

Peer reviewed article

A review of augmented reality applications for ship bridges

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Abstract

We present a state-of-the art analysis of Augmented Reality (AR) applications for ship bridge operation. We compiled and reviewed what type of use cases were published, what type of maritime applications have been adapted to AR, how they were prototyped and evaluated and what type of technology was used. We also reviewed the user interaction mechanisms, information display and adaptation to maritime environmental conditions.

Our analysis shows that although there are many examples of AR applications in ship bridges, there is still much work that needs to be done before these solutions can be suitably adapted to commercial settings. In addition, we argue there is a need to develop design requirements and regulations that can guide the safe development of AR.

Keywords: Augmented reality, user interface design, ship bridge applications

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1 DESIGNING MARITIME AR USER INTERFACES

Augmented Reality (AR) technologies superimpose digital information over the physical world (1); this can be implemented with head-mounted displays, directly on (or reflected by) glass surfaces or rendered on video images on screens (2). Multiple authors argue that AR may benefit ship operation by improving situational awareness, reducing head-down time (e.g. 3, 4, 5, 6). However, even though many use cases of AR for ship bridges which have been proposed (e.g. 7, 8), it has not been widely adopted for use on commercial ships. This may, however, change as technology develops, becoming better suited to maritime needs.

When wearing a head-mounted display (HMD) AR headset while engaging with operational tasks on a ship, users may be able to access and deal with information that is relevant to their tasks in a new way. For example, for complex navigation tasks such as ice navigation (Fig. 1), AR enables the user to access speed, heading

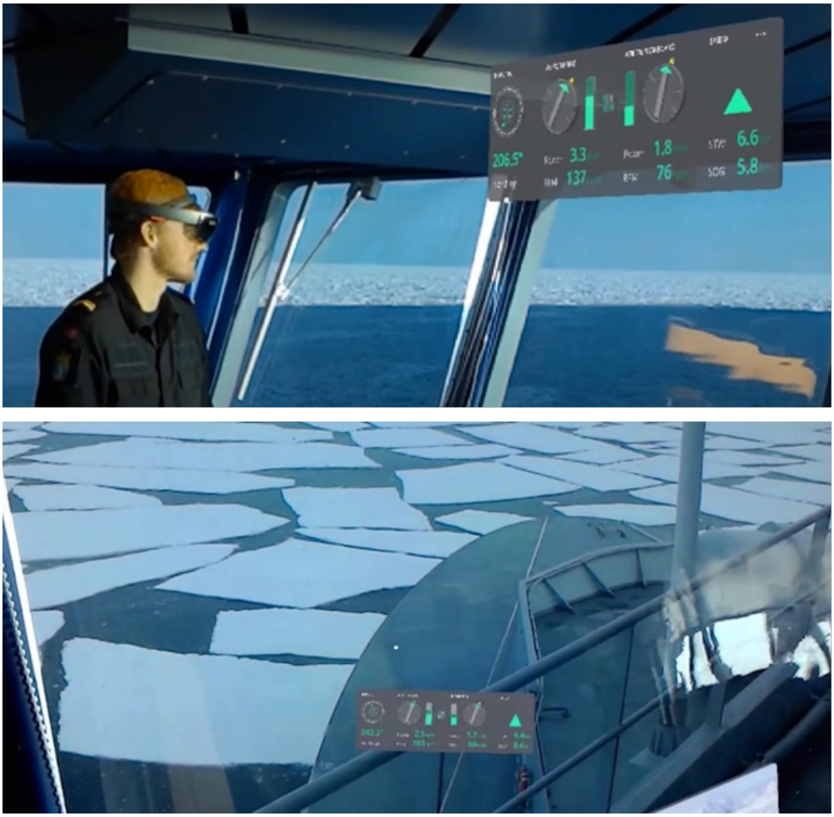

Fig. 1. Experiments with HMD for ice navigation support at Svalbard, showing different alternatives for positioning and design of AR user interfaces (20). Credit: Ocean industries concept lab (OICL), The Oslo School of Architecture and Design

and power information while looking out for ice movements. Without AR, the user has to look down at the navigation instruments to obtain the same information. This indicates that AR may enable avoidance of loss of eye contact with important information outside the ship. In the case of a heads-up display (HUD), augmented information is displayed on a fixed, transparent surface, that does not follow the movements of the user. HUDs have been used in cases were the user can work from a fixed position, for instance plane pilots, or car drivers. In ship bridges there is an expectation that users may move freely around the bridge, hence HMDs have gathered more research attention.

