solution . . . . .	40
6.1	Tester Professional Backgrounds . . . . .	48
6.2	Tester Level of Experience . . . . .	49
6.3	Tester Experience With XR Implementation . . . . .	50
6.4	Tester Experience With XR Quest 3 Platform . . . . .	51
6.5	Tester Experience With AI Components . . . . .	52

# List of Tables

5.1 Popular XR Devices . . . . .	26
7.1 Common themes in results . . . . .	57

# 1 Introduction

Shipbuilding is amongst the longest standing branches of industry. Throughout its tenured path starting in 5000-6000 B.C [1] up to the modern day, the craft of designing and manufacturing ships has undergone numerous revolutions and advancements. The 21<sup>st</sup> century brought along with it the advent of the fourth industrial revolution and the term "Industry 4.0". Industry 4.0 refers to the integration of digital smart technologies to industrial processes [2]. These smart technologies can refer to specific technologies, such as: the internet of things (IoT), use of extended reality (XR) and artificial intelligence (AI). As with other manufacturing industries, shipbuilding began to adopt these new technologies.

The adoption of modern technologies has brought with it many advancements in crucial aspects of shipbuilding, such as efficiency and sustainability, but there are still faults throughout the ship manufacturing process. While much of the design, logistics and assembly associated with building a ship have been streamlined using smart technologies, the final and very manual step of sea trials and commissioning is still dependent on human verification and can only be completed at the end of the production cycle. This manual commissioning process has been identified as a target for improvement [3], since issues rising during commissioning can lead to extensive delays and increased labor requirements. These setbacks are costly for both; the shipyard responsible for building the ship, as well as the client purchasing the ship.

AI assisted virtualization and simulation could be utilized to combat potential

setbacks arising during the final commissioning phases. One such phase is the inspection and validation of interfaces within the ship during sea trials. Traditionally, in order to validate the functionality of interfaces such as control units, displays and gauges in areas like a ships bridge or other technical spaces, the entire infrastructure tied to these interfaces must be in place and operational. Resolving issues arising during this validation can be challenging and time consuming due to the massive scale of a modern shipbuilding operation: with tens or even hundreds of suppliers, and limited standardization, the access to concise documentation is severely lacking. However, with the use of technologies associated with Industry 4.0, such as artificial intelligence and extended reality, the information regarding these interfaces can be virtualized. These virtualizations could be used to compound, search for, and present the crucial information related to the testing and validation of interfaces, which in turn would expedite processes like debugging and instruction during commissioning.

## 1.1 Virtual Sea Trial

This thesis is conducted as part of the Virtual Sea Trial (VST) research project [4]. The aim of the VST project is to research the virtualization of ship commissioning. Research is conducted collaboratively among the University of Turku, Novia University of Applied Sciences, Åbo Akademi University, the University of Oulu, as well as, industry partners and other international university partners.

## 1.2 Research Questions

Considering the potential uses of artificial intelligence enhanced extended reality for aiding during ship commissioning, this thesis aims to answer the following research questions:

1. **How can extended reality technologies be used as part of ship commissioning?**
2. **How can extended reality technologies provide value for users in ship commissioning?**
3. **Which current extended reality technologies are best suited for ship commissioning?**
4. **How can artificial intelligence be used to enhance extended reality solutions aimed for ship commissioning?**

### 1.3 Thesis Structure

This thesis has three main parts, the first part consists of chapters 1-4, which offer definitions for ship commissioning, extended reality technologies, and artificial intelligence. Based on this context, the second part, consisting of Chapter 5, focuses on the development and testing of a proof of concept, which can be used to aid in ship commissioning. This proof of concept is presented to professionals in the ship-building and software development fields alongside a user feedback questionnaire regarding the potential of such a solution. The feedback and outcomes are analyzed in chapters 6-8, which make up the third and final part of this thesis. In addition to analysis, the final part also suggests future development ideas and directions from the perspective of the developer.

In more detail, the chapters are written as follows: Chapter 2 describes the overall process of commissioning, what the current technologies used for commissioning are, and finally the typical problems, which may arise during commissioning, and how they impact the manufacturing of a ship. Chapter 3 acts as an introduction to extended reality technologies and their uses. The point of view will concentrate on

---

the use of extended reality in industrial applications, and specifically in shipbuilding. Some extrapolations regarding potential uses of extended reality during the commissioning of a ship are also made. Chapter 4 outlines the growth and spread of artificial intelligence from an extended reality point of view. Some remarks regarding the utilization of artificial intelligence for interaction and data analysis in ship commissioning, as well as, with extended reality use, are made. Chapter 5 outlines the development of an extended reality solution for ship commissioning. Chapter 6 analyses the solution described in the previous chapter through the use of a questionnaire presented to professionals of both, the software development, and the shipbuilding industries. Chapter 7 consists of a free form discussion of the results of the thesis thus far, as well as, some suggestions for future development to be made in order to turn the proof of concept into a valuable tool for ship commissioning. The conclusion is in the final 8th chapter.

## 2 Commissioning

This chapter describes the overall process of commissioning. Section 2.1 discusses the overall process of ship commissioning, Section 2.2 examines typical problems arising during the commissioning phases and identifies needs for improvement.

### 2.1 Overview of Ship Commissioning

The definitions and contents of ship commissioning vary based on sources, but this thesis will treat ship commissioning as referring to the final phase of shipbuilding, which begins with inspection and validation of onboard systems [5][6] and ends with transferring custody of a vessel to the client responsible for ordering the ship [7][8]. Historically, commissioning has included a variety of rituals and spectacle, such as the ceremonial act of christening a ship by breaking a bottle of champagne against the ships hull [9]. Nowadays, commissioning remains important, arguable more so than before, since the scale of shipbuilding operations has grown drastically when compared to the past [10]. Compared to the christening ceremonies of before, the commissioning process has shifted towards a more official series of rigorous tests, throughout which the ships functionality and compliance with standards is confirmed.

In order to provide realistic testing scenarios for the ship, a sea trial is conducted. During sea trials, a ship is taken out to sea and onboard systems are tested in both: normal and abnormal operation. Navigating this complexity inherently takes time,

and time comes at a high cost: during the sea trial phase of commissioning, a single hour of test conduction can cost the shipyard upwards of 32 000 euros [11].

## 2.2 Challenges Arising During Commissioning

Commissioning is the final part of a shipbuilding project, and problems rising during it will inevitable cause delays in the delivery of the ship. These delays cause the customer to then have to delay deploying the ship, which results in monetary losses. Since successful commissioning is the only thing standing in between handing over a ship, it is, necessary, and the interest of every stakeholder, that the commissioning process be expedited as much as possible in order to identify potential issues and validate correctly functioning components efficiently.

The main challenges for the successful commissioning of a ship are tied to the scale of the project, as well as, the dispersed and decentralized nature of the building process. With numerous suppliers, each responsible for providing some component of a ships overall system, the interconnectivity of these components is often only tested during the commissioning process. Engineers are faced with having to test a large variety of components with limited time available [7][12]. In order to successfully navigate this complexity, access to information in the forms of manuals, standards and common practices is of paramount importance.

# 3 Extended Reality

In order to discuss the modern technologies associated with Industry 4.0, and their potential uses in ship commissioning, it is important to define the characteristics and examine the histories of these technologies. This chapter defines the general extended reality technologies and outlines their usefulness in industry, as well as, in ship commissioning. Section 3.1 defines the common terms and offers a brief overview of their history, as well as modern day use. Section 3.2 examines the use of extended reality technologies in an industrial setting and specifies how these technologies are being, or could be, utilized during ship commissioning.

## 3.1 Overview of Extended Reality

### 3.1.1 Need, Development and Adoption

Advancements in technology allow for massive amounts of data collection, storing and processing. According to Statista, as of 2024, the total amount of data produced world wide is estimated to be 147 zettabytes ( $1.47 \times 10^{23}$  bytes) [13], and the collection of big data within the industrial setting has grown accordingly [14]. Despite an enormous investment into data collection, the way to apply this data is lacking [15]. This poses the question: how to best interact with this data in a way, which is efficient and provides value to the user, while not obstructing their other tasks?

Human-computer interaction (HCI) represents the process of a person interacting with the interfaces present in a computer system [16]. Early, widely employed forms of human-computer interaction were punch cards used to program computers. In conventional personal computer systems, the visual representation of data has been achieved with the use of a computer monitor, while the human inputs are conducted via a mouse and keyboard. As technology develops further, so do the interfaces for human computer interaction, which in turn are the key for allowing humans to interact with more of the massive amounts of collected data. The latest forms of HCI, with the aim of increasing the bandwidth of interaction, have completely forgone the use of a traditional computer mouse and loose monitor, and have instead moved towards the direction of head mounted displays (HMD) allowing the user increased freedom in their interaction. These interactions with data through a head mounted device fall under the definition of extended reality (XR).

The term "extended reality" is relatively recent (and disputed) [17], and is used as an umbrella term for technologies, which make up the reality-virtuality continuum presented by Milgram & Kishino (see Figure 3.1). The reality-virtuality continuum (or just virtuality continuum) is a spectrum spanning from the real environment to the virtual environment, representing the increase of virtual elements known as mixed reality (MR) [18]. Noteworthy points along the continuum are: augmented reality (AR), which represents a real world setting with virtual elements overlaid in it. As technologies move towards full virtuality, the next key point on the virtuality continuum is augmented virtuality (AV), which aims to bring real world elements, such as an avatar of the user, into a virtual setting. Finally, full virtual reality (VR) represents a completely virtual environment. Extended reality, then, is an all encompassing concept, and can be used to refer to any of the aforementioned types of technologies, and will be used as such in this thesis.

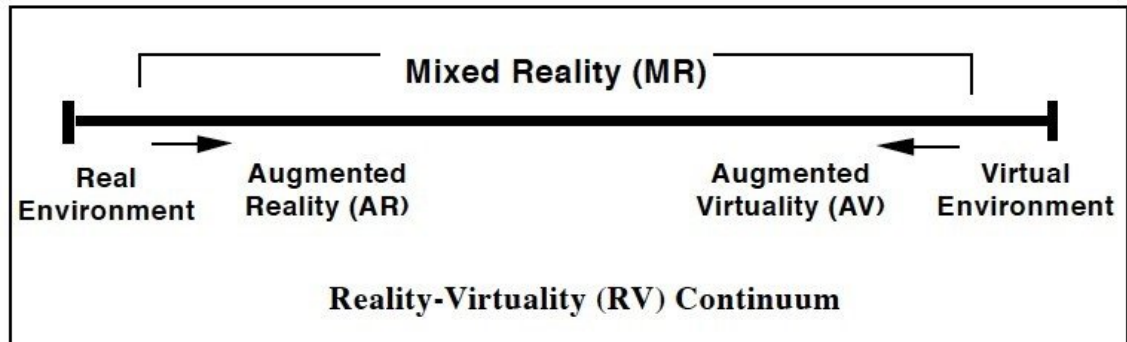


Figure 3.1: The reality-virtuality continuum presented by Milgram & Kishino used to portray the increase of virtual content within within a mixed reality solution. [18]

The first uses of technologies, which could be considered as extended reality can be traced back to 1961 with the development and release of the Sensorama by Morton Heilig. The Sensorama was an entertainment device comprised of three dimensional video capability, haptic actuators in the form of wind and vibration, stereo sound, as well as, a source for aromas [19]. Though the Sensorama failed to be a commercial success, it served as an inspiration for future XR development. Under the umbrella of XR, the Sensorama falls under the definition of virtual reality. Some of the earliest widespread and commercially viable adoptions of XR were the introduction of flight simulators developed by the United States Air Force in 1966 [20]. The military applications for XR technology in the form of flight simulators provided valuable funding to XR research.

Since the 2010s, extended reality devices have become increasingly commonplace and widely available in both consumer and industrial sectors. Crucial advancements in promoting the availability of XR for individual consumers were made with the introduction of the Oculus Rift and the HTC Vive in 2015. These devices represented a combination of affordability and functionality, which allowed XR to enter the homes of everyday users. HTC [21] and Oculus (later acquired by Meta [22]) remain major XR device manufacturers to this day. In 2024, the global sale of

modern head mounted extended reality devices, like the Vive developed by HTC and the Quest by Meta, was forecast to reach 54 billion dollars with projections for further growth [23]. Technological advancements are not solely responsible for the rising popularity of XR. The effects of the Covid-19 pandemic on the adoption of extended reality devices cannot be ignored. The global pandemic forced individuals to work remotely when possible, as well as, spend more of their leisure time in the confinements of their homes. This increase in remote presence and need for virtual escapism is evident in the growth in numbers of extended reality devices sold [24]. The global pandemic also represents a shift in the culture around XR devices. Traditionally, outside hardcore enthusiasts, XR was a niche technology employed in office spaces and shared between users. With the hygiene and safety requirements set by the pandemic, this sharing of physical devices had to cease and the use of individual XR rose. The current development trends for XR closely follow this individual user ethos, with companies and Apple using marketing slogan like "A more engaging way to get together" [25].

### 3.1.2 Extended Reality Platforms and Interactions

With the multitude of different types of extended reality experiences, an equally substantial amount of ways to interact with those experiences become necessary. It remains constant, that the user is presented information through digital format; either by portraying a virtual setting (AV and VR) or by overlaying digital content to a real world setting (AR). How the user then interacts with these varying degrees of virtuality depends on the type of device used to create the XR experience. Basic forms of AR can be achieved with the use of mobile devices like phones and tablets with cameras and screens. Mobile device based XR solutions tend to be more approachable, due to the less intrusive and more familiar interface. Mobile device based XR is often practical due to the user not having to carry additional devices

(besides their personal mobile device), but still allow for virtual environments to be created with the capabilities of the device. Many of the most popular extended reality solutions are mobile device based, with examples such as the popular chatting and image sharing software Snapchat by Snap Inc. [26].

As the technology becomes more complex and all encompassing, the users shift to head mounted devices, where a traditional touchscreen interface is forgone. Instead, depending on the HMD platform, the user may perform inputs with controllers, hands, gestures, body movements, voice, and in some cases even by moving their eyes. A fundamental set of interactions with a HMD are the three degrees of freedom (3DoF) of the users head: by tracking the movements along the X, Y and Z axes, in other words the pitch, yaw and roll of the users head, the XR solution can react accordingly and show the user new content tied to the direction, which their head took. 3Dof tracking is the cornerstone for most modern XR solution, allowing the user to be immersed in the virtual environment by looking around and seeing their surroundings react accordingly. As the system gets more complex, three new degrees of freedom are introduced. A six degree of freedom (6DoF) system not only tracks the users head, but also body position and orientation in respect to the surrounding of the user. This process is called pose estimation or positioning. Compared to 3DoF, a 6DoF system requires additional sensors to track the user within their setting. Despite this need for additional sensors, modern HMDs are typically 6DoF solutions, due to the variety of added possibilities enabled by 6DoF.

Across the most popular HMDs in the market in 2023 (Meta Quest series, Sony VR and PICO headsets) [27], all are primarily shipped or paired with controllers, which, in conjunction with the tracking system of the HMD, can be used to interact with virtual content. The use of controllers allows for precise manipulation of virtual elements present in an XR environment through solutions like ray interaction, which casts a precise targeting beam providing the user with a clear point for interaction, or

controller buttons, which can be tied to specific actions like grabbing an interactable object or moving within the XR environment. While controllers allow for precise interaction, they can often become intrusive for solutions, where the user would like to perform actions with their hands. In order to free the user of extra obstructions, novel HMDs have introduced advanced interaction methods, such as tracking the hands and eyes of the user, or receiving voice commands. These interaction methods allow the user to interact with XR elements while eliminating the need for additional physical interfaces.

