Heads Up! Supporting Maritime Navigation using Augmented Reality

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Abstract

Augmented Reality (AR) is a technology that shows potential for the improvement of maritime safety. Today, the ship bridge suffers from a lack of standardization and integration. Head-Mounted Displays (HMDs) may alleviate these challenges by showing information when relevant and enhancing operator mobility. Microsoft HoloLens 2 (HL2) is such a HMD. Prior research shows the potential of HMDs in the *Maritime AR* domain (Rowen et al., 2019). Limited research has been conducted however on the design of AR User Interfaces (UIs) for maritime applications leveraging HMDs. As a result, no framework exists to test new UI designs in the real world, which is necessary due to many variables that cannot be accurately modelled in a lab setting. This led to the Research Questions (RQs) 1. *What makes an effective head-mounted AR UI for maritime navigation?* (RQ1); and 2. *How can HL2 be used as a ship bridge system?* (RQ2)

A Research through Design (RtD) process is detailed where a UI design and functional prototype was developed in collaboration with end-users. The prototype, named *Sjør*, implements the aforementioned interface, provides a framework for in-context UI testing and can be viewed as the next step towards standardizing AR UIs for the maritime industry. The design and development process led to three contributions to the Maritime AR domain. Firstly, a framework for the visualization of location-based data about points of interest on predefined canvases co-located in the real world was developed (Technology Readiness Level (TRL) 6), which runs on the HL2. This first contribution is defined in Section 4 and provides an answer to RQ2. Secondly, using this framework, an interface design (including interactions) is developed in collaboration with end-users and proposed as an answer to RQ1. This process is described in Section 5. The third contribution is a research agenda which provides insights into how contemporary and future research can leverage the developed framework. Section 7 discloses this research agenda.

List of acronyms

2D	Two-Dimensional
3D	Three-Dimensional
AHO	The Oslo School of Architecture and Design
AIS	Automatic Identification Systems
API	Application Programming Interface
AR	Augmented Reality
ARPA	Automatic Radar Plotting Aid
ATC	Air Traffic Control
BCR	Bow Crossing Range
BCT	Bow Crossing Time of target
BR	Body-Relative
BRG	Vessel True Bearing
CCTV	Closed-Circuit Television
COG	Course Over Ground
CPA	Closest Point of Approach
DGT	Draught
DP	Dynamic Positioning
DTO	Data Transfer Object
EBL	Electronic Bearing Line
ECDIS	Electronic Chart Display and Information System
FOV	Field of View
FPS	Frames Per Second
FSD	Functionally Separate Display

GPRMC	Global Positioning
GPS	Global Positioning System
HCD	Human-Centered Design
HDG	Heading
HDT	Head-Down Time
HL	Microsoft HoloLens
HL1	Microsoft HoloLens 1
HL2	Microsoft HoloLens 2
HMD	Head-Mounted Display
HUD	Head-Up Display
ID	Integrated Display
Immeks	Immersive Media Experiments
M-AR	Marine Augmented Reality
MAR	Monitor Augmented Reality
MBS	Multivendor Bridge System
MRTK	Mixed Reality Toolkit
MVP	Minimum Viable Product
OICL	Ocean Industries Concept Lab
PSV	Platform Supply Vessel
RNG	Vessel Range
RNoN	Royal Norwegian Navy
RQ	Research Question
RQ1	Research Question 1
RQ2	Research Question 2
RtD	Research through Design
SA	Situation Awareness
SEDNA	"Safe maritime operations under extreme conditions: the Arctic case"
SOG	Speed Over Ground
SR	Screen-Relative

SSD	Spatially Separate Display
SUS	System Usability Scale
TCPA	Time to Closest Point of Approach
TRL	Technology Readiness Level
TSA	Team Situation Awareness
UFO	Unidentified Floating Object
UI	User Interface
UML	Unified Modeling Language
VR	Virtual Reality
VRM	Variable Range Marker
WIAR	Wearable, Immersive Augmented Reality
WLAN	Wireless Local Area Network
WR	World-Relative

Definitions

Clipping Plane	A clipping plane is a plane in 3D space where all (or parts of) Three-Dimensional (3D) objects that are positioned behind the clipping plane are made invisible (Qi and Martens, 2005).
Littoral Waters	Bodies of water close to the coast, which are often high traffic areas
Mental Model	A mental model is a form of knowledge that allow operators to describe, explain and predict phenomena within their environment (Rouse and Morris, 1984).
Minimum Viable Product	Minimum Viable Product (MVP) is a term used in the Scrum agile software development cycle to describe a piece of software that has just enough features to satisfy early customers and to provide feedback for future product development (Som de Cerff et al., 2018).
Situation Awareness	Situation Awareness (SA) is the ability to acquire and interpret information from an environment (Endsley, 1995).
Shared Mental Model	Shared mental models go beyond simply sharing task-specific knowledge. They illustrate a common organisation of knowledge, leading to a similar way of processing and communicating information (Mathieu et al., 2000).
Ship Bridge System	A ship bridge system is a piece of technology that is part of the ship bridge and integrates with vessel functionality
Team Situation Awareness	Team Situation Awareness (TSA) is defined as "the degree to which every team member possesses the SA required for his or her responsibility" (Endsley, 1995, p. 39).
Timestep	One update iteration in the Unity game engine, often

	$\frac{1}{60}$th of a second in a scene that is configured at 60 Frames Per Second (FPS)
Unified Modeling Language	Unified Modeling Language (UML) A language that has become widely accepted as a modeling standard for object-oriented software development (Dobing and Parsons, 2006).
Walking Skeleton	In the domain of software development, a walking skeleton is "a tiny piece of usable system function, very often not much more than the ability to add an item to the system database and then look at it" (Cockburn, 2004). As such, it depict the minimum software requirements to complete a transaction.

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Section 1

Introduction

For thousands of years humans have roamed the oceans and navigated waters with nothing more than the feeling of the wind and the sight of the stars. Exposure to the elements was a requirement for successful maritime navigation. Thereafter, environments began to be mapped out, which turned into information on which humans became dependent. Instead of watching the thrust trail behind the vessel and using the stars to navigate, the main object of focus became a paper chart. This technological advancements attempted to solve issues concerning navigation but introduced new challenges concerning the position of the own vessel on maps, diverting attention and introducing Head-Down Time (HDT), reducing the navigators' awareness of their surroundings. Recently, electronic charts have simplified relating vessel positions to the chart, but the reduced awareness of the environment persists. Additionally, the screens this information is communicated through pack usability challenges, such as hardly legible information and reduced operator mobility. These developments characterize a transition from being submerged in the maritime context to the avoidance of exposure altogether.

Augmented Reality (AR) is a technology that renders computer graphics directly into the real world (Azuma, 1997). Moreover, informational graphics can be superimposed on physical objects, showing information those objects in relation to the current position and direction of the user. As a result, AR simplifies the process of complying with core design principles, including affordances (Gibson, 1977) and mapping (Norman, 2013).

In recent years, AR technology has been applied in the maritime context. The domain that focuses on AR visualizations in a maritime context is named *Maritime AR*. Solutions that utilise a Closed-Circuit Television (CCTV) system with graphics overlaid on that image have been explored and developed (Leite et al., 2022; Bergström et al., 2018; Oh et al., 2016). Such solutions alleviate the challenge of relating information to objects in the real world. These systems are challenged by inherent flaws. Their fixed position on the bridge renders the user unable to move around whilst using the information and focus on such a screen distracts from the direct surroundings beyond the Field of View (FOV) of the camera capturing the scene. Operator mobility and the decrease of HDT would be better supported using Head-Mounted Displays (HMDs). The use of HMDs in the maritime context is an emerging field, but there has been a growth in contributions in this domain (Laera et al., 2021b).

Already existing practical implementations in the domain of Maritime AR are characterized by their lack of consistency among the different contributions, depicting the lack of a standard in interface designs. This is not the first time that the maritime domain desires standardization. Ocean Industries Concept Lab (OICL) (OICL, 2021) at the The Oslo School of Architecture and Design (AHO) proposed a design guideline that streamlines user interfaces across the traditional ship bridge (OpenBridge, 2022). Leveraging the experience OICL has gained about standardization in the maritime domain, a collaboration with domain experts at OICL was established. Before a standard for Maritime AR - more specifically, HMDs using AR - can be proposed however, a definition of what makes such an interface successful is required. Therefore, the first research question (RQ1) is: *What makes an effective head-mounted AR User Interface (UI) for maritime navigation?*

The many variables in a ship bridge environment are hard to model accurately. Therefore, a prerequisite for the definition and testing of an interface standard is that the interface can be evaluated in a ship bridge context. Software for Microsoft HoloLens 2 (HL2) (Microsoft, 2021a), a head-mounted AR display provided by TekLab (TekLab, 2021), was developed, enabling it as a testbed for the development of an AR UI relating to RQ1. The process of using HL2 on a ship bridge happened not to be trivial and therefore led to the definition of a second research question (RQ2): *How can the HL2 be used as a ship bridge system?*

This study aimed to close the gap between functional, monitor AR and the theoretical advantages of using HMDs on the ship bridge through the answering of the Research Questions (RQs). This study takes a Research through Design (RtD) approach that focuses on generating practice-based design knowledge encapsulated in a technological artefact (Zimmerman et al., 2007). Based on the data gathered throughout the RtD process, the RQs are answered and contributions to the field of head-mounted AR have been derived. These contributions include

1. a practical contribution of a framework supporting location-based information retrieval, visualization and interaction for HL2;
2. a hybrid contribution of a theoretical interface and interaction design and a practical, extendable implementation of said interface for HL2, designed in collaboration with OICL; and
3. a research agenda proposing different problem framings of the two aforementioned contributions.

The scope of this thesis work includes the development of a system that supports the evaluation of interface and interaction designs. To achieve a high level of accuracy of the placement of AR graphics, HL2 should be connected to the vessel directly. Although the framework developed supports this direct connection to the vessel through Wireless Local Area Network (WLAN), the scope of this study does not extend beyond 'best-effort'-precision of the system, meaning that slight misalignment of AR graphics should be expected.

Section 2

Background

2.1 Maritime Growth and Accidents

Over the last century, the number of seaborne vessel has almost quadrupled (Figure 2.1). During that time, the total transported tonnage has experienced a twentyfold increase (Allianz, 2021), caused by both increased vessel count and size. The maritime industry has become a high-stakes game in which accidents can have catastrophic consequences. Despite the growth rate of the maritime industry and the inevitably added complexity of problems occurring, the number of accidents remains stable. That depicts the improved maritime safety over the last century, enabled through technological advancement, better training and regulatory developments (Acejo et al., 2018; Allianz, 2021).

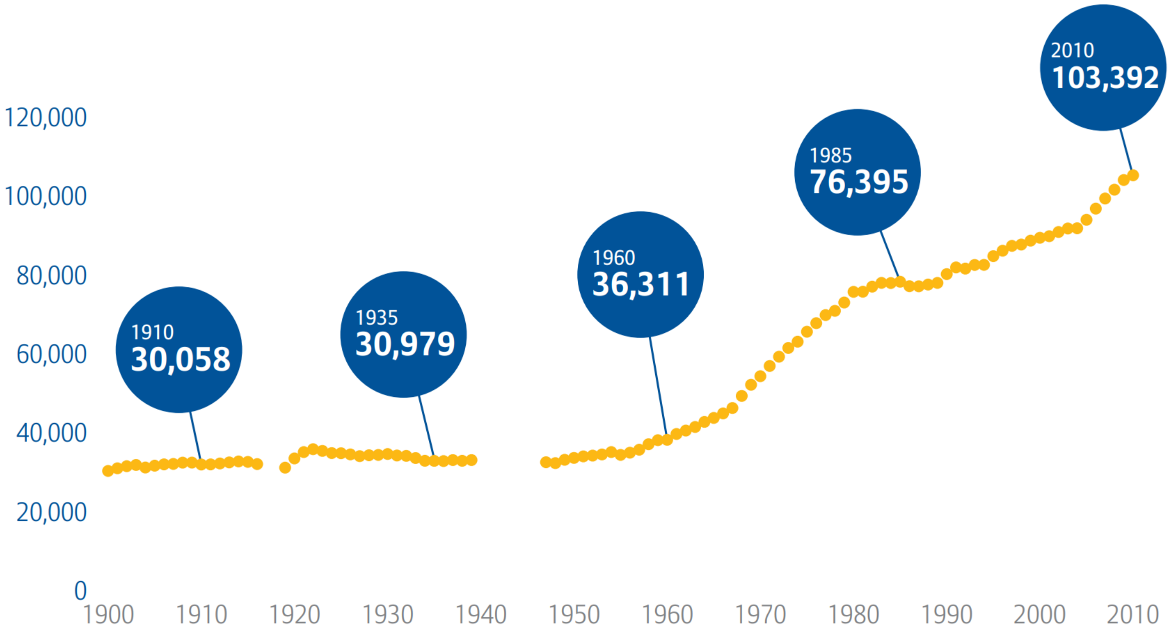


Figure 2.1: Growth in the world fleet size from 1910 to 2010 (Allianz, 2021)

In spite of increased safety measures, Acejo et al. (2018) report 693 accidents that occurred at sea during navigational or operational tasks in the period of 2002-2016. This number only includes accidents reported by the United Kingdom, Australia, US, Germany and Denmark. The majority of the accidents could be explained by human error leading to collision, grounding or another severe consequence (Acejo et al., 2018). In line with those findings, Rothblum (2000) reports that 75% to 96% of marine casualties are caused by human error. Human error in navigation and operations can potentially be mitigated by applying Human-Centered Design (HCD) to the maritime industry (Rothblum, 2000).

2.1.1 Usability Challenges on the Ship Bridge

Despite the introduction of standardization in ship bridge design (International Organization for Standardization, 2007) there is a lack of constraints which facilitates poor usability of the ship bridge (Mallam and Nordby, 2018; van Beek, 2021). This lack is exemplified by the "integrated ship bridge", which contains equipment from around 30 different manufacturers (Oltedal and Lützhöft, 2018; van Beek, 2021). Each creates their own design, which leads to a workflow with limited consistency (Guo et al., 2021) and redundancy across bridge systems (van Beek, 2021). Combining these factors with fatigue of the operators, it causes incorrect operation of electronic aids and thereby accidents (Guo et al., 2021). As such, the need for initiatives that streamline user interface design, such as OpenBridge (OpenBridge, 2022; Nordby et al., 2019) is identified.

A usability study of the ship bridge of high speed crafts was conducted by Hareide and Ostnes (2017) in which eye tracking was used to detect the fixations of the eyes of the operator (the operators "attention direction") on the environment. Challenges regarding tooling specific to high speed crafts are not relevant in this study. Nonetheless, the strategies used by the operator to navigate a vessel at high speeds are relevant at lower speeds (Hareide, 2020). Therefore, the findings from Hareide and Ostnes (2017) generalize to slower vessels too.

In their studies, Hareide and Ostnes (2017) observed the operators focus returning to the same point either directly or after a while. These phenomena are defined as a "backtrack" and a "revisit" respectively. They state that the main focus of an operator must be in the surroundings of the ship during littoral navigation. Threats to maintained attention to the surroundings have been identified. These threats include:

- The difficulty to understand and interpret heading information in the Automatic Radar Plotting Aid (ARPA), which is compensated by revisiting the ARPA to double-check information (Hareide and Ostnes, 2017); and
- A usability challenge indicated by the large number of backtracks located between outside and the Electronic Chart Display and Information System (ECDIS) (50%+). Moreover, most attention is draw to ECDIS chart, instead of the ships' surroundings (Hareide and Ostnes, 2017).

2.2 Mental Models

The definition of mental models used in this study is extended by Mathieu et al. (2000) with the belief that a mental model focuses on the structure of the knowledge, more than the knowledge itself. Therefore, they call mental models "individual knowledge structures" (Mathieu et al., 2000).

The focus on knowledge structure is endorsed by Johnson-Laird (1983), stating that extra information does not imply increased usefulness of the mental model beyond a certain level. E.g., there is no need to understand display technology if the only goal is to display images. As such, a mental model contains abstractions of the world. As long as abstractions function as expected, they reduce the complexity of a mental model. If not, a processing overhead to understand the misfire occurs. In short, a mental model is meta-knowledge that forms an inference engine an individual uses to infer current and future states of the environment.

Even when individuals are co-located in an environment, they can still construct distinct mental models. Sharing the same knowledge structure across individuals in the same environment is a characteristic of a high performance team: a concept called "a shared mental model" (Mathieu et al., 2000). When individuals have constructed similarly structured mental models, each individual can select actions coherent with the expected behaviour of others (Mathieu et al., 2000), improving team performance.

2.2.1 Situation Awareness

Situation Awareness (SA) leans strongly on the notion of mental models in its explanation. Mogford (1997, pg. 332) rightfully claims "a lack of distinction between mental models and SA". In this study, the definition of SA by Wickens (2002) is most fitting. Wickens describes spatial awareness, system awareness and task awareness as the three pillars for SA. These types of awareness respectively entail awareness of vessel position and factors that influence said position, awareness of the complexity of the system in use and awareness related to the current navigational task (Hareide, 2020). Similar to Air Traffic Control (ATC), a mature mental model is the foundation of the operators SA (Mogford, 1997) and this is likely to grow naturally within a watch as operators become more familiar and involved in the specific ambient setting (Sauer et al., 2002).

Like shared mental models, Banks and McKeran (2005) coin the term Team Situation Awareness (TSA). Communication is the pillar on which TSA is built (Banks and McKeran, 2005; Orasanu and Statler, 1994). For non-routine tasks however, Banks and McKeran (2005) found that solely communication is not sufficient. In addition to communication, they suggest the use of a shared physical display to facilitate TSA.

2.3 Vessel Movements

Vessel movements along and around the axes of the vessel have been formalized. This formalization is described by Haward et al. (2009) and depicted in Figure 2.2.

2.4 Augmented Reality (AR)

In recent years, a new technology that shows potential of alleviating human errors in the maritime context had its uprising. Augmented Reality (AR) is a technology that superimposes computer graphics upon the real world in real-time, essentially mixing a

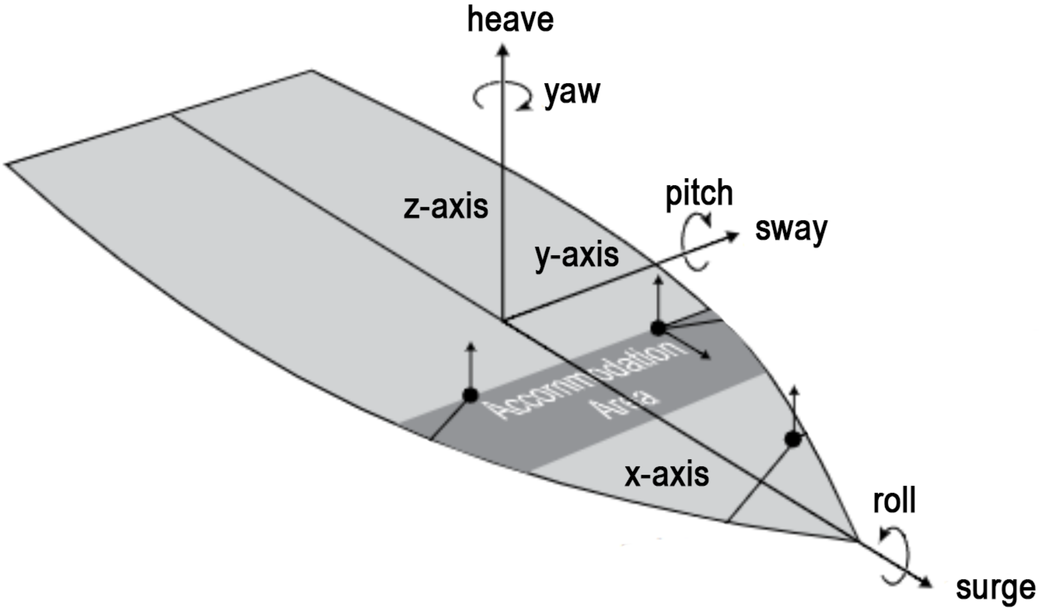


Figure 2.2: Movements of a vessel formalized. Rotation around the X, Y and Z axis are called roll, pitch and yaw respectively (Haward et al., 2009, fig. 1). The figure has been adapted by the author to include movements parallel to the respective axes, namely sway, surge and heave

digital world with the real world (Azuma, 1997). AR technology often scans the physical space around the user, allowing virtual objects to interact with physical objects in the real world (Figure 2.3). AR can be practised using various technologies, which can be distilled into using either of two display technologies: monoscopic and stereoscopic solutions (Laera et al., 2021a).

Monoscopic	Monoscopic AR can be practiced using a camera and display. The camera feed is displayed on the display, onto which an overlay is placed containing graphics that augment the original camera image. Monoscopic AR is exemplified by smartphone applications, such as Snapchat Filters (Oikonomou et al., 2021) and Pokémon Go (Althoff et al., 2016). Arguably, Head-Up Displays (HUDs) can be categorized as monoscopic AR.
Stereoscopic	Stereoscopic AR is depicted by Head-Mounted Displays (HMDs). HMDs are sets of glasses which can be worn by the user placing a transparent display in front of the their eyes. Recently, large technology companies have been pushing the development of HMDs that implement AR, such as Microsoft with the Microsoft HoloLens (HL) (Microsoft, 2021a), Magic Leap with its Magic Leap 1 (Magic Leap, 2021) and Snapchats Spectacles (Snap Inc., 2021).

Moreover, there is a large variation in placement and spatiality that characterizes AR assets. For example, AR graphics visualized by a HMD can be fixated to the rotation

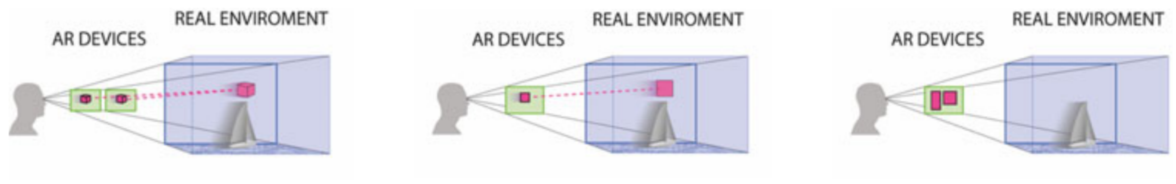
Figure 2.3: An example of AR showing a real desk and a virtual lamp and two virtual chairs (Azuma, 1997)

of the head of the user or be co-located in the real world. These graphics can be a Two-Dimensional (2D) visualization, mimicking a traditional screen in AR, or a 2D object, as depicted by the chairs in Figure 2.3. The spatiality of AR assets can be categorized in 6 groups by leveraging terminology coined by Laera et al. (2021a); the permutations of the characteristics of being either 2D or Three-Dimensional (3D) and being either World-Relative (WR), Body-Relative (BR), WR or a hybrid solution (H). This spatially is expounded upon in Table 2.1 and Figure 2.5.

2.4.1 Potential of AR in a Maritime Context

Accidents and usability challenges in the maritime world have been detailed. In short, it is the way technology is designed and integrated which is keeping operators from reaching their full potential. Therefore, it is key to look beyond state-of-the-art work practices exploring new uses of technology supporting ship bridge operators in their work. The most prominent of those technologies is AR. Lukas (2010) argues that there is no phase in the lifecycle of a seaborne structure that would not benefit from 3D modeling, simulation and AR. The goal for AR as a bridge system is to overlay key information onto the real world, reducing Head-Down Time (HDT) and increase SA (Hareide and Porathe, 2019). The introduction of such new technology can however have consequences for operator performance and decision-making

Figure 2.4: Microsoft HoloLens 2 (HL2) is the stereoscopic AR Head-Mounted Display (HMD) (Microsoft, 2021a) that is used in this study



(a) 3D World Relative *(b) 3D Screen Relative* *(c) 2D Screen Relative*

Figure 2.5: Illustration of spatiality of AR assets (Laera et al., 2021a). AR devices include both monoscopic and stereoscopic solutions.

(Grabowski et al., 2018). In this section, the theoretical usefulness of AR as a ship bridge system is described.