We present a state-of-the-art review of the use of AR in maritime user interfaces, specifically focusing on applications for ship bridges. Our analysis, however, extends previous state-of-the-art reviews (e.g. 9, 10, 11) placing a particular focus on user interface design and on ship bridge applications.

Until now, AR has been regarded as a standalone device with highly specialized functionality. However, the current and upcoming versions of AR hardware can potentially render any information and even replace screens. We argue that since AR uses the entire world as a canvas, it should not be considered as a single-purpose system. Instead, we assert that it is useful when addressing AR as an extension of any ship bridge system. However, in seeing AR as an extension of the many current ship bridge systems, there is a risk that usability problems found in existing ship bridges are repeated and reinforced. This may include inconsistent design, cluttered interfaces and information overload (12, 13). To avoid these problems, we aim to lay the foundation for a generic integration system that can use AR applications and enable system vendors to deliver applications that can safely share the real world as an information space. The current review is part of the SEDNA project, a study that aims to develop this type of generic integration system for maritime AR (14). Because of this, the present review emphasizes topics related to user interface design.

2 AR REVIEW

A two-steps approach to finding references for the review was applied. First, we targeted journals and conference proceedings that were likely to contain references to AR use cases. Second, we carried out an open search in Google and Google Scholar, where we looked for additional references, grey literature, as well as patents and industrial products. In both steps, we used the same set of search keywords: augmented reality, AR, heads-up display, HUD, head-mounted display, HMD, mixed reality, MR, extended reality and XR. The keywords were selected to cover a wide array of technical terms related to AR, for instance “mixed reality” and “extended reality;” abbreviated MR and XR respectively. “Mixed reality” refers to “the merging of real and virtual worlds,” without a specific focus upon how it is technologically achieved (1, p2.). “Extended reality” is a more recent term used to designate both augmented reality and virtual reality technologies.

In the first step, the following source material was consulted: proceedings of the Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT), proceedings of the International Marine Design Conference (IMDC), transactions of the *International Journal of Marine Design* (IJMD) and the Journal of Applied Ergonomics. For each article we found, we looked for references that pointed to other potential uses and consulted these references as well. This extended our initial search for additional conferences and journals.

To review the collected source material, a database that systematizes the source material was built. The database contains the specific use case presented, what existing applications had been adapted to AR, the technology used (both hardware and software), how the technology was tested, and how the use case was conducted as well as the findings.

The database also charts information about the user interfaces of each use case. This includes how information is displayed in the world, how users interact with the AR systems (single and multiuser, gesture, vocal command etc.), and how the system might address the specific challenges of the maritime context (ship motions, changing light conditions). Each specific aspect of the user interaction and system functionalities is explained in more details in the subsequent sections. All the tables containing data from the review are placed in the Appendix at the end of this article.

2.1 Identified source material

We identified a total of 40 publications that present the use cases of AR in maritime workplaces (Fig. 2). We sorted the types of use cases into two main categories: navigation aid and bridge systems (19 out of 40 references) and other types of use cases (21 out of 40).

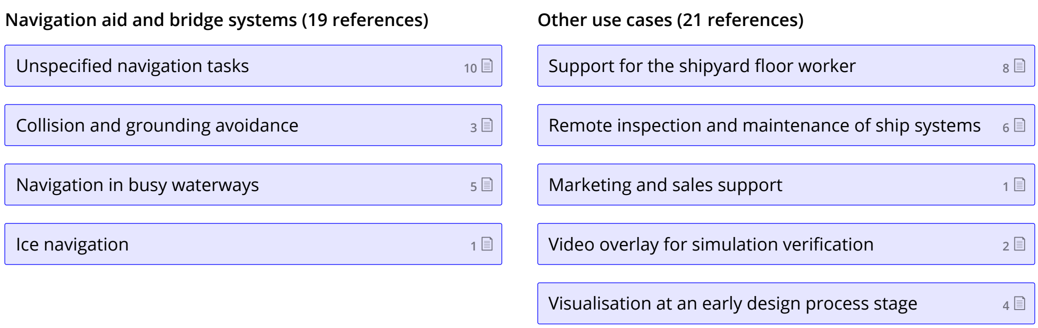

Fig. 2. Types of AR use cases identified, and number of references per type of use case. The review focuses only on navigation aid and bridge system use cases (left).