Beyond user inputs, equally substantial are the ways, in which users receive information from the HMD. Depending on the type and purpose of the head mounted device in question, the information relayed to the users maybe shown via a digital screen (like in VR devices) or through the use of lenses, onto which digital content is cast. In devices developed for virtual reality use, the defacto means of displaying information is via screens located within the headset. Screens are well suited for displaying a VR world to the user, but can also be used for AR purposes: by employing the data from sensors present in an HMD, like depth and colour cameras, the displays within the headset can be used to portray the physical surroundings of the user. This digital visualization of the real world setting is called video passthrough, and allows for modern VR headsets to also perform AR functions, although the setting shown to the user is still digital, as opposed to the real world visuals used by AR devices. Video passthrough functionality is a popular direction for XR development as seen in the release of recent XR HMDs like the Vision Pro by Apple [28], the Quest 3 [29] and Quest Pro [30] by Meta, the Playstation VR 2 [31] by Sony, as well as, the Pico 4 by Pico [32], all having passthrough video capability. Passthrough video has, however, traditionally come with a limitation: since the information relayed to the user has to be processed before being displayed, there has typically been an inherent lag between the users actions and the devices capability to respond. Thus, traditionally,

for devices developed solely for AR use, the displaying of information via a screen can be avoided, which has resulted in a more natural user experience [33][34]. In these solutions, the user will, instead, look through a transparent lens, showing them their real world surroundings as though having nothing between. These devices are considered as optical see through. In order to relay digital AR content to the user in an optical see through solution, the digital content is projected onto the devices lenses. Example of current and popular optical see through devices are the HoloLens 2 released by Microsoft in 2019 [35], and the Magic Leap 2 released by Magic Leap in 2022 [36]. Although AR devices, showing the "real" user environment via a lens, this type of solution also comes with a specific drawback; the field of view (FOV) of the platforms are limited significantly when compared to video passthrough based HMDs. Partly due to the limited FOV of optical see through and also due to the advancements in technology, video passthrough capable devices are on the rise as seen by the aforementioned list of recent XR HMDs.

A final point of consideration when differentiating between XR systems and their uses is the reliance on coupled devices or peripherals. The Rift and Vive, released in 2015 and regarded as the first modern consumer VR headsets, both required a VR capable computer, which the headsets were attached to via link cable. The coupled computer is used to provide the computing capacity required by the XR solutions. Coupling remains topical in some modern XR HMDs, like gaming HMDs, where performance is key: The Vive Pro series, Playstation VR series, and Index VR headsets by Valve all require a physical link to a computer or console. Besides coupling with a computer, XR devices can require other physical peripherals, like beacons used for pose estimation. Physical coupling sets limitations for the XR solution: the presence of external cables limits usage distances, presents tripping hazards within the usage area, and reliance on external peripherals like beacons requires additional setup within the usage area. Uncoupled, or standalone

XR solutions, which do not require a connection to a stationary device, but rather hold all the necessary performance tools onboard the HMD are being developed. The popularity of especially the Quest series (as shown in [27]), as well as, Vision Pro being developed by Apple, serve as evidence for the demand for standalone XR.

## 3.2 Extended Reality in an Industrial Settings

### 3.2.1 Development of Industrial Extended Reality

The use of human-computer interfaces in industry begins with the development and release of the first commercially available computers. The Mark 1 developed by Ferranti and the Univac 1 by Remington Rand released to the market in 1951 were mainly adopted by public institutions and corporate entities. Historically, the industrial sector, with hopes of increasing their output, has been an early adopter of disruptive technologies like the personal computer, automation and the internet [37][38]. A similar trend is visible when examining the development and propagation of XR technologies. In a survey conducted by Perkins Coie in 2021, stakeholders and executives from a variety of industries, such as healthcare, automotive and education, expected the adoption and investment into XR technologies to grow [39].

Since enterprises can afford to invest more into developing tailored XR solutions than adopters of general commercial XR solutions, the device requirements are set by the use case. Without specifying nuances between specific devices, in general, virtual reality devices are most developed for health and safety training, as well as for use in construction, while AR can be well suited for design and assembly tasks. [40]

### 3.2.2 Extended Reality as Part of Ship Commissioning

The shipbuilding industry, with its long roots and traditions, as well as a relatively low R&D intensity [41], was not amongst the first to adopt XR, but has been making substantial XR integrations during the past years [42]. Most notably, XR technologies have been developed for visualizing design models as demonstrated by G. Šikić [43] by utilizing a computer attached VR HMD and R. Pérez Fernández et al. [44] by utilizing projectors in a room scale. In their VR solution R. Pérez Fernández et al. identify the heterogeneous data structures, complexity, and high levels of collaboration and interaction between suppliers and customers as major challenges within the shipbuilding. VR technologies are suggested as a solution for solving these challenges.

Another substantial use for XR technologies in shipbuilding is training purposes: K. Shankhwa et al. propose an HTC Vive Pro based VR solution for welding training [45] and A. Vidal-Balea et al. develop a HoloLens based AR solution for training [46]. K. Shankhwa et al. conclude, that the integration of VR training demonstrated tangible benefits and significantly improved the performance of novice welders. Similarly, A. Vidal-Balea et al. identify the possibilities of industrial internet of things interactions, possibility for collaborative training, as well as, expediting manufacturing processes as being enabled by AR.

These aforementioned solutions demonstrate a variety of technologies, ranging from VR systems tied to PCs and rooms with projectors, to standalone AR solutions utilizing the HoloLens. From a contemporary perspective, however, video passthrough based solutions are missing from the list of devices used when creating XR solutions for the shipbuilding industry. A potential reason for the lack of video passthrough XR in the shipbuilding industry is associated with the technology not being mature enough until recently. P. Fraga-Lamas & al. in their review of industrial augmented reality solutions conducted in 2018 note that: "video-based display

technologies should be avoided, since they incur in delays that harm the user experience. Optical and retinal projection are then recommended." As a continuation, the same authors mention, that the field of view (FOV) of the used HMD should be as wide as possible and recognize the need for controller free interactions, suggesting the use of voice commands for interaction [42]. Additionally, U. von Lukas & al. in their review of augmented reality technologies for the maritime sector [41] identify the need for robust tracking capabilities, both inside challenging spaces like the hull of a ship, and challenging environments like in dark spaces, as crucial advancements required for maritime AR to be feasible. In spite of the challenges presented in the reviews, video passthrough XR has advanced substantially in the recent years, and contemporary technologies may fair better than their legacy counterparts. As such, video passthrough XR should be re visited as a platform for XR solutions aimed at the shipbuilding sector.

Despite the quickly growing acceptance of XR technologies (disregarding video passthrough XR) within the shipbuilding industry, commissioning has yet to see substantial advancements or introductions of XR technologies or adequate virtualization what so ever [3]. Significant factors in this lack of deployments are likely the historical precedence for low R&D intensity within the shipbuilding industry. Despite the unwillingness to invest in R&D, the complex nature of the commissioning process makes it a great target for XR. As discussed in the previous chapter (see Section 2.2), commissioning consist of multiple parties made up by the shipyard and its numerous subcontractors. Due to the high complexity and cost of the commissioning process, developments aiding in simplifying data visualization and the propagation of knowledge would be welcome. An XR solution reducing the time spent on shifting through technical schematics, user manuals or checking readings by half an hour a day, would result in 112 000 euros in cost savings over a week long sea trial ( $\frac{0.5h}{day} \times 7 days \times 32000 e$ ).

# 4 Artificial Intelligence

When discussing the evolution and adaption of modern technologies, the topic of artificial intelligence is inevitable. This chapter defines general concepts of AI and its uses. Section 4.1 discusses the perceived rise of artificial intelligence and Section 4.2 specifically examines the use of AI and AI systems in extended reality solutions. Section 4.3 discusses how AI could be employed when developing XR solutions for ship commissioning.

## 4.1 Artificial Intelligence Overview

The concept of artificial intelligence has recently gained massive mainstream popularity. A contributing factor in this mainstream adoption has been the launching of ChatGPT in November of 2022. ChatGPT is a companion chatbot developed by OpenAI [47]. It utilizes the GPT (Generative Pre-trained Transformer) family of large language models (LLMs) from OpenAI to generate dialogue with the user of the application. LLMs are artificial intelligence algorithms designed especially for natural language processing. ChatGPT has colloquially gained the be-all and end-all title of artificial intelligence. In reality, however, the development of artificial intelligence and the technologies leading up to modern day LLMs, like the GPTs, began in the 1940s and 1950s [48]. The term "artificial intelligence" is, in fact, a generalization of any solution, where a computer performs tasks, which would generally be considered to "require human intelligence" [49]. These tasks can vary, but typically

refer to solutions like machine vision, where computers perform analysis based on images or other visual input, natural language processing, where computers analyze patterns in language or text to produce human language, and speech recognition, where computers analyze audio inputs like voice commands and harvest the wanted context from the command. Combined, all these technologies and methods form the umbrella of artificial intelligence.

Even though ChatGPT popularized the consumer usage of AI, the greater AI market has seen consistent growth and is projected to keep expanding [50]. This growth is not only present in consumer solutions, like ChatGPT, but also in industrial use cases. The IBM global AI adoption index notes that a majority of enterprises have adopted or are exploring the possibilities of AI [51].

## 4.2 Artificial Intelligence in Extended Reality

Artificial intelligence and extended reality generally have different primary objectives, but can be used in conjunction with each other to create AI enhanced XR solutions [52]. As discussed in the beginning of the chapter, AI comes in many forms, and as such, it can also be utilized in numerous different ways in XR solutions. Notably, many HMD manufacturers already use integrated AI in their headsets. Examples include AI enhanced visual-inertial simultaneous localization and mapping (vSLMA) algorithms used for positioning [53] and object recognition algorithms used to track the hands of a user, employed by Meta. These onboard AI capabilities integrated into the HMD are all encompassing for that HMD, and are likely to be present in all use cases for the device. Conversely, artificial intelligence can also be used in the application side of an XR solution: machine learning algorithms are used for performing tasks like finding information from a database with the help of natural language processing, performing computer vision analysis on imaging captured with the use of XR, or gesture recognition using traditional

machine learning methods [52].

In general, AI enhancement in XR solutions is a clear development direction and multiple studies have been conducted regarding different ways of enhancing XR with AI. Based on a 2023 review of the state of the art in AI enhanced XR by Teresa Hirzle et al., the most common use (37.6% of papers) for AI in XR solutions was creating XR worlds by using AI to improve tracking accuracy, scaling geometries, as well as, improving light and audio in XR environments. The second most common application (25.3%) was using AI in order to understand users: predicting movements, predicting VR sickness and predicting user characteristics. A third major cluster of applications was using AI in support of XR interactions: gesture recognition, locomotion techniques and novel devices [54].

### 4.3 Artificial Intelligence in the Context of Commissioning

When focusing specifically on XR tools supporting the commissioning of ships, artificial intelligence can play an important role. As presented in previous chapters, the typical problems in ship commissioning are related to complexity and scale, especially in the form of convoluted and large sets of user manuals, instructions and documentations.

Problems regarding complexity and prohibitively large amounts of data can be addressed using artificial intelligence. Especially natural language processing can be used to summarize and find information from the large sets of documentations. Having information alone is not sufficient, however. Accessing this AI gathered information in a way, which does not obstruct the user can be as crucial as gathering the data in the first place. For access to data, advanced interactions like speech recognition is another example of AI assisted XR technology, which could be of

use during commissioning. This resulting solution would be very reminiscent of a companion chatbot with access to the context documentation.

Another potential approach could involve scene understanding. Performing object detection and recognition on the surroundings of the user, in order to recognize the present interfaces. This would serve as a way for XR tools to interact with their physical surrounding. Yet again, in order to then receive information regarding those interfaces, an AI capable of natural language processing could perform the information gathering and summarizing.

# 5 Proof of Concept

This chapter outlines the development of an XR tool for debugging and setup use during ship commissioning. The design philosophies lean on the context provided by the previous chapters, and follow typical technology development methodologies. Section 5.1 specifies the real world problem, which this tool will address. Section 5.2 performs requirement analysis based on the stakeholders involved. The technical design of the solution is described in Section 5.3, and the user experience design in Section 5.4.

## 5.1 Problem Statement

The adoption of new technologies, especially in a long standing and traditional field, such as shipbuilding, is challenging. Conversely, however, there is a clear need for innovations, especially ones aimed at expediting the commissioning process. Since there is little precedence regarding XR solutions aimed for ship commissioning, a proof of concept is developed in order to evaluate the suitability of modern XR platforms for the shipbuilding, and especially the commissioning environment. Based on this evaluation, the research questions of this thesis can be addressed.

In order to introduce the capabilities of modern XR to the shipbuilding experts, and to create a scalable solution, which can be further developed, this proof of concept should display as much of the potential functionality of modern XR devices, but do it in a way, which is ultimately aimed at providing value to the shipbuilding

professional. Such a solution reduces the burden of adopting a new technology, while still implementing the cutting edge of contemporary XR.

## 5.2 Requirement Analysis

Analysing the requirements for this proof of concept begins with the identification of stakeholders. Stakeholder identification refers to developing an understanding of the target users and other individuals with interest, influence and stake in the development of a technology solution [55]. An understanding of the target demographic is critical in identifying the functional requirements for a solution. The functional requirements refer to the needs and expectations for the practical capabilities of a solution: what should the solution do?

In order to identify these functional requirements based on a set of stakeholders, user stories are formed. User stories are glimpses into the way, in which prospect users act or work, and how a potential technology solution would fit into these actions [56].

### 5.2.1 Stakeholder Analysis

The stakeholders associated with this solution can be identified as participants of the Virtual Sea Trial research project. These project members can be broadly divided into three groups: shipbuilding professionals working for companies participating in the research, and researchers working for the institutions of higher education, who are conducting the research. The final group consists of business interests formed by institution and company level entities associated with the research project.

The shipbuilding professionals with first hand knowledge about the commissioning process and experience in the functional testing and validation of interfaces and devices found throughout a ship are the primary stakeholders and end users of this

solution. The primary stakeholders needs dictate much of the functional requirements. Secondary stakeholders consist of the researchers involved in this research project. They set requirements for the scalability and technical implementation from a research point of view.

The following list of user stories are formulated based on the current understanding of the commissioning process:

- As a shipbuilding professional performing validation testing on interfaces during sea trials, I want the solution to recognize interfaces automatically, allowing me to cut time on reading documentation.
- As a shipbuilding professional performing validation testing, I want the solution to enhance my working capacity, without intruding on my work.
- As a new user without experience with extended reality technologies, I want the solution to be as simple to use as possible.
- As a researcher working on XR solutions for a new user demographic, I want the solution to display as much of the potential of modern XR technologies as possible.
- As a researcher I want the solution to be modular and scalable based on the feedback provided by research partners.

### 5.2.2 Functional Requirements

Based on these user stories and the current understanding of the commissioning process, this solution should be an XR solution capable of recognizing or remembering target interfaces, and then providing the user information about those interfaces in a manner, which does not disrupt the workflow of the user. This type of solution utilizes the strengths of the technologies involved, represents a clear and concise

solution to a real world problem, and can be made into a scalable implementation based on a number of different XR technologies and platforms.

In order for the implementation to be as non-intrusive to the user as possible, while also reducing the amount of learning required from the user, a solution utilizing hand tracking is chosen. This allows for users to work without having to hold devices like a laptop, tablet or HMD controllers, while also reducing the need to learn new ways of interacting with digital content (i.e. learning controller button schema). A hands free approach does set further constraints on the development of the solution, since the interactions have to be made in a way, which is intuitive to the user and does not force users to learn complex gestures. Designing the interactions is addressed further in Section 5.4 where user experience is specified more clearly.