For an operator, it is most important to look outside (Hareide and Ostnes, 2017). Moreover, the ECDIS is the most important piece of technology on the ship bridge. Hareide and Ostnes (2017) reported both the difficulty of interpreting the ECDIS and the backtracking between the ECDIS and the outside. AR enables crucial information from ECDIS to be overlaid onto the real world, allowing the operator to look at both technology and outside simultaneously, potentially facilitating decision-making (Porathe, 2006). Additionally, this application of AR may reduce cognitive ergonomics (Guo et al., 2021), since a computer can supplant the spatial mapping from a 2D display to the 3D world.

The aforementioned advantage extends to the ability of graphics to mimic natural phenomena, such as the position of graphics on top of the physical object they provide information about or visualize movements using that same movement in AR graphics. When graphics follow natural laws, the mental model the operator develops can omit information about placement. Additionally, this enables the operator to approach the physical object itself to get information about that object, facilitating goal-directed behaviour. In short, AR enables the coupling between human experience and intuition with the computational power of computers (Sielhorst et al., 2008). Therefore, SA is more easily maintained (Endsley, 1995).

Sauer et al. (2002) investigated the benefits of different display types on a ship bridge,

Table 2.1: Spatiality of AR assets (Laera et al., 2021a)

Spatiality	Frame of Reference	Explanation
2D	World-relative (WR)	A single planar area co-located in the world. These are perceived as a HUD.
	Screen-relative (SR)	A single planar area fixed onto the screen. These are perceived similarly to 3D Screen-Relative (SR) (Figure 2.5c).
	Body-relative (BR)	A single planar area fixed to the body position (and possibly body rotation).
3D	World-relative (WR)	3D objects co-located in the world (Figure 2.5a).
	Screen-relative (SR)	3D object fixed onto the screen. These are perceived similarly to 2D SR (Figure 2.5b).
	Body-relative (BR)	3D object fixed to the body position (and possibly body rotation).

distinguishing between an Integrated Display (ID) (single display that combines the ARPA and ECDIS), a Functionally Separate Display (FSD) (single display that switches between ARPA and ECDIS) and a Spatially Separate Display (SSD) (pair of displays that show ARPA and ECDIS respectively). The ID showed superior navigational performance at the cost of increased levels of concentration. The comparison between the FSD and the SSD brings to light the context switch overhead of the FSD, rendering the SSD superior due to its continuous information availability. Smeaton et al. (1995) too report the benefit of IDs over traditional bridge systems in collision avoidance and mapping manoeuvres against a navigational chart. These studies illustrate the good practice of combining relevant types of information in a single display to reduce cognitive load. Thus, evidence is provided for the benefit of overlaying graphics onto the real world using AR.

Another area that AR can improve is organisational ergonomics (Guo et al., 2021). Currently, operators undergo a long training process to learn where information is located on the bridge and how to operate that technology. Simplifying this process, Frydenberg et al. (2018) argue for the internal movement of an operator on the ship bridge. They state that using AR, the information could appear on-demand, vanishing when irrelevant. This reduces distractions, increases operator mobility and helps to attain and maintaining SA (Rowen et al., 2021).

Collaboration on the ship bridge may also benefit from the use of AR. Banks and McKeran (2005) proved that sharing a physical screen improved TSA. Despite that AR displays are head-mounted and personal, the same graphics are visualized in different glasses, simulating a single shared display. This correspondence can improve shared mental models and thus TSA on ship bridges. Moreover, by highlighting real-life landmarks in AR, AR provides crew members with a precise vocabulary to discuss their surrounding. In AR, one operator could mark a point of interest, which shows in the glasses of other operators. This definite type of communication can supercharge the exchange and development of shared mental models on the ship bridge (Orasanu and Statler, 1994) and thus TSA.

2.5 Technology Readiness Levels (TRLs)

The use of AR - HMDs in particular - on the ship bridge is still a novelty. Introduction of this new technology requires a vocabulary to describe the maturity of the specific solution at hand, such that implementations can be compared. Technology Readiness Levels (TRLs) (Horizon 2020, 2014) provide such a common language for discussing the maturity of new technology, both within and between different domains (Hareide, 2020). This exchange is important, since knowledge about a new technology in one domain can generalize to other domains.

There are 9 different TRLs, as described in Table 2.2. TRLs range from merely an idea (TRL 1) and paper prototypes (TRL 3) to full implementations of a system, validated in context (TRL 9). A high TRL entails a product of high-fidelity and facilitates real-world testing, which is vital in domains where the physical environment cannot be simulated effectively. Moreover, a high TRL using end-hardware enables the exploration of native interaction methods, such as gestures, voice and eye-tracking; features that are not offered when designing interfaces in common prototyping tools, such as Figma (Figma, 2021).

The maritime domain is such a domain, where HL has reached TRL level 6 (Hareide, 2020). However, the majority of recent research using stereoscopic AR solutions is still rudimentary, sporting a TRL of 2 (Laera et al., 2021a). On the other hand have monoscopic AR solutions in the maritime domain reached a TRL of 8, as argued by Hareide (2020) and Oh et al. (2016).

In other domains, the TRL of AR exceeds the TRL of the maritime domain. In the gaming industry, HL has a TRL of 8 (Itzstein et al., 2019). Solely focusing on the TRL of monoscopic AR solutions reveals a TRL of 9 in the aviation industry (Hareide, 2020).

The Royal Norwegian Navy (RNoN) published its intentions of pushing the TRL of stereoscopic AR in the maritime industry to level 7. No further reports have been published however. With that, the importance of enabling technology for the achievement of higher TRLs in the maritime domain is depicted. This study aims to provide such enabling technology by implementing, among others, 3D WR AR assets visualizing real-time information.

Table 2.2: Technology Readiness Levels (TRLs) (Horizon 2020, 2014)

TRL	TRL Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

2.6 Existing AR Systems

Over the past two decades, AR has been considered as a technology supporting maritime operation (Hugues et al., 2010; May, 2004). The idea to take charts out of their 2D canvas and display them in a 3D perspective dates back even further (Porathe, 2006). Since then, a handful of institutions have picked up AR as a viable technology in both research and commercial settings. This section features a critical approach to the research and products published throughout recent years.

2.6.1 Commercial Systems

Commercially, Furuno Product Solutions (2019) has released a monoscopic AR navigation system they call "Envision", as shown in Figure 2.6. The Envision system can be considered the state-of-the-art. It consists of a camera facing the bow of the ship and monitor placed on the bridge. Navigational information is overlaid onto the video feed. Furuno Product Solutions (2019) deems that this is a "very intuitive way to display and share information between captain and the bridge team that provides enhanced situational awareness". This system does however not reduce HDT and its effectiveness can therefore be questioned (Hareide and Porathe, 2019). Envision combines 2D SR graphics with 2D and 3D WR assets, showing - among other things - Automatic Identification Systems (AIS) information, route and waypoint information and no-go areas Porathe and Billesø (2015). The system suffers from the same limitations as the RNoN HUD implementation. In addition, the Envision system is overlaying information on the water surface. This area should only contain a limited amount of information, because it might obstruct important. Furuno Envision can be installed on vessel today, but it is unclear if the system qualified or has been installed on vessels in operation. Therefore, no TRL can be assigned.

Ulstein (2013)) undertook an elaborate design process in designing Ulstein Bridge Vision (Figure 2.7), which was awarded with DNB's Innovation Award 2012. In collaboration with designers at The Oslo School of Architecture and Design (AHO) they designed a ship bridge that utilises HUDs that incorporate all bridge functions. The system designed by Ulstein uses 2D SR graphics. Ulstein Bride Vision is beyond the state-of-the-art and shows what the ship bridge can look like in the future. For now, it is a design concept that has not been implemented yet. Therefore, it receives a TRL of 2.

AR is not solely being applied as navigational aid, but also has other use-cases on a vessel. Wärtsilä Corporation (2016) uses stereoscopic AR as assisting tool for operations on vessels. Recently, Wärtsilä has also moved into the field of hands-free remote collaboration with onshore experts using AR (Wärtsilä Corporation, 2018).

2.6.2 Academic Prototypes

While industry had to adopt the field-ready monoscopic AR technology (Laera et al., 2021a), the research community has been exploring stereoscopic AR following the technological developments in hardware supporting stereoscopic AR, such as the release of HL2 (Microsoft, 2021a).

Extensive research on the use of AR as a bridge system has been conducted by the RNoN in the Marine Augmented Reality (M-AR) project. In the M-AR project they explored both monoscopic AR using HUDs, reaching TRL 8 in the maritime domain and stereoscopic AR

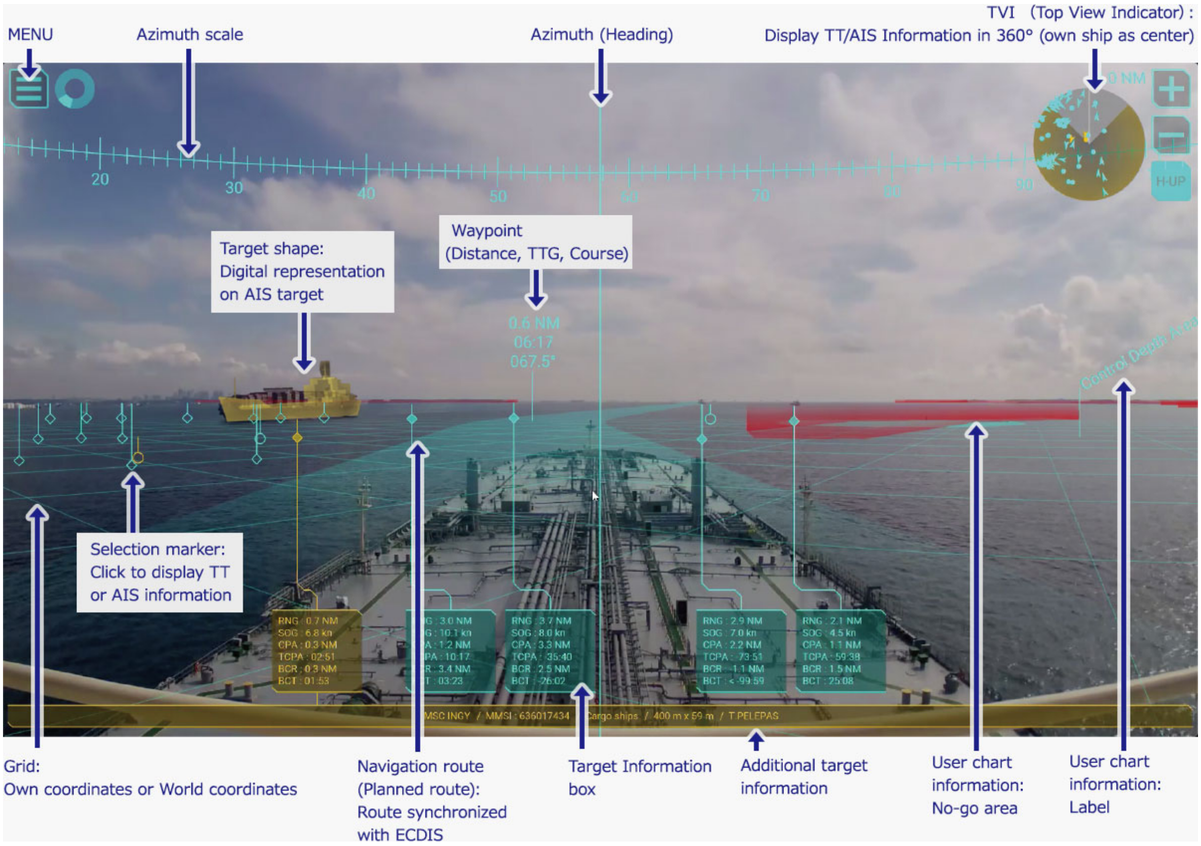


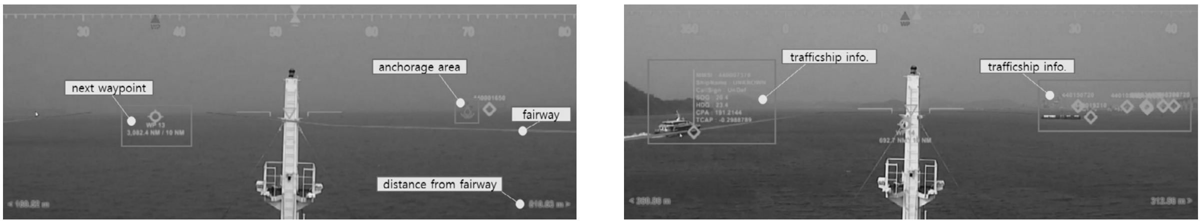
Figure 2.6: Furuno Envision AR Navigational System (Furuno Product Solutions, 2019)

using HL, reaching TRLs 6 in the maritime domain. The RNoN found that using HUDs imposes challenges concerning the difference in focal distance between the HUD itself and the obstacles outside. Additionally, HUDs suffer from light pollution in the dark (Hareide, 2020). The stereoscopic implementation of the RNoN appears to be in early stages and no further reports have been published yet.

Laera et al. (2021a) reviewed 11 scientific papers that concern AR systems for maritime navigation. Their review shows that within the maritime domain stereoscopic AR is a little explored field, with only three out of the 11 selected papers using an stereoscopic AR device. The TRL of those stereoscopic implementations does not exceed two, potentially due to a lack of frameworks that describe how maritime systems can be designed to enable efficient exploitation of AR on a ship bridge (Nordby et al., 2020). Since this study focuses on the visualization of AIS information and ARPA targets, the selected papers that implementation those are explored further; Oh et al., 2016; Lee et al., 2016; Frydenberg et al., 2018. Additionally, a recent paper on maritime navigational assistance by Leite et al. (2022) will be considered in this study.

Oh et al. (2016) present their monoscopic AR solution, combining 3D and 2D WR graphics with 2D SR AR assets (Figure 2.8). They visualized 12 informational elements in total, including compass, obstacle, heading, route, boat speed, latitude and longitude, waypoint, distance to waypoint, traffic information, course over ground, rudder angle and depth (Laera et al., 2021a). Their prototype was assessed in both a simulator and in a real ocean setting. The visualization of the information about ones own ship was rated high by the participants. On the other hand, traffic information received a low score, presumably because of the difficulty in distinguishing data due to excessive amount of information displayed on the horizon. As a

Figure 2.7: Ulstein Bridge Vision (Ulstein, 2013)



(a) Traffic information *(b) ECDIS information*

Figure 2.8: AR prototype of navigational aids system showing traffic and ECDIS information (Oh et al., 2016)

consequence, information started overlapping (Oh et al., 2016). Oh et al. (2016) found participants to be sceptical about the workload required to use the new navigational equipment. Therefore, the importance of user interface optimization is emphasized.

Lee et al. (2016) take a more technical approach, proposing a computer vision application to locate nearby vessels (Figure 2.9). They argue that noise is produced by environmental factors (e.g., darkness, waves and sun-reflection) and therefore additional location-based information is required to recognize vessels. Finally, Lee et al. (2016) visualize AIS information in 2D WR assets and own ship information as 2D SR graphics, using a monoscopic AR technology. They do not propose a framework for data visualization.

Similar to Lee et al. (2016), Leite et al. (2021) describe a mathematical approach using computer vision to pinpoint objects on the ocean surface (Figure 2.10). They implement simple obstacle highlighting using bounding rectangles and zoomed-in views of the detected obstacles combining 3D WR with 2D SR respectively. Additionally, planar and circular areal highlighting is implemented; functionality that is similar to the ECDIS Electronic Bearing Line (EBL) and Variable Range Marker (VRM) functions. Leite et al. (2021) use this areal highlighting to visualize distances by dividing the highlighted area in grid cells of know dimensions. Despite their well-though-out concepts, Leite et al. (2021) do not propose a framework that builds on these concepts. Lastly, they argue that usability research on such a prototype should be per-

Figure 2.9: Rudimentary AR prototype outlining vessels using 2D WR graphics (Lee et al., 2016)

(a) Grid ocean overlay

(b) Zoomed-in view on obstacles

Figure 2.10: AR prototype of navigational aids system showing a planar grid overlaid on the water surface using 3D WR assets and an obstacle zoomed-in using 2D SR graphics (Leite et al., 2021)

formed in simulator, such that all geometrical parameters are known and AR can be accurate. This is a valid approach, but a more cost-effective usability test could be achieved by using Virtual Reality (VR) in accordance with Nordby et al. (2020) and more realistic evaluations should take place on the ship bridge itself.

Frydenberg et al. (2018) present five AR concepts for stereoscopic AR through which they attempt to gain an initial understanding of the problem space, containing among others visualizations of AIS information (Figure 2.11). They tested their concepts on crew members using the Microsoft HoloLens 1 (HL1) in the "Safe maritime operations under extreme conditions: the Arctic case" (SEDNA) project; an innovative and integrated risk-based approach for safe Arctic navigation, ship design and operation was (Frydenberg et al., 2021). Moreover, the gathered knowledge is formalized by in Nordby et al. (2020) who try to remedy the lack of AR framework and guidelines by suggesting a User Interface (UI) architecture with five application components (Figure 2.12) and five areas to pin that information (Figure 2.13).

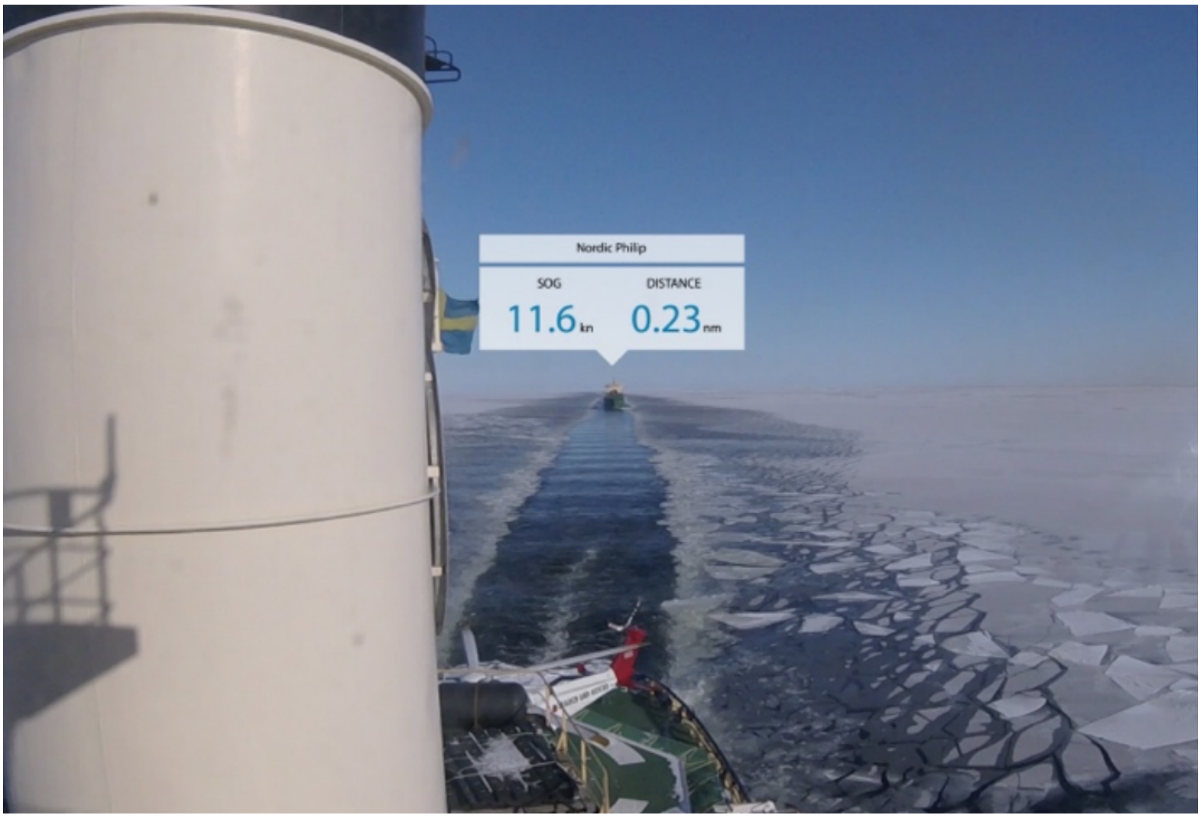


Figure 2.11: An AR prototype showing AIS information of a vessel using 2D WR graphics (Frydenberg et al., 2018)

2.7 Limitations of Current Research

Provided the novelty of the use of AR technology on the ship bridge, an unbiased, but critical approach is required, since previous research project provides mere guidelines to a solution and do not guarantee a definitive approach. Additionally, emerging fields benefit from an exploratory approach, as well as validation of solutions previously developed.

As depicted in this section, monoscopic displays have been favored in studies within the Maritime AR domain. Cutting and Vishton (1995) argue that monoscopic displays provide sufficient depth perception for objects located in *vista space*; objects that are located further than 70 meters away from the user. The reason for is the decreased importance of binocular disparity cues at longer distances (Cutting and Vishton, 1995). Therefore, monoscopic displays are suitable for the visualization of information at open sea, where distances generally exceed 70 meters. Maritime operations however - and littoral water navigation in particular - are often dynamic in nature where distances between obstacles can dip below 70 meters (Laera et al., 2021a). Therefore, stereoscopic displays should be favored over monoscopic displays to ensure applicability of the developed application across the ship bridge.

Laera et al. (2021b) argue that the real limitation for the development in the Maritime AR domain is the lack of dedicated hardware that can be used in a maritime environment. The issue is that no dedicated hardware will be developed without evidence for the usefulness and feasibility of the use of AR in a maritime context. To gather this evidence and to gain insight into what form dedicated hardware should take, existing hardware should be carefully used in the maritime context and strengths and weaknesses should be assessed. Subsequently, the industry will see the applicability of AR hardware dedicated to the maritime environment

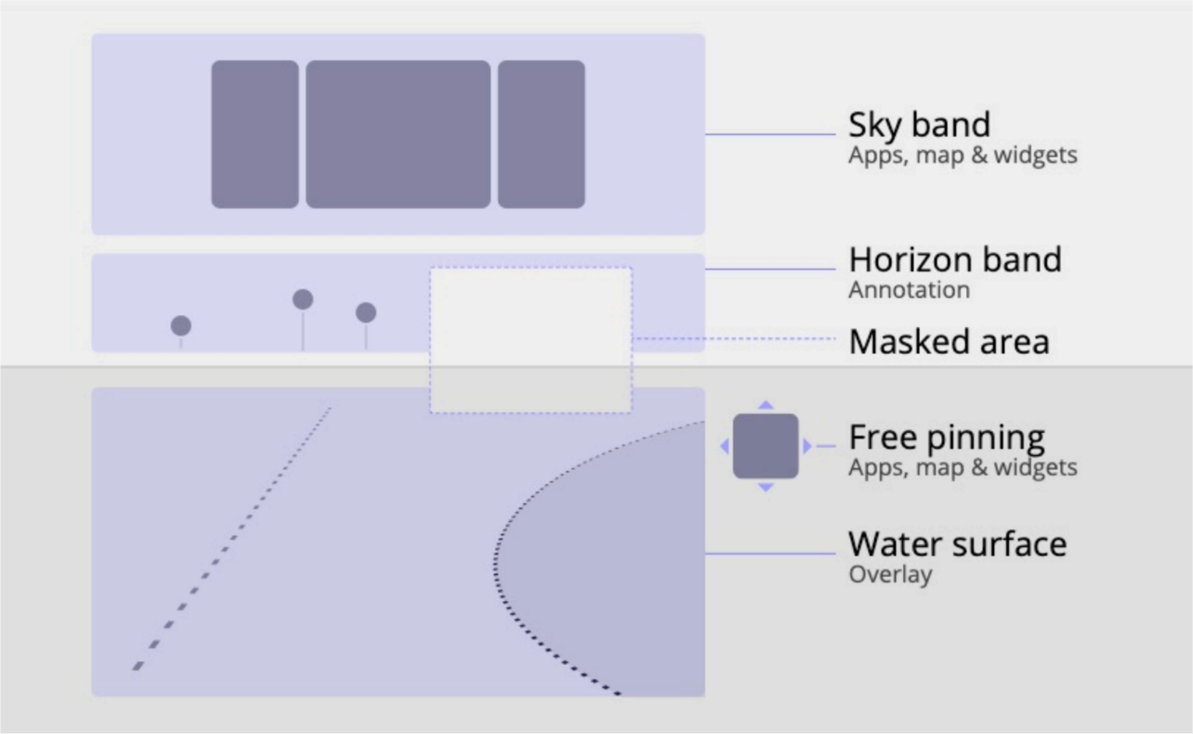


Figure 2.12: Five types of AR application components in stereoscopic AR (Nordby et al., 2020)

and push towards its development, such as Microsoft (2021b) is pushing for with its *Moving Platform Mode*.