We identified four types of use cases in the category of navigation aid and bridge systems, summarized in Table 1 in Appendix. *Unspecified navigation tasks* refer to cases where AR is presented as useful for navigation, although no specific example is given. We found 10 references of this type, with for example Erlandsson and Jansson (27) discussing the potential of using AR to support the operation of High-speed Crafts, or Walther et al. (34) discussing the potential of using AR to support shore-side assistance of remote-controlled tugs. *Collision and grounding avoidance* refer to cases where AR is applied to navigation support, with the aim to avoid collision and grounding outside harbor areas and other dense traffic waterways. We found three references of this type, with for example Procee et al. (4) presenting a concept for computing and visualizing in AR potential threats of collision. *Navigation in busy waterways* refers to similar cases, although with a specific focus on harbor areas and other dense traffic waterways. We found five references of this type, with for example Oh et al. (36) presenting a concept for visualizing the name, course and speed of surrounding ships in the field of view of the navigator. Finally, *Ice navigation* yielded only one reference, with Frydenberg et al. (20) presenting concepts for supporting the lookout work of navigators in ice waters.

In the other cases (Table 2 in Appendix) not related to navigation aid and bridge systems, we identified the following types of use cases: support for the shipyard floor worker, remote inspection and maintenance of ship systems, marketing and sales support, video overlay for simulation verification and visualization at an early design process stage.

We focused our analysis only on the navigation aid and bridge system cases and did not review in detail the other types of use cases. As a result, in the rest of the current article, only the references presented in Table 1 (in Appendix) are further analyzed. One reference (11) includes several use cases, hence it appears several times in Tables 1 and 2. When several references presented the same use case, only the reference that describes the use case in the most comprehensive way was included. Some references were excluded for this reason (15, 16, 17, 18, 19).

To give the reader an idea over the type of use case encountered, we redrew a selection of graphical user interfaces (GUIs) presented in the reviewed references (Fig. 3). We used a systematic representation of each GUI to ease the reading and comparison: the horizon line is always placed at the middle of the figure, a black-grey-white palette is used, and the same font is used for all the cases. Whenever possible we reproduced the actual content of the reviewed GUI, although most of the time we had to interpret the content, because of poor readability of the GUI figures in the original references, and lack of detailed textual explanations. As such the content of Fig. 3 is not meant to be accurate, but only representative, and the reader is kindly referred to each individual reference for more details about the reviewed use cases. A first look at the different redrawn GUIs redrawn in Fig. 3 shows the variety of information rendered in AR, and the variety of ways to render it in AR. The differences across AR use cases are analyzed in further detail in the subsequent sections.

As a side note, one reference in the source material was written by researchers in the research group of the current article's authors (20).