As discussed in Chapter 2, the validation tasks conducted during commissioning involve a vast array of interfaces supplied by any number of suppliers. Thus, no single target interface present in a ship is chosen for this proof of concept. Rather, generic devices representing different interfaces, and the technical challenges associated with them, would be used as targets for this solution. For example, rather than focusing on a specific obscure screen or dial, which one might find in a ship, the interfaces used to present this technology to users should be something widespread and available. In order to simulate tasks, which one might find in various testing and validation events, two main focus groups were chosen: a complex interface, which users are likely unfamiliar with, and need further context in order to operate, as well as, a cabling setup tutorial, which requires the user to work with physical equipment while following instructions presented in XR. Specifically, the final target devices chosen for this solution were: a Hung Chang model 3502c oscilloscope [57], which represents an adequately complex interface, while also providing a responsive target, where the user will be able to see the results of their actions. The other target device chosen for this solution was a HTC Vive Pro 2 [58] HMD, which represents a cabling

problem, during which the user will be instructed to setup an XR headset interfaced with the back panel of a tower computer. Between these two targets, the user will be presented two different use cases; one presents the user information regarding a complex interface, such as an oscilloscope, and the other provides the user a tutorial style guide for setting up a device.

## 5.3 System Design

The system design phase of development involves translating the functional requirements of a solution into a technical plan. In the case of this XR solution, the technical plan will involve outlining the key technologies and capabilities associated with the functional requirements in the form of a system architecture and device choices. Based on the architecture and subsequent device choice, a suitable software framework capable of supporting this architecture will be decided. The final task will be designing and implementing the software solution.

### 5.3.1 Hardware Choice

The next phase in development will be deciding a target device capable of supporting this architecture. In order to evaluate the potential of different device options, a table consisting of XR devices was formed. The table's horizontal rows represent the XR platforms, while the vertical columns represent device specifications and other relevant information. The devices were chosen based on the following factors: popularity and suitability for industrial applications. The columns are defined as follows:

- **Device Name:** The name of the device.

- **Price:** The retail price of the platform in Euros (€). Prices cited via the official website of the device manufacturer in July 2024.<sup>12</sup>
- **Device Type:** The type of XR device. Options are: VR (for virtual reality), Video Passthrough (For VR with video passthrough capability), and AR (For optical see through AR).
- **Standalone:** Whether of not the platform is capable of standalone functionality (does not require additional infrastructure like beacons or physical computer connection). Options are: Yes/No.
- **Interaction:** The interaction methods supported by the device. The different options for interaction methods will be discussed in detail later.

Table 5.1: Popular XR Devices

Device Name	Price	Device Type	Standalone	Interaction
Google Cardboard	-	VR	Yes	Head tilt
Meta Quest 3	570	Video Passthrough	Yes	Hands / Controllers
Apple Vision Pro	4000	Video Passthrough	Yes	Hands
HoloLens 2	3500	AR	Yes	Hands
Magic Leap 2	3553	AR	Yes	Hands / Controllers
Valve Index	1079	VR	No	Controllers
Vive Pro 2	900	VR	No	Controllers
Tablet XR	-	Video Passthrough	Yes	Touchscreen

When examining the system architecture section from earlier in the chapter, certain device options can be disregarded. The Vive Pro 2 and Valve Index represent VR technologies, which are not suitable for the target solution, since with a VR implementation, the user would not be able to see and interact with their surroundings. Additionally, the suitability of a VR solution on a ship, which sways while on

<sup>1</sup>The Vision Pro by Apple does not have an official quoted price, so the price displayed is chosen from an European retailer.

<sup>2</sup>Tablet XR & Google Cardboard prices vary significantly based on the device, so no single price is displayed.

sea could result in increased risk of sea sickness due to sensory mismatch between sensory organs sensing movement and the perception of movement.

Another device, which can be disregarded is the tablet XR solution. Tablet XR requires the user to keep the device at hand during use, which may disturb the workflow of the user, since they would continuously have to pick up and put down their XR device between working with their hands. Additionally, with the aim of this proof of concept being the demonstration of new technologies, tablet (and smartphone) based solutions are somewhat outdated and do not represent the cutting edge of modern extended reality. Similar to tablet XR, Google Cardboard represents a technology, which has not seen significant development in years. Additionally, the Google cardboard (and other smartphone mounting solutions) do not generally support 6DoF tracking, and would require the user to stay in place. Due to these reasons, the cardboard is not considered a viable target for this proof of concept.

The final decision, then, is choosing between the augmented reality and the video passthrough platforms. Modern AR has, since the inception of the HoloLens in 2016, been marketed towards industrial uses. Virtual reality, especially VR from the same era as the HoloLens, like the Oculus Rift, has typically been marketed for entertainment purposes. As discussed in Chapter 3 Subsection 3.2.2 when examining industrial XR solutions, the use of passthrough XR has not traditionally been viable for industrial purposes. Recent advancements in tracking and passthrough video technology, however, allows VR HMDs to bridge to gap between AR and VR technologies. Devices like the Quest 3 and Vision Pro can be used much like AR glasses by utilizing their passthrough capabilities. Additionally, unlike in traditional optical see through, where FOV is quite narrow (which was identified as an issue in industrial applications) due to the optical limitations involved in designing AR HMDs, video passthrough devices allow for a significantly wider FOV. As a final

addition, evaluating the capabilities of modern video passthrough devices in tasks, which have typically involved AR solutions, serves the research targets of this thesis. Based on these factors, the two video passthrough glasses were chosen as finalist devices.

Of the remaining two platforms, the Quest 3 represents similar core capabilities as the Vision Pro, while boasting a significantly lower price. When considering factors, such as a the willingness of a company to invest in new technology, presenting a cheaper alternative is beneficial. Additionally, from a research perspective, evaluating the capabilities of the cheaper device alternatives presents valuable information about the current quality of more accessible XR technology. Thus, the Quest 3 is chosen as the final target device.

### 5.3.2 System Architecture

In order to begin development on the software implementation of the solution described in the functional requirements, a software framework is chosen. The Quest 3 does not allow users direct access to the device hardware (like cameras and other sensors), but instead provides developers application-program interfaces (APIs), which allow developers to utilize the capabilities of the HMD. These APIs are supported in the two most common software development frameworks: Unity3D [59] and Unreal Engine [60]. Both frameworks are capable of accommodating the level of solution planned for this proof of concept. Unity is chosen as the development framework.

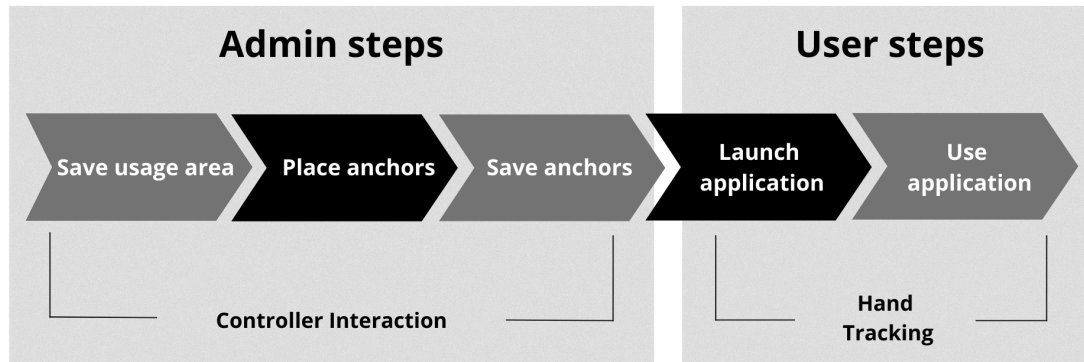


Figure 5.1: Workflow of the entire XR solution, starting with administrator steps, which include saving the usage area, placing spatial anchors and saving the anchors. Followed by the user steps, which only require launching the solution and getting to work within the premade environment.

Key considerations in developing for the Quest 3 are the ways in which the device recognizes its surroundings. Especially in the case of this solution, where recognizing or remembering targets in the use area is required. As outlined in the user stories and technical requirements, the initial plan for development was to implement a solution, which recognizes wanted interfaces within a setting. Since the Quest 3, however, does not allow developers direct access to the camera feed of the device, a machine vision algorithm capable of conducting this recognition is not possible and a workaround is required. Instead of dynamically recognizing interfaces within the physical environment of the user, the solution will rely on digital models of the interfaces. These digital models can be placed on top of their real world counterparts and can simulate those interfaces in the virtual environment. The spatial anchor API by Meta, allows for the placement and saving of these models into the use area by an administrator. When a future user (like a testing engineer using the application for validation or setup tasks during ship commissioning) opens the solution, those

anchors will remain where they were placed, allowing the user to start working without having to do any form of setup. The entire use workflow is visualized in Figure 5.1. While administrators will use the Quest 3 controllers for setting up the solution, users will be able to interact with the virtual environment via the hand tracking capabilities of the Quest 3 (as denoted by the "Admin steps" and "User steps" sections of Figure 5.1). This interactive content tied to the anchors will vary between animations, pressable buttons and grabbable virtual objects produced in the Unity3D framework, to text to speech based scripts provided by an LLM.

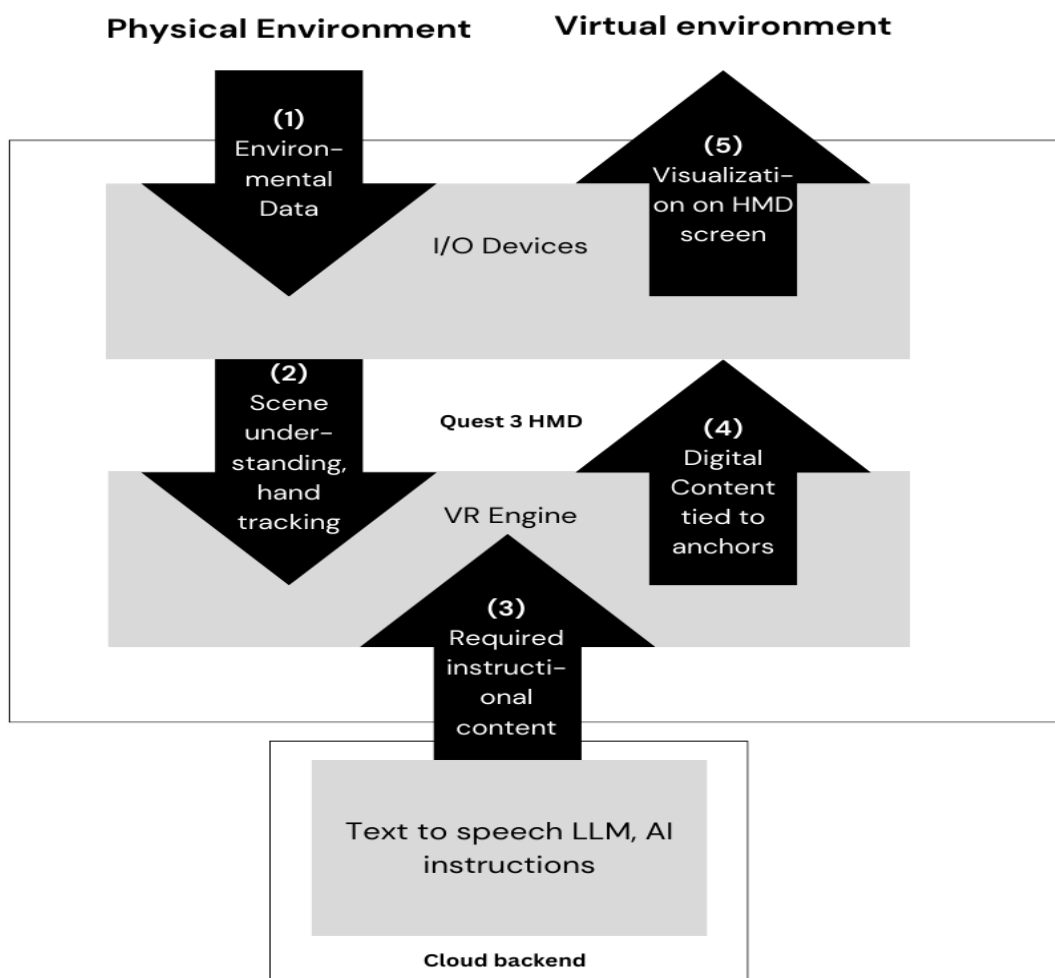


Figure 5.2: Numbered dataflow diagram of the entire XR system. Beginning with the physical environment and ending with the projected virtual environment.

---

The entire dataflow, or how the data travels through the system, is visualized in Figure 5.2. Different steps in the system are numbered 1-5. The initial step (*Environmental data*) is gathering information about the physical environment of the user with input devices (part of the input/output or *I/O devices* of the Quest 3 platform), such as cameras, light detection and ranging, and inertial measurement units. This data of the physical environment is translated into scene understanding in step two (*Scene understanding, hand tracking*) in the VR engine of the HMD. Step three (*Required instructional content*) involved receiving instructional content regarding the interfaces present in the solution from a cloud-based LLM. During step four (*Digital content tied to anchors*), a virtual environment is created. The virtual environment consists of digital content placed into the vicinity of the user, tracking user interactions with this digital content, and by tying the AI instructions to the digital content. Finally, the entire virtual environment is visualized to the user in step five (*Visualization on HMD screen*) via the output devices of the HMD like screens and speakers.

### 5.3.3 Software Implementation



Figure 5.3: The digital model of a oscilloscope within the finalized solution. Included are a mock signal generator and oscilloscope probes.

After the architecture of the system is outlined, the solution can be implemented. Initial phases of the software development involved setting up the Unity environment with the necessary packages. The packages required for this solution will be included in the All-In-One Software Development Kit (SDK) [61] by Meta. The SDK includes the necessary APIs for video passthrough, hand tracking, spatial anchors and depth perception, which are required in order to utilize the capabilities of the Quest 3. The first development task was the implementation of the passthrough video API, enabling the user to see through the cameras of the HMD. Following passthrough video, was the implementation of spatial anchor functionality, allowing for the placement, saving and loading of Unity GameObjects within the surroundings of the user. These saveable GameObjects will later serve as the digital models

of target interfaces. The 3D modeling software Blender [62] was used for modeling the digital versions of the target devices. The final digital model for the oscilloscope is shown in Figure 5.3 and the model for the PC and Vive HMD are shown in Figure 5.4.

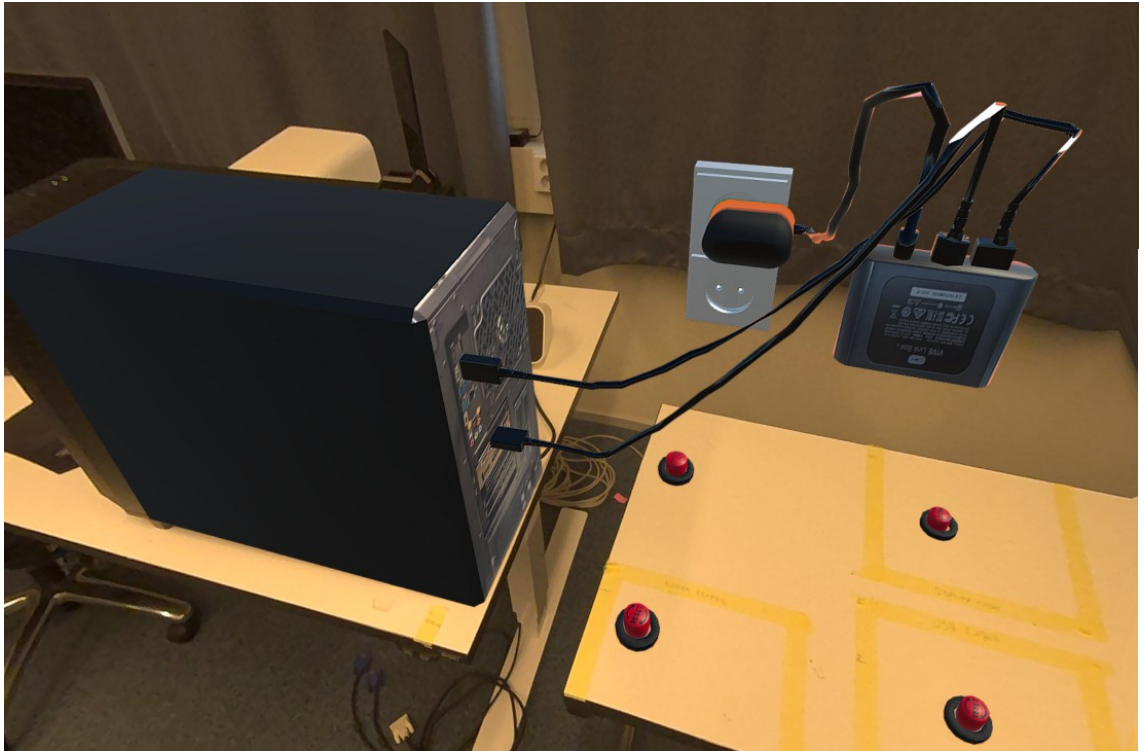


Figure 5.4: The digital model for the wiring required for an HTC Vive HMD within the finalized solution. The red buttons present on the table activate the animations for the digital wires.