Oh et al. (2016) argue for the importance of intuitiveness of the navigation data provided by stating that intuitiveness can resolve issues caused by excessive information. An AR interface can never be truly intuitive if interaction is disregarded. Previous studies applying AR technology to the ship bridge do however not emphasize interactions between the user and the technology. The author therefore coins a threesome of interactions that should be considered in the development of an AR interface for the ship bridge. This paradigm aligns with the 3D model that described AR coined by Lukas (2006) and includes interactions between 1. the user and AR; 2. AR and the environment; and 3. the environment and the user. In these definitions it is important to note that the "environment" considers both interaction with the physical workplace and the outside world. Consideration of these interactions should lead to the development of an AR system that can be deemed intuitive.

2.8 Towards a Framework

Throughout this literature review it is found that there is an inherent lack of guidelines for interface design for bridge systems (Mallam and Nordby, 2018; Nordby et al., 2020). The research group Ocean Industries Concept Lab (OICL) at AHO has developed an open-source framework that attempts to streamline a Multivendor Bridge System (MBS) to "realize a consistent user experience, as well as improve maritime workplaces" (Nordby et al., 2019). Nordby et al. (2019) hint at the added value of augmenting such a framework into AR. Groundwork has been done to creating a coherent AR experience (Frydenberg et al., 2018; Nordby et al., 2020), but a functioning implementation of stereoscopic AR as a bridge system is yet to be developed. Testing such a prototype in a maritime context allows for the discovery of new in-

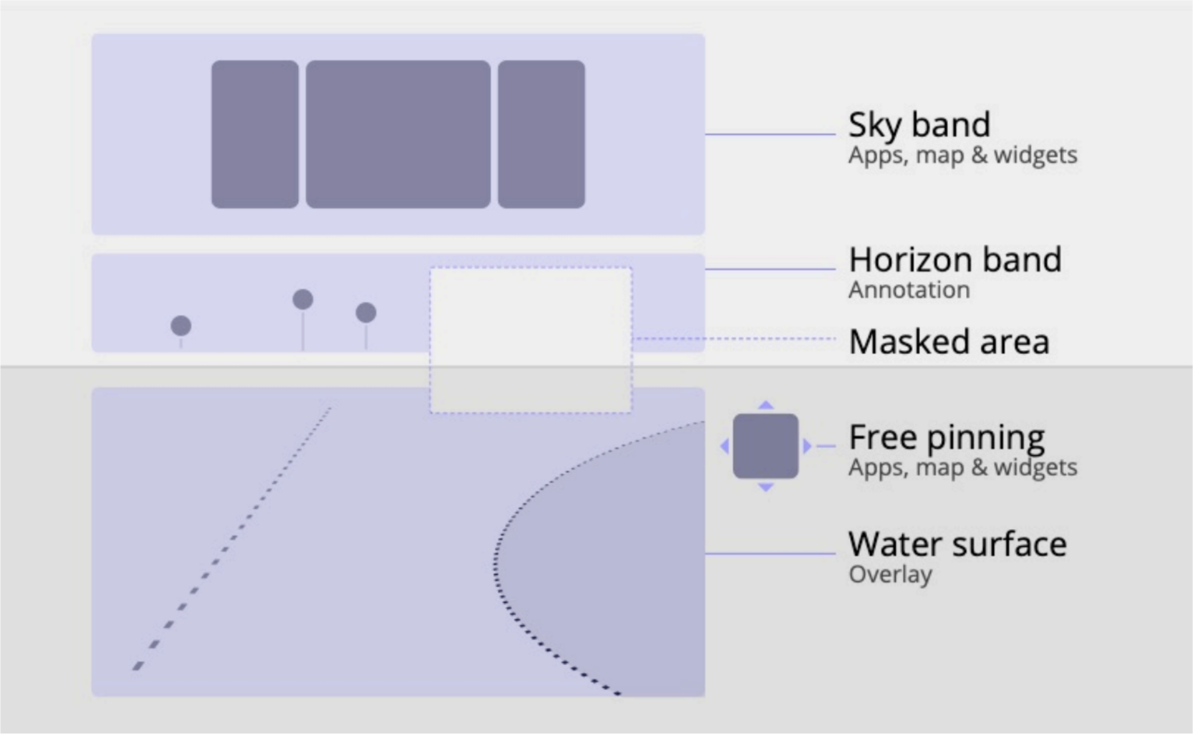


Figure 2.13: Five areas for the placement of graphics in stereoscopic AR (Nordby et al., 2020)

teraction potential and the evaluation of the current framework. Subsequently, the framework can re-designed and re-evaluated according to the new findings (Nordby et al., 2019).

Additionally, it is unclear if AR is the solution to the usability problems in the maritime industry today. Researchers agree that AR shows the potential of solving issues related to limited workflow consistency and cognitive challenges. There is consensus among seafarers that AR is believed to be the future of the ship bridge (van Beek, 2021). Until this hunch is confirmed, continuous development, implementation and evaluation of AR frameworks is required.

Section 3

Methodology

This study aims to develop a framework of an AR bridge system running on Microsoft HoloLens 2 (HL2) that can assist navigation of a seaborne structure. This technology is to be designed in conjunction with domain experts and end-users in order to answer as precisely as possible Research Question 1 (RQ1) *What makes an effective head-mounted Augmented Reality (AR) User Interface (UI) for maritime navigation?* During this study, development of such a system proved to not be trivial. As such, Research Question 2 (RQ2) *How can HL2 be used as a ship bridge system?* manifested.

3.1 Research through Design (RtD)

Research through Design (RtD) integrates true knowledge about theories with the knowledge of technical implementations (Zimmerman et al., 2007). It is a way for interaction designers to engage in so-called wicked problems: in formulating the problem a direction of treatment is specified (Rittel and Webber, 1973). Although the development of a ship bridge system is not a wicked problem in a traditional sense, it is a wicked problem that cannot be accurately modeled or addressed using reductionist approaches (Zimmerman et al., 2007). Therefore, the RtD methodology can be leveraged. The outcome of a RtD approach is an artefact that transforms the world into a preferred state (Zimmerman et al., 2007), which enables designers and researchers to not just evaluate the artefact in itself, but evaluate the preferred state the world is transitioned into. As such, the design artefact can be both the method and the result.

The RtD methodology is canonically exemplified by projects as - among others - the Drift Table (Gaver et al., 2004) and the Emotional Alarm Clock (Djajadiningrat et al., 2004), according to a critical approach to RtD by Zimmerman et al. (2010). Therefore, this study will report its findings in a similar fashion.

In a complex domain, it is only natural that those who will use the technology have a voice in its design, to arrest the "escalating problems of the man-made world" (Cross, 1972). A common issue is that non-designers do not know what they want from a design process (Robertson and Simonsen, 2012). Through collaboration during the design process, designers and end-users can exchange knowledge about envisaging future technologies and practices in which they can be embedded (Robertson and Simonsen, 2012). This process is called *co-design*, or participatory design. Co-design is a subset of Human-Centered Design (HCD), the importance of which in the maritime domain is emphasized by Rothblum (2000). Sanders and Stappers (2008) argue that users can become part of the design team as "expert of their experiences", but they need to be given appropriate tools to express themselves. Therefore, LEGO bricks (Cantoni et al., 2009) were leveraged as generative design method during collaborative workshops as a means to bring the language of creation to non-designers (Sanders and Stappers, 2008).

To succeed in designing an AR system that improves the usability of traditional navigational equipment, extensive understanding of the users context and how technology applies to that context is required (Hareide and Porathe, 2019). Therefore, this thesis takes "the collective creativity as it is applied across the whole span of the design process" (Sanders and Stappers, 2008) as definition for co-design. This type of HCD is essential when introducing new technology to the navigator (Hareide and Ostnes, 2017; Hareide, 2020; Guo et al., 2021).

3.2 Framework

Prototypes focus on the creation of knowledge about the final design of a product using purposeful manifestations of design ideas (Lim et al., 2008). Lim et al. (2008) provide an anatomy of prototypes that dissects a prototypes effective form, introducing filter- and manifestation dimensions that define a focus area and manifestation medium respectively. This terminology is summarized in Table 3.1.

Table 3.1: Filtering- and manifestation dimensions (Lim et al., 2008, table. 2 & 3)

Dimension	**Definition**	**Example Variables**
Filtering	Appearance	size; shape; proportion
	Data	data size; data type; privacy
	Functionality	system function; users' functionality need
	Interactivity	input behaviour; feedback behaviour
	Spatial Structure	arrangement of interface elements; relation between elements
Manifestation	Material	medium used to form the prototype
	Resolution	level of detail
	Scope	level of contextualization

Lim et al. (2008) disclose their prototyping process evaluating the usability of a text messaging feature on a smartphone. The first iteration of the prototype is a paper prototype, that benefits early concept evaluation and user involvement (Rudd et al., 1996). The use of alternative materials reduces costs and increases iteration speed, for the development process is swift. Subsequent iterations increase the resolution of the prototype using insights from earlier iterations, leading up to a prototype that runs on final hardware, where insights also contain contextual meaning.

The artefact supporting the RtD process in this study is a prototype. This prototype is iterated upon in a similar manner, each cycle increasing its resolution. There is a parallel between the fidelity of the prototype and the assigned Technology Readiness Level (TRL), as described in Section 2.5. The terminology coined by Lim et al. (2008) enables granular depiction of the prioritization of different variables and is therefore a useful addition to the TRLs. This terminology will be used to report on the prototype throughout this study.

In this exploratory context, one could argue for the use of a *technology probe*. A technology probe is an instrument that aids the collection of information about its usage and end users. Moreover, a technology probe facilitates field-testing for engineers and out-of-the-box thinking for designers (Hutchinson et al., 2003). Compared to a prototype, functions in a technology probe are open-ended, do not change during trial periods and log information to generate new ideas. In this study, the technology has an intended way of use and instead of provoking its users, the goal of the prototype is to proof a concept. Therefore, a prototyping process is preferred over the design of a technology probe.

Bravo et al. (2021) used a RtD approach to designing hybrid presentation with data visualization in augmented reality. In their approach, they iteratively developed two prototypes. They condensed the five phases of design thinking, coined by Kimbell (2011) into a three staged process that they applied on those prototypes. Given the tight coupling between design artefact and evaluation in a RtD study, this type of reporting maintains that tight coupling. Therefore, and in line with Gaver et al. (2004) and Djajadiningrat et al. (2004), this study followed a similar approach to designing and evaluation the artefact. Thus, each iteration followed a process consisting of three subsequent processes; 1. user research; 2. design process; 3. user evaluation. These processes were followed by a reflection on the process and artefact developed in the respective iteration. This flow is illustrated in Figure 3.1.

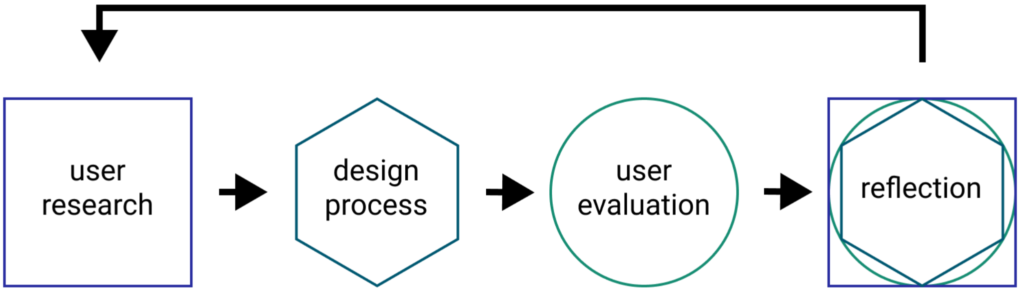


Figure 3.1: The flow of each iteration in this study

3.3 Data Collection

Table 3.2: Data collection

Iteration	Phase	Method	n (duration)	Description
Iteration 1	**User Research**	**Expert Interviews**	6 (45 mins)	Semi-structured interviews with 1. those who research AR applications for the maritime domain; 2. those who are in the maritime domain; 3. those who are in the maritime domain and those who were in the maritime domain and are now researchers.
		Vessel Visit	1 (2 days)	Platform Supply Vessel (PSV) Energy Duchess was explored through a guided tour, semi-structured interviews with crew and an observational study
	Design Process	**Use Case Workshop in Context**	2 (120 mins)	After showing a Virtual Reality (VR) mock-up of AR demonstration, Post-its and whiteboard markers were used to mimic AR functionality on the ship bridge windows with the captain and two first-mates
	User Evaluation	**Use Case Workshop at Ocean Industries Concept Lab (OICL)**	1 (120 mins)	With domain experts at OICL the ultimate use case was decided
Iteration 2	**User Research**	**Layered-Scenario Mapping (Lurås, 2015)**	1 (180 mins)	Captain Karl Robert Røttingen simulated a coastal journey using LEGO props, tested AR in HL2 and designed AR representations of important information

	Design Process	**Design Workshop**	3 (180 mins)	At OICL, Figma sketches of AR components were evaluated in a VR scene of a ship bridge
	User Evaluation	**Evaluation on local ferry**	1 (90 mins)	The prototype was evaluated by the author on the ferry between the ports Strandkaien and Kleppestø in Bergen, Norway
		Presentation	2 (30 mins)	Project review with OICL and experts in immersive media at the University of Stavanger
Iteration 3	**User Research**	**Attending OpenBridge and OpenAR seminar**	2 (1 day)	Exploring the current state-of-the-art in standardization and development of ship bridge systems with industry experts in the OpenBridge and OpenAR consortium at The Oslo School of Architecture and Design (AHO)
		Dissemination	1 (60 mins)	Review of prototype and RtD process with industry experts in the OpenAR consortium
	Design Process	**Remote Co-Design OICL**	1 (60 mins)	The prototype was demonstrated remotely to domain experts at OICL
	User Evaluation	**Expert Evaluation on Sailing Vessel**	1 (1 day)	The prototype was evaluated by a captain on a sailing vessel in the fjords "Byfjorden" and "Åmøyfjorden" in Stavanger, Norway

Figure 3.2: PSV Energy Duchess, produced by Ulstein (Ulstein, 2019)

3.4 Participants

To exercise effective co-design, it is important to source a varied pool of co-designer who have different beliefs and experiences. Aside from the end-users of the AR technology, the physical environment of those users should be considered. Additionally, valuable knowledge can be gained by collaborating with fellow researchers in the field. Recruitment of these user groups occurred in various ways.

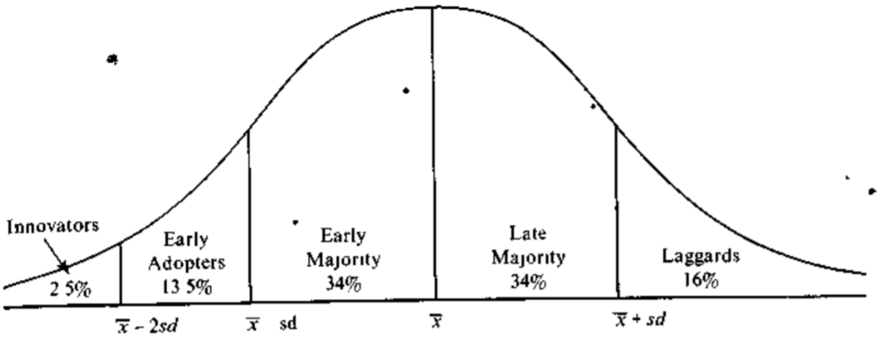


Figure 3.3: Adopter categorization on the basis of innovativeness (Rogers, 1971)

Firstly, a group of six researchers investigating maritime topics regarding human factors, safety and AR were recruited (van Beek, 2021). Secondly, collaboration with OICL at AHO was established. Besides being competent researchers and designers, they authored an open-source design guideline for bridge systems and have led various consortia that focused on ship bridge design in, among other regions, the Arctic using technologies ranging from tradition tangible interfaces to bridge virtualization in mixed reality (Frydenberg et al., 2018, 2021). The co-designers from OICL are considered innovators in the adopter categorization in Figure 3.3. They also supplied the author with access to the PSV Energy Duchess (Figure 3.2) and its crew. To test hypotheses and gain insights into the maritime domain, a captain from the Institute of Marine Research was recruited. To test the applicability of the prototype on pleasure crafts, a captain of a sailing vessel was asked to participate. Besides experts in the maritime domain, the technology was also evaluated as a software product by the Immersive Media Experiments

(Immeks) research group at the University of Stavanger, Norway.

This composition originates from the idea by Von Hippel (2006) and Seybold (2006) that lead users have already explored innovative ways to get things done. They are denoted the truly creative by Seybold (Sanders and Stappers, 2008). The goal of this study is to create a generic tool for coastal navigation. Therefore, the participant pool includes regular users to ensure grounding of truly innovative ideas, since the maritime industry is generally an incremental-innovation industry (Makkonen et al., 2013).

Section 4

Sjør: A Prototype for AR Navigation

In this thesis, an open-source piece of software named *Sjør* has been developed. This section elaborates on the development process of the prototype, and therefore seeks to provide insights to answer Research Question 2 (RQ2). Information about installation of the prototype on Microsoft HoloLens 2 (HL2) is provided on the authors GitHub page (van Beek, 2022).

Development of this prototype followed the agile Scrum development process as described by Schwaber (1997) to ensure maximum responsiveness to additional requirements discovered during the ongoing development (Schwaber, 1997). To support this development process, user requirements have been acquired throughout development iterations. These have been arranged in user stories using the user story mapping (Kaley, 2021), which is shown in Appendix B. Appendix B served as a knowledge base for prioritization throughout the Research through Design (RtD) process.

4.1 System Architecture

The software architecture is depicted in the Unified Modeling Language (UML) diagram in Appendix C. The software is built modularly to ensure flexibility and extensibility of the system. It consists of two independent pipelines that are tied together by an extension on the rendering engine in the Unity game engine. Additionally, two groups of classes are defined that interact with HL2 and provide global utility functions respectively. All these components and their responsibilities are disclosed in Table 4.1.

Positioner, as mentioned in Appendix C, translates real world Global Positioning System (GPS) coordinates to Three-Dimensional (3D) Cartesian world coordinates used by the Unity game engine. This translation is made using instructions provided by van Schaik (2016), who developed an airplane tracker in Microsoft HoloLens 1 (HL1) using the same algorithm. Moreover, the system sports a variable update frequency, enabling rendering of Augmented Reality (AR) graphics in real-time, which is only limited by the update frequency of the information sources the framework is connected to.

Sjør has been developed in the Unity game engine (Unity, 2022), supported by the C# programming language. In short, the prototype is built upon 1. Unity 2020.3.17f1; 2. Mixed Reality Toolkit 2.7.2; and 3. .NET Standard 2.0. A full overview of the software stack and a user manual is provided on the GitHub repository (van Beek, 2022).

Table 4.1: Functions of the parts within the prototype

Part	Function	Output
Data Pipeline	This pipeline creates a connection to external information provides and provide an interface to retrieve this information.	Data Transfer Objects (DTOs) containing information associated with the called data source.
Graphics Pipeline	This pipeline takes an an informational object that is ready to be drawn to the screen and provides it with the correct 3D model and text on that 3D model. Thereafter, it renders the 3D model to the correct location in the world.	A 3D model in AR.
Scene Renderer	This renderer interfaces with the Unity Game Engine, retrieves information from the Data Pipeline, process that with in-game meta-information (a.o. eye-tracking) and passes this information on to the Graphics Pipeline.	DTOs that have been converted into generic InfoItem classes.
Global Player and Camera Object	This module keeps track of HL2's current location and orientation according to the ship. Therefore, this module can also calculate Unity coordinates for other objects using their latitude and longitude.	A vector containing the position of an instance of the InfoItem class.
Global HelperFunction	This module contains utility functions that are used throughout the program, including functions for unit conversion and mathematical functions for positioning object on informational element.	A vector containing the position of an instance of the Global H.

4.2 Interface Design

The AR interface for ship navigation is a product of co-design with both domain and industry experts. The final design disclosed in Figure 4.1 has been designed by Ocean Industries Concept Lab (OICL) at The Oslo School of Architecture and Design (AHO) in collaboration with the author. Thereafter, the design were adapted by the author to function in the Unity game engine. The enumerated components in Figure 4.1 represent 1. a vessel; 2. a group of vessels; 3. a ruler visualizing the distance to the vessels; 4. a targeted vessel; and 5. extended information about the targeted vessel.

Information about different topics (e.g., Automatic Identification Systems (AIS), lighthouses, way points) are visualized in different horizontal layers in the horizon plane. This keeps the different informational categories visually separated from each other, whilst all physically visible. This provides a good overview of what is happening in the users' vicinity.

The prototype defines a state machine for each information element that can be in on

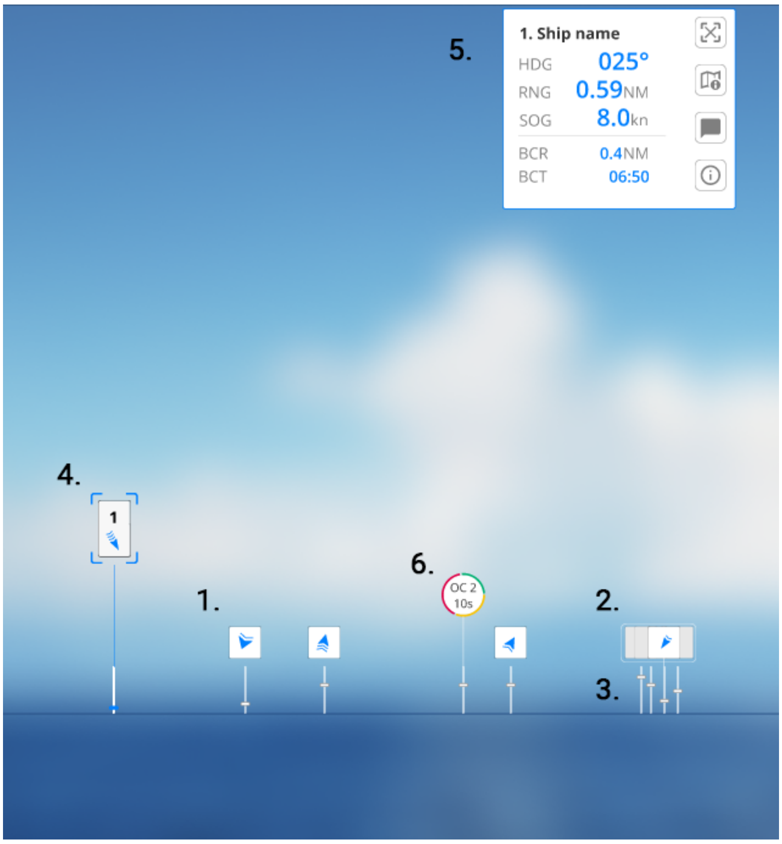


Figure 4.1: AR interface designed by OICL at AHO

of the following states: 1. idle; 2. hover; and 3. target. These states can be altered using interactions described in Table 4.3. The hover state expands information about that specific element. Hence, the importance of the information can be determined. If the information is important, it can be pinned using the target state. Each state provides different information, implementing knowledge gained in co-design sessions. The target layer shows informational elements that are targeted, even when the information category associated to that element has been hidden from the interface. This allows the user to customize the interface to what they deem important at the time. These states and their respective information that is provided to the user is summarized in Table 4.3.

Sjør implements various forms of interaction, including input using hand gestures, eye movement and voice. The prototype supports multimodal interaction to ensure maximum flexibility in an unpredictable environment. If there is ample surrounding noise, voice interaction can be unreliable, but gestures work regardless. If it is too dark, gestures are hard to recognize, but voice still functions. When wearing gloves, hand interactions are unreliable, but a combination of voice recognition and eye-tracking can obtain similar results. This is a handful examples of the importance of multimodal interaction in such a variable context. The functionalities linked to these multimodal interactions are described in Table 4.3.