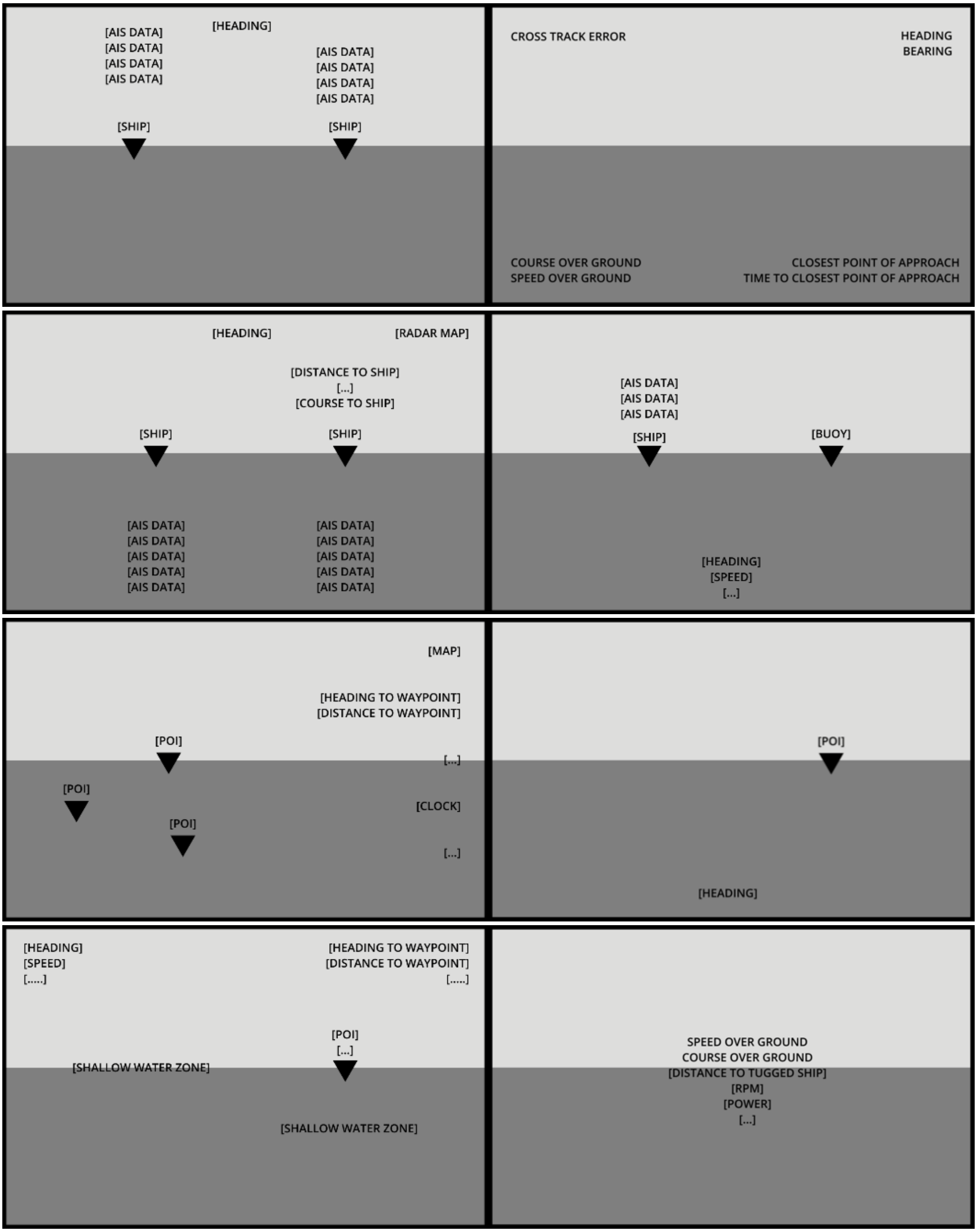

Fig. 3. Examples of GUIs from reviewed AR use cases, systematically redrawn. Left column, from top to bottom: (5), (7), (17), (19); right column from top to bot-tom: (6), (8), (28), (34). Key: [AAA]: interpreted content; […]: unable to interpret content; AAA: actual content; POI: Point of Interest.

2.2 Maritime functions rendered in AR

Although we envision that any function may be mediated through AR, certain functions would lend more naturally to an AR interface. Fig. 4 shows an example of maritime functions rendered in AR onboard a coast guard vessel, when the user is wearing a HMD and looking aft.

Fig. 4. Maritime functions rendered in AR, from left to right: heading information from a compass, power information about azipod thrusters, and speed. Credit: OICL.

We reviewed the selected references and looked for the following types of functionalities, using the following assumptions:

- Navigation functionalities related to dealing with ship traffic surrounding the vessel are commonly associated with Automatic Identification System (AIS) applications and include some indication of the position, name and compass reading of other ships in the area. We refer to this type of functionality as 'ship traffic.' For example, Rolls Royce (8) presented a concept where the name, speed and compass reading of surrounding vessels are rendered in AR to support navigation in busy waterways.
- Maneuvering functionalities are commonly associated with conning applications and include some indication of heading, rudder angle, speed, and power (or load) for different engines. For example, Holder and Pecota (30) presented a concept where heading and speed are rendered in AR to help with low visibility conditions.
- Charting functionalities are commonly associated with ECDIS applications and include some indication of heading, GPS position and all other information present on navigation charts. For example, Morgère et. al (32) presented a concept for generating maps with augmented information such as 3D view and highlighting of buoys.

- Depth monitoring functionalities are commonly associated with echo/depth sounders and sonar applications and include some indication of water depth. For example, Oh et. al (36) presented a concept where the depth in the immediate path of the ship is rendered in AR, together with information about speed, heading, and more.
- Radar functionalities are commonly associated with radar applications and include some indication of objects present in the surroundings of the ship that can be identified with radar technology. Mitsui O.S.K lines (7) presented a concept where a mini radar map is added to the top right corner of the user's field of view in AR, alongside with information about surrounding ships' position, heading and speed.
- For functionalities not covered by the descriptions above, we include an 'other' category.