Following the placement and recall of the digital models, further interactivity with the interfaces was required. In order to achieve this interactivity, user inputs were implemented. For this task, maintaining the design principles of a non-intrusive solution, the hand tracking API by Meta was utilized. Hand tracking gives the user an interface, through which to interact with the digital content without having to rely on controllers. For the digital content to be interactive, though, further functionality has to be implemented to the digital models placed within the XR environment.

The interactivity with the oscilloscope came in the form of mimicing the real world counterpart by allowing the user to power on the device by pressing the power button on the oscilloscopes digital model, placing the probes of the oscilloscope into place, accessing information regarding the dials present in an oscilloscope, and finally being able to manipulate the dials in the digital model in order to see a real-time effects on the screen of the oscilloscope. Digital oscilloscope dials are shown in Figure 5.5.

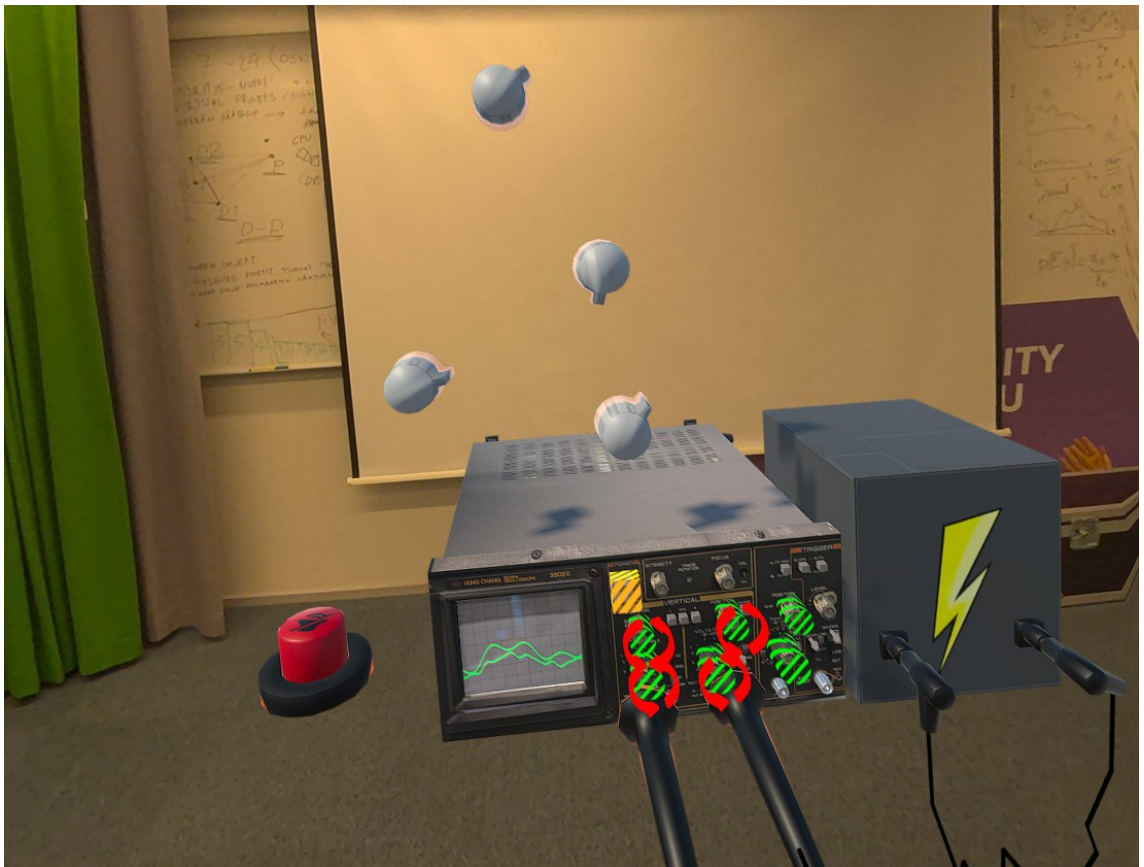


Figure 5.5: Oscilloscope model with interactable digital dials placed above the device, as well as pressable buttons on the oscilloscope highlighted in green and yellow. The buttons, which have been pressed and are currently active have a red outline to indicate, that their corresponding dials can be turned. Finally, the digital probes have been placed onto the oscilloscope body.

The interactivity with the Vive HMD cabling task came in the form of receiving animated and spoken instructions for setting up the HMD. The user could press

buttons appearing in the digital environment and engage different phases of the cabling setup dynamically. These interactions were triggered by a combination of tracking the hands of the user and placing virtual buttons into the environment. The buttons functioned as triggers to play animations and activate the instructional voice lines prompting users to connect the various cables present in the solution. The hand tracking did not only act as a means of activating buttons but also measured distance to the digital models. As a user moves their hand(s) towards the digital model of the computer, animations are faded out, so the user has a clear view of the physical interface, without any interference from digital content. An example of fading digital content is shown in Figure 5.6.

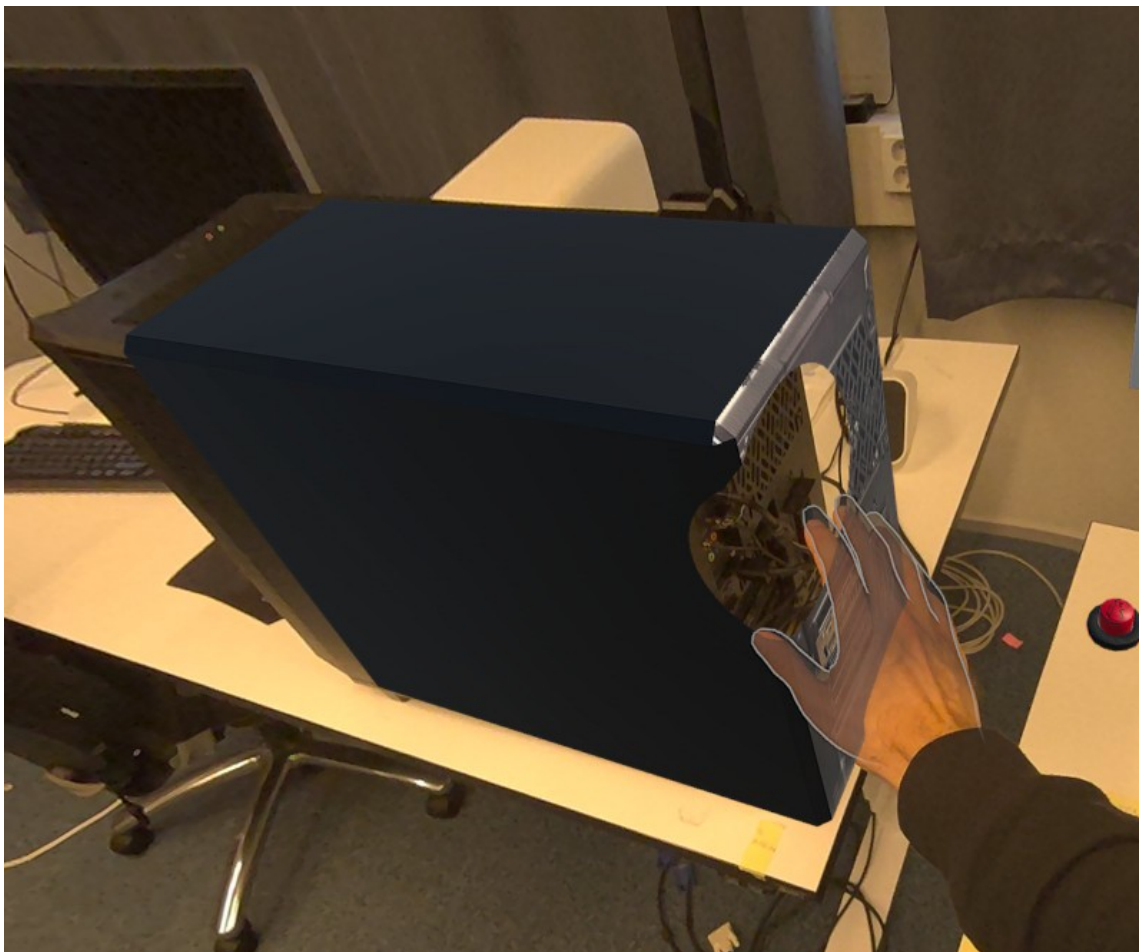


Figure 5.6: Example of fading digital models in response to the proximity of the user in order to visualize the real world counterpart present under the digital model.

The final major development step was integrating the necessary AI functionality to the digital content. In order to simulate a fully AI based experience, text prompts regarding the functionality of the oscilloscope interface, as well as, prompts resulting in instructions for setting up the Vive cabling were fed to a LLM. These LLM results were then turned to voiced instructions and informational speech by using a text to speech AI. As described in the previous paragraph, users would access these AI instructions by interacting with the digital content tied to the anchors within the XR environment.

## 5.4 User Experience Design

In all technology development, the user experience (UX) is the aspect, which dictates whether or not a solution will be successful. The concept of user experience is broad, but generally refers to the benefits, which users may derive from a product [63]. This experience is naturally made up of a multitude of factors. Some of these factors will be inherently tied to the limitations and capabilities of the available technologies. For instance, when developing an XR solution utilizing a HMD, the user experience will always be partly tied to (and often limited by) the hardware capabilities onboard the HMD. Some governing factors in HMDs are: FOV (especially limited in optical see through devices), device frame rate (relevant in VR HMDs, and when subpar, can lead to nausea), and battery life (effecting the use time of a solution). Other factors regarding user experience, however, can (and should) be addressed during development. While presenting a new form of technology to users can be challenging, presenting an unfamiliar user interface (UI) to users is often even more daunting. The experience of what feels intuitive to the user and what does not will instantly impact their overall satisfaction with a solution. Thus, the UI design should be amongst the main focuses when developing extended reality.

### 5.4.1 Defining Principles

In order to aim for the best possible outcome, this solution follows the general principles for user interface design by Jakob Nielsen (also known as Nielsen heuristics). Nielsen heuristics present general principles (or heuristics) for good UI design as outlined in his 1994 book and later revised on his website. These heuristics have also been applied to XR systems recently [64]. The full set of heuristics are defined as follows:

1. **Visibility of System Status:** *The design should always keep users informed about what is going on, through appropriate feedback within a reasonable amount of time.*
2. **Match Between System and the Real World:** *The design should speak the users' language. Use words, phrases, and concepts familiar to the user, rather than internal jargon. Follow real-world conventions, making information appear in a natural and logical order.*
3. **User Control and Freedom:** *Users often perform actions by mistake. They need a clearly marked "emergency exit" to leave the unwanted action without having to go through an extended process.*
4. **Consistency and Standards:** *Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform and industry conventions.*
5. **Error Prevention:** *Good error messages are important, but the best designs carefully prevent problems from occurring in the first place. Either eliminate error-prone conditions, or check for them and present users with a confirmation option before they commit to the action.*

6. ***Recognition Rather than Recall:*** *Minimize the user's memory load by making elements, actions, and options visible. The user should not have to remember information from one part of the interface to another. Information required to use the design (e.g. field labels or menu items) should be visible or easily retrievable when needed.*
7. ***Flexibility and Efficiency of Use:*** *Shortcuts (hidden from novice users) may speed up the interaction for the expert user such that the design can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.*
8. ***Aesthetic and Minimalist design:*** *Dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility.*
9. ***Help Users Recognize, Diagnose, and Recover from Errors:*** *Error messages should be expressed in plain language (no error codes), precisely indicate the problem, and constructively suggest a solution.*
10. ***Help and Documentation:*** *It's best if the system doesn't need any additional explanation. However, it may be necessary to provide documentation to help users understand how to complete their tasks.*

List quoted from the website of Jakob Nielsen. [65]

### 5.4.2 Applied Design Principles

These heuristics were followed in the UX and UI development for this proof of concept when applicable. Heuristic one suggests, that the user should be made aware of the system status. This was achieved via a combination of functions built

into the Quest 3, and design choices made during development. The Quest 3 does a good job of showing users what application is currently running and what the status (battery charge, system errors etc.) of the system is. The application itself greeted users with a main menu (see Figure 5.7), indicating that the experience was beginning, as well as highlighting interactable content with a noticeable colour and/or visual indicator (see Figure 5.8), which denoted to the user their current options.

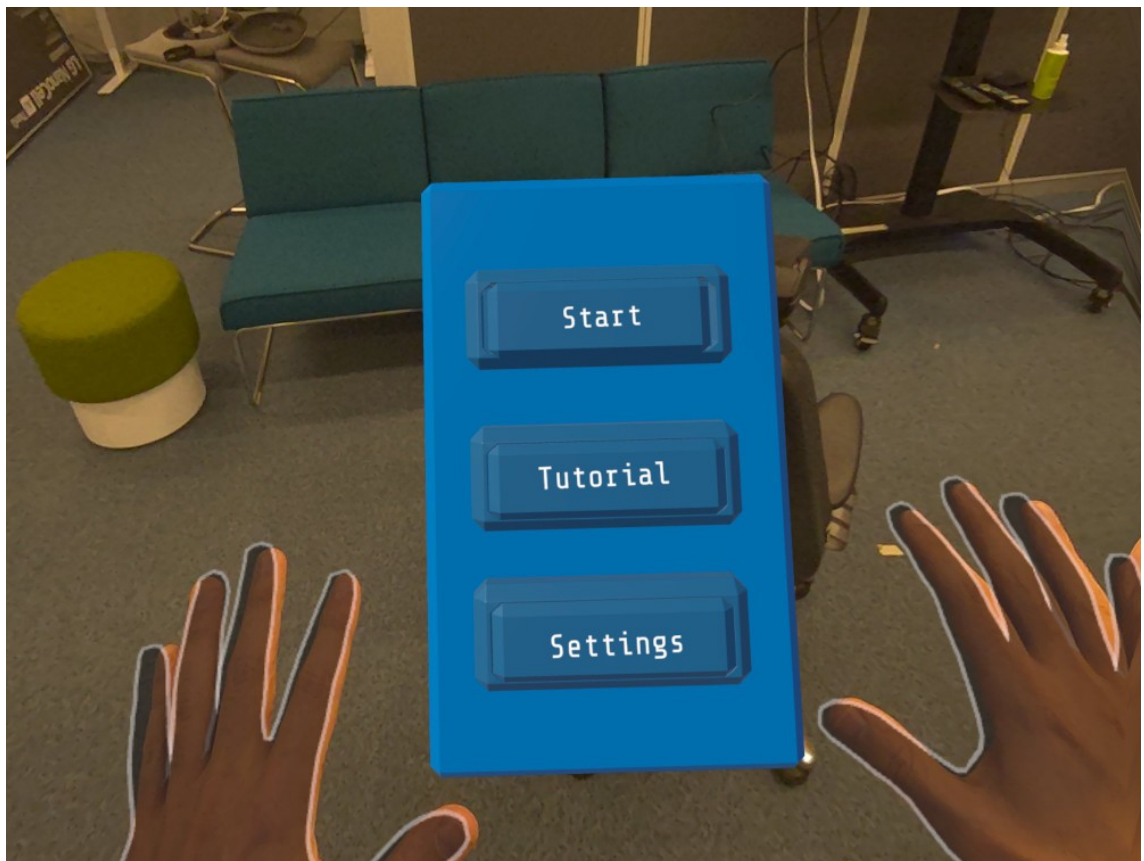


Figure 5.7: Example of heuristic one: a hand tracking based menu used in the finalized solution.