4.3 Formalization of Positioning Functions

For consistent implementation of abstract display areas depicted in Figure 2.12, their definition needs to be formalized. These formulas can be used to understand and reproduce positioning of informational elements in isolation. This section provides formulas that transform coordinates

Table 4.2: Information provided to the user in the various states of the prototype and their form of visualization

State	Information	Visualization
Untarget	Distance	Distance ruler
	Heading (HDG)	Rotation of ship icon
	Speed Over Ground (SOG)	Number of arrows behind ship icon
Hover	HDG	Text & Rotation of ship icon
	Vessel Range (RNG): the vessel closest to own ship, or - if position data is unknown (N/A) - is listed	Text & Distance ruler
	SOG	Text & Number of arrows behind ship icon
	Bow Crossing Range (BCR)	Text
	Bow Crossing Time of target (BCT)	Text
Target	HDG	Text & Rotation of ship icon
	RNG	Text & Distance ruler
	SOG	Text & Number of arrows behind ship icon
	BCR	Text
	BCT	Text

of objects to be visualized (e.g., vessels in the vicinity), defined in a 3D vectors in the Cartesian coordinate system and retrieved from the algorithm provided by van Schaik (2016), from their position in the world to the horizon plane or sky area respectively. It is important to note that when developing for HL2 in the Unity game engine, the Cartesian distance between two points reflects meters in the real world. That means that the distance between $(0\ 0\ 0)$ and $(0\ 0\ 1)$ in AR is exactly one meter in the real world.

In all formulas below, 3D vector P represents the position of the user and 3D vector O the position of the object the informational element belongs to. Both are using the 3D Cartesian coordinate system that the Unity game engine supports. Firstly, the horizon plane and the sky area are formalized. Thereafter, the calibration function to align HL2 and the vessel is disclosed.

The horizon plane is positioned in a cylindrical shape around the user at a configurable distance d, which has been configured at five meters. Distantiating elements further rendered

Table 4.3: Interactions

Input Action	Interaction method	Use case
Expand element	Eye-tracking	Look at an informational element for it to expand and show more information
Target element	Point-and-click gesture	Point at an informational element and click to target the element
	Eye-tracking and voice command	Look at an object for it to expand itself and say "select" in order to target the element
	Eye-tracking and click gesture	Look at an element and click anywhere in order to select the element one is looking at

them invisible, due to issues with the clipping plane in HL2. The height of the user *Py* is adjusted to the provided ship bridge height, such that AR graphics are aligned with the horizon. *O* is the normalized directional vector between the user and the regarded object.

$$HorizonPlane = \begin{bmatrix} Px \\ Py - h \\ Pz \end{bmatrix} + dO,$$

$$where\ h = ship\ bridge\ height,\ d = 5\ and\ O = (\begin{bmatrix} Ox \\ Oy \\ Oz \end{bmatrix} - \begin{bmatrix} Px \\ Py \\ Pz \end{bmatrix})/||(\begin{bmatrix} Ox \\ Oy \\ Oz \end{bmatrix} - \begin{bmatrix} Px \\ Py \\ Pz \end{bmatrix})||$$

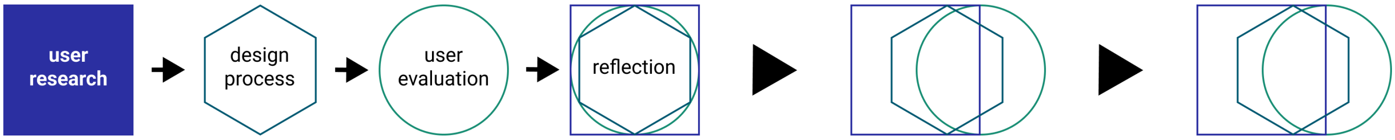
Elements in the sky area are placed using a similar definition as the horizon plane, with the subtle difference that sky area graphics are placed above horizon element by either one or two meters depending on the hover and target state of the object, related to the states described in Table 4.3.

$$SkyArea = HorizonPlane + \begin{pmatrix} 0 \\ q \\ 0 \end{pmatrix},\ where\ q = 1\ on\ target\ and\ q = 2\ on\ hover$$

Lastly, in order to align graphics in HL2 to geodetic north, the offset between the heading of the vessel and the rotation around the Y axis of HL2 needs to be aligned. Therefore, and similar to the calibration procedure used by Leite et al. (2021), both the camera position and orientation with respect to the ship must be known. A rotation matrix *C* is introduced that transforms objects from their original positions in the world, defined in 3D Cartesian coordinates, to their desired positions. As such, *C* needs to be applied to all objects. Rotation matrix *C* needs to be initialized with HL2 orientation parallel to the vessel. Each timestep, rotation matrix *C* is updated and reapplied to all objects, since the current vessel heading is continuously updated.

$$C = -\begin{bmatrix} 0 \\ c+u \\ 0 \end{bmatrix}, \; where\ c = vessel\ heading - HL2\ rotation\ around\ Y\ at\ calibration,$$

$$and\ u = current\ vessel\ heading - HL2\ rotation\ around\ Y\ at\ calibration$$



Section 5

Research through Design: Prototype Design and Evaluation

This section describes the Research through Design (RtD) process, including intermediate outcomes in the form of an artefact; the prototype. The prototype was iterated over three times. Each iteration consisted of three active processes and one passive, reflective step that summarizes the knowledge gained in that iteration, serving as input for the next iteration. This process is visualized in Figure 5.1.

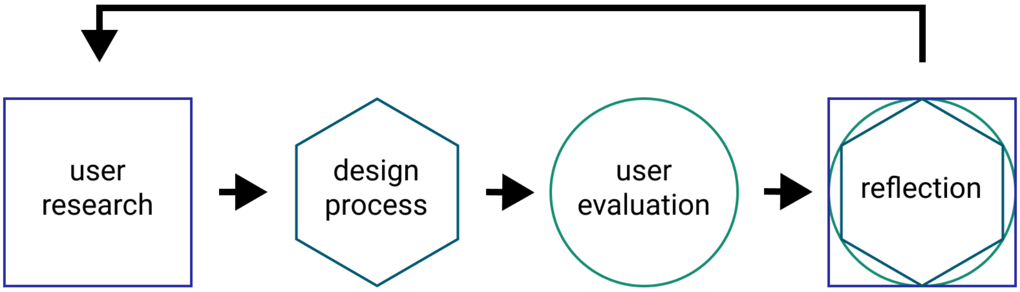


Figure 5.1: The flow of each iteration in this study

With each iteration, the developed artefact encapsulates the insights gained in that iteration. These insights and meta-insights about the method are also explicated in the reflective section at the end of the description of the iteration. The author has assigned a Technology Readiness Level (TRL) to the resulting artefact of each iteration to quantify the technological advancement compared to the previous iterations. Table 5.1 summarizes the three iterations by briefly describing the technological advancement and the TRL linked to that iteration.

5.1 Iteration 1

5.1.1 User Research

Semi-Structured Interviews

Firstly, domain knowledge about the maritime domain had to be gained to subsequently find a use case for Augmented Reality (AR) on the ship bridge. Therefore, six remote semi-structured

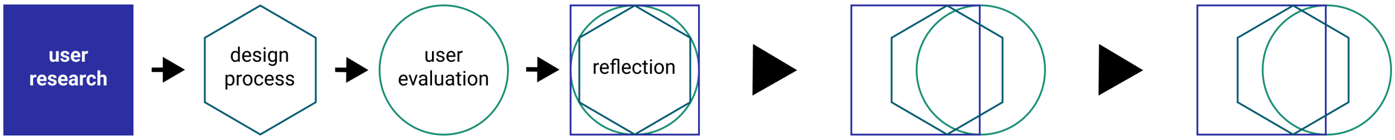


Table 5.1: A summary of the three iterations executed in this study

Iteration	Outcomes	TRL
1	Picked a use case that is depicted by co-designed sketches	2
2	Developed a functional prototype that has been tested on a ferry	5
3	Evaluated the prototype on a sailing vessel and extended the prototype using insights gained, with particular focus on interaction and visualization	6

45-minute-long expert interviews were conducted, targeting a threefold of participants, including 1. those who research AR applications for the maritime domain; 2. those who are in the maritime domain; 3. those who are in the maritime domain and those who were in the maritime domain and are now researchers.

In the interviews, in-depth questions were asked about current occupation and background. Thereafter, artefacts were shown to explain and spark a discussion about the topic of AR. Depending on the participants' expertise, different angles were taken on the shown AR artefacts (e.g. feasibility, usability, usefulness) (van Beek, 2021). These interviews followed the interview guide in Appendix D (for operators) or Appendix E (for researchers). An analysis of these interviews can be found in a prior study (van Beek, 2021).

Field Study to Platform Supply Vessel (PSV)

To acquire knowledge about the physical maritime domain, a field study to Platform Supply Vessel (PSV) Energy Duchess was conducted by the author and a researcher from the University of Bergen. The field study had been prepared for in accordance with the guidelines provided by Lurås and Nordby (2014, fig. 4). Various research activities were conducted with the captain and two first-mates present at time. These activities, combined with a brief description are listed below.

Guided tour of bridge and relevant areas To start the visit, the author got a guided tour of the vessel by one of the chief officers. They walked through the various ship areas and discussed what kind of work is done in each area and how people collaborate and use information.

Semi-structured interviews about operations conducted on this bridge Semi-structured interviews were held on the bridge with the two chief officers. During the interviews, the chief officers showed their workstations to describe the maritime operations they carry out. These interviews focused on answering the question *In what maritime operations can collaboration be improved using AR?* Operations that were of specific interest to the author were operations that are complex and short-lasting, avoiding the weakest points of Microsoft HoloLens 2 (HL2) whilst maximizing relevant findings. The interviews roughly followed the interview guideline in Appendix D.

Virtual Reality (VR) demonstration and discussion of mock-ups of AR applications To provide the captain and two chief officers with insight into what AR is and what potential it has for maritime applications, they were given a demonstration. VR mock-ups of AR bridge elements for a vessel bridge were used, developed by Ocean Industries Concept Lab (OICL) for the "Safe maritime operations under extreme conditions: the Arctic case" (SEDNA) project (Frydenberg et al., 2018). Since the VR set-up did not function, the VR mock-ups were shown on a laptop screen instead. Whilst demonstrating VR, AR applications for the operations that the PSV Energy Duchess carries out were discussed. Discussion continued after the VR demonstration and moved itself to the workstation of the front bridge. During the demonstration, the participants were encouraged to think-aloud (Fan et al., 2020).

The initial interviews disclosed issues on the ship bridge regarding information overload and ergonomic issues. In addition, the interviews conducted in context proved fruitful, since the participants could physically show their workstations to describe the maritime operations they carried out. This provided important context that would otherwise be left out in remotely conducted interviews, such as interaction methods with the bridge system, varying design paradigms, the copious information and the crew members' point-of-view from the workplace.

Through these interviews was found that AR should first and foremost be an extension of the ship bridge, instead of replacing it. As such, clarity can and should be favored over the inclusion of all data in AR, with a special focus on relevance of information.

Figure 5.2: Impression of the workshop on PSV Energy Duchess with the two first-mates. One of them is showing an idea he has on the windows of the ship bridge using Post-its and a whiteboard marker.

5.1.2 Design Process

Leveraging the knowledge about the maritime operations that was gained on this vessel, the potential use cases were narrowed down to 1. Dynamic Positioning (DP); and 2. Littoral water navigation. Two co-design workshops were conducted on the second day of the field study to the PSV Energy Duchess. Each workshop lasted approximately 120 minutes. During these workshops, the author and a fellow researcher from the University of Bergen were present as facilitators, whilst the captain and the two first-mates took part when they were not required at other tasks on the vessel. Post-its and whiteboard markers were used as playful, low fidelity means to simulate AR graphics on the windows of the ship bridge, engaging the crew members. From the perspective of the captain and the DP chair respectively, the graphics aligned with landmarks in the real world.

During the workshops it became evident that the crew members are often busy and initially not engaged in the research project. When the facilitators started drawing and sticking Post-its on the windows, the curious crew members joined the workshop excited to share their experiences and how that applies to the AR graphics that were being designed.

The two outcomes of this co-design workshop include sketches accompanied by a list of users stories. Firstly, Figure 5.3 shows the outcome of the coastal navigation workshop.

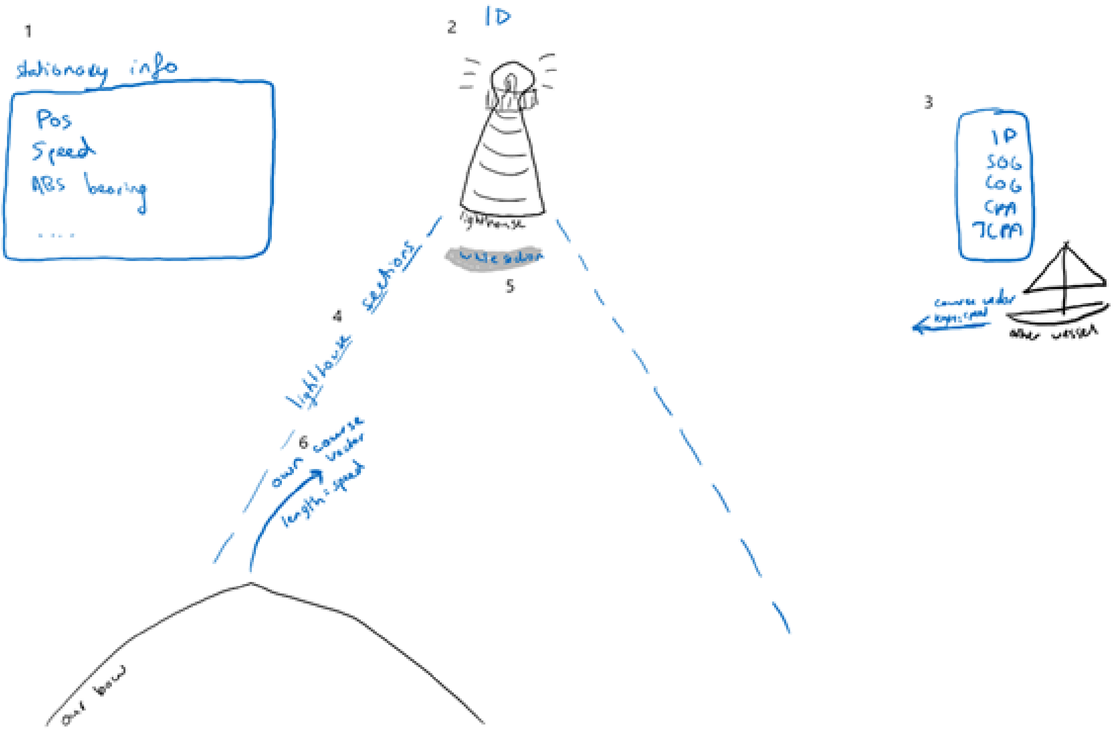


Figure 5.3: Result of the coastal water navigation use case workshop

The AR elements are labelled and include 1. a stationary AR element displaying information about the own vessel, such as the position, speed and absolute bearing; 2. identifying information above lighthouses, making it easier to spot them; 3. Identifying information above other vessels, including their Integrated Display (ID), Speed Over Ground (SOG), Course

Over Ground (COG), Closest Point of Approach (CPA) and Time to Closest Point of Approach (TCPA). This can be visualized using vectors on the water surface too; 4. Lines on the water surface delineating the boundaries between lighthouse sectors; 5. An indicator of which sector of a specific lighthouse the vessel is now in; and 6. A vector showing the own ship course and speed.

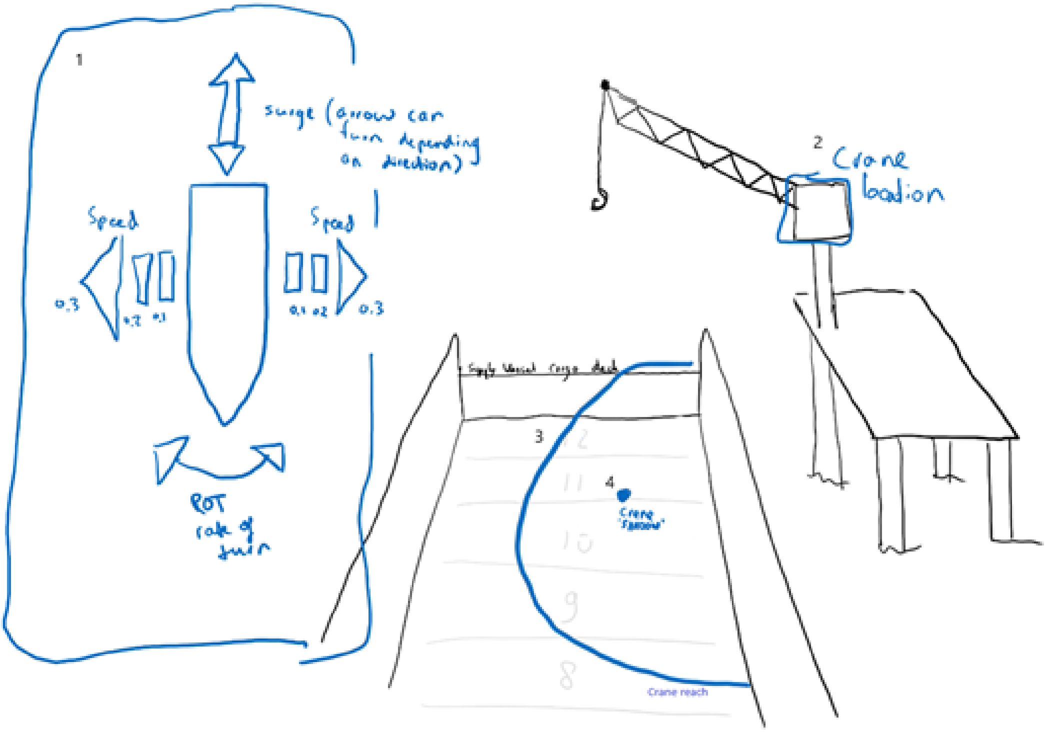
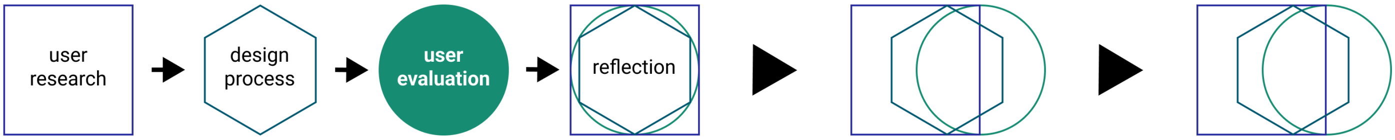


Figure 5.4: Result of the Dynamic Positioning (DP) use case workshop

Secondly, Figure 5.4 shows the outcome of the DP workshop. The AR elements are labelled and include 1. a stationary AR element displaying information about the own vessel surge, sway and yaw. The size of the arrows can display the momentum of each movement. Numerical information is also necessary; 2. an indicator of where the crane is, either the crane cabin or whole crane; 3. an indicator of the range of the crane; and 4. A shadow vertically underneath the crane hook, showing where it will be when it goes down. The user stories accompanying each illustration depict the functionality of an AR interface for those use cases. These user stories were aggregated in a user story map (Kaley, 2021) that served as a priority map in the development of the artefact (Appendix B).

Additionally, the crew members mentioned general points of advice for the development of AR as a ship bridge system, stating that 1. it can be expected that maritime operators are welcoming to AR technology; 2. they see potential in AR as a information display, more than AR as a control system; 3. relevant information differs based on the position on the ship bridge; 4. it is unwise to implement more alarms and warnings in AR; and 5. color schemes in AR should follow contemporary color schemes in ship bridge systems, but not interfere with important landmarks such as lighthouses.



5.1.3 User Evaluation

The outcome of the first iteration was evaluated by four domain experts from OICL in Oslo, Norway. The results of the preceding field study to PSV Energy Duchess were presented, with great emphasis on the illustrations that resulted from the co-design workshops. On the one hand, a large industry interest in a dynamic positioning interface in AR in the form of Head-Up Display (HUD) was identified. An interface as depicted in Figure 5.4 is deemed feasible with today's' technology. On the other hand, an interface for navigation provides an extendable framework that requires organization of different types of information. The development of such a framework could support development of AR for the maritime domain in the years to come.

A third use-case workshop was conducted with the goal to broaden the perspective of the workshops on PSV Energy Duchess. During the workshop at OICL, the four individuals came up with use cases for AR in maritime operations individually. Then, these use cases were shared with the group in a collaborative ideation session. The use cases "Dynamic Positioning (Windmill)" and "Tugboats" were explored by each duo respectively and were provided with context and AR graphics. Lastly, results were presented to each other.

Re-evaluating the four expounded use cases, as shown in Table 5.2, revealed that AR has great potential to increase Situation Awareness (SA) in the maritime domain and thus safety and efficiency. Due to limited access to relevant vessels and the complexity of operations "Dynamic Positioning (Windmill)" and "Tugboats" these are out of the scope of this study. The author favors navigation over supporting DP, since the information and visualization pipeline required for navigational tasks cover core functionality required for other maritime operations to boot. Therefore, the creation of that framework shows potential beyond the use-case of navigation.

5.1.4 Reflection

The maritime domain is a diverse domain due to the large variety in operations that take place on a vessel and multitude of parties involved in those operations. As shown in preceding phases of the RtD process is AR applicable in great quantity. In these early stages of in the maritime domain it is important to provide practical projects with context and a scope to understand where projects fit into the ecosystem of AR applications for maritime.

During the design process and user evaluation, the need for separation of different types of information was established. To accommodate for this need, the author coined a scene switching feature, where the program displays one category of information at a time and fades between them, such as Automatic Identification Systems (AIS) information, lighthouses and waypoints. Then, using interactions, the next scene could be determined based on user input.

Iteration one has been purely speculative in exploring AR solutions in the maritime domain. Operations that can be augmented using AR have been evaluated and designs have been created for a selection of those. No functional software has been developed, but sketches for such software was provided. Therefore, the TRL of iteration one is 2.

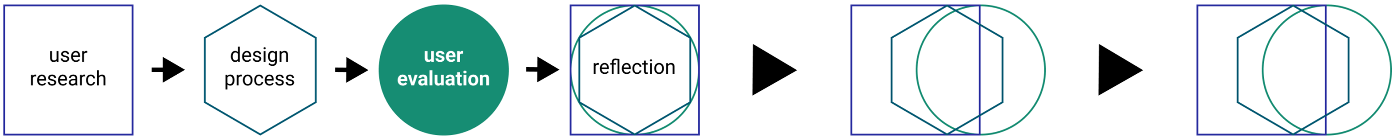


Table 5.2: The four use cases considered with a short description and the need for AR assessed.

Use case	Use case description	Potential of AR
(Littoral water) Navigation	These waters are treacherous because of narrow channels, lots of traffic and Unidentified Floating Objects (UFOs) (Venkatrayappa et al., 2020)	Lots of information to process simultaneously. AR shows potential to relieve the stress by showing information where the obstacles are to not compromise SA.
Dynamic Positioning (Oil Rig)	A high-risk operation where the vessel stabilizes itself next to an oil rig, such that cargo can be unloaded. A DP situation is a negotiation between crane and vessel operator, juggling speed and safety.	AR can provide insight into the ships current status without compromising SA. Additionally, AR can provide insight into crane reach and the crews' location on deck to improve safety.
Dynamic Positioning (Windmill)	A high-risk operation in which the vessel stabilizes itself next to an offshore windmill. A dynamic bridge is rolled out to the windmill over which crew members enter the windmill	A lot of information needs to be monitored by the DP and bridge operator to decide whether to abort or not. Having this information directly in a HUD can potentially increase SA and thus safety.
Tug Boats	Tug boats guide large vessels in tight harbours. Tug boats collaborate to dock large vessel in the correct position.	Lots of collaboration is required between tug boats to coordinate movements. AR has the potential of providing insight into the actions of other tug boats and create a visual broadcast channel of the next collective objective, improving visibility.