Table 3 (in Appendix) gives an overview of recurring functions that have been adapted to AR in the source material which we have reviewed. The reviewed data are based on our interpretation of the textual and visual material present in the analyzed publications. The visual material consists of screenshots of GUIs and data flowcharts showing the data inputs and outputs of the proposed AR application. In most references, the data flowcharts indicate a non-exhaustive list of input data, explaining that the AR application was designed with the possibility of including additional types of data in future iterations. As a result, the content of the table needs to be read as indicative information only, and the provided list is not exhaustive.

The examples in Table 3 show that there is a wide range of maritime-related functions considered in the studies when it comes to mediation through AR. In several references, several functions are combined into a single AR application. Charting functionalities are the most recurring, depth monitoring the least. Maneuvering and ship traffic functionalities occur in respectively 10 and 9 references out of a total of 19 references. Radar functionalities occur in 7 references. In the 'other' functionalities, we found, for example, functionalities dealing with the display of real-time video feeds from cameras outside the bridge, displays from the engine control room and displays related to the vessel traffic service (VTS).

In general, the results show that AR may offer an extensive set of functions to end users. However, many functions sharing AR space may lead to information overload and a cluttered outside view. Because the functionality is offered by multiple industry actors, there is also a need to understand how they can share AR space, how to support new functions and how to avoid an inconsistent design of the interfaces on a potentially shared AR platform. This is a problem well-known within current multivendor ship bridges, where a lacking integration of user interfaces is a central cause of suboptimal maritime workplaces (13). Given the many types of applications that may be rendered in AR, AR will meet similar problems.

2.3 State of advancement for AR system

Although there are many use cases of AR in the maritime literature, there is a lack of commercially proven systems. Table 4 (in Appendix) gives an indication of the state of advancement of each reviewed case. We looked for information specifying:

- if a prototype of the AR application had been built
- if the prototype had been tested in a simulator, and/or onboard a ship
- the type of users involved in user testing
- the type of methods employed in user testing

In some cases, we were not able to distinguish if a prototype was built but not reported, or if no prototype was built at all. Similarly, in some cases we were not able to distinguish if a user test was carried out, but not reported, or if no test was carried out at all. In the overview table (Table 4), we used 'Not specified' in such cases, meaning that no sufficient information is reported in the consulted reference.

The data in Table 4 show that most of the concepts (16 out of 19) present the use case through a prototype. Despite this, the testing or evaluation of the use case are often not specified (13 out of 19). When a test or evaluation is specified, it is a fair distribution between tests in a simulator (six cases) and tests onboard ships (four cases). In two instances, Frydenberg et al. and Oh et. Al (20, 36), the tests are carried out on both simulators and onboard the ship. Tests done in simulators are mostly carried out in traditional simulators, except from Frydenberg et al. (20) who used virtual reality (VR) to test AR concepts.

The results show that there are many experiments of early phase AR use in the maritime sector, but there is a significant lack of rigorous testing. One potential reason for this is that both the hardware and software are in very early development, so rigorous testing in real cases is challenging. We have discovered this in our own work, where for instance, the Hololens hardware has significant problems in moving water. However, by bringing a prototype to sea, we understood much more about the requirements of designing AR for ships bridges, even though the prototype was not robust enough to support all maritime conditions (20).

Our own experiences from field studies on ships (21,22) suggest that the maritime workplace poses significant contextual challenges for end users that may greatly affect the use of AR. We argue that in moving towards AR for the maritime sector and with rapidly improving technology, research should further

Fig. 5. Screenshot from a VR-based simulator used to prototype and test AR ap-plications. Credit: OICL.

emphasize developing prototypes testable in real maritime conditions. Traditional and VR-based simulator testing is useful since many variables and parameters may easily be changed in the simulator. A limitation with traditional simulators based on projectors and screens holds that they will not be able to provide a realistic perspective for connecting AR graphics to the outside world. VR-based simulators do not have this type of problem (Fig. 5). However, because of the shifting and demanding context and operations at sea, we suggest that maritime AR needs to be developed in close relation to real sea trials. An iterative testing procedure could be based on combining testing in simulators and at sea.