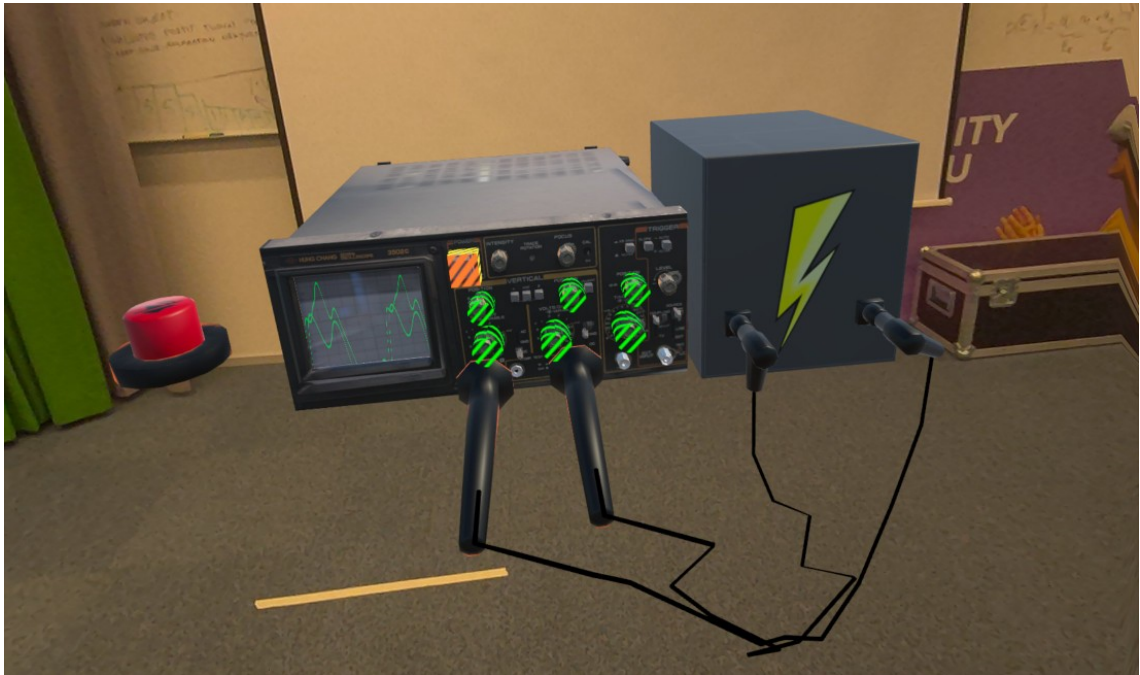


Figure 5.8: Example of heuristic one: highlighting options for the user. The orange button has been pressed and the green buttons can currently be activated.

Heuristic two encourages developing a link between the system and the real world. In order to comply with this heuristic, the prompt given to the AI providing the voice lines and instructions regarding system interfaces to the user were engineered so, that the resulting script was accessible and in layman terms. The interactions provided to the users were designed in a way, which copied real world conventions, such as pressing buttons and turning dials. Some omissions regarding realism were made, however, especially when designing the probes, which users would connect to the digital oscilloscope: the initial design of the probes involved gravity mechanics, which would see the probes fall to the ground if let go off. After further consideration, however, it was deemed cumbersome for users to have to pick up the digital probes from the ground, and that it would be beneficial for the experience to leave the probes suspended mid air if disengaged. Similarly, the digital dials present in the oscilloscope were made to appear above the device, rather than over their natural location within the device interface due to space constraints.

Heuristic three discusses user control and freedom. Users were given freedom in the order of operations they wished to do: when being introduced to the oscilloscope, after following the instructed setup phase, users could explore the different dials present in any order they wished. Similar to the oscilloscope, the cabling tutorial could be completed in any order wanted by the user. An option to reset all the available interfaces was planned, but failed to be implemented in time for the user testing.

Heuristic four suggests following standards and a consistency of design. In order to comply with general principles employed by the Quest 3 platform, the interaction methods used by this proof of concept purposely did not include any complex gestures, which required users would have to learn, or require distinction between different actions. The interaction methods available to the user were simple poke and grab interactions, which are well supported and documented as part of the Quest 3 development resources and the Meta All-In-One SDK.

Heuristic five deals with error states and messages. To ensure users would not take actions, which would lead to errors, the administration mode and user mode of the application were separated. Admins were provided an error log with system status messages and access to advanced options, while users were only given access to basic interactions, which was designed as error proof as possible by limiting the options of a user to basic interactions. This error proofing was achieved through digital interactions and content often not requiring multiple steps, but rather relying on separate and independent actions, which would lead to specific ends, and not being chained together. The only recognized error situation was caused by the default gesture of the Quest 3 to open the device menu. As part of the design of the Quest 3, this menu gesture cannot be disabled from the device, thus the gesture had to be left into the solution.

The sixth of the Nielsen heuristics encourages recognition over recall. In the

development of the proof of concept, users are made aware of the potential options by highlighting the interactable content. Previously used content was also highlighted in a different colour, in order to visualise the past actions of the user. Location for different content within the digital environment (the two target interfaces) were also displayed by arrows, which indicated where the user should move to.

Heuristic seven suggests providing flexibility in the use of a solution. This heuristic is addressed by plans of including in depth tutorials for novice users, which may be skipped by more experienced users. Additionally, all dialogue can be skipped and/or muted by reactivating the interaction triggering said dialogue, or pressing the universal mute buttons present at both target interfaces. Due to the nature of the application, more advanced user shortcuts are not considered crucial for the user experience.

The eight Nielsen heuristic refers to minimalist design. The dialogue options and instructions provided to users is based on a script produced with artificial intelligence. This script has been prompt engineered in way, which minimizes unnecessary information, but still aims to give users all the basic information they require about the task or interface at hand. For example: when receiving information regarding dials present in an oscilloscope, the AI prompt is limited to a set amount of words, resulting in a script no longer than 30 seconds. Similarly, when users are being instructed to connect cabling as part of the HMD setup task, the instructions are designed to be of limited length.

Heuristic nine encourages design, which helps users recognize, diagnose and recover from errors. Due to the short nature of individual interactions with digital content, no error or problem state solving for users was planned for this proof of concept. The admin mode is given error messages and detailed information regarding the state of anchors and system logs. Heuristic ten refers to providing users with the instructions and documentation necessary to ensure they can effectively

use the solution. An optional detailed tutorial is planned for the solution, ensuring that all users receive all the context required by the solution. The content of these instructions would involve: a guide for the basic interactions, like pokes and grabs, as well as, instructions on where and how to access the digital content.

## 6 Testing and Results

This chapter presents findings from the user testing of the proof of concept described in the previous chapter. These findings are based on a questionnaire presented to users testing the proof of concept during a testing session, as well as, observations regarding the actions of the users during the session. Section 6.1 describes the procedure of the testing session and Section 6.2 outlines the observations made by test conductors during these tests. Section 6.3 outlines the contents of the questionnaire presented to the testers. Section 6.4 presents the results of the questionnaire.

### 6.1 Testing Methodology

Two testing sessions, in which the solution described in Chapter 5 was presented to a total of 23 testers, were conducted. Since the testers backgrounds varied from researchers (some researching XR, others not) to shipbuilding professionals, all testers were walked through a sequence of tasks and actions, which they should complete while using the XR proof of concept. The point of view of of the tester was also shared to the test conductors via the screen sharing software Oculus Cast [66]. This allowed the test conductors to follow the actions of the user from both: an outside and a first person view. The other testers were not shown this cast in order to keep the experience fresh and uninformed by the actions of the previous users.

The first task presented to the users was ensuring that the hand tracking and position estimation were working correctly, by letting the user walk around while

wearing the HMD and inspect their hands. If the hand tracking functioned correctly, a gray outline appeared around the hands of the user. Once the user was ready and acclimated to the the XR environment, they were instructed to approach one of the two locations with digital content indicated by a red arrow. As users reached one of the two arrows, the full content came into view. The users were then walked through a task, they had to accomplish without relying on any additional assistance than that, which the solution already offered.

The Vive HMD task began with the HMD cables disconnected, and the user were tasked with setting up all the cables present. The oscilloscope task began with the virtual oscilloscope powered off and its probes disconnected. The users were instructed to power on the device, connect the probes, and access information about the dials of the oscilloscope. The task was considered complete once the user had tried out multiple different dials by first listening to the informational content and then interacting with the virtual dials.

After testing the proof of concept, the users were asked to fill out a questionnaire regarding their experience with the solution. The answers to this questionnaire serve part of the answer to the research questions of this thesis and are discussed later in this chapter.

## 6.2 Testing Observations

While the users were testing the proof of concept, the developers and other researchers made observations regarding the users actions and their experience from an informed outside perspective, as well as, from a first person perspective utilizing the screen cast of the device. Based on these testing observations, some key details can be outlined:

1. Average testing time between users was 7 minutes.

2. Users were generally excited and did not get frustrated when testing the solution.
3. Users in general had some difficulties locating the digital dials appearing above the oscilloscope, but all users managed to locate the dials during their testing.
4. Pressing highlighted dials in the digital oscilloscope, as well as, turning the digital dials was initially challenging for some testers. All the testers managed to access the content during their testing.
5. Tall users had problems interacting with the digital content.
6. Towards the end of the testing session, the Quest 3 platform began misidentifying between users hands and the quest controllers, resulting in a situation where the last few users had to test the solution using only one hand.

### 6.3 Questionnaire Design

In order to analyze how the proof of concept was received, a questionnaire was presented to the testers. The data from this questionnaire will be used when answering the research questions of this thesis.

The questionnaire opened with a few questions regarding the occupation of the user, as well as, their experience using XR systems. These questions were designed in order to identify key demographics within the already specific set of respondents. The System Usability Scale presented by John Brooke in 1995 [67] was used as a starting point for the questionnaire, and some of the original questions (such as "I thought the solution was easy to use") were included in the final questionnaire. There were three sets of multiple choice questions ranging from "completely disagree" to "fully agree" regarding different aspects of the solution: the quality of the extended reality experience (i.e. how intuitive were the interactions and the digital

content), the capability of the Quest 3 platform (for example the video quality and hand tracking accuracy of the device), and finally the relevance and quality of the artificial intelligence component of the solution.

The multiple choice questions were developed in order to receive responses to the research questions 2-4 respectively. The first set of multiple choice questions concerning the quality of the XR experience are closely tied to the research question 2: "How can extended reality provide value for users in ship commissioning?", as well as, research question 3: "Which current extended reality technologies are best suited for ship commissioning?". By examining the user experience pertaining to the quality of the XR solution, as well as, the capabilities of the XR device, these research questions can be partially answered. Questions regarding the user experience with artificial intelligence components of the solution in turn are directly tied to the RQ4: "How can artificial intelligence be used to enhance extended reality solutions aimed for ship commissioning".

After the three sets of multiple choice questions, the users were also provided two open answers regarding real world targets for implementation in the ship commissioning environment, as well as, aspects of the proof of concept, which the users would like to see developed further. The users were encouraged to specify their answers to the two open questions with as much detail as possible. Finally, there was an optional free word at the end of the questionnaire for additional comments the users would like to leave. These open questions, again, are directly tied to the research questions of this thesis. Especially RQ1: "How can extended reality technologies be used as part of ship commissioning?" is partly answered by open questions directed towards especially shipbuilding professionals. Similarly, the open question regarding development directions for the solution helps answer RQ2.

## 6.4 Questionnaire Results

This section will address answers to each set of questions within the questionnaire in one or both of two different ways: a general overview of all responses to the question, and sets of responses to the question from key demographics. Specific key demographics include: experiences with solution and system quality of experienced XR users, experiences with solution and system quality of inexperienced XR users, and comments on viability of a similar solution in the shipbuilding space by shipbuilding professionals. These key demographics will be taken into account when analyzing the questionnaire responses in later chapters.

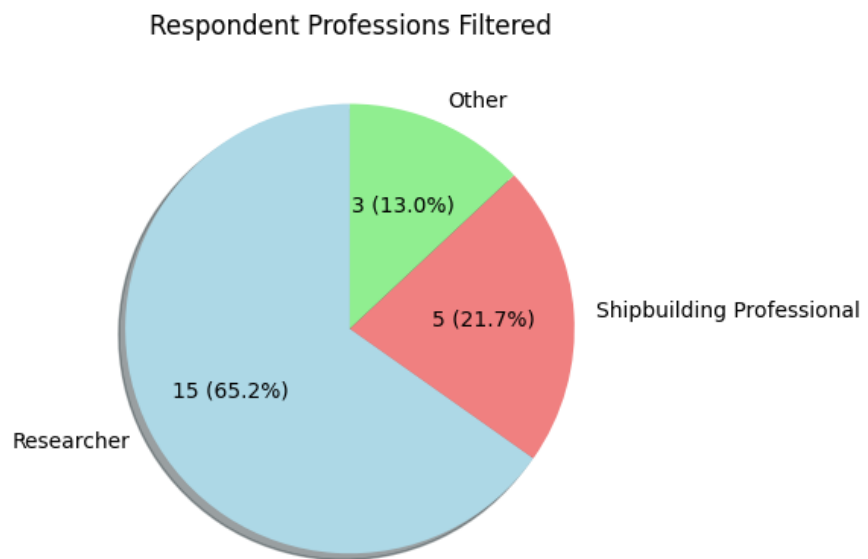


Figure 6.1: Pie chart displaying the professional backgrounds of users testing the XR proof of concept.

Between all 23 respondents, one user denoted themselves as a shipbuilding professional, 15 as researchers and seven as "other". Of the users answering "other", four respondents specified themselves as personnel associated with the shipbuilding industry (incl. innovation financier, propulsion sales director, business unit director and technical lead) and the rest as research or otherwise academic personnel. For

the purposes of this thesis, the four respondents associated with the shipbuilding industry will be considered as part of the shipbuilding professionals. The finalized numbers are visualised in Figure 6.1.