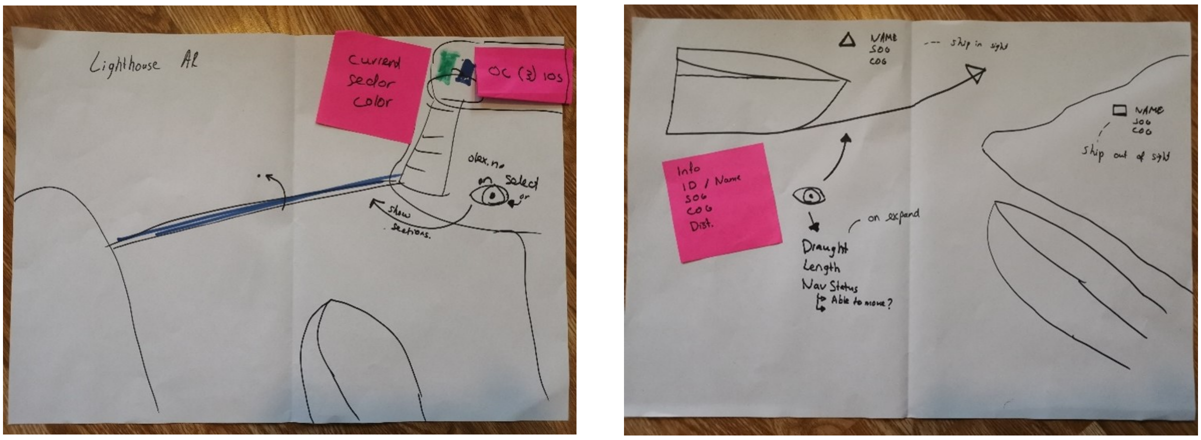
5.2 Iteration 2

5.2.1 User Research

A co-design workshop was conducted with Karl Robert Røttingen, captain of research vessel Kronprins Haakon from the Institute of Marine Research in Bergen. The goal was to gain direct insight into coastal water operations by leveraging layered-scenario mapping (Lurås, 2015) to define operations, associated tasks and information required for those tasks. Thereafter, this information could be used to discuss AR implementations for littoral navigation aid.

Figure 5.5: Karl Robert Røttingen and the author in a co-design workshop where sea charts and LEGO blocks are being used to simulate a journey in littoral waters

The first half of the workshop, Røttingen simulated a coastal journey using LEGO blocks (Cantoni et al., 2009) and a sea chart of the home harbour of Kronprins Haakon, the Arctic waters of Tromsøysundet and Sandnessundet. The journey started at the Hurtigruten dock, north through Tromøysundet turning to portside going south through Sandessundet. The encountered challenges included, but were not limited by, blind corners, bridge crossings and lighthouse navigation. These challenges were dissected and summarized in the layered-scenario mapping in Appendix A. This part of the workshop disclosed tasks associated with navigation. Therefore, and aware of the inability to implement all information in HL2, the author focused on visualization of nearby vessels in coastal waters in HL2 by showing AIS information.



(a) Lighthouse AR

(b) Blind corner AR

Figure 5.6: Sketches of AR elements designed with Karl Robert Røttingen in a co-design session.

In the second half of the workshop, Røttingen tested HL2 through the Mixed Reality Toolkit (MRTK) Examples Hub (Microsoft Design Labs, 2021). Using his newly gained AR experience, designs of AR interfaces for lighthouse navigation and blind corners were created, as shown in Figure 5.6.

The new scene switching feature was discussed with Røttingen, who dismissed it immediately. He stated that "When I am ready to take information [about a certain topic], the system is in a different mode". Thus, the user should be in control which information is interesting at every point in time. Therefore, the scene switching feature was omitted. Instead, a system where all information can be separated, but shown simultaneously, seems adequate. The implemented scene switching feature can be re-purposed in later iterations to switch between different interfaces depending on the position of the wearer of HL2 on the ship bridge, but has been deactived for now.

5.2.2 Design Process

The author returned to OICL in Oslo to translate the newly gained domain knowledge into sound AR elements. In a discussion with research lab head Professor Kjetil Nordby it became evident that AR graphics should have a predictable, dedicated area in the world, such as the *horizon band* and *sky area* as defined by Nordby et al. (2020). To avoid clutter of AR elements, a filtering system should be instantiated. This filtering system should be manipulable through interaction methods. These revelations are summarized in Table 5.3.

The anatomy in Table 5.3 served as basis for a sketching session. Mirroring the target functionality in Electronic Chart Display and Information System (ECDIS), two-staged informational elements were introduced for obstacles and landmarks. A layer system was introduced to replace the scene switching feature that was written off by Røttingen, allowing for structured visibility. The outcome is shown in Figure 5.8. These sketches were transformed into digital sketches in Figma (2021), which could be loaded into and tested in a virtual ship bridge and shown using an Oculus Quest 2 (Figure 5.7).

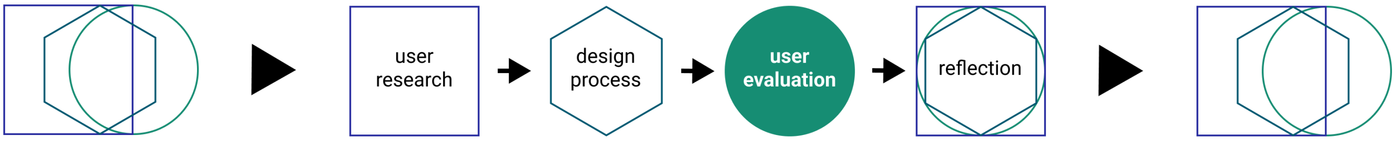


Figure 5.7: The author testing out Figma sketches of AR elements on a ship bridge in VR at OICL in Oslo

5.2.3 User Evaluation

The prototype was tested on a moving vessel, retrieving real-time information about the vessels in the vicinity. The evaluation was conducted by the author on the ferry between Strandkaien and Kleppestø in Bergen, Norway. The goal of the test was to evaluate the adequacy of the formulas that formalize calibration of HL2 and positioning of the information areas, as described in Section 4. Initially, nearby vessel were positioned correctly, but moved in the opposite direction when they or our vessel started moving. The inclusion of the negative sign in the calibration equation in Section 4.3 remedied this.

To overcome the limitation of not having direct access to the position and heading of the vessel, HL2 has been connected to a smartphone that provides Global Positioning (GPRMC) strings (NovAtel, 2022) containing positional and directional information. An issue emerged causing the graphics to move in the opposite direction compared to the respective vessels. After remedying this issue, the prototype was presented in two half-an-hour sessions to domain experts at OICL in Oslo, Norway and experts in immersive media at the University of Stavanger, Norway. Rather than a user evaluation, these sessions should be seen as dissemination of knowledge. Feedback from these sessions is not essential for the understanding of the RtD process and is therefore omitted.

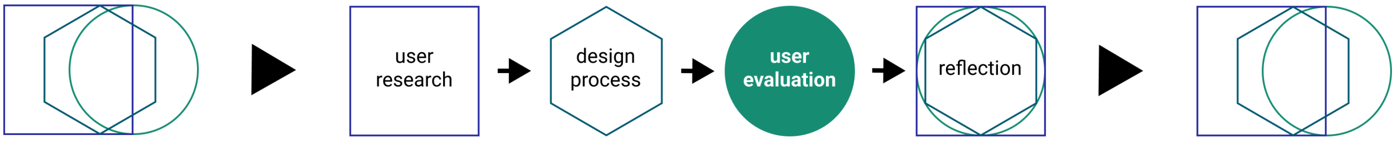
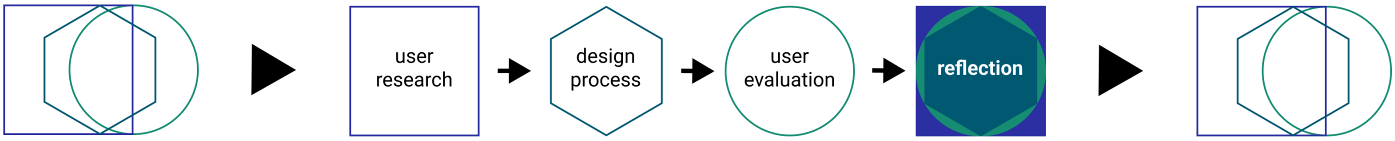
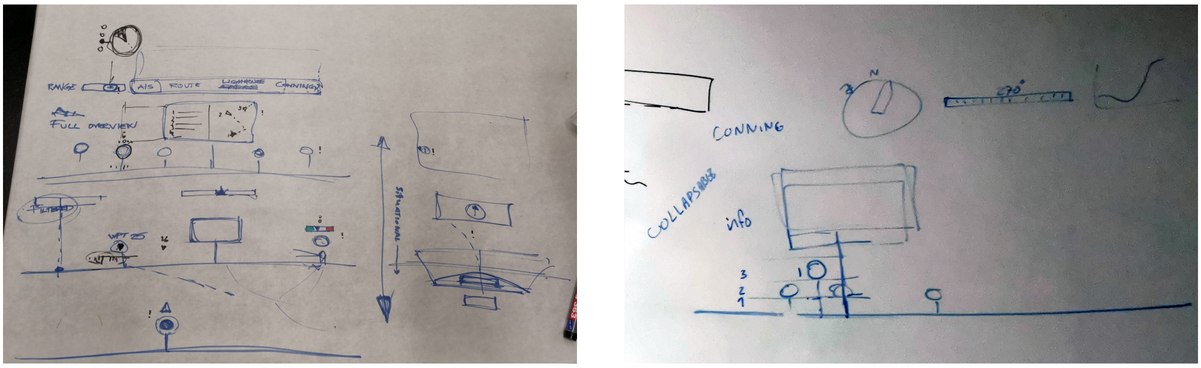


Table 5.3: *The anatomy of the prototype*

Function	**Function Description**	**Parameter**
Filtering system	In high-traffic areas, a lot of vessels will show up in the AR system. Therefore, a filtering system is required. In addition to category based filtering, a manual target system is advised to persistently show important obstacles. Moreover, the smart select filter filters obstacles according to a predefined rule set (e.g., vessels that are on collision course).	• AIS • Route • Lighthouse • Target only • Smart select
Interaction method	To interact with AR elements, different types of (combinations of) interactions should be defined. Since in different situations, different types of interaction are preferred, multi-modal interactions should be instantiated. The building blocks of these interactions are gaze (where one looks), speech (what one says), point (where one points their index finger) and *AirTap* (tapping thumb and index finger together).	• Gaze x Speech • Gaze x AirTap • Point x Speech • Point x AirTap
Visualization area	These areas define where AR elements can be placed in the real world, following the areas defined by Nordby et al. (2020). These constraints on placement of AR elements should avoid AR elements overlapping with safety essential areas.	• Horizon band • Sky band • Water surface





(a) Shapes

(b) Layers

Figure 5.8: Sketches depicting two-stage informational elements on the horizon band that can be targeted on-demand, divided into layers per filtering dimension denoted in Table 5.3.

5.2.4 Reflection

The harbour of Tromsø, Norway, was picked as a case study for the co-design session with Karl Robert Røttingen. Tromsø is the home harbour of the research vessel Kronprins Haakon, of which Røttingen is captain. Therefore, he could provide in-depth insights into challenges he faces there using his own experience. This benefited the co-design session greatly, since detailed knowledge of the concrete situations encountered resulted in detailed information for the layered-scenario mapping and sketches of the AR system, as shown in Figure 5.6.

During the co-design session, layered-scenario mapping was used to generate a knowledge base of coastal navigation tasks and operations. Although a thorough method, layered-scenario mapping is a time-consuming process. Instead of filling out the layered-scenario mapping during the co-design session, recording of the session (with permission of the participant(s)) and filling out the layered-scenario mapping after the session should be preferred. Results can subsequently be validated by the participant(s).

The production of innovative ideas can be challenging in co-design sessions. It is hard for established seafarers to think outside the box. When talking about navigational aid, Røttingen suggested visualizing buoys with their respective colors in AR, instead of visualizing waypoints that can be followed. It is possible that unidentified information is embedded in buoy placement and color and that therefore this visualization is preferred.

In line with the design session at OICL, the need for a predictable, dedicated information area was identified. This resulted in an issue of mapping the Three-Dimensional (3D) world to a Two-Dimensional (2D) information area, causing a problem concerning maintenance of spatial relations. As a solution to this challenge, a distance ruler was suggested, denoting the absolute distance from the respective vessels graphically. An example of this distance ruler can be found at Label 3 in Figure 4.1.

At this stage, the prototype had become a functional piece of technology that had been validated in both a lab setting at OICL, Oslo, Norway and in a relevant environment on a ferry in Bergen, Norway. As such, the TRL of this iteration is 5.

5.3 Iteration 3

5.3.1 User Research

The author visited OICL in Oslo to attended two full-day seminars concerning the OpenBridge and the OpenAR project ran by OICL. In these two days, large shipping companies presented their approach to standardizing ship bridge interfaces using the OpenBridge design guidelines (OpenBridge, 2022) and discussed adaptations and additions to the design library in detail.

In addition, the prototype was demonstrated to members of the OpenAR consortium in an hour-long dissemination session that consisted of a presentation of the background of this study, followed by a presentation of domain experts at OICL about the reasoning behind the AR interface design. Thereafter, the prototype was tested by three employees of large shipping companies.

The main takeaways from these sessions are that large shipping companies are invested in standardization of the user interfaces on ship bridge and AR as a ship bridge system in general. Moreover, more than once has the prototype presented in this study been deemed "the future of ship bridge system", depicting relevance of this work. Nonetheless, the development of AR systems, more specifically AR systems that are using Head-Mounted Displays (HMDs), remain in early stages of development.

During these sessions, a need for simplification of implementation of standardized graphics in traditional ship bridge interfaces was identified. The author suggests that this need can be met by the development of an extension on top of the OpenBridge design library that allows these graphics to be imported into popular web frameworks, such as React (2022) of Vue.js (2022). It is expected that this need will emerge in the field of AR in the coming years.

5.3.2 Design Process

In collaboration with OICL, low-fidelity clickable prototypes of AR graphics were created in Figma (2021). These prototypes continued to built on the ideas coined in the design process of iteration two (Section 5.2.2), visualizing solutions to problems such as issues with graphics overlapping when vessel are close to each other and the suggested distance ruler in AR graphics. A complete version of the clickable prototype is depicted in Figure 4.1.

After internal evaluation of these clickable prototypes, the author implemented the newly suggested features in the HMD. During this process, technical challenges were encountered with the packaging of the new AR graphics in the Unity game engine (Unity, 2022) project. These issues were solved after the inclusion of an object which sole purpose was to load the 3D models, which it then passed on to the elements that actually used those objects. Sadly, this solution was found after the succeeding user evaluation, resulting in an older version of the prototype being evaluated.

5.3.3 User Evaluation

To evaluate the prototype in context, HL2 was taken to Stavanger, Norway, where it was subjected to a field trial by Bjørn Aage Krane (pensionist), captain of a Bavaria 38 Cruiser sailing vessel. A sailing vessel was not the intended target audience of the prototype, but given the commonality of navigational tasks on vessels it proved an adequate testbed regardless. Due to technological and temporal constraints, an earlier version of the prototype has been tested on the sailing vessel. That entails that eye tracking was not yet implemented on this field study and information provided by the AR graphics was not yet finalized.

Three sessions with HL2 were conducted; one ashore and two whilst out at sea. During these sessions, Krane was encouraged to think-aloud (Fan et al., 2020). The first session focused on the interaction with HL2 and the prototype using MRTK Examples Hub (Microsoft Design Labs, 2021). Thereafter, the vessel took to the sea, where two sessions with HL2 were conducted: the first close to harbour of Stavanger with strong wind and many circumposing vessels; the second in calm water with fewer surrounding vessels at dusk. The trial setting is shown in Figure 5.9. These sessions were followed by a debriefing session focusing on both AR and the software.

Figure 5.9: The captain interacting with HL2 whilst the vessel is out on the fjord. The vessel is being operated by a crew member.

Both the HL2 and the prototype were designed with industrial settings on large, stable vessels in mind. With some exceptions, they performed well on smaller pleasure craft using Microsoft's Moving Platform Mode (Microsoft, 2021b). Alignment of AR graphics was affected when the roll of the vessel changed after HL2 had booted up, the only fix being a device reboot. This issue could be fixed by compensating for the roll of the vessel using the built-in gyroscope in HL2.

Due to the increased exposure to wind and water on a sailing vessel, compared to a commercial vessel, the author showed extreme care for HL2. Disregarding the fragility of HL2, other issues in this exposed environment persisted. The wearing of gloves made hand-tracking inconsistent, even when using a glove where index finger and thumb were cut off. This shows the need of multimodal interactions with the interface.

On the other hand was the added mobility of HL2 a success. During the sessions, Krane was required to work the ropes on the sailing vessel. HL2 did not inhibit his workflow and he stated that "the glasses do not make it more difficult to navigate". Moreover, the informational graphics were shown regardless of view obstruction by the sail: a feature Krane loved.

The spatial structure of the prototype does not include a ruleset to handle overlapping AR informational elements. As a result, the information that overlaps is hard to read and interact with. Other difficulties experienced are issues tied to the use of HL2 in the maritime domain and include 1. the absence of a built-in compass, forcing the prototype to rely on the inconsistent smartphone compass; and 2. the low brightness of AR graphics render the graphics illegible in bright sunlight. This issue can be remedied by taping car foil to HL2, mimicking sunglasses (Eikenes, 2019).

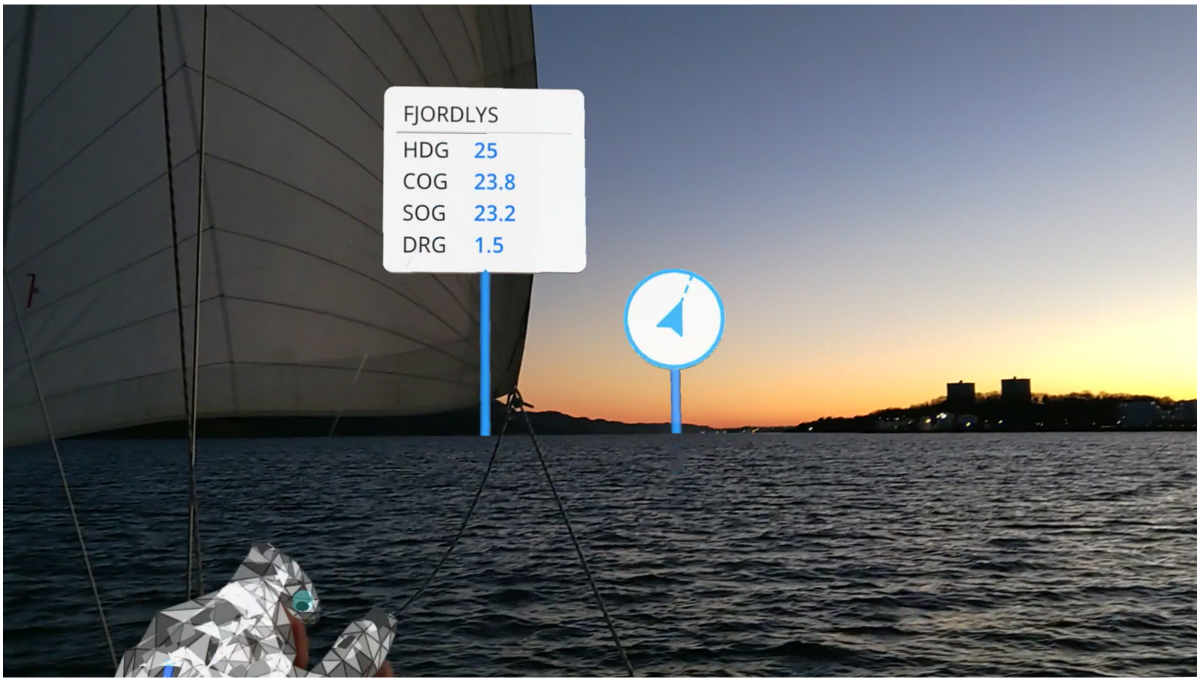


Figure 5.10: A mixed reality capture of the prototype, taken at dusk on the sailing vessel. HL2 is tracking the captains hand in the bottom left corner.

5.3.4 Reflection

The sailing vessel did not provide an interface to connect directly to the Global Positioning System (GPS) information of the vessel. To overcome this shortcoming, HL2 collected the current position and heading from a Huawei Mate 20 Pro smartphone running the NetGPS (Meowsbox, 2019) application. The connection between the smartphone and HL2 using mobile data tethering was stable, but the directional information from the smartphone proved to be inaccurate. Both raw and interpolated directional calculations were tested, but accuracy did not improve. On average, the smartphone showed a deviation of 30 degrees compared to the on-board heading provided by bridge equipment. The smartphone connection does provide an interface for other data sources that provide GPRMC strings and should therefore be easily adaptable to other data sources. The author suggests two solutions, which include 1. a direct connection to the bridge equipment using technology like the BlueCtrl BlueBox (BlueCtrl, 2020); and 2. leverage the BarentsWatch Application Programming Interface (API) provided by Kystverket and extract live information about the current vessel using a vessel identifier, such as the vessel name.

The prototype has been demonstrated on a sailing vessel to a captain whilst the vessel was in operation. Key technologies have been evaluated and these findings have been documented and implemented in the prototype. The TRL can therefore be defined as 6. The latest improvements and suggestions to the prototype enables the opportunity of a demonstration of the prototype in an operational, industrial environment, such as a field test on a charting on PSV Energy Duchess. Accordingly, TRL 7 could be achieved in the next iteration with little adaption to the prototype in its current state.

Section 6

Discussion

The knowledge gained from the Research through Design (RtD) process, as contained in the artefact described in Section 4, will serve as a basis for the answers to the two Research Questions (RQs). In the resolvement of these questions, three major contributions to the field of AR as a bridge system could be derived: 1. a practical contribution of a framework supporting location-based information retrieval, visualization and interaction for Microsoft HoloLens 2 (HL2); 2. a hybrid contribution of a theoretical interface and interaction design and a practical, extendable implementation of said interface for HL2, designed in collaboration with Ocean Industries Concept Lab (OICL); and 3. a research agenda proposing different problem framings of the two aforementioned contributions. Moreover, numerous observations and findings supporting design choices made are reported in the discussion of their significance.

Given the close coupling between the RQs coined in Section 3, it is inevitable that overlap will be introduced between the two in an attempt to answer them. Therefore, significant results will be labeled **(RQ1)** or **(RQ2)**, signifying the corresponding research question being 1 or 2 respectively. Moreover, the RQs do not have one unambiguous answer. Instead, this study works towards resolvement of the RQs using processes for which guidelines are sketched in this section.

6.1 Evaluation of the RtD Process

The validity of this study is characterized by the execution of the RtD process as a method. Zimmerman et al. (2007) define four evaluation criteria for a RtD contribution: 1. process; 2. invention; 3. relevance; and 4. extensibility. Using these criteria, the process of this study is evaluated in the following paragraph.

Firstly, this study reported extensively on the process executed, including relevant appendices for past and future work. Re-execution of the same steps are not guaranteed to lead to the same outcome, but such deviations can provide valuable insights and broaden the perspective of the development of Augmented Reality (AR) frameworks for maritime.

Secondly, this study builds upon existing research in various significant ways. It is novel in that it uses a stereoscopic Head-Mounted Display (HMD) implementing new interactions methods in the maritime context. It is important that information should not only be the reproduction of existing system symbology the augmented way (Procee et al., 2017). Therefore, the prototype implements an innovative interface that has the potential to support an unparalleled level of portability and mobility on the ship bridge.

Thirdly, current bridge systems provide little integration among each other. Additionally, information about the world is displayed on screens which distract from the real world. On the contrary, this prototype aims to keep the attention of the operator on the outside world, whilst providing relevant information about that world.

Lastly, the contributions as outcomes of this RtD study can be leveraged in future implementations of AR as a bridge system. Moreover, the AR framework supporting data retrieval and visualization is built for extension and opens the door for a multitude of evaluations of HMDs in the maritime context with the focus on among others mobility (Rowen et al., 2021), collaboration and interface design.

6.2 Co-Design

The combination of the RtD process and co-design was extremely fruitful. It enabled the extension of the maritime context to a lab setting and as such generates ideas that would otherwise only develop on a field study. This context is important, since operations are deeply rooted in the maritime context, as argued in Section 6.5. Some challenges were faced however, mainly concerning the degree of innovation of the ideas coined in co-design sessions.