2.4 Information rendition in AR space

In seeing AR as a shared resource across bridge systems, we need to address how AR renders information in the environment. In the SEDNA project (14), we developed a simplified model of how to show information in the world based on the requirements gathered in the project (Fig. 6 and Fig. 7). The model includes the following information objects:

- *App display*. This component allows the display of full applications in the AR view. Examples: ECDIS and radar.
- *Widget display*. This allows the display of smaller stackable information containers. Examples: compass and speed indicator.
- *Annotation*. These are small information containers connected to Points Of Interest (POIs) in the world. Example: information about surrounding vessels and objects.
- *Ocean overlay*. This allows the display of information directly on the ocean. It typically shows routes and no-go zones.
- *AR map*. This is a flat map interface placed above the horizon, able to display any map-related information.

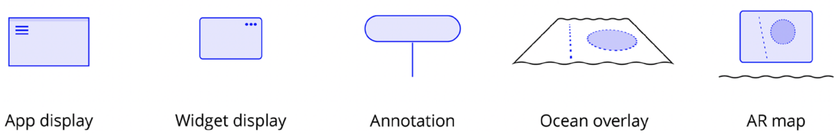

Fig. 6. Types of information components developed in the SEDNA project (14) and used to analyse the AR use cases in the current review article.

In Table 5 (in Appendix), we have charted whether the use cases employ similar formats. As in the previous tables, the contents of Table 5 are based on the textual and visual descriptions of the applications in the reviewed references. As such, to a large extent, the contents are interpreted based on the definitions of the information objects given above.

Fig. 7. Examples of information components developed in the SEDNA project (14). From top: Widget display with data from a wind sensor, Annotation connected to Points of Interests outside the ship (Iceberg and vessel passing by), Map linking a point in the map with a position in the world with information. (All examples shown are explorative concept and prototypes).

The data in Table 5 show that Full app display and AR map are the least used ways to render information, used respectively in only two and three references. Displayed apps are conning (17) and unspecified bridge systems (34). The AR maps are navigational maps in 3D (17), positions of other vessels in the area of the considered ship (7) and a specific type of display called a 'velocity obstacles diagram' (4), which combines the position, heading and speed of surrounding vessels into one type of information display. Widget, annotation and ocean overlay are the most common way to display information, used respectively in fifteen, fifteen and thirteen references. They are often used in combination, with, for example, information about surrounding vessels displayed as annotation, combined with a compass widget in the top or bottom part of the field of view and a conning widget displayed in the corners of the field of view.

The analysis shows that many of the AR applications rely on similar types of visual representations. However, we did not observe any consistent use of specific text formatting, colour palettes, line types, geometry types, or icon formatting across the references. Because of this, we argue that there is a need to develop generic models for how to render most applications into a common integration system.

2.5 Adaptation to maritime context

AR interfaces for maritime usage need to consider a range of contextual challenges specific to the maritime sector. Aspects such as ship motion, maritime operations, fatigue, seasickness, contrast and light conditions all affect user interface design. In our review, we found only four references that mention ways to deal with maritime environmental challenges. These include the following:

- Minimum interface luminosity for use of AR with HMD (32)
- Using AR in different light conditions (27)
- Ability for the user to adjust the data display colour (36)
- Position of user, projection on different surfaces, adaptation to different lighting contexts (20)

The analysis shows that most of the current use cases do not significantly address how to adapt AR to maritime contexts. This is an important limitation of current work, and we suggest a greater emphasis in this area to make sure AR works in most maritime contexts and conditions. In our own work, we have found that interface luminosity and contrast are challenging to deal with in changing light conditions. We have experimented with different color palettes for day, night, sunset and sunrise conditions. We also have developed simple Do-It-Yourself protections to wear on top of the HMD to block some light in full sunlight conditions.

2.6 Interaction with AR HMDs

Interaction with head-mounted AR interfaces in other domains often use advanced multimodal interactions such as gaze, voice and gestures. In AR, gaze may be used similarly to a mouse, to move a pointer to a specific location. Voice in

AR may be used similarly to give instructions to a digital personal assistant like Siri or Alexa, as well as giving GUI specific instructions such as zooming in/out, displaying or removing the display of parts of a GUI, or interactions similar to a mouse click. Gesture in AR is inspired from gestures now common in touch screens, although the gestures may be using the end user' s hands and arms, instead of just fingers. It is currently uncertain how all these types of interactions may be applied in different maritime use contexts. In analyzing the current use cases, we found only four references that mention user interaction mechanisms. Hareide and Porathe (29) refer to AR information that may be always displayed in the user' s field of view, and information that will be displayed only when the user is looking in specific directions. Erlandsson and Jansson (27) briefly explore a similar concept. Walther et al (34) show a concept where the user may perform zooms in and out of the AR application using gestures. Frydenberg et al (20) present preliminary concepts about how the user's location may be used to define requirements for how to display information in AR, given the fact that the surfaces upon which AR may be displayed (for example bridge wall or bridge window) depend on the user's location.