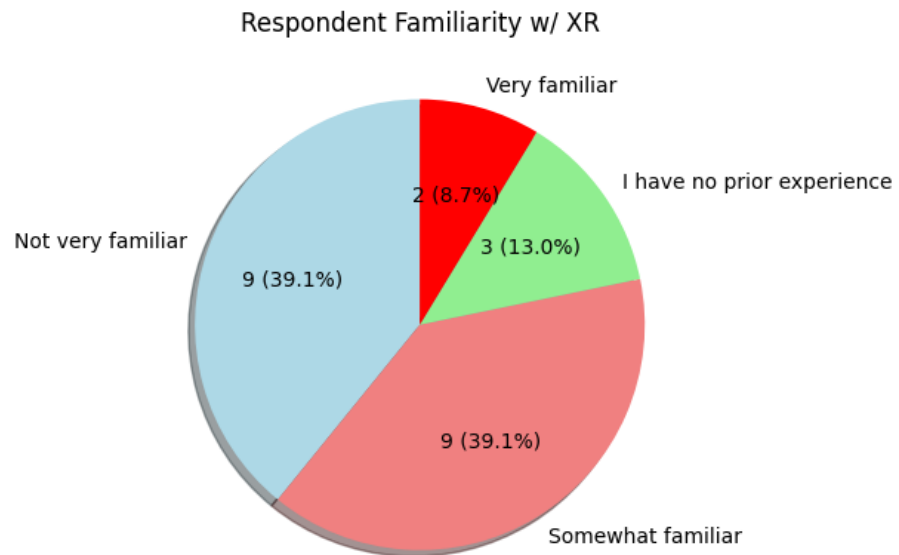


Figure 6.2: Pie chart displaying the level of experience with extended reality of users testing the XR proof of concept.

As part of the background questions, users were asked about their level of familiarity with XR technologies. The answer choices were: "I have no prior experience", "Not very familiar (I have tried XR once or twice)", "Somewhat familiar (I have used XR multiple times)", "Quite familiar (I use XR monthly)", and "Very familiar (I use XR weekly)". Of the 23 respondents, three had no prior experience with XR. Nine claimed to have tried XR once or twice, nine had used XR multiple times in the past and the remaining two were very familiar with XR and used it weekly. The responses are visualised in Figure 6.2.

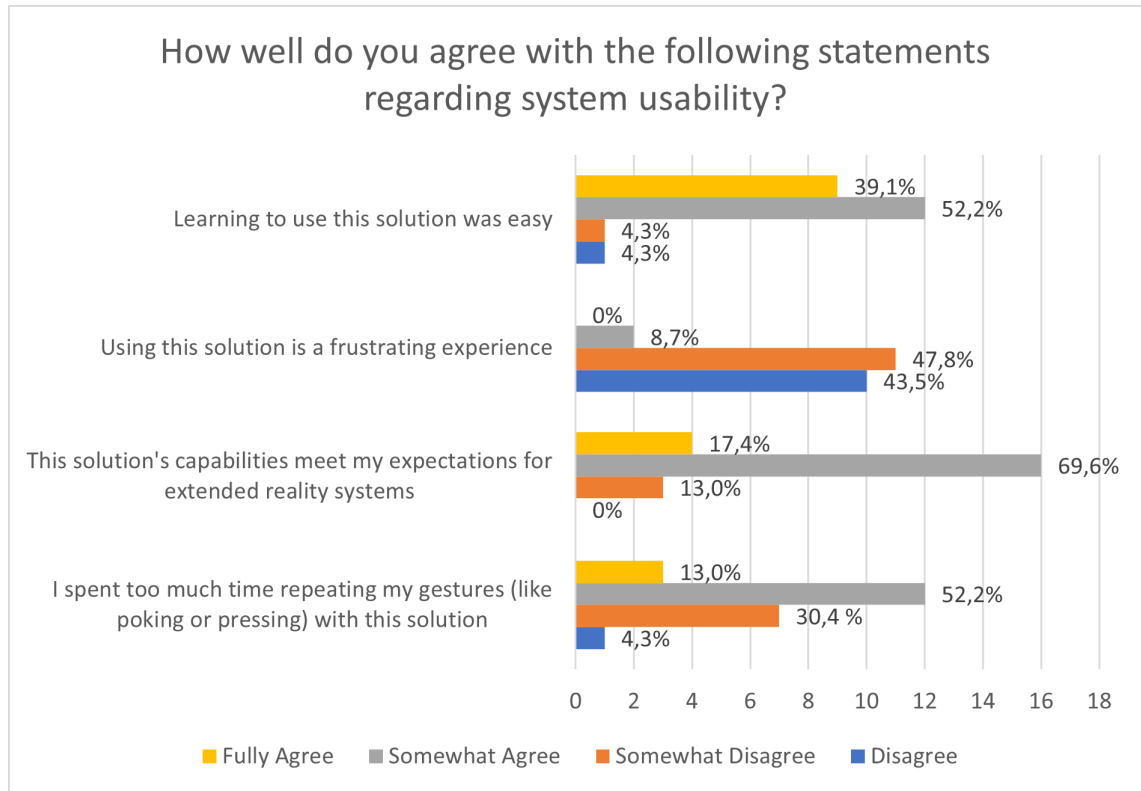


Figure 6.3: Bar chart results for the users responses to questions about their experience with the XR implementation.

The third set of questions addressed the experience of the users with regards to application quality. These questions are designed to chart the user experience and reflect upon the UX design of this proof of concept. 91% of users either agreed or somewhat agreed that learning to use the proof of concept was easy. Similarly, 91% of users either fully or partly disagreed with the statement that: "Using this solution is a frustrating experience". 70% of users somewhat agreed that the proof of concept met their expectations for extended reality systems. A total of 65% of users either fully or somewhat agreed, that they spent too much time repeating gestures with the proof of concept. The responses to these questions are visualised in Figure 6.3. Between the respondents with high prior experience ("Very familiar") using XR, the interactions with digital content (i.e. activating and turning digital dials or pressing digital buttons using their hands) were unsatisfactory. At the same time, however,

both respondents found the solution easy to learn and did not find it frustrating to use. Between the respondents with little to no prior experience using XR (two lowest choice options in the questionnaire), there was a similar consensus on spending too much time interacting with the digital content, as well as, finding the solution non frustrating and easy to learn. User experience did not play a significant role in how usable the testers found the solution.

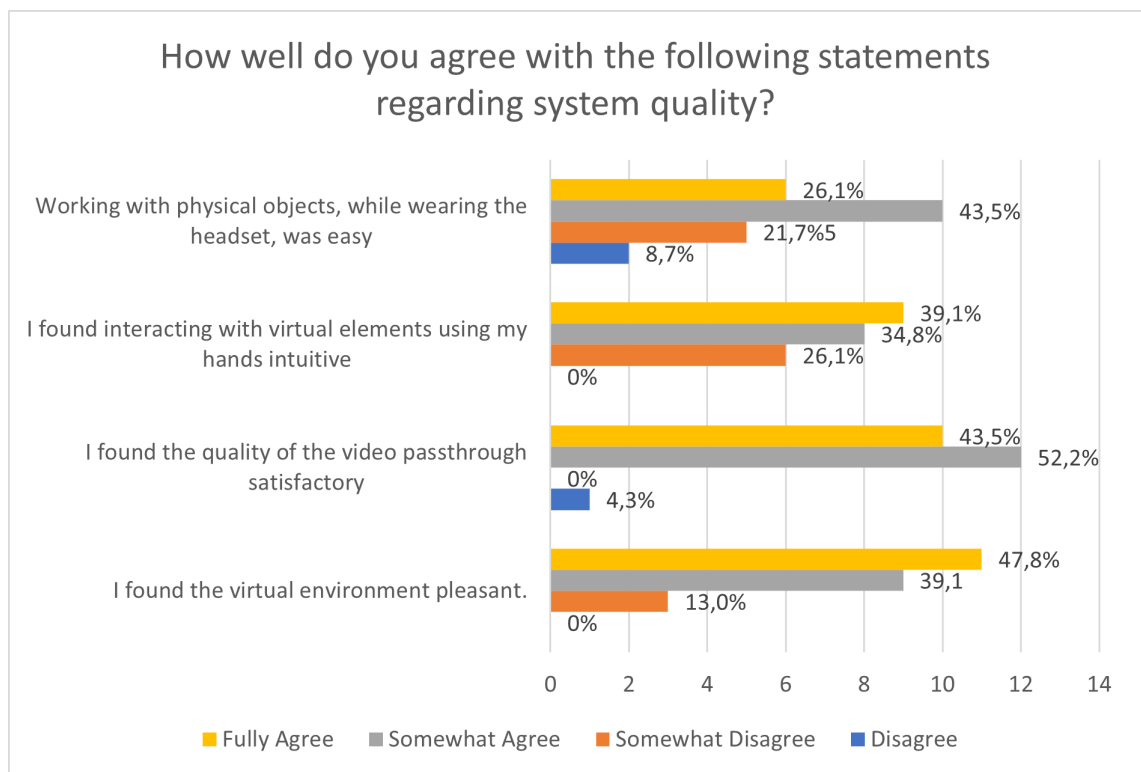


Figure 6.4: Bar chart results for the users responses to questions about their experience with the Quest 3 platform.

The fourth set of questions inquires users about their experience with the Quest 3 platform. 70% of users either somewhat or fully agreed, that working with physical objects, while wearing the headset was easy. 74% of respondents agreed or somewhat agreed, that using their hands to interacting with virtual elements was intuitive. 96% of users agreed or somewhat agreed, that the quality of the video passthrough was satisfactory. Finally, 86% of users either agreed or somewhat agreed, that the virtual

environment was pleasant. The responses to these questions are visualised in Figure 6.4. The respondents who noted their prior experience with XR to be high, answered that the quality of the passthrough video was good, working with virtual content while wearing the HMD was somewhat easy (both answering somewhat agree), and that interacting with virtual content was cumbersome (all answers being "somewhat disagree"). Users with little to no prior experience using XR had otherwise similar answers, but found interacting with virtual content to be generally intuitive.

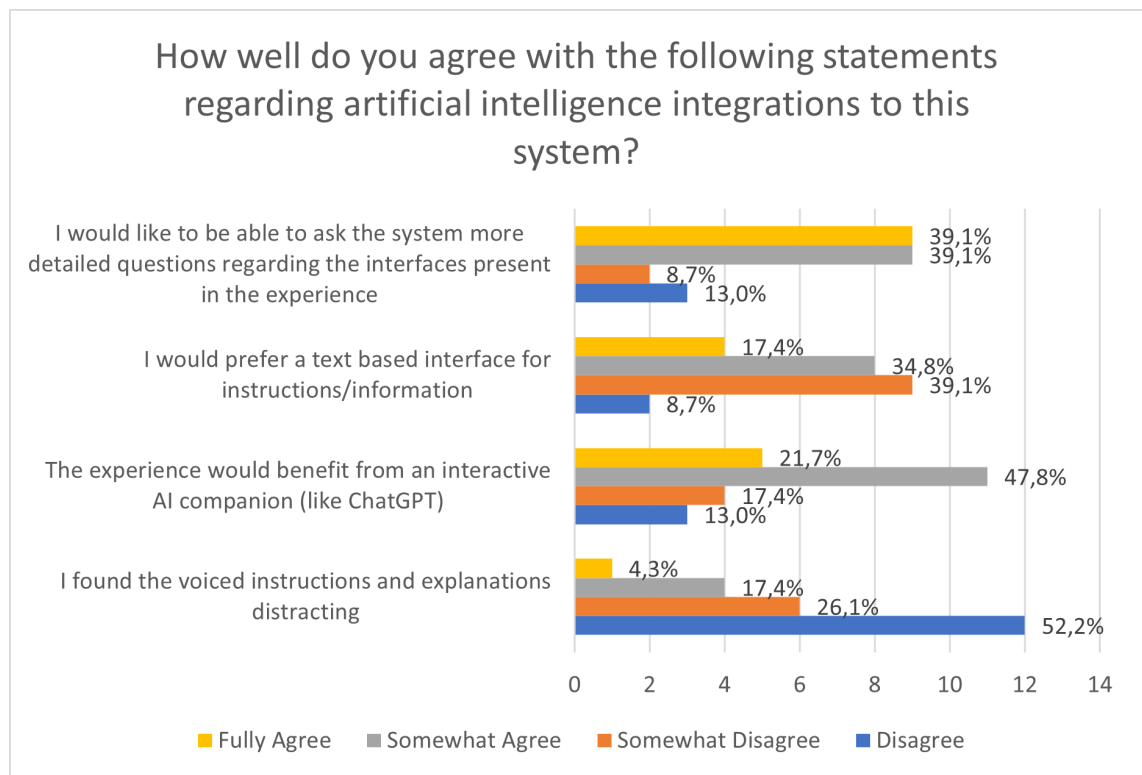


Figure 6.5: Bar chart results for the users responses to questions about their experience with the AI components of the XR implementation.

The final set of multiple choice questions addressed the AI content, and how it was delivered, present in this proof of concept. 78% of respondents agreed or somewhat agreed, that they would like to be able to ask the system more detailed questions regarding the interfaces present in the experience. When asked, if users would prefer a text based interface for instructions/information, the responses were

split: 52% of respondents either agreed or somewhat agreed to preferring a text based interface, while the remaining 48% either disagreed or somewhat disagreed. 70% of users either agreed or somewhat agreed, that the experience would benefit from an interactive AI companion. 78% of respondents either somewhat or fully disagreed when asked, if the voiced instructions and explanations were distracting. The response are visualised in Figure 6.5.

Following the multiple choice questions were open answer questions. The first of the open answer questions addressed the proof of concepts suitability for ship building and especially ship commissioning by asking: "Can you imagine a similar solution being used during ship commissioning? (Please specify)". General themes within the open answers agreed, that the solution would fit for training, installation and informational purposes. A breakdown of all the answers is as follows:

- Yes, but no specified use case (7 answers)
- Yes, as training content (3 answers)
- Yes, as a remote presence tool (1 answer)
- Yes, as a tool for verifying the functionality of components (3 answers)
- Yes, as a tool for supporting installations (3 answers)
- Cannot say / answer not applicable (6 answers)
- No (0 answers)

The respondents who answered, that they are shipbuilding professionals, as well as the four respondents answering "other", but still working in the shipbuilding industry, responded in following ways (answers anonymized):

- Yes. for process includes functions that humans cannot normally see during the commissioning or there are steps in the process that are needed to do in certain order.

- Yes, for service and installation.
- Yes, for training and installations.
- Yes, for training and system commissioning.
- Yes, for verifying machine operations and working inside tight spaces.

After questions regarding suitability in commissioning, the users were asked what they would like to see developed further in the experience. Some general themes could be distinguished from these answers:

- Inclusion of written instructions alongside the voiced instructions (3 answers)
- Improved interaction with digital content, such as buttons (8 answers)
- Hand tracking visualization got in the way of interacting with physical objects (2 answers)
- Inclusion of an interactable AI companion (5 answers)

# 7 Analysis, Discussion and Future Work

This chapter analyzes the findings, as well as, provides discussion and ideas for future work regarding the subject matter of this thesis. Section 7.1 presents analysis on the proof of concept detailed in Chapter 5 and the results of the questionnaire presented in Chapter 6. Section 7.2 presents ideas for future work and research regarding the topics of this thesis.

## 7.1 Proof of Concept Analysis

### 7.1.1 Testing Results

As detailed in the observations and questionnaire results in Chapter 6, all the testers were able to complete the tasks presented to them when testing the proof of concept. Some challenges did occur, and reoccur between testers, however. Additionally, other generalities in the user testing could also be identified. Based on these findings, the following themes regarding the proof of concept can be made:

- Tracking worked, albeit inconsistently at times: the HMD had no problem maintaining pose estimation within the usage area throughout the user tests. The quality of hand tracking varied; after prolonged usage, HMDs started recognizing users left hands as controllers, forcing the final testers to perform

the tasks using only one hand. Additionally, some open answers noted, that the default visualization of tracked hands performed by the Quest 3 HMD was distracting, and that it got in the way of performing tasks.