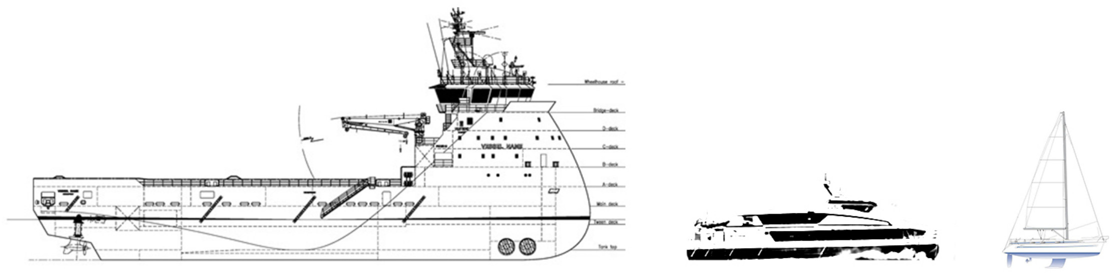
This is illustrated by the question as to how navigational information could be visualized in a helpful way. This question often yielded answers that are a direct translation from the way Electronic Chart Display and Information System (ECDIS) visualizes information to an AR visualization. A captain was asked how safe littoral passages could be visualized in AR. He replied that *buoys should be visualized, emphasizing the blue and red colours in AR*, instead of ideas coined more recently such as a line over the water depicting the course or *NoGo zones* (Porathe and Billesø, 2015). The degree of innovation of these proposed ideas can be discussed, but the connection between traditional navigational methods and the proposed AR visualization by the captain is undeniable. This issue is potentially grounded in the experience of the captain, which he used as framing for the visualization problem at hand. This captain is not categorized as a lead user. As such, the question as to "whether lead users can represent and speak for the majority of the people using a service" (Sanders and Stappers, 2008) remains unanswered, whilst evidence is provided that a mix of lead and regular users in co-design sessions should be preferred.

6.3 Considerations of AR as Bridge System

As a bridge system, AR is a mediating technology, connecting the user to the environment and information related to that environment. Therefore, Rothblum (2000) deems "[...] the maritime system a people system". This paradigm plays an important role in the design process of an interface for maritime navigation. AR should not be regarded as a tool for automation (yet). Instead, it can augment the capabilities of the operators, potentially improving safety and efficiency of operations. Hardware such as HMDs can become an extension of traditional ship bridge equipment, transferring important, docked information from the workstation to a portable display. As a result, one should be aware that such a system might raise unrealistic expectations concerning the nullification of maritime accidents.

6.4 Issues of Scale

During the RtD process, the prototype has been exposed to vessels of different sizes. These vessels are illustrated in Figure 6.1. Each of these vessels have different characteristics on the water and serve different purposes. Due to these factors, it was found that generalizing AR functions is challenging.



(a) PSV Energy Duchess (83m)

(b) Ekspressen High Speed Craft (33m)

(c) Bavaria 38 Cruiser (12m)

Figure 6.1: Different scales of vessels the prototype has been tested on. The imagery has been scaled proportionately with respect to their actual size.

Table 6.1 illustrates the large variety in environmental and operational factors on the threesome of vessels the prototype has been tested on. The importance of consideration of environmental factors is emphasized by Rothblum (2000), stating that the environment affects performance of a system in the maritime domain. An effective AR interface should provide multimodal interaction methods, ensuring interaction possibilities, regardless of environmental factors, such as the wearing of gloves in cold weather or a loud background noise **(RQ1)**. The exposure to bright sunlight is an omnipresent issue, rendering AR graphics invisible on the bright ocean surface. The author suggests a solution similar to ND filters in camera system, but a makeshift solution using car foil has proved effective too **(RQ2)** (Eikenes, 2019).

The variable bridge height and vessel stability introduce the need for adjusting bridge height in HL2 **(RQ2)**. Moreover, enabling Moving Platform Mode on HL2 (Microsoft, 2021b) compensates (although with limited success) for vessel roll and the inhibited functionality of input actions on a moving vessel. To truly accommodate for vessel roll, the gyroscope of HL2 should be leveraged to actively align horizon and AR graphics by applying a negative rotation offset to the world rotation of the AR graphics in the forward axis of the main camera object **(RQ2)**.

The variety in operations suggest a system modularity that mimics the generalizablity offered by smartphones, where by default a home screen visualizes key information, which can be augmented using widgets specifically designed for the operation at hand. In the development of these widgets it is of upmost importance that 1. the same design language is followed; 2. the widgets can share computed information; and 3. co-location of widgets in the physical world is supported. **(RQ1)**.

Additionally, it was anticipated that extended use of HL2 would be uncomfortable, as reported by (van Beek, 2021). Throughout this study, participants have not confirmed this discomfort for HL2, despite the execution of AR sessions that lasted up to 45 minutes. This observation opens the doors to research on other operations than the short and the complex **(RQ2)**.

6.5 AR as an Ecosystem

Using the findings of this study, the need for deep-rootedness of AR as a bridge system can be argued for. Therefore, and in correspondence with the support for integration of widgets as

Table 6.1: Summary of vessel differences and the effect on AR in relation to Figure 6.1

Characteristic	*Figure 6.1 (a)*	*Figure 6.1 (b)*	*Figure 6.1 (c)*
Exposure	Ship bridge protected from the elements	Ship bridge protected from the elements	Exposed to wind, precipitation and splashing salt water
Vessel Movement	Generally steady, but rough conditions can cause the vessel to tilt	Steady and fast moving	Vessel tilt is strongly influenced by waves and wind
Number of Crew Members on Bridge	Captain, 2 first mates and lower ranked crew member	Captain and deck personnel assisting docking and passengers	One captain accompanied by passengers (who can work with the sails simultaneously)
Variety in Operations	Widely varying	Short high speed voyages with brief docking moments	Slow paced, long voyages
Mobility Required for Operations	Varying operations with different ideal positions on the ship bridge entail lots of movement	Small ship bridge does not allow for a lot of movement	Lots of movement when fixing and adjusting sails; standing and sitting

described in Section 6.4, reasoning for these design choices are provided in this section.

The focus of this study has shifted throughout the RtD process. In the first iteration of the prototype, navigation was selected as the focus for this study. Upon further investigation, the operation of navigation includes many actions that use information from various sources simultaneously. These sources include information about the own vessel, vessels in the vicinity and landmarks, such as lighthouses and buoys. Aside from operational data, information about important events, including *man overboard* should be supported. This characterizes the deep-rooted interconnections in the maritime domain. Given the limited scope of this study, a framework that allows for information retrieval and visualization in AR was identified as a valuable contribution. This solution should be extended to support this deep-rooted nature of the maritime context **(RQ1)**.

Moreover, the AR system developed by Lee et al. (2016) indicates the propriety of the feature prioritization as defined in Appendix B, since the defined Minimum Viable Product (MVP) visualizes the same information. More recently, Leite et al. (2021) too have developed an AR system that visualizes other vessels (and in addition obstacles) in AR. The relevant works mentioned above implement advanced algorithms using computer vision. Although this thesis implements a more simplified approach (described in Section 4.1), accuracy is high enough to evaluate input methods and the combination of different information types in a single interface, which are both novel additions. Nevertheless, future iterations should consider the addition of computer vision **(RQ2)**.

Standardization of bridge systems should be inherent part of the development and integration process, instead of an afterthought. Current industry practices show that the maritime industry develops slowly. Newly proposed standardization cannot and will not be followed-up directly, due to the long life-cycle of vessels. Therefore, the implementation of OpenBridge (2022) has been an important and overdue process. With the introduction of AR, a new opportunity for standardization before integration arises. If guidelines for the use of AR on the ship bridge can be provided early, the development and integration of the system will benefit greatly **(RQ1)**, and as a result, the maritime industry as a whole.

6.6 Evaluation of Interactions

In Section 2.7, a threesome of interactions in an AR environment are depicted, based on writings of Lukas (2006). These interactions characterize a framework that can be used to argue for the intuitiveness of an AR interface. Considering these interactions between user, AR and the environment as such, the rest of this section argues for the potential intuitiveness of the system.

Firstly, interaction between the user and AR has been extensively reported upon in Table 5.3 and Table 4.3. During the evaluation of interaction methods between the user and AR, the importance of multimodal interactions arose, for uncertainty of the conditions (e.g., wet conditions and loud environments) often renders - at least one - form of interaction unusable at that time **(RQ1)**. Moreover, hands-free interaction can be of importance on smaller vessels, such as sailing vessels, where successful charting is characterized by manual labor involving both hands.

Secondly, interaction between AR and the environment is provided through the placement of information about obstacles in physical proximity to that object, depicting a connection between the physical and virtual object (Norman, 2013). As such, accuracy of the system has as big influence on the intuitiveness of the system **(RQ1)**. Evaluating and improving accuracy of the system beyond 'best-efforts' is out of the scope of this study, but is important for the future of Maritime AR. Under "environment" the physical workplace should be considered too. AR offers the possibility to dock AR widgets right at the workplace, seamlessly integrating the physical bridge context and AR display technology **(RQ1)**. Additionally, different color schemes should be considered, such that the brightness of AR graphics can be adjusted to brightness levels of the surroundings **(RQ1)**.

Lastly, the interaction between user and the environment is considered. AR should not restrict visual access to the ocean surface **(RQ1)**. The framework proposed in Section 4.2 describes a framework that combines multiple information source in a single display, similarly to an Integrated Display (ID) Sauer et al. (2002). Yet, the interface also takes into consideration the interface guidelines defined by Nordby et al. (2020) to avoid clutter on the ocean surface. HMDs support mobility natively, enabling the rendering of different types of information whilst the user moves along different locations on the ship bridge (Frydenberg et al., 2018). The latter has not yet been implemented. Reconsidering the interactions between user and AR, the support of not only hands-free interaction with the system, but also executing other tasks, such as operating bridge equipment or working sails should not be inhibited by wearing a HMD.

Section 7

Limitations and Future Work

The Research through Design (RtD) process, as conducted in this study, disclosed limitations related to the hardware and technology used. Additionally, interesting new perspectives were identified, which could be subject of future research projects. These limitations and future research questions are described in this section.

7.1 Limitations

7.1.1 Technology Readiness of HL2 in the Maritime Domain

As a generic Head-Mounted Display (HMD), Microsoft HoloLens 2 (HL2) is widely applicable across industries. As a result, HL2 does not excel in extreme conditions. With maritime environments being challenging ones (Rowen et al., 2021), HL2 struggles to adjust to dynamic parameters, such as altering weather conditions. This characterizes HL2 as a bridge system. Therefore, the use of HL2 on a ship bridge - being it exposed to the environment or enclosed on a ship bridge - is challenging in its current state. These issues are described in Table 7.1 with where applicable a suggestion solution by the author. Several of these issues are hardware limitations, such as waterproofing of HL2 and the risk of the HMD falling of the head of the operator, whilst other problems are remediable through continued development of the framework described in this study. The last column in Table 7.1 describes categorizes the issue as either a hardware limitation (L), an issue that is remediable with (makeshift) solutions (R) or an issue that can temporarily be overcome using a makeshift solution, but requires an industrial solution in the future (LR).

Table 7.1: Issues concerning the use of HL2 as a bridge system. The last column describes whether the issue is a hardware limitation (L), remediable (R) or a combination of the aforementioned (LR).

Problem	Affected area	Description	Suggested Solution	Cat (L/R)
Fragility in humid environments	Mainly crafts without enclosed ship bridge	Rain and splashes of (salt) water can penetrate the system and destroy it	Enclosure of HL2 should be waterproof, but issues such as water drops on the glasses and salt water stains can not be expected to be solved by waterproofing	L
Limited stability during vigorous head movement	Operations that require a plenitude of movement from the wearer. For example deck workers on a Platform Supply Vessel (PSV) or fixing sails on a sailing vessel	Vigorous movement can cause the HL2 to shift or even fall of in extreme cases	A chin strap could be included with HL2, securing the glasses tightly to the bearers head	LR
Poor visibility in bright sunlight	All seaborne structures	The reflection of sunlight on the ocean surface cannot be overcome by the brightness of graphics rendered by HL2	Build in sunglasses in HL2 using ND filters can provide visibility in bright situations where otherwise visibility would be nullified	LR

Misalignment of graphics on tilting vessel	All seaborne structures	HL2 defines 'horizontal' as horizontal when the device boots, causing the horizon to be misaligned after a shift in vessel tilt	Moving Platform Mode (Microsoft, 2021b) should include an option to force horizontal align of Augmented Reality (AR) graphics using the sensors in HL2, including the accelerometer and gyroscope. A real implementation should ensure proper alignment between real and virtual marks (Leite et al., 2021)	R
Inaccuracy of external Global Positioning System (GPS) receivers	All seaborne structures	Provided the lack of GPS in HL2 (and the inevitable inaccuracy, had it be included), a smartphone was used as GPS receiver. Inaccuracy of the smartphone GPS caused graphics to be misaligned, due to an observed error in vessel heading of up to 40 degrees compared to the onboard GPS system	A direct connection between HL2 and the bridge system allows for the use of the vessels Global Positioning (GPRMC) strings (NovAtel, 2022), providing the highest possible quality GPS information	R
Limited FOV	All HL2 use cases	AR graphics do not span across the whole with of the glasses, but only provide a Field of View (FOV) of 54 degrees (Microsoft, 2021a). As a result, AR graphics can be overlooked, unless the user fully rotates their head	As AR technology develops, the FOV will become wider. Nevertheless, other technologies could be considered, such as passthrough Virtual Reality (VR) (Meta, 2022) offering wider viewing angles, but introduce other drawbacks, such as loss of peripheral vision	L

7.1.2 Cruxes of Co-Design

As discussed in Section 6.2, co-design was a fruitful collaboration method, but it is not without limitations. In addition to the aforementioned possible lack of innovation, generalizability is at risk. The co-design sessions conducted in this study were often conducted with either a single individual or individuals from the same team. As a result, there was little discussion on the coined ideas in co-design sessions. The usefulness from gathering participants with varying age, education and experience will severely outweigh the extra recruitment costs. Thus, this and future studies that use co-design as a method would benefit from subjecting the designs to a diverse audience. A follow-up study could subject the designs proposed in this study to such an audience and validate the results.

7.1.3 Technical Challenges

In addition to the hardware limitations described in Section 7.1.1, the prototype was limited by time-consuming technical shortcomings.

Firstly, there are unknown ships and floating objects in the ocean which are not installed with identification devices and thus do neither shown in Electronic Chart Display and Information System (ECDIS) nor HL2 (Venkatrayappa et al., 2020). The AR solution created by Lee et al. (2016) utilizes camera imaging and computer vision to recognize these Unidentified Floating Objects (UFOs) around the vessel and tag them. A similar service should be implemented in the framework provided in this study in the future. The author notes however that it is not guaranteed that computer vision recognizes all obstacles and that therefore there is a need for development of a system that can deal with this uncertainty in a manner that puts safety first (e.g., provides ample white space on the ocean surface).

Secondly, the presented framework does not provide a way to integrate with the physical ship bridge environment. The system would benefit greatly from spatial awareness of the ship bridge, enabling the implementation of features such as 1. docking of AR graphics when located at a work space; and 2. shifting of AR graphics depending on the location on the ship bridge and information relevant to that location. The features mentioned would improve operator mobility even more. Rowen et al. (2021) indicate a link between increased operator mobility, improved operator performance and Situation Awareness (SA).

7.2 Research Agenda

Due to its exploratory nature, the RtD process conducted in this study has disclosed an abundance of unexplored directions concerning AR for maritime. In this section, a research agenda is provided that describes different problem framings of the knowledge and the prototype presented in this study. It is important to note that neither research on maritime AR nor further research and development of the prototype is limited by the suggestions made in the proposed research agenda, but it serves as a guideline to increase the Technology Readiness Level (TRL) of HL2 in the maritime domain. Table 7.2 presents this research agenda, depicting for each entry one of three focus areas - spanning across disciplines - including interaction design, human factors and computer science and engineering. Additionally, a suggested research method, a description and the expected outcome are provided.

Table 7.2: Research agenda for AR in the maritime domain using the prototype developed in this study

Focus	Method	Extended Description	Expected Outcome
Interaction Design	RtD; Co-design	Reproduction of this study (possibly focus on a different operation, e.g., Dynamic Positioning (DP)) and merger of results	Extended functionality and generalizability of the prototype, taking in consideration Section 7.1.2
	RtD; Co-design; Development	Extension of the framework provided in this study using widgets, as argued in Section 6.4	A framework that is more generally applicable
		Extend the framework by implementing information provision that is bridge location-dependent	A framework that can be used for evaluation of the effect of operator mobility and a step forward towards a complete AR framework
	Agreement Analysis; System Usability Scale (SUS)	Expert evaluation of prototype in-context consisting of a user test, followed by filling out the SUS and a semi-structured interview (interview guide in Appendix F)	Valuable insights into applicability of current prototype concerning interface, interaction and accuracy
	User Interface (UI) Design; Co-design	The provision of guidelines for the standardization of an AR system on the ship bridge, including graphics and rules for interactions, as described in Section 2.7	Moving towards a evaluated, generic UI design
Computer Science and Engineering	Development	Resolve overlapping AR graphics by implement an algorithm that 1. positions AR graphics abreast; and 2. groups co-located vessels	More complete and versatile interface and new interactions to explore
		Connect the HL2 to a vessel directly (using BlueBox (BlueCtrl, 2020)), enabling collection of GPRMC strings from the vessel directly. Possibly combined with the implementation of computer vision (Lee et al., 2016; Leite et al., 2021)	Increased accuracy of the prototype

Human Factors	User Testing	Explore the potential of individual HMDs as shared displays supporting collaboration and communication	Evidence for the development of inter-HMD communication
		Evaluate the effect of the prototype on decision-making and SA	Insights into the effect of the hardware and software on the operator
	Wearable, Immersive Augmented Reality (WIAR) Technology Evaluation Research Model (Grabowski et al., 2018)	Evaluate the effect of the hardware and software on the operator	Knowledge about the impact of the WIAR system on performance and safety in marine transportation (Grabowski, 2015)
	Eye-tracking	A usability study using methods similar to Hareide and Ostnes (2017) can pinpoint anomalies to evaluate the interface	Valuable insights on the usefulness and challenges of using the prototype

Section 8

Conclusion

Augmented Reality (AR) technology has unlocked the world as a canvas for the display of information. In the maritime context, AR has potential of improving operator performance and Situation Awareness (SA) by increasing operator mobility and head-up time. Through a practice-based Research through Design (RtD) process, this study aimed to answer two Research Questions (RQs): 1. *What makes an effective head-mounted AR User Interface (UI) for maritime navigation?*; and 2. *How can Microsoft HoloLens 2 (HL2) be used as a ship bridge system?* A prototype was iterated over three times, following a condensed design-thinking process coined by Bravo et al. (2021), consisting of three phases for each iteration: user research, design process and a user evaluation, followed by a reflection on that iteration. This study extended this approach with the inclusion of co-design workshops with domain experts to ensure applicability of the findings, since the maritime domain is extremely context-dependent.

This process led to three contributions and it provides answers to the two RQs. Firstly, a framework for the visualization of location-based data about points of interest on predefined canvases co-located in the real world was developed (Technology Readiness Level (TRL) 6), which runs on the HL2. This contribution can be installed on HL2 and enables the integration of HL2 on ship bridge, simultaneously answering RQ2. Secondly, using this framework, a UI design (including interactions) is proposed that defines dedicated information areas, implements the filtering of information and supports multimodal interactions. This artefact provides an answer to RQ1. The third contribution is a research agenda which provides insights into how contemporary and future research can leverage the developed framework.

Although the use of AR technology in the maritime industry is still in early stages (TRL 6), its future looks promising with both the research environment and industry investing in its development. With the framework presented in this study, the achievement of TRL 7 has become low hanging-fruit. As the TRL of HL2 increases in the maritime domain and large companies continue to invest in the development of AR for the maritime industry, general AR technology (including HL2) will transition into domain-specific AR devices that do not suffer from the same limitations (Table 7.1). Whilst development on AR interfaces for the maritime domain continues, the inclusion of co-design and in-context evaluations in the development process become increasingly important to assure the adequacy of the system.

References

Acejo, I., H. Sampson, N. Turgo, N. Ellis, and L. Tang (2018), The causes of maritime accidents in the period 2002-2016.

Allianz (2021), Safety and Shipping 1912-2012: From Titantic to Costa Concodia. An Insurer’s perspective from Allianz Global Corporate and Specialty., *Tech. rep.*

Althoff, T., R. W. White, and E. Horvitz (2016), Influence of Pokémon Go on Physical Activity: Study and Implications, *J Med Internet Res*, *18*(12), 315, DOI: https://-doi.org/10.2196/jmir.6759.

Azuma, R. T. (1997), A survey of augmented reality, *Presence: Teleoper. Virtual Environ.*, *6*(4), 355385, DOI: https://doi.org/10.1162/pres.1997.6.4.355.

Banks, A., and W. McKeran (2005), Team Situation Awareness, Shared Displays, and Performance, *International Journal of Cognitive Technology*, *10*, 23–28.

Bergström, M., S. Hirdaris, O. Valdez Banda, P. Kujala, G. Thomas, K.-L. Choy, K. Nordby, Z. li, J. Ringsberg, M. Lundh, and P. Stefenson (2018), *Towards holistic performance-based conceptual design of Arctic cargo ships.*

BlueCtrl (2020), Blue Box, `https://bluectrl.io/bluebox`, Accessed on 25.04.2022.

Bravo, A., A. M. Maier, and P. J. Cash (2021), Watch that seam! Designing hybrid presentations with data visualisation in augmented reality, *International Journal of Design*, *15*(2).

Cantoni, L., L. Botturi, M. Faré, and D. Bolchini (2009), Playful holistic support to HCI requirements using LEGO bricks, in *International Conference on Human Centered Design*, pp. 844–853, Springer, DOI: https://doi.org/10.1145/1621995.1622032.

Cockburn, A. (2004), Crystal clear a human-powered methodology for small teams.

Cross, N. (1972), Proceedings of the Design Research Society International Conference, 1971: Design Participation.

Cutting, J., and P. Vishton (1995), Perceiving layout and knowing distances: The interaction, relative potency, and contextual use of different information about depth, in *Perception of Space and Motion*, vol. 5, edited by W. Epstein and S. Rogers, pp. 69–177, Academic Press.

Djajadiningrat, T., S. Wensveen, J. Frens, and K. Overbeeke (2004), Tangible products: Redressing the balance between appearance and action, *Personal and Ubiquitous Computing*, *8*, 294–309, DOI: https://doi.org/10.1007/s00779-004-0293-8.

Dobing, B., and J. Parsons (2006), How UML is used, *Commun. ACM*, *49*(5), 109113, DOI: https://doi.org/10.1145/1125944.1125949.

Eikenes, J. O. (2019), How to create your own HoloLens sun screen, `https://medium.com/ocean-industries-concept-lab/how-to-create-your-own-hololens-sun-screen-68c466071a01`, Accessed on 03.06.2021.

Endsley, M. R. (1995), Toward a Theory of Situation Awareness in Dynamic Systems, *Human Factors*, *37*(1), 32–64, DOI: https://doi.org/10.1518/001872095779049543.

Fan, M., S. Shi, and K. N. Truong (2020), Practices and Challenges of Using Think-Aloud Protocols in Industry: An International Survey, *Journal of Usability Studies*, *15*(2).

Figma (2021), Figma: the collaborative interface design tool, `https://www.figma.com/`, Accessed on 31.01.2022.

Frydenberg, S., K. Nordby, and J. O. Eikenes (2018), *Exploring designs of augmented reality systems for ship bridges in arctic waters*.

Frydenberg, S., K. Aylward, K. Nordby, and J. O. H. Eikenes (2021), Development of an Augmented Reality Concept for Icebreaker Assistance and Convoy Operations, *Journal of Marine Science and Engineering*, *9*(9), 996, DOI: https://doi.org/10.3390/jmse9090996.

Furuno Product Solutions (2019), Driving the Digitalization of Navigation: ENVISION, `https://www.furuno.com/special/en/envision`, Accessed on 21.01.2022.