Maritime work conditions are very diverse, and users move between workstations, operate other equipment, suffer from fatigue, and must work in a moving environment (22). It is currently unknown how these conditions affect the design of AR interaction, and the works we reviewed have not addressed these issues in any significant way. The use cases tend to treat AR systems as information displays, without addressing how to enter data or manage AR-mediated information.

2.7 AR technologies in use

The reviewed use cases have been comprehended as a wide range of technologies. From studying the application of hardware and software technologies, contextual information has been added to use cases. Table 6 (in Appendix) lists the specified hardware and software of the AR technologies for each use case. More recent publications tend to use off-the-shelf technology, such as Microsoft Hololens (20, 29), Google glass 1.0 (37) and Google glass 2.0 (6). Earlier publications often consist of custom-built technology, which presents several limitations and might have prevented further exploration of AR use cases.

As explained in the 'state of advancement section', the use of not off the shelf type technology implies the use of custom-built technology both for hardware and software, which limits the extent to which the use of the technology could be assessed because these studies focus on whether the hardware worked instead of what the users might be able to do with it. As a possible consequence of the complexity of maintaining custom-built software libraries, several software libraries that are presented for authoring in AR are apparently not in use anymore, e.g. the Instant reality framework (23). None of the reviewed material referred to open source AR libraries such as AR ToolkitX (57) or OpenXR (58).

The data in Table 6 show that the technologies used in the various studies underline the state of AR technologies in general. Many of the systems relied on technologies that are now obsolete. It is likely that forthcoming AR hardware will solve many of the problems with current generation technologies. In addition, it is likely that current and forthcoming platforms for AR software will also simplify the development of AR solutions. As a result, we argue that research in future AR technology should increase its focus on design principles.

3 DISCUSSION

Based on the reviewed use cases, we argue that AR might play an important role in the future of maritime workplaces. However, its application depends on a relationship between the increasingly more capable AR technologies and AR's usefulness in different use cases. As technology improves, it is likely to become useful to a wider range of maritime operations. We foresee a similar development as mobile phones, where new usages appeared with the development of technology: reading emails, browsing internet, playing games or having a personal assistant. As shown in Fig. 8, with current technology such as Hololens, we are only at the beginning of the use area / technology development curve, and new usages will most likely become more common with technology development.

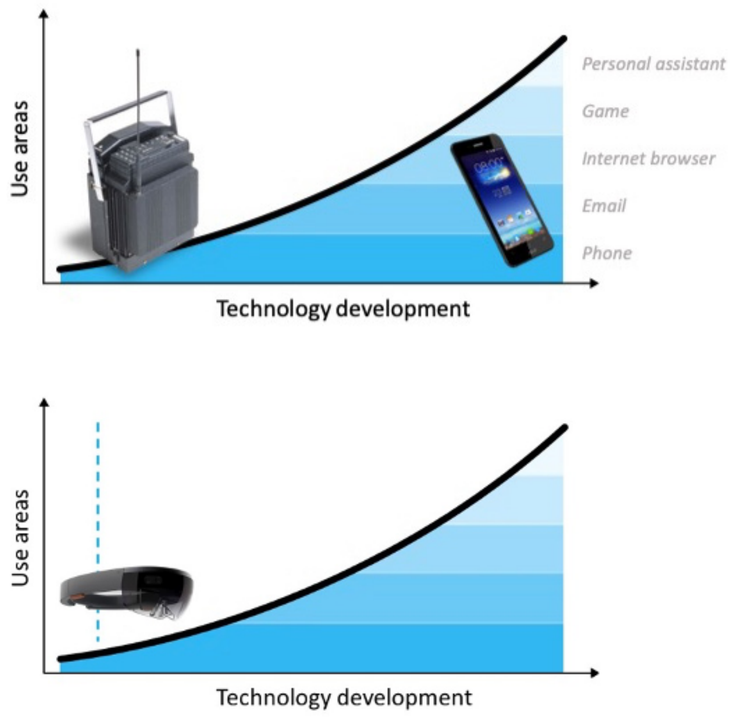

Fig. 8. Use areas vs. technology development. We foresee a similar evolution for AR (bot-tom) as for mobile phones (top), where the types of usages expanded together with techno-logical improve-ments. We are currently only at the beginning of this pattern (blue dotted line).