- No issues with passthrough quality: users responded to questions regarding the video passthrough (how pleasant the virtual environment was, and if passthrough quality was satisfactory) positively. The same could be noted when observing the users; no signs of nausea, getting lost in environment, or lacking detail when working with the headset could be detected.
- Quality of digital content lacking: testers who were tall generally had issues with engaging the virtual content in the solution and would have to crouch down in order to interact with some of the aforementioned content. This was an observation made by the test conductors.
- Quality of digital content lacking: Some testers had trouble locating where digital content appeared after activating it, as well as, finding the highlighted objects in the UI misleading. Engaging with some digital content (especially the oscilloscope dials) was challenging to some testers and was seen as "buggy" or finicky in the open question answers for the questionnaire. Similar results can be detected from the other questionnaire results, where over half of the respondents noted that they had to spend too much time repeating interactions with virtual content. When observing users, the same problems could be detected; users not finding UI elements or failing to interact with the elements without having to repeat their actions.
- General attitude towards test (and XR in common) positive: generally users found using XR a positive experience as noted by the open answers and the approval of the demo quality in the questionnaire. Similar positive themes were present, when asking about the suitability of XR in the commissioning

of ships. The same can be observed from the user tests: working with the headset did not cause issues in users and even users who were less tech savvy and had no prior experience with XR enjoyed the experience.

- Addition of AI instructions and voice over was well received: enhancing the experience using AI was supported and generally the addition of more AI content was requested. Users would have liked a full AI companion, with which they could converse regarding the digital content present in the demo.

### 7.1.2 Discussion

The common themes in the questionnaire and user observations can be split into two main categories: application specific issues and platform related issues. Application specific issues are related to takeaways pertaining to the proof of concept application: factors such as software quality, bugs and design choices are categorized into this list. Conversely, platform related issues have more to do with the choice of platform for the usage purpose in question, as well as, the limitations brought forth by the chosen platform. Table 7.1 shows a table with issues separated by type.

Table 7.1: Common themes in results

	<b>Application Specific</b>	<b>Platform Specific</b>
Tracking		x
Passthrough Quality		x
Digital Content Quality	x	
Attitude Towards XR	x	x
AI Content	x	

For the purposes of this thesis, platform related issues are generally more relevant than application specific ones. A proof of concept is designed to validate the suitability of a chosen technology. When answering research questions regarding suitability of AI assisted XR technologies for ship commissioning, more value can be

derived from the platform related results than specific issues in application design and implementation. This discussion section will, however, briefly address application specific issues in addition to the platform specific issues, which will be used to answer the research questions of this thesis.

As a starting point, the tracking and passthrough issues are closely related to the suitability of XR HMDs in ship commissioning, since they are directly evaluating the capabilities of the XR technology being used. When evaluating the Quest 3 platform for industrial use in ship commissioning, based on the user responses and observations: the technology, in terms of passthrough and tracking capabilities, meets the necessary requirements. The questionnaire responses and observations regarding digital environment quality, passthrough quality, as well as, questions regarding working with physical objects when wearing the HMD, all received positive responses (see Figure 6.4). Hand tracking was not as well received, with responses to questions, such as repeating gestures (see Figure 6.3) and interacting with virtual elements (see Figure 6.4) being more split between "somewhat agree" and "somewhat disagree". Based on observations, however, users managed to complete all tasks set for them. The mixed results for hand tracking can also be partly associated to the design and implementation of the proof of concept: by making the hitboxes for interactive content better defined and sized, many of the hand tracking related issues could potentially be rectified. Additionally, the bug where the HMD mistakenly recognized the hands of users as controllers, forcing users to work with a single hand, affects the experience with tracking. This bug can only be addressed and fixed by the device manufacturer. Considering the previous, the passthrough and tracking capabilities of the Quest 3, for use in commissioning tasks, are deemed satisfactory.

Themes of digital content quality are mostly tied to the proof of concept application. Aspects of the proof of concepts, such as, the target content within the

XR environment (oscilloscope and Vive Pro), the UX design, and the practical implementation of these concepts are not as closely tied to the successful evaluation of the suitability of AI enhanced XR in ship commissioning, as themes related to the XR platform are. A few issues related to digital content quality can also be associated with the target platform: namely the visualization of users hands when the device is performing hand tracking. Allowing for developers to disable the hand tracking visualization would further enable the Quest 3 HMD to be used as an XR tool. Based on the application specific issues, some general takeaways regarding UX design can be made. An obvious issue is the height related problems when interacting with digital content: this design flaw can be rectified by adjusting the position of the intractable content within the digital environment. The other stand out issue was the quality of digital dials (see Figure 5.5). This issue can partly be addressed by reducing the polling rate of the dials: by reducing the polling rate, the dial reacts to users inputs at a more manageable pace, rather than sporadically adjusting whenever a touch interaction is registered. Since the digital dials are fully virtual and do not offer any haptic feedback, making interactions require a level of experience with the application. Not much else can be done to improve the user experience with the dials. If the dials are deemed as a negative user experience, even after reducing polling rates, another form of interaction with the oscilloscope maybe required. Examples for interacting with a sliding scale (such as turning a dial) include sliders, which could be used to replace the current digital dials. Based on the aforementioned issues, it is clear, that the demonstration in its current state is not fully suitable for daily use in an industrial setting, but could be further developed into an efficient tool.

Issues addressing the attitude towards XR are tied to both: the platform in use, as well as, the application developed for this platform. The capabilities of the platform set constraints for applications developed for said platform. Additionally, the

form factor of the device (weight, bulk and ergonomics) impact the user experience of any application ran on the device. Ultimately, however, the experience that a user has with XR is deemed by the solution they are using. Based on questionnaire responses regarding learning to use the solutions and how frustrating of an experience using the solution was (see Figure 6.3), as well as, observations regarding the same issues, it can be deemed, that the general attitude towards an XR tool for ship commissioning was positive. This sentiment is further enforced by the generally positive responses to the open questions asking about the suitability of the technology for commissioning tasks.

The final set of issues are those tied to the AI content present in the solution. These issues are almost entirely application specific. Barring the inability to perform image recognition on the front cameras of the Quest 3, the platform does not prevent the use of AI content in applications, and the Unity development framework lends itself to AI integrations without issue. The quality of the AI instructions provided to users was not challenged in any of the open feedback, nor could problems understanding the AI be observed when users performed tasks with the solution. Based on the questionnaire responses, users found the AI content useful and would have liked more interactivity and increased use of AI, with 78% of users responding either "Fully Agree" or "Somewhat Agree" when asked if they would like to ask the platform more questions regarding interfaces present in the experience, and 70% of users agreeing that the solution would benefit from an AI companion (see Figure 6.5). The form in which the AI content was delivered to the users was more controversial: 52% of users answered that they would prefer ("Fully Agree" and "Somewhat Agree") a text based delivery of AI instructions, while the remaining 48% disagreed with this statement (see Figure 6.5). Despite about half of the users requesting a text based delivery of AI instructions, most (52% "Disagree" and 26% "Somewhat Disagree" when asked if the voiced content was distracting) responded

that the voiced content did not distract them when using the solution. In short, the addition of AI content for such a tool is supported, but the best means of delivering the content was disputed amongst users.

## 7.2 Future Work

The future work section of this thesis will focus on ways to further develop the proof of concept used to demonstrate capabilities of XR technologies presented in Chapter 5. As a starting point, the release of new state of the art XR platforms should be followed closely, and new target platforms should be adopted with little hesitation, since the best way to demonstrate the capabilities of the state of the art XR platforms is to in fact employ those said platforms. An example of a more recent XR platform, when compared to the Quests 3, is the Vision Pro by Apple. This platform was discussed when deciding a target platform for the demonstration, but was not chosen at that point, since the Quest 3 was more viable in terms of price and availability, while representing similar technical capabilities.

This thesis has focused heavily on demonstrating the capabilities of modern XR in use cases similar to those, which would be present in a ship commissioning setting. As a proof of concept and as an initial phase of development, this type of solution was suitable. When considering further development, however, the proof of concept should be brought into the real world usage setting as quickly as possible. In order to present the proof of concept in a real world setting, target devices from an actual ship should be used and preferably testing should be conducted in an actual ship during commissioning, or in a simulation environment, which could closely mimic a ship setting. By doing so, practical issues, such as suitability of the HMD with work wear, such as hardhats or uniforms, can be evaluated. Correspondingly, the applicability of video passthrough technology in a swaying setting like a ship can also be tested.

---

Besides applying the proof of concept into a realistic setting, further development can also be made within the application itself. As mentioned in the discussion section of this chapter, UX improvements can be made in the interactive digital content present in the current proof of concept. Similarly, integrating more AI functionality should be a priority when moving forward. Especially accessing databases of technical documentation of target devices present in a commissioning environment would be a valuable addition. Finally, the user should have a way of interacting with the AI content gathered based on the technical documentation. Thus, some form of AI companion (as requested by many users) would be a fitting priority for future development.

As a summary, the current state of the proof of concept detailed and tested during this thesis serves as a demonstration of the capabilities of XR technology imagined for a ship commissioning environment and has served as a starting point for developing a tool. However, in order to provide value for commissioning tasks, further development is required. To address specific needs of the target user demographic, co-development between the users and application developers has to be initiated. As part of the Virtual Sea Trial, a co-development project between researchers and shipbuilding professionals will be initiated, and this proof of concept will serve as a starting point for this development.

## 8 Conclusions

Ship commissioning refers to the process of testing and validating the systems on-board a vessel and leads up to the handing over of the ship to the customer. A shipbuilding project consists of multitudes of contractors, subcontractors and suppliers, and the commissioning of ships is reliant on commissioning engineers navigating documentation and manuals from each of these parties, which is challenging and time consuming. It is estimated that a single hour of sea trials, which is one of the final phases of commissioning, costs a shipyard as much as 32 000 euros. As such, every minute spent unnecessarily shifting through documentation is needlessly expensive. For these purposes; a solution capable of presenting key data from a selection of complex and often unstructured documents is necessary. For a solution to be valuable during the daily tasks of commissioning, it must, in addition to being able to present the necessary data, be non-obstructive to the user. Extended reality technologies present a new paradigm of human computer interaction, and can be utilized to present data in revolutionary ways. Extended reality has been and currently is being adopted by various industries and is developing rapidly. Still, industrial extended reality solutions have traditionally leaned towards using optical see through devices, rather than video passthrough capable ones. Modern video passthrough has seen significant improvements over the last years, and should be considered as a candidate for industrial extended reality. The shipbuilding industry, especially for the purpose of commissioning tasks, has yet to fully adopt extended reality tech-

nologies. Another critical technology able to structure and fetch the data related to ship commissioning is artificial intelligence. Artificial intelligence has seen major development in recent times, and could be leveraged to support an extended reality headset in order to create an artificial intelligence enhanced extended reality tool for ship commissioning. This thesis provides a set of research questions discussing the viability and adoption of such a tool, as well as, presents a proof of concept. The proof of concept was tested and the results of the testing, as well as, the background information presented in the earlier chapters are then used to answer the research questions.

Research question one is presented as: "How can extended reality technologies be used as part of ship commissioning?". When examining the landscape of ship commissioning in Chapter 2, the common issues are presented as: challenges in managing the dispersed information brought on by the large scale of the shipbuilding process. Based on these common problems occurring during commissioning, Chapter 3 presents extended reality technologies as a way of expediting the process of displaying information required during commissioning tasks. A proof of concept which presents users two different tasks to complete while using an extended reality headset is devised and outlined in Chapter 5. The results of the testing are presented in Chapter 6. An analysis of the results conducted during Chapter 7 states that users reacted positively toward the proof of concept presented to them and could envision similar technology being implemented to the commissioning process.

Research question two extends the previous research question by asking: "How can extended reality technologies provide value for users in ship commissioning?". The end of Chapter 3 states, that by reducing time spent reading manuals and other documentations during commissioning, and especially the sea trial phase, by 30 minutes per day, a total 112 000 euros in cost savings over a week long sea trial could be achieved. Chapter 4 presents the use of artificial intelligence and especially natural

language processing as a tool for finding and summarizing large sets of information. In order to allow users to interface with the information compounded using artificial intelligence, Chapter 5 provides a set of requirements for an extended reality solution aimed at providing value during ship commissioning based on stakeholder analysis. The main features aimed at making the solution valuable for commissioning purposes are deemed as: automatically recognizing or remembering interfaces in the commissioning environment, being non-intrusive to work capacity and easy to use and learn for new users. Throughout Sections 5.3 and 5.4 the development of a hand tracking and video passthrough based virtual reality head mounted display solution is detailed. This proof of concept is presented to testers linked to the shipbuilding industry. Chapter 7 analyses and discusses results of the testing and concludes that the proof of concept was welcomed by users, met the requirements from a technical point of view in terms of passthrough and tracking quality, required further software development to iron out bugs, and provided users useful information with the assistance of artificial intelligence. Based on these findings, an extended reality solution capable of providing users context information on interfaces present in the commissioning environment with the use of artificial intelligence, without intruding the users workflow by allowing them to keep their hand free by utilizing hand tracking, and maintain awareness of their surroundings by relying on video passthrough, would provide value during commissioning.

Research question three is presented as: "Which current extended reality technologies are best suited for ship commissioning?". The type of extended reality solution detailed in the previous paragraph sets the following requirements for an extended reality tool suited for ship commissioning. The main technical features required are: passthrough or see through, and hand tracking capability. A list of modern, popular extended reality platforms (see Table 5.1) suited for the is offered in Chapter 5. Based on the requirements for the wanted solution, the finalist de-

vices were the Quest 3 by Meta, the Vision Pro by Apple, the Magic Leap 2, and the HoloLens 2 by Microsoft. All the finalist platforms were head mounted displays utilizing either of the two perception technologies and capable of hand tracking. The finalist platforms can be divided into: video passthrough VR and optical see through AR devices. Video passthrough devices were chosen as the target platform for the proof of concept due to their status as an emerging technology and their improved field of view when compared to the optical see through counterparts. In terms of capabilities, though, any of either the video passthrough, or optical see through, devices would fill the technical requirements for suitability for ship commissioning purposes.

Research question four asks: "How can artificial intelligence be used to enhance extended reality solutions aimed for ship commission?". As discussed in Chapter 4, artificial intelligence has multiple applications in extended reality technologies, and can be further implemented to support the commissioning process. Chiefly, as detailed in Section 4.2, many of the features, like hand tracking, which are considered crucial for a commissioning tool, leverage artificial intelligence to function properly. Additionally, as discussed in Section 4.3, recent advancements in large language model and natural language processing technology have enabled the use of artificial intelligence to analyze and convey information from documents such as technical manuals. These capabilities are employed in the proof of concept detailed in Chapter 5, which was presented to testers in order to evaluate the viability of the solution. Analysis and discussion of the results of the testing is presented in Chapter 7. The results show, that users found the quality of the artificial intelligence generated instructions to be good, they would have preferred increased interaction with the instructions (in the form of an artificial intelligence assistant), and that preferences for the form (text/spoken) in which content was received varied greatly between users.

---

To conclude, a proof of concept extended reality solution was presented to testers linked with the shipbuilding industry. Based on the testing results, extended reality solutions allowing for hands free operability achieved by hand tracking, combined with stand alone platforms capable of tracking their surroundings, are a promising prospect for ship commissioning. When these extended reality solutions are combined with artificial intelligence, capable of compounding and retrieving wanted information, these prospects are further increased. Despite the promising results of the proof of concept, further development is required before the solution can be adopted. Areas of future work include: honing the software to account for the diverse nature of potential users (especially in terms of user height), further developing the interactions with virtual content (especially virtual dials and buttons), and removing the hand tracking visualization animations from the solution. Additionally, in order to deploy the solution in actual ship commissioning, real world targets present in the commissioning setting are required. To identify these targets, co-development with the potential end user is required. A co-development project has been started as part of the Virtual Sea Trial research project, and it will expand upon the proof of concept presented in this thesis.