Gaver, W. W., J. Bowers, A. Boucher, H. Gellerson, S. Pennington, A. Schmidt, A. Steed, N. Villars, and B. Walker (2004), The drift table: designing for ludic engagement, DOI: https://doi.org/10.1145/985921.985947.

Gibson, J. J. (1977), The theory of affordances, *Hilldale, USA*, *1*(2), 67–82.

Grabowski, M. (2015), Research on Wearable, Immersive Augmented Reality (WIAR) Adoption in Maritime Navigation, *Journal of Navigation*, *68*(3), 453–464, DOI: https://doi.org/10.1017/S0373463314000873.

Grabowski, M., A. Rowen, and J.-P. Rancy (2018), Evaluation of wearable immersive augmented reality technology in safety-critical systems, *Safety Science*, *103*, 23–32, DOI: https://doi.org/10.1016/j.ssci.2017.11.013.

Guo, F. B., Z. Yang, E. B. Davis, A. Khalique, and A. Bury (2021), Does Being Human Cause Human Errors? Consideration of Human-Centred Design in Ship Bridge Design, in *International Conference on Applied Human Factors and Ergonomics*, pp. 302–309, Springer.

Hareide, O. S. (2020), Coastal Navigationin a digital era, *Necesse*, *5*(1), 202–221.

Hareide, O. S., and R. Ostnes (2017), Maritime Usability Study by Analysing Eye Tracking Data, *Journal of Navigation*, *70*(5), 927–943, DOI: https://doi.org/10.1017/S0373463317000182.

Hareide, O. S., and T. Porathe (2019), Maritime Augmented Reality, *Coordinates*, *15*(2), 31–35.

Haward, B. M., C. H. Lewis, and M. J. Griffin (2009), Motions and crew responses on an offshore oil production and storage vessel, *Applied Ergonomics*, *40*(5), 904–914, DOI: https://doi.org/10.1016/j.apergo.2009.01.001.

Horizon 2020 (2014), Technology readiness levels (TRL), `https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf`, Accessed on 18.05.2021.

Hugues, O., J.-M. Cieutat, and P. Guitton (2010), An experimental augmented reality platform for assisted maritime navigation, DOI: https://doi.org/10.1145/1785455.1785467.

Hutchinson, H., W. Mackay, B. Westerlund, B. B. Bederson, A. Druin, C. Plaisant, M. Beaudouin-Lafon, S. Conversy, H. Evans, H. Hansen, N. Roussel, and B. Eiderbäck (2003), Technology probes: inspiring design for and with families, DOI: https://doi.org/10.1145/642611.642616.

International Organization for Standardization (2007), ISO 8468:2007.

Itzstein, G. S. V., M. Billinghurst, R. T. Smith, and B. Thomas (2019), Augmented Reality Entertainment: Taking Gaming Out of the Box, in *Encyclopedia of Computer Graphics and Games*, DOI: https://doi.org/10.1007/978-3-319-08234-9_81-1.

Johnson-Laird, P. N. (1983), *Mental models: Towards a cognitive science of language, inference, and consciousness*, Harvard University Press.

Kaley, A. (2021), Mapping User Stories in Agile, `https://www.nngroup.com/articles/user-story-mapping/`, Accessed on 30.01.2021.

Kimbell, L. (2011), Rethinking Design Thinking: Part I, *Design and Culture*, *3*, 285–306, DOI: https://doi.org/10.2752/175470811X13071166525216.

Laera, F., M. Fiorentino, A. Evangelista, A. Boccaccio, V. M. Manghisi, J. Gabbard, M. Gattullo, A. E. Uva, and M. M. Foglia (2021a), Augmented reality for maritime navigation data visualisation: a systematic review, issues and perspectives, *Journal of Navigation*, pp. 1–18, DOI: https://doi.org/10.1017/S0373463321000412.

Laera, F., V. M. Manghisi, A. Evangelista, M. M. Foglia, and M. Fiorentino (2021b), Augmented Reality Interface for Sailing Navigation: a User Study for Wind Representation, in *2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pp. 260–265, DOI: https://doi.org/10.1109/ISMAR-Adjunct54149.2021.00060.

Lee, J. M., K. H. Lee, B. Nam, and Y. Wu (2016), Study on Image-Based Ship Detection for AR Navigation, in *2016 6th International Conference on IT Convergence and Security (ICITCS)*, pp. 1–4, DOI: https://doi.org/10.1109/ICITCS.2016.7740373.

Leite, B. G., H. T. Sinohara, N. Maruyama, and E. A. Tannuri (2021), Maritime navigational assistance by visual augmentation, *Journal of Navigation*, pp. 1–19, DOI: https://doi.org/10.1017/S0373463321000795.

Leite, B. G., H. T. Sinohara, N. Maruyama, and E. A. Tannuri (2022), Maritime navigational assistance by visual augmentation, *Journal of Navigation*, *75*(1), 57–75, DOI: https://doi.org/10.1017/S0373463321000795.

Lim, Y.-k., E. Stolterman, and J. Tenenberg (2008), The anatomy of prototypes, *ACM Transactions on Computer-Human Interaction*, *15*, 1–27, DOI: https://-doi.org/10.1145/1375761.1375762.

Lukas, U. F. v. (2006), Virtual and augmented reality in the maritime industry, Accessed on 14.12.2021.

Lukas, U. F. v. (2010), Virtual and augmented reality for the maritime sector applications and requirements, *IFAC Proceedings Volumes*, *43*(20), 196–200, DOI: https://-doi.org/10.3182/20100915-3-DE-3008.00045.

Lurås, S. (2015), Guide: Layered scenario mapping, `http://hdl.handle.net/11250/294118`, Accessed on 01.10.2021.

Lurås, S., and K. Nordby (2014), *Field Studies Informing Ship's Bridge Design at the Ocean Industries Concept Lab*, DOI: https://doi.org/10.3940/rina.hf.2014.05.

Magic Leap (2021), Magic Leap 1 is a wearable computer for enterprise productivity, `https://www.magicleap.com/en-us/magic-leap-1`, Accessed on 17.02.2022.

Makkonen, T., T. Inkinen, and J. Saarni (2013), Innovation types in the Finnish maritime cluster, *WMU Journal of Maritime Affairs*, *12*(1), 1–15, DOI: https://doi.org/10.1007/s13437-013-0039-4.

Mallam, S., and K. Nordby (2018), Assessment of current maritime bridge design regulations and guidance, *The Oslo School of Architecture and Design, Oslo, Norway*.

Mathieu, J. E., T. S. Heffner, G. F. Goodwin, E. Salas, and J. A. Cannon-Bowers (2000), The influence of shared mental models on team process and performance, *Journal of Applied Psychology*, *85*(2), 273–283, DOI: https://doi.org/10.1037/0021-9010.85.2.273.

May, M. (2004), Wayfinding, ships and augmented reality, in *Virtual applications*, pp. 212–233, Springer, DOI: https://doi.org/10.1007/978-1-4471-3746-7_10.

Meowsbox (2019), NetGPS, `https://play.google.com/store/apps/details?id=com.meowsbox.netgps&hl=en&gl=US`, Accessed on 26.04.2022.

Meta (2022), What is passthrough?, `https://support.oculus.com/articles/in-vr-experiences/oculus-features/what-is-passthrough/`, Accessed on 22.04.2022.

Microsoft (2021a), Microsoft HoloLens 2: For precise, efficient hands-free work, `https://www.microsoft.com/en-us/hololens`, Accessed on 17.01.2022.

Microsoft (2021b), Moving Platform Mode on Low Dynamic Motion Moving Platforms, `https://docs.microsoft.com/en-us/hololens/hololens2-moving-platform`, Accessed on 10.12.2021.

Mogford, R. H. (1997), Mental models and situation awareness in air traffic control, *The International Journal of Aviation Psychology*, *7*(4), 331–341, DOI: https://-doi.org/10.1207/s15327108ijap0704_5.

Nordby, K., S. C. Mallam, and M. Lützhöft (2019), Open user interface architecture for digital multivendor ship bridge systems, *WMU Journal of Maritime Affairs*, *18*(2), 297–318, DOI: https://doi.org/10.1007/s13437-019-00168-w.

Nordby, K., E. Gernez, S. Frydenberg, and J. O. Eikenes (2020), *Augmenting OpenBridge: An open user interface architecture for augmented reality applications on ship bridges*.

Norman, D. A. (2013), *The design of everyday things*, revised and expanded edition. ed., Basic Books, New York.

NovAtel (2022), GPRMC: GPS specific information, `https://docs.novatel.com/OEM7/Content/Logs/GPRMC.htm`, Accessed on 22.04.2022.

Oh, J., S. Park, and O.-S. Kwon (2016), Advanced Navigation Aids System based on Augmented Reality, *International Journal of e-Navigation and Maritime Economy*, *5*, 21–31, DOI: https://doi.org/10.1016/j.enavi.2016.12.002.

OICL (2021), Ocean Industries Concept Lab, `https://medium.com/ocean-industries-concept-lab`, Accessed on 26.04.2022.

Oikonomou, K., E. Chatzilari, S. Nikolopoulos, I. Kompatsiaris, D. Gavilan, and J. Downing (2021), Snapwear: A Snapchat AR filter for the virtual tryon of real clothes, in *2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pp. 46–51, IEEE, DOI: https://doi.org/10.1109/ISMAR-Adjunct54149.2021.00019.

Oltedal, H. A., and M. Lützhöft (2018), *Managing Maritime Safety*, Routledge.

OpenBridge (2022), OpenBridge Design System: An open source platform enabling the development of cost effective, safe and efficient maritime workplaces, `http://openbridge.no/`, Accessed on 23.05.2021.

Orasanu, J., and I. Statler (1994), Shared Problem Models and Crew Decision Making.

Porathe, T. (2006), 3-D Nautical Charts and Safe Navigation, Doctoral thesis, monograph, Institutionen för Innovation, Design och Produktutveckling.

Porathe, T., and M. B. Billesø (2015), Human Factors in e-Navigation: a study of Dynamic NoGo Area Visualization in Electronic Nautical Charts, `http://hdl.handle.net/11250/2398911`.

Procee, S., C. Borst, M. van Paassen, M. Mulder, and V. Bertram (2017), Toward functional augmented reality in marine navigation: a cognitive work analysis, in *Proceedings of COMPIT*, pp. 298–312.

Qi, W., and J.-B. Martens (2005), Tangible User Interfaces for 3D Clipping Plane Interaction with Volumetric Data: A Case Study, in *Proceedings of the 7th International Conference on Multimodal Interfaces*, ICMI '05, p. 252258, Association for Computing Machinery, New York, NY, USA, DOI: https://doi.org/10.1145/1088463.1088507.

React (2022), React - A JavaScript library for building user interfaces, `https://reactjs.org/`, Accessed on 14.04.2022.

Rittel, H. W. J., and M. M. Webber (1973), Dilemmas in a general theory of planning, *Policy Sciences*, *4*(2), 155–169, DOI: https://doi.org/10.1007/BF01405730.

Robertson, T., and J. Simonsen (2012), Participatory design: An introduction, *Routledge International Handbook of Participatory Design*, pp. 1–17.

Rogers, E. M. (1971), *Diffusion of Innovations*, The Free Press, New York.

Rothblum, A. M. (2000), Human error and marine safety, in *National Safety Council Congress and Expo, Orlando, FL*, vol. 7.

Rouse, W., and N. Morris (1984), On Looking Into the Black Box. Prospects and Limits in the Search for Mental Models, *Psychological Bulletin*, *100*, DOI: https://doi.org/10.1037/0033-2909.100.3.349.

Rowen, A., M. Grabowski, and J. Rancy (2019), Through the Looking Glass(es): Impacts of Wearable Augmented Reality Displays on Operators in a Safety-Critical System, *IEEE Transactions on Human-Machine Systems*, *49*(6), 652–660, DOI: https://doi.org/10.1109/THMS.2019.2944384.

Rowen, A., M. Grabowski, and J.-P. Rancy (2021), Moving and Improving in Safety-Critical Systems: Impacts of Head-Mounted Displays on Operator Mobility, Performance, and Situation Awareness 22 September 2020, *International Journal of Human-Computer Studies*, *150*, 102,606, DOI: https://doi.org/10.1016/j.ijhcs.2021.102606.

Rudd, J., K. Stern, and S. Isensee (1996), Low vs. High-Fidelity Prototyping Debate, *Interactions*, *3*(1), 7685, DOI: https://doi.org/10.1145/223500.223514.

Sanders, E. B. N., and P. J. Stappers (2008), Co-creation and the new landscapes of design, *CoDesign*, *4*(1), 5–18, DOI: https://doi.org/10.1080/15710880701875068.

Sauer, J., D. G. Wastell, G. R. J. Hockey, C. M. Crawshaw, M. Ishak, and J. C. Downing (2002), Effects of display design on performance in a simulated ship navigation environment, *Ergonomics*, *45*(5), 329–347, DOI: https://doi.org/10.1080/00140130110116128.

Schwaber, K. (1997), Scrum development process, in *Business object design and implementation*, pp. 117–134, Springer, DOI: https://doi.org/10.1007/978-1-4471-0947-1_11.

Seybold, P. B. (2006), Outside innovation: how your customers will co-design the future of your business, *Collins, New York*.

Sielhorst, T., M. Feuerstein, and N. Navab (2008), Advanced Medical Displays: A Literature Review of Augmented Reality, *Journal of Display Technology*, *4*(4), 451–467, DOI: https://doi.org/10.1109/JDT.2008.2001575.

Smeaton, G. P., W. O. Dineley, and S. M. Tucker (1995), Display Requirements for ECDIS/ARPA Overlay Systems, *Journal of Navigation*, *48*(1), 13–28, DOI: https://doi.org/10.1017/S0373463300012467.

Snap Inc. (2021), The next generation of Spectacles, `https://www.spectacles.com/`, Accessed on 17.01.2022.

Som de Cerff, W., J. van de Vegte, R. Boers, T. Brandsma, M. de Haij, W. van Moosel, J. W. Noteboom, G. A. Pagani, and G. van der Schrier (2018), Agile Development in Meteorological RD: Achieving a Minimum Viable Product in a Scrum Work Setting, *Bulletin of the American Meteorological Society*, *99*(12), 2507–2518, DOI: https://doi.org/10.1175/bams-d-17-0273.1.

TekLab (2021), Om TekLab, `https://teklab.uib.no/om-teklab/`, Accessed on 26.04.2022.

Ulstein (2013), 2013: ULSTEIN BRIDGE VISIONő - DNBS INNOVATION AWARD 2012, `https://ulstein.com/news/2013-ulstein-bridge-vision-dnbs-innovation-award-2012`, Accessed on 20.01.2022.

Ulstein (2019), ENERGY DUCHESS, `https://ulstein.com/references/energy-duchess`, Accessed on 26.01.2022.

Unity (2022), 3D Software for Architecture, Engineering Construction, Accessed on 13.04.2022.

van Beek, A. (2021), Report of a field study: maritime challenges and opportunities for augmented reality, `https://www.dropbox.com/s/htcxswidkfijb4l/05-16%20Report%20of%20a%20field%20study%20-%20maritime%20challenges%20and%20opportunities%20for%20augmented%20reality.pdf?dl=0`.

van Beek, A. (2022), Sjør: AR Supported Maritime Navigation, `https://github.com/Imable/sjoer`.

van Schaik, J. (2016), DotNetByExample - The Next Generation: Converting lat/lon coordinates to local coordinates for HoloLens apps, `https://localjoost.github.io/converting-latlon-coordinates-to-local/`, Accessed on 25.04.2022.

Venkatrayappa, d., A. Desolneux, J.-M. Hubert, and J. Manceau (2020), *Unidentified Floating Object detection in maritime environment using dictionary learning*.

Von Hippel, E. (2006), *Democratizing innovation*, the MIT Press.

Vue.js (2022), The Progressive JavaScript Framework, `https://vuejs.org/`, Accessed on 14.04.2022.

Wickens, C. D. (2002), Situation Awareness and Workload in Aviation, *Current Directions in Psychological Science*, *11*(4), 128–133, DOI: https://doi.org/10.1111/1467-8721.00184.

Wärtsilä Corporation (2016), Wärtsiläs service ensures a reliable and pleasant cruise for passengers of M/S Artania, `https://www.wartsila.com/media/news/02-11-2016-wartsilas-service-ensures-a-reliable-and-pleasant-cruise-for-passengers`
Accessed on 20.01.2022.

Wärtsilä Corporation (2018), Augmented reality creates a new dimension in marine maintenance services, `https://www.wartsila.com/media/news/31-07-2018-augmented-reality-creates-a-new-dimension-in-marine-maintenance-service`
Accessed on 21.01.2022.

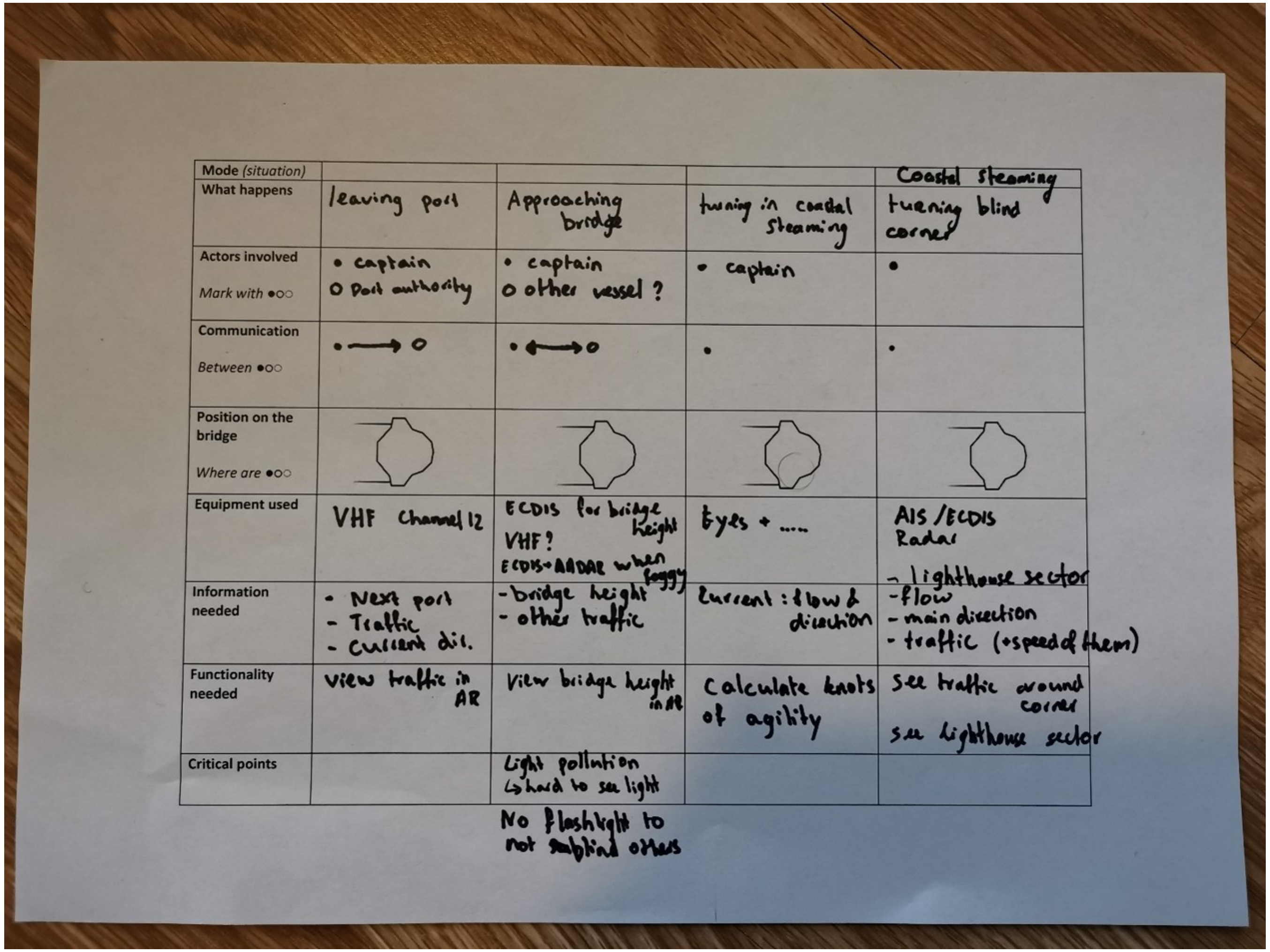
Zimmerman, J., J. Forlizzi, and S. Evenson (2007), Research through design as a method for interaction design research in HCI, DOI: https://doi.org/10.1145/1240624.1240704.

Zimmerman, J., E. Stolterman, and J. Forlizzi (2010), *An Analysis and Critique of Research through Design: towards a formalization of a research approach*, vol. 2010, DOI: https://-doi.org/10.1145/1858171.1858228.

Microsoft Design Labs (2021), MRTK Examples Hub, `https://www.microsoft.com/en-us/p/mrtk-examples-hub/9mv8c3912sj4#:~:text=MRTK%20is%20an%20open%2Dsource,ms%2FMRTK%20for%20more%20information`, Accessed on 31.01.2022.

Appendix A

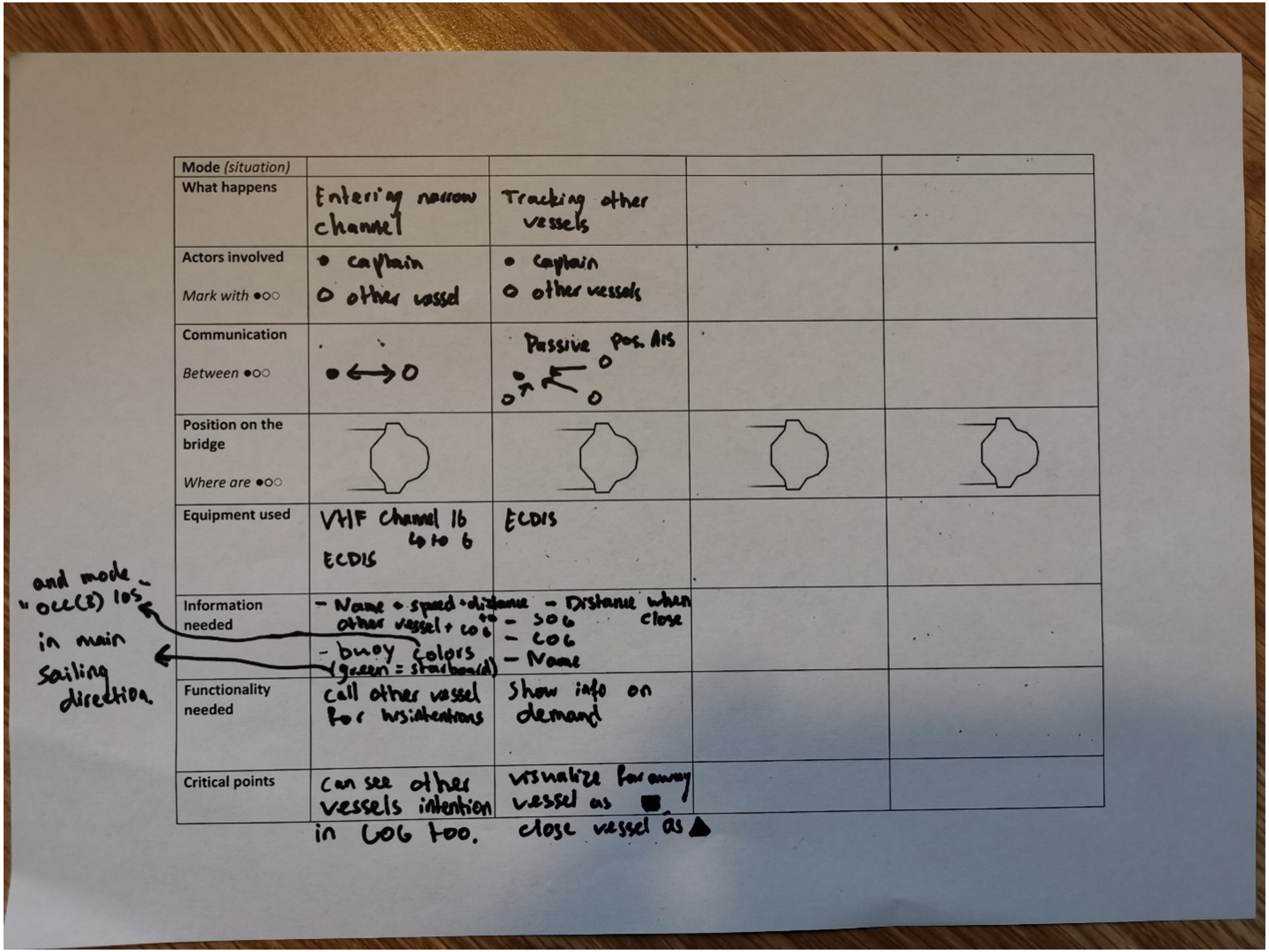
Layered-Scenario Mapping



Mode *(situation)*				Coastal steaming
What happens	leaving port	Approaching bridge	turning in coastal steaming	turning blind corner
Actors involved *Mark with* ●○○	• captain o Port authority	• captain o other vessel ?	• captain	•
Communication *Between* ●○○	• ⟶ o	• ⟷ o	•	•
Position on the bridge *Where are* ●○○				
Equipment used	VHF Channel 12	ECDIS for bridge height VHF ? ECDIS+RADAR when foggy	Eyes + ...	AIS / ECDIS Radar
Information needed	- Next port - Traffic - Current dir.	- bridge height - other traffic	Current : flow & direction	- lighthouse sector - flow - main direction - traffic (+speed of them)
Functionality needed	view traffic in AR	View bridge height in AR	Calculate knots of agility	See traffic around corner see lighthouse sector
Critical points		Light pollution ↳ hard to see light		

No flashlight to not blind others

Figure A.1: Results from Layered-Scenario Mapping with Karl Robert Røttingen



Mode *(situation)*				
What happens	Entering narrow channel	Tracking other vessels		
Actors involved *Mark with* ●○○	● captain ○ other vessel	● captain ○ other vessels		
Communication *Between* ●○○	● ⟷ ○	Passive pos. AIS		
Position on the bridge *Where are* ●○○				
Equipment used	VHF Channel 16 to 6 ECDIS	ECDIS		
Information needed	- Name + speed + distance other vessel + COG - buoy colors (green = starboard)	- Distance when close - SOG - COG - Name		
Functionality needed	call other vessel for his intentions	Show info on demand		
Critical points	Can see other vessels intention in COG too.	visualize far away vessel as ■ close vessel as ▲		

and mode - "occ(3) 10s"

in main sailing direction.

Figure A.2: Results from Layered-Scenario Mapping with Karl Robert Røttingen

Appendix B

User Story Mapping

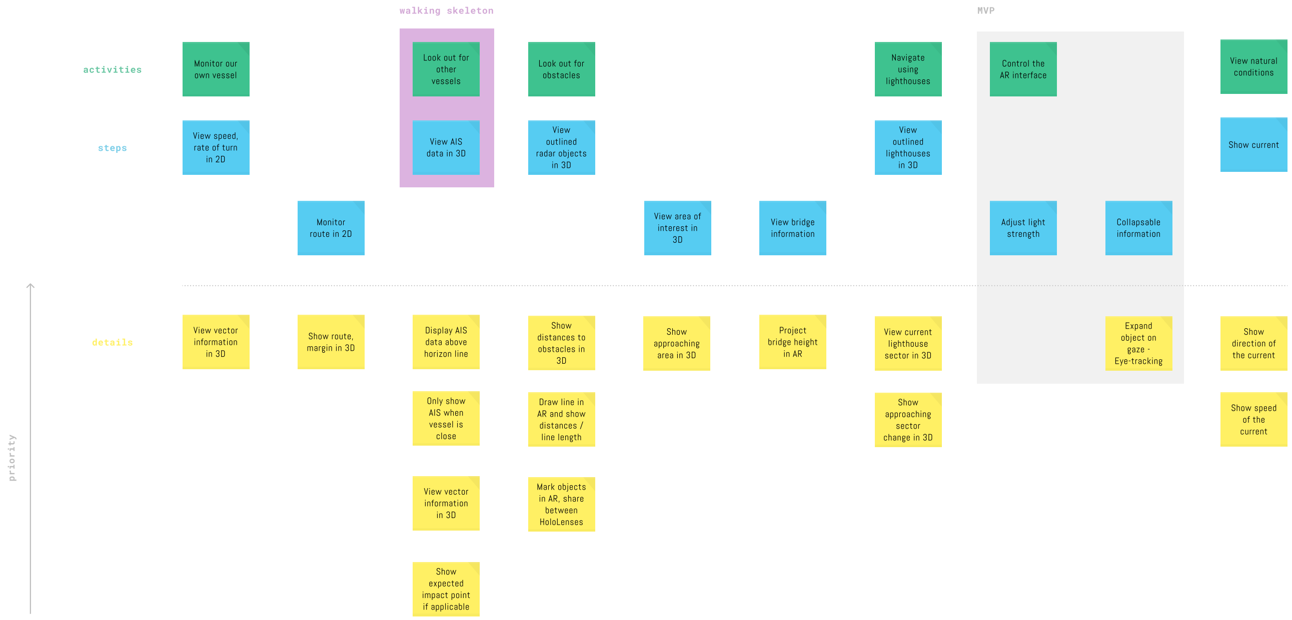


Figure B.1: A user story mapping describing user requirements that can be fulfilled by features in the prototype. The Walking Skeleton is visualized using the purple marker. The Minimum Viable Product (MVP) is denoted using the grey marker

Appendix C

UML Diagram

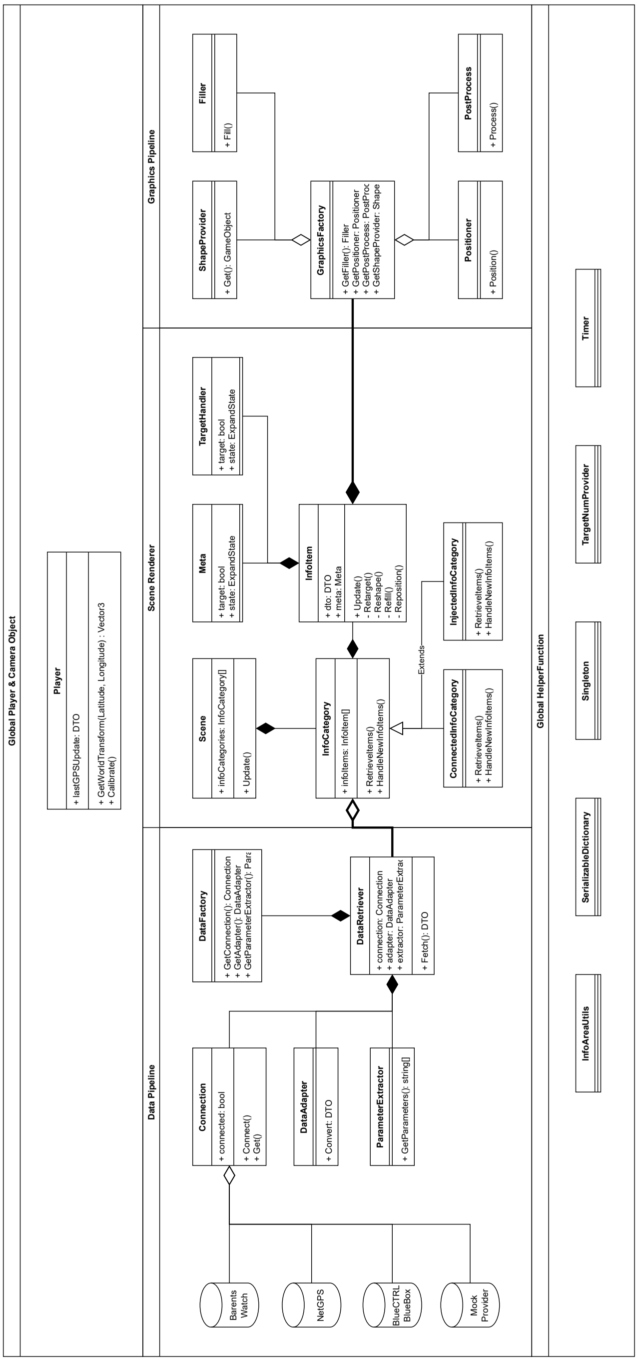
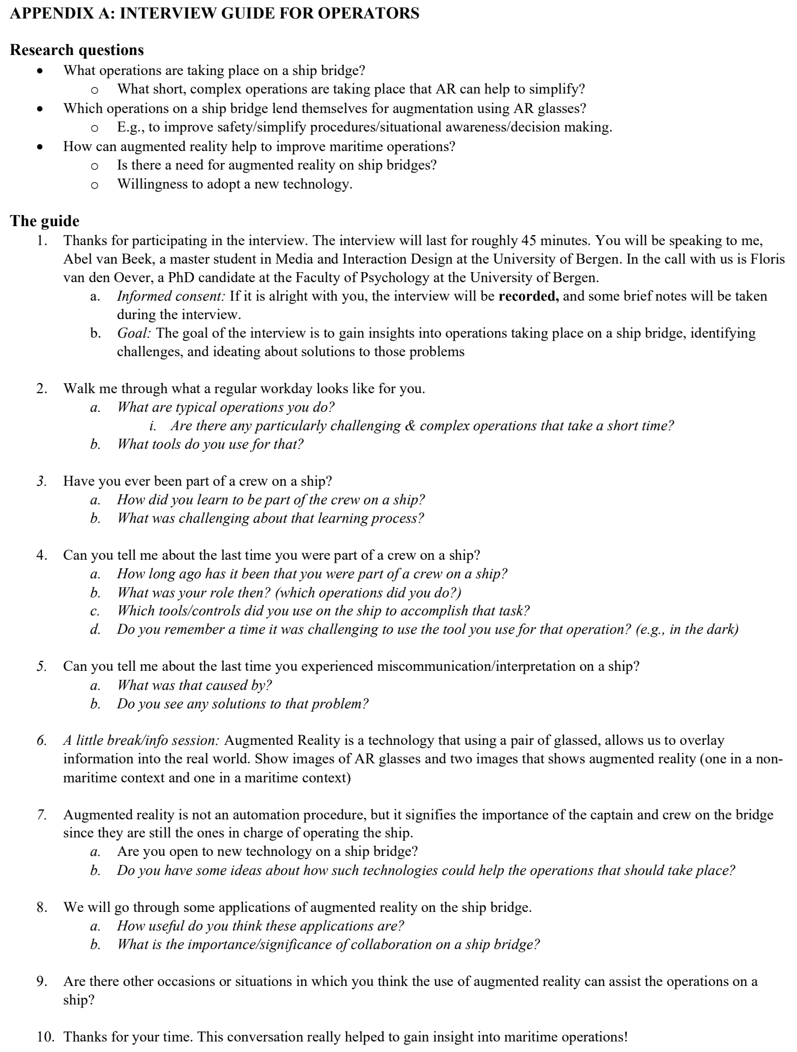


Figure C.1: Unified Modeling Language (UML) diagram disclosing the interconnection between classes in the prototype

Appendix D

Interview Guide for Operators



APPENDIX A: INTERVIEW GUIDE FOR OPERATORS

Research questions

- What operations are taking place on a ship bridge?
  - What short, complex operations are taking place that AR can help to simplify?
- Which operations on a ship bridge lend themselves for augmentation using AR glasses?
  - E.g., to improve safety/simplify procedures/situational awareness/decision making.
- How can augmented reality help to improve maritime operations?
  - Is there a need for augmented reality on ship bridges?
  - Willingness to adopt a new technology.

The guide

1. Thanks for participating in the interview. The interview will last for roughly 45 minutes. You will be speaking to me, Abel van Beek, a master student in Media and Interaction Design at the University of Bergen. In the call with us is Floris van den Oever, a PhD candidate at the Faculty of Psychology at the University of Bergen.
   a. *Informed consent:* If it is alright with you, the interview will be **recorded,** and some brief notes will be taken during the interview.
   b. *Goal:* The goal of the interview is to gain insights into operations taking place on a ship bridge, identifying challenges, and ideating about solutions to those problems

2. Walk me through what a regular workday looks like for you.
   a. *What are typical operations you do?*
      i. *Are there any particularly challenging & complex operations that take a short time?*
   b. *What tools do you use for that?*

3. Have you ever been part of a crew on a ship?
   a. *How did you learn to be part of the crew on a ship?*
   b. *What was challenging about that learning process?*

4. Can you tell me about the last time you were part of a crew on a ship?
   a. *How long ago has it been that you were part of a crew on a ship?*
   b. *What was your role then? (which operations did you do?)*
   c. *Which tools/controls did you use on the ship to accomplish that task?*
   d. *Do you remember a time it was challenging to use the tool you use for that operation? (e.g., in the dark)*

5. Can you tell me about the last time you experienced miscommunication/interpretation on a ship?
   a. *What was that caused by?*
   b. *Do you see any solutions to that problem?*

6. *A little break/info session:* Augmented Reality is a technology that using a pair of glassed, allows us to overlay information into the real world. Show images of AR glasses and two images that shows augmented reality (one in a non-maritime context and one in a maritime context)

7. Augmented reality is not an automation procedure, but it signifies the importance of the captain and crew on the bridge since they are still the ones in charge of operating the ship.
   a. Are you open to new technology on a ship bridge?
   b. *Do you have some ideas about how such technologies could help the operations that should take place?*

8. We will go through some applications of augmented reality on the ship bridge.
   a. *How useful do you think these applications are?*
   b. *What is the importance/significance of collaboration on a ship bridge?*

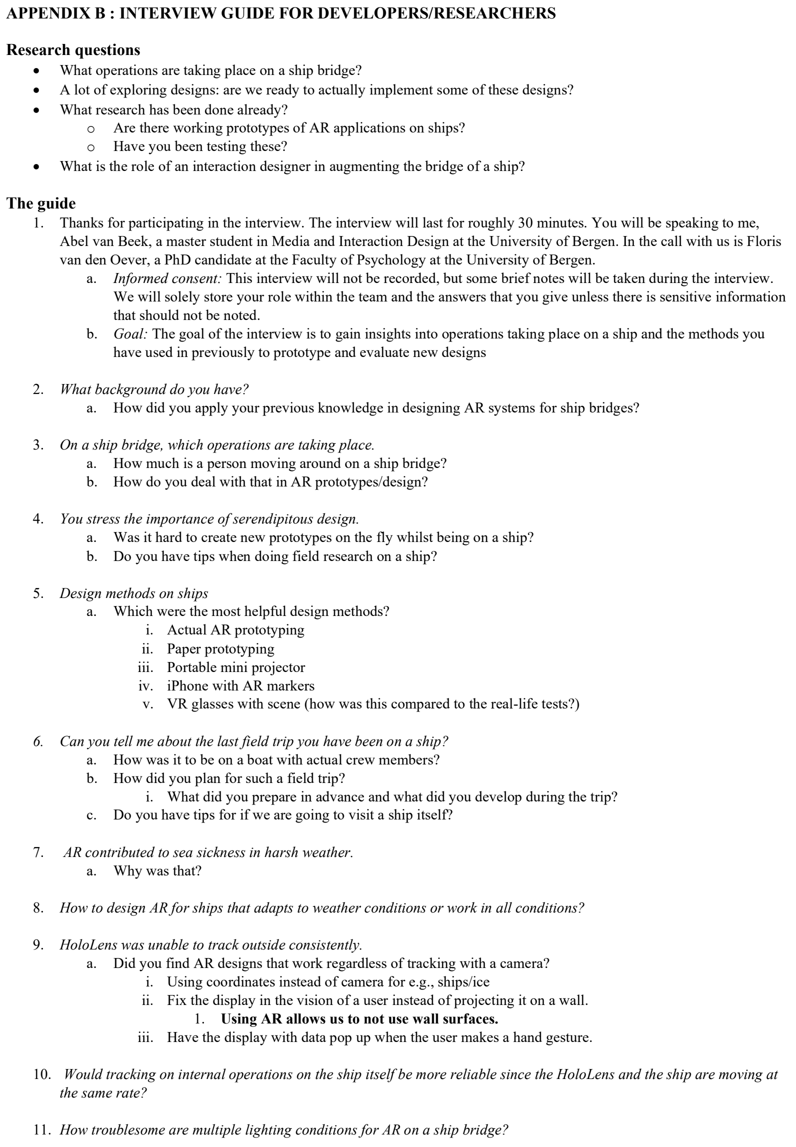
9. Are there other occasions or situations in which you think the use of augmented reality can assist the operations on a ship?

10. Thanks for your time. This conversation really helped to gain insight into maritime operations!

Figure D.1: Interview guide that was used in the initial semi-structured interviews with operators

Appendix E

Interview Guide for Researchers



APPENDIX B : INTERVIEW GUIDE FOR DEVELOPERS/RESEARCHERS

Research questions

- What operations are taking place on a ship bridge?
- A lot of exploring designs: are we ready to actually implement some of these designs?
- What research has been done already?
    - Are there working prototypes of AR applications on ships?
    - Have you been testing these?
- What is the role of an interaction designer in augmenting the bridge of a ship?

The guide

1. Thanks for participating in the interview. The interview will last for roughly 30 minutes. You will be speaking to me, Abel van Beek, a master student in Media and Interaction Design at the University of Bergen. In the call with us is Floris van den Oever, a PhD candidate at the Faculty of Psychology at the University of Bergen.
    a. *Informed consent:* This interview will not be recorded, but some brief notes will be taken during the interview. We will solely store your role within the team and the answers that you give unless there is sensitive information that should not be noted.
    b. *Goal:* The goal of the interview is to gain insights into operations taking place on a ship and the methods you have used in previously to prototype and evaluate new designs

2. *What background do you have?*
    a. How did you apply your previous knowledge in designing AR systems for ship bridges?

3. *On a ship bridge, which operations are taking place.*
    a. How much is a person moving around on a ship bridge?
    b. How do you deal with that in AR prototypes/design?

4. *You stress the importance of serendipitous design.*
    a. Was it hard to create new prototypes on the fly whilst being on a ship?
    b. Do you have tips when doing field research on a ship?

5. *Design methods on ships*
    a. Which were the most helpful design methods?
        i. Actual AR prototyping
        ii. Paper prototyping
        iii. Portable mini projector
        iv. iPhone with AR markers
        v. VR glasses with scene (how was this compared to the real-life tests?)

6. *Can you tell me about the last field trip you have been on a ship?*
    a. How was it to be on a boat with actual crew members?
    b. How did you plan for such a field trip?
        i. What did you prepare in advance and what did you develop during the trip?
    c. Do you have tips for if we are going to visit a ship itself?

7. *AR contributed to sea sickness in harsh weather.*
    a. Why was that?

8. *How to design AR for ships that adapts to weather conditions or work in all conditions?*

9. *HoloLens was unable to track outside consistently.*
    a. Did you find AR designs that work regardless of tracking with a camera?
        i. Using coordinates instead of camera for e.g., ships/ice
        ii. Fix the display in the vision of a user instead of projecting it on a wall.
            1. **Using AR allows us to not use wall surfaces.**
        iii. Have the display with data pop up when the user makes a hand gesture.

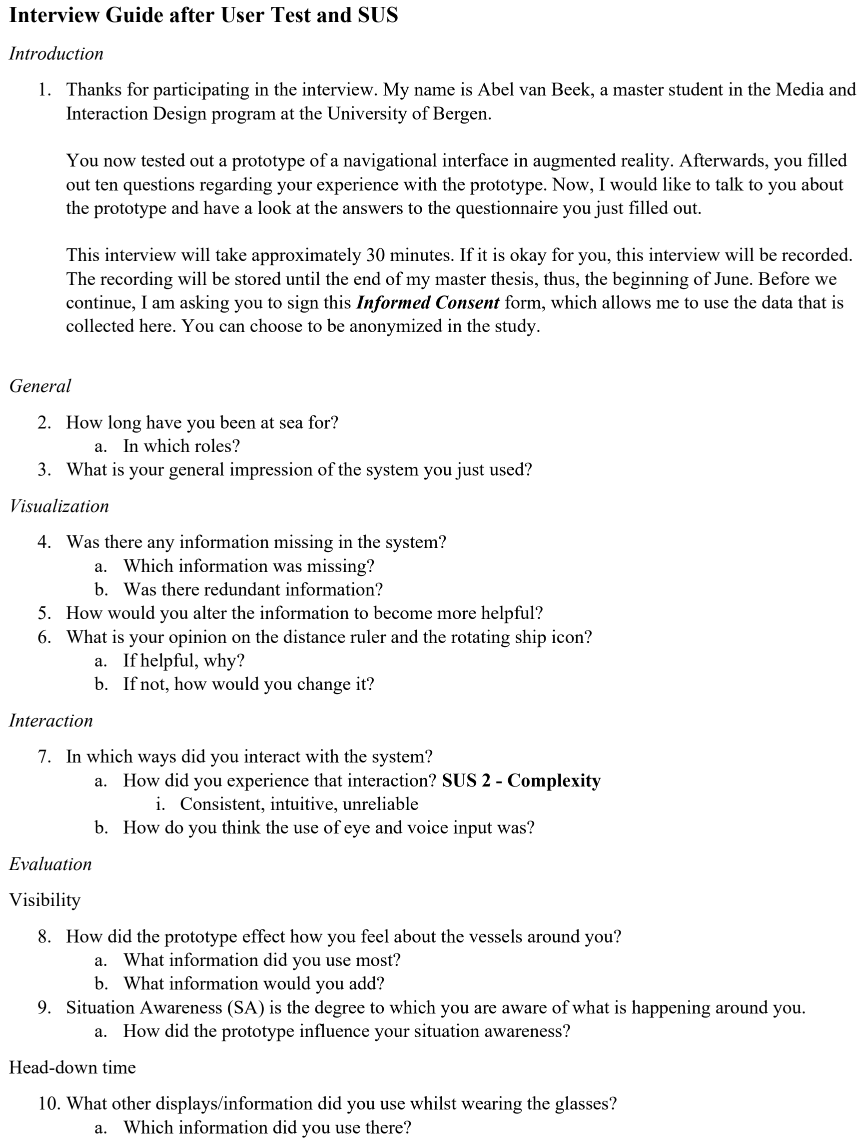
10. *Would tracking on internal operations on the ship itself be more reliable since the HoloLens and the ship are moving at the same rate?*

11. *How troublesome are multiple lighting conditions for AR on a ship bridge?*

Figure E.1: Interview guide that was used in the initial semi-structured interviews with researchers

Appendix F

Interview Guide after User Test and SUS



Interview Guide after User Test and SUS

Introduction

1. Thanks for participating in the interview. My name is Abel van Beek, a master student in the Media and Interaction Design program at the University of Bergen.

   You now tested out a prototype of a navigational interface in augmented reality. Afterwards, you filled out ten questions regarding your experience with the prototype. Now, I would like to talk to you about the prototype and have a look at the answers to the questionnaire you just filled out.

   This interview will take approximately 30 minutes. If it is okay for you, this interview will be recorded. The recording will be stored until the end of my master thesis, thus, the beginning of June. Before we continue, I am asking you to sign this ***Informed Consent*** form, which allows me to use the data that is collected here. You can choose to be anonymized in the study.

General

2. How long have you been at sea for?
   a. In which roles?
3. What is your general impression of the system you just used?

Visualization

4. Was there any information missing in the system?
   a. Which information was missing?
   b. Was there redundant information?
5. How would you alter the information to become more helpful?
6. What is your opinion on the distance ruler and the rotating ship icon?
   a. If helpful, why?
   b. If not, how would you change it?

Interaction

7. In which ways did you interact with the system?
   a. How did you experience that interaction? **SUS 2 - Complexity**
      i. Consistent, intuitive, unreliable
   b. How do you think the use of eye and voice input was?

Evaluation

Visibility

8. How did the prototype effect how you feel about the vessels around you?
   a. What information did you use most?
   b. What information would you add?
9. Situation Awareness (SA) is the degree to which you are aware of what is happening around you.
   a. How did the prototype influence your situation awareness?

Head-down time

10. What other displays/information did you use whilst wearing the glasses?
    a. Which information did you use there?

Figure F.1: Interview guide that can be used after conducting a user test and filling out the System Usability Scale (SUS)