There is no reason to believe that the pace of AR development will slow down in the years ahead (24). We suggest that research in maritime AR should increase and emphasize the development of frameworks that can extend into future technology generations. To do so, we suggest an increased focus on the development of design principles and guidelines that can support maritime AR development. Grabowski (3) presents an example of such work by providing a list of research questions that are important to consider when dealing with AR. Grabowski embeds the research questions in a conceptual framework that links technology features with task complexity and topics for evaluation of AR implementations, including the following: perceived ease of use, perceived usefulness, decision performance and decision processes.

There is a need to describe the categories of maritime use cases that may be supported by AR, and in our review, we have found that there are several recurring use cases. However, the use cases have not been described in detail in ways that can be used as requirements in the design of new AR applications. Better descriptions of the use cases might help the development of improved AR systems. For instance, Vu et al. (25) present a survey about how frequently seafarers use different functions and information on integration navigation systems when performing navigation tasks. This type of research is useful for AR, and it can be extended to include evaluations of what functions may benefit from AR visualization. Procee et al. (4) propose a methodology (cognitive work analysis) to identify what functions and tasks might be relevant to bring to AR.

Increased focus has been placed on AR as a platform for multiple ship systems. As mentioned earlier, ship bridges are usually made up of many systems. If we see AR as an extension of a ship's bridge, it is necessary to see the AR system as a shared resource for any application. Similarly, Rowen (6) concludes that future research should consider AR in combination with all the other systems and interfaces present on a bridge. However, to fulfil this vision, there is a need to develop an integrated platform for AR applications. Our review found no available design guidelines for maritime AR interfaces. Nordby et al. (13) argue for the need for design processes that cater to consistency across medias, platforms, and vendors. Their argumentation is introduced for the context of the bridge as a workplace, and the development of AR applications is an example of the need to deal with consistency.

Finally, many of the problems related to using AR at sea are generic and apply to any maritime function. Indeed, issues such as contrast, readability and anchoring information in the world can be applied to any maritime system. Because of this, we contend there is a need to develop interaction and user interface principles specifically for a maritime context (22, 26). In doing so, we can develop a robust AR infrastructure that will simplify the development of AR functions, achieving safer maritime operations.

4 CONCLUSION

AR may be a significant technology that could enhance maritime safety by strengthening operators' situational awareness. However, to take advantage of the technology, there is a need to adapt it to the maritime user's context and needs. Our analysis has shown that although there are many examples of maritime AR use cases, it is still in its infancy. Our review found few use cases with clearly specified user needs and use scenarios, concept testing or evaluation, demonstrating a limited focus on human-centred design perspectives of designing AR interfaces.

Based on our review, we suggest that because this is rapidly developing technology, more research should address user-centred design of AR systems. This includes design requirements, design principles and design guidelines. Also, because future AR systems will work in combination with existing, non-AR systems, it is necessary to understand AR as an extension of current bridge systems. Further, given the existing usability problems on ship bridges, research must lay the ground for future development to avoid the current problems related to multivendor ship bridges related to inconsistent design and a lack of user interface integration. We refer to ongoing development of a design framework for AR applications expanding the OpenBridge design system to address these issues (59).

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6 APPENDIX

Table 1. Overview of references for navigation aid and bridge systems

Ref.	Title	Type of use case	Tech.
(27)	Augmented reality as a navigation aid for the manoeuvring of high-speed crafts	Unspecified navigation tasks	HUD
(28)	AR binocular: Augmented reality system for nautical navigation	Unspecified navigation tasks	Binocular
(29)	Maritime augmented reality	Unspecified navigation tasks	HMD
(30)	Maritime head-up display: A preliminary evaluation	Unspecified navigation tasks	HUD
(17)	An experimental augmented reality platform for assisted maritime navigation	Unspecified navigation tasks	HUD
(31)	Real-time infinite horizon tracking with data fusion for augmented reality in a maritime operations context	Unspecified navigation tasks	HUD
(32)	Electronic navigational chart generator for a marine mobile augmented reality system	Unspecified navigation tasks	HUD
(33)	Marine navigation binoculars with virtual display superimposing real world image	Unspecified navigation tasks	Binocular
(34)	Shore-side assistance for remote-controlled tugs	Unspecified