# References

- [1] R. Carter, “Boat remains and maritime trade in the persian gulf during sixth and fifth millennia bc.”, *Antiquity*, vol. 80, Mar. 2006. DOI: 10.1017/S0003598X0009325X.
- [2] M. Elnadi and Y. O. Abdallah, “Industry 4.0: Critical investigations and synthesis of key findings”, *Management Review Quarterly*, vol. 74, no. 2, pp. 711–744, Jun. 1, 2024, ISSN: 2198-1639. DOI: 10.1007/s11301-022-00314-4.
- [3] “Development of applied research platforms for autonomous and remotely operated systems”, ISSN: 1457-7925. [Online]. Available: <http://www.theseus.fi/handle/10024/815628>.
- [4] *Virtual Sea Trial – Software Engineering Laboratory*. [Online]. Available: <https://tt.utu.fi/sweng/virtual-sea-trial/> (visited on 06/14/2024).
- [5] M. Virta, *HVAC Commissioning Guidebook (1st ed.)* 2021, pp. 5–6. DOI: 10.1201/9781003173014.
- [6] H. Pepliński, *Ship and Mobile Offshore Unit Automation - A Practical Guide*. Elsevier, 2019, pp. 159–160, ISBN: 978-0-1281-8723-4. [Online]. Available: <https://app.knovel.com/hotlink/toc/id:kpSM0UAAP2/ship-mobile-offshore/ship-mobile-offshore>.
- [7] O. Berndt, U. von Lukas, and A. Kuijper, “Functional modelling and simulation of overall system ship - virtual methods for engineering and commissioning

- in shipbuilding”, in *European Conference on Modelling and Simulation*, 2015. [Online]. Available: <https://api.semanticscholar.org/CorpusID:6970252>.
- [8] Caterpillar inc., *Marine Commissioning Procedure and Sea Trial Guide*. 2018, pp. 7–8. [Online]. Available: [https://www.pon-cat.com/application/files/5616/7524/4531/LEBM0025\\_-\\_Marine\\_Commissioning\\_Procedure.pdf](https://www.pon-cat.com/application/files/5616/7524/4531/LEBM0025_-_Marine_Commissioning_Procedure.pdf).
- [9] J. C. Reilly, *Christening, Launching, and Commissioning of U.S. Navy Ships*, Jan. 2021. [Online]. Available: <https://www.history.navy.mil/research/histories/ship-histories/christening-launching-and-commissioning-of-u-s-navy-ships.html>.
- [10] CIE Manufacturing. “How container ship sizes have grown over time | cie manufacturing”. (Jun. 29, 2021), [Online]. Available: <https://ciemufacturing.com/how-container-ship-sizes-have-grown-over-time/> (visited on 11/07/2024).
- [11] *Virtual sea trial project plan*.
- [12] H. Pepliński, *Ship and Mobile Offshore Unit Automation - A Practical Guide*. Elsevier, 2019, pp. 467–484, ISBN: 978-0-1281-8723-4. [Online]. Available: <https://app.knovel.com/hotlink/toc/id:kpSM0UAAP2/ship-mobile-offshore/ship-mobile-offshore>.
- [13] *Data growth worldwide 2010-2025 | Statista*, Nov. 2023. [Online]. Available: <https://www.statista.com/statistics/871513/worldwide-data-created/> (visited on 05/25/2024).
- [14] *Global big data industry market size 2011-2027 | Statista*, Feb. 2024. [Online]. Available: <https://www.statista.com/statistics/254266/global-big-data-market-forecast/> (visited on 05/25/2024).

- 
- [15] *Topic: Big data*, Mar. 2024. [Online]. Available: <https://www.statista.com/topics/1464/big-data/#topic0verview> (visited on 05/25/2024).
- [16] S. K. Card, T. P. Moran, and A. Newell, *The Psychology of Human-Computer Interaction*. May 2018. DOI: 10.1201/9780203736166.
- [17] P. A. Rauschnabel, R. Felix, C. Hinsch, H. Shahab, and F. Alt, “What is XR? Towards a Framework for Augmented and Virtual Reality”, *Computers in human behavior*, vol. 133, p. 107289, Aug. 2022. DOI: 10.1016/j.chb.2022.107289.
- [18] P. Milgram and F. Kishino, “A taxonomy of mixed reality visual displays”, *IEICE Trans. Information Systems*, vol. vol. E77-D, no. 12, pp. 1321–1329, Dec. 1994.
- [19] *The first VR device, Sensorama, created by Morton Heilig. | IEEE Communications Society*. [Online]. Available: <https://www.comsoc.org/node/19151> (visited on 06/01/2024).
- [20] I. Thomas A. Furness, “The super cockpit and its human factors challenges”, *Proceedings of the Human Factors Society Annual Meeting*, vol. 30, no. 1, pp. 48–52, 1986. DOI: 10.1177/154193128603000112.
- [21] H. VIVE, *VIVE European Union | Discover Virtual Reality Beyond Imagination*. [Online]. Available: <https://www.vive.com/eu/> (visited on 11/18/2024).
- [22] *Meta*, 2024. [Online]. Available: <https://www.meta.com/> (visited on 11/18/2024).
- [23] *XR market size worldwide 2021-2026 | Statista*, Mar. 2023. [Online]. Available: <https://www.statista.com/statistics/591181/global-augmented-virtual-reality-market-size/> (visited on 06/01/2024).

- 
- [24] C. Ball, K.-T. Huang, and J. Francis, “Virtual reality adoption during the covid-19 pandemic: A uses and gratifications perspective”, *Telematics and Informatics*, vol. 65, p. 101728, 2021, ISSN: 0736-5853. DOI: <https://doi.org/10.1016/j.tele.2021.101728>.
- [25] Apple, *Apple Vision Pro*. [Online]. Available: <https://www.apple.com/apple-vision-pro/> (visited on 06/14/2024).
- [26] *Snapchat daily active users 2024 | Statista*, May 2024. [Online]. Available: <https://www.statista.com/statistics/545967/snapchat-app-dau/> (visited on 06/02/2024).
- [27] *XR headset market share by quarter 2023 | Statista*, Apr. 2024. [Online]. Available: <https://www.statista.com/statistics/1222146/xr-headset-shipment-share-worldwide-by-brand/> (visited on 06/02/2024).
- [28] Apple, *Apple Vision Pro - Technical Specifications*. [Online]. Available: <https://www.apple.com/apple-vision-pro/specs/> (visited on 06/14/2024).
- [29] *Meta Quest 3*, 2024. [Online]. Available: <https://www.meta.com/ai/en/quest/quest-3/> (visited on 06/14/2024).
- [30] *Meta Quest Pro*, 2024. [Online]. Available: <https://www.meta.com/ai/en/quest/quest-pro/> (visited on 06/14/2024).
- [31] *PlayStation VR2 tech specs*, 2024. [Online]. Available: <https://www.playstation.com/en-us/ps-vr2/ps-vr2-tech-specs/> (visited on 06/14/2024).
- [32] *Live the Game with PICO 4 All-in-One VR Headset | PICO Global*. [Online]. Available: <https://www.picoxr.com/global/products/pico4> (visited on 06/14/2024).
- [33] J. P. Rolland and H. Fuchs, “Optical versus video see-through head-mounted displays in medical visualization”, *Presence*, vol. 9, no. 3, pp. 287–309, 2000. DOI: 10.1162/105474600566808.

- [34] J. Rolland, R. Holloway, and H. Fuchs, “Comparison of optical and video see-through, head-mounted displays”, *Proceedings of SPIE - The International Society for Optical Engineering*, Jan. 1994. DOI: 10.1117/12.197322.
- [35] *HoloLens 2—Overview, Features, and Specs | Microsoft HoloLens*. [Online]. Available: <https://www.microsoft.com/en-us/hololens/hardware#document-experiences> (visited on 06/14/2024).
- [36] *Magic Leap 2*, 2023. [Online]. Available: <https://www.magicleap.io/magic-leap-2> (visited on 06/14/2024).
- [37] I. Society, *A brief history of the internet - internet Society*, May 2024. [Online]. Available: <https://www.internetsociety.org/internet/history-internet/brief-history-internet/> (visited on 06/05/2024).
- [38] D. M. Herold, M. Cwiklicki, K. Pilch, and J. Mikl, “The emergence and adoption of digitalization in the logistics and supply chain industry: An institutional perspective”, *Journal of Enterprise Information Management*, 2021, ISSN: 1741-0398. DOI: 10.1108/JEIM-09-2020-0382.
- [39] *XR Industry Insider: 2021 XR Survey*. [Online]. Available: <https://www.perkinscoie.com/content/designinteractive/xr2021/> (visited on 06/18/2024).
- [40] L. Adriana Cárdenas-Robledo, Ó. Hernández-Uribe, C. Reta, and J. Antonio Cantoral-Ceballos, “Extended reality applications in industry 4.0. – a systematic literature review”, *Telematics and Informatics*, vol. 73, p. 101 863, 2022, ISSN: 0736-5853. DOI: <https://doi.org/10.1016/j.tele.2022.101863>.
- [41] U. von Lukas, M. Vahl, and B. Mesing, “Maritime applications of augmented reality – experiences and challenges”, in *Virtual, Augmented and Mixed Reality. Applications of Virtual and Augmented Reality*, R. Shumaker and S. Lackey, Eds., Cham: Springer International Publishing, 2014, pp. 465–475, ISBN: 978-3-319-07464-1.

- [42] P. Fraga-Lamas, T. M. Fernández-Caramés, Ó. Blanco-Novoa, and M. A. Vilar-Montesinos, “A review on industrial augmented reality systems for the industry 4.0 shipyard”, *IEEE Access*, vol. 6, pp. 13 358–13 375, 2018. DOI: 10 .1109/ACCESS.2018.2808326.
- [43] G. Šikić, “Using virtual reality paradigm to present ship structures in cad environment”, Cited by: 3, vol. 2, 2017, pp. 18–25. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85064516771&partnerID=40&md5=4d582a07f884e78abff702c1c29ddcf1>.
- [44] R. Pérez Fernández and V. Alonso, “Virtual reality in a shipbuilding environment”, *Advances in Engineering Software*, vol. 81, pp. 30–40, 2015, ISSN: 0965-9978. DOI: <https://doi.org/10.1016/j.advengsoft.2014.11.001>.
- [45] K. Shankhwar, T.-J. Chuang, Y.-Y. Tsai, and S. Smith, “A visuo-haptic extended reality-based training system for hands-on manual metal arc welding training”, *The International Journal of Advanced Manufacturing Technology*, vol. 121, Jul. 2022. DOI: 10.1007/s00170-022-09328-4.
- [46] A. Vidal-Balea, O. Blanco-Novoa, P. Fraga-Lamas, M. Vilar-Montesinos, and T. M. Fernández-Caramés, “A collaborative augmented reality application for training and assistance during shipbuilding assembly processes”, *Proceedings*, vol. 54, no. 1, 2020, ISSN: 2504-3900. DOI: 10.3390/proceedings2020054004. [Online]. Available: <https://www.mdpi.com/2504-3900/54/1/4>.
- [47] *Introducing ChatGPT*, Nov. 2022. [Online]. Available: <https://openai.com/index/chatgpt/> (visited on 07/02/2024).
- [48] R. Forghani, *Machine Learning and Other Artificial Intelligence Applications, An Issue of Neuroimaging Clinics of North America*. 2020, vol. 30, pp. 393–394, ISBN: 9780323712453. [Online]. Available: <https://shop.elsevier.com/books/machine-learning-and-other-artificial-intelligence-appli>

- cations-an-issue-of-neuroimaging-clinics-of-north-america/forghani/978-0-323-71244-6.
- [49] *Artificial intelligence*. DOI: 10.1093/oi/authority.20110803095426960.
- [50] Statista, *Artificial Intelligence - Global | Statista Market Forecast*. [Online]. Available: <https://www.statista.com/outlook/tmo/artificial-intelligence/worldwide> (visited on 07/02/2024).
- [51] *Data Suggests Growth in Enterprise Adoption of AI is Due to Widespread Deployment by Early Adopters*, Jan. 2024. [Online]. Available: <https://newsroom.ibm.com/2024-01-10-Data-Suggests-Growth-in-Enterprise-Adoption-of-AI-is-Due-to-Widespread-Deployment-by-Early-Adopters> (visited on 07/02/2024).
- [52] D. Reiners, M. R. Davahli, W. Karwowski, and C. Cruz-Neira, “The combination of artificial intelligence and extended reality: A systematic review”, *Frontiers in Virtual Reality*, vol. 2, 2021, ISSN: 2673-4192. DOI: 10.3389/frvri.2021.721933.
- [53] J. Hesch, A. Kozminski, and O. Oskar Linde, *Powered by AI: Oculus Insight*, 2024. [Online]. Available: <https://ai.meta.com/blog/powered-by-ai-oculus-insight/> (visited on 07/02/2024).
- [54] T. Hirzle, F. Müller, F. Draxler, M. Schmitz, P. Knierim, and K. Hornbæk, “When XR and AI Meet - A Scoping Review on Extended Reality and Artificial Intelligence”, Apr. 2023, pp. 1–45. DOI: 10.1145/3544548.3581072. [Online]. Available: <https://doi.org/10.1145/3544548.3581072>.
- [55] K. Power, “Stakeholder identification in agile software product development organizations: A model for understanding who and what really counts”, in *2010 Agile Conference*, 2010, pp. 87–94. DOI: 10.1109/AGILE.2010.17.

- [56] G. Lucassen, F. Dalpiaz, J. M. E. M. v. d. Werf, and S. Brinkkemper, “The use and effectiveness of user stories in practice”, in *Requirements Engineering: Foundation for Software Quality*, M. Daneva and O. Pastor, Eds., Cham: Springer International Publishing, 2016, pp. 205–222, ISBN: 978-3-319-30282-9.
- [57] *Protek P-3502C User/Service Manual*, Feb. 2024. [Online]. Available: [https://archive.org/details/protek\\_p-3502c\\_user\\_sm/mode/2up](https://archive.org/details/protek_p-3502c_user_sm/mode/2up) (visited on 11/21/2024).
- [58] HTC, *VIVE Pro 2 Headset - High-Resolution Virtual Reality for PC*, 2024. [Online]. Available: <https://www.vive.com/us/product/vive-pro2/overview/> (visited on 11/21/2024).
- [59] *Unity Real-Time Development Platform | 3D, 2D, VR & AR Engine*. [Online]. Available: <https://unity.com/> (visited on 11/21/2024).
- [60] *Unreal Engine*, 2024. [Online]. Available: <https://www.unrealengine.com/en-US> (visited on 11/21/2024).
- [61] *Meta XR All-in-one SDK*, Aug. 2024. [Online]. Available: <https://developer.oculus.com/downloads/package/meta-xr-sdk-all-in-one-upm/> (visited on 09/05/2024).
- [62] Blender Foundation. “About — blender.org”. (), [Online]. Available: <https://www.blender.org/about/> (visited on 11/21/2024).
- [63] E. L.-C. Law, V. Roto, M. Hassenzahl, A. P. Vermeeren, and J. Kort, “Understanding, scoping and defining user experience: A survey approach”, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '09, Boston, MA, USA: Association for Computing Machinery, 2009, pp. 719–728, ISBN: 9781605582467. DOI: 10.1145/1518701.1518813.

- 
- [64] A. Joyce, *10 Usability heuristics applied to virtual reality*, Jul. 2021. [Online]. Available: <https://www.nngroup.com/articles/usability-heuristics-virtual-reality/> (visited on 07/15/2024).
- [65] J. Nielsen, *10 Usability heuristics for user interface design*, Feb. 2024. [Online]. Available: <https://nngroup.com/articles/ten-usability-heuristics> (visited on 07/15/2024).
- [66] *Meta Quest casting*, 2024. [Online]. Available: <https://www.oculus.com/casting> (visited on 11/21/2024).
- [67] J. Brooke, "Sus: A quick and dirty usability scale", *Usability Eval. Ind.*, vol. 189, Nov. 1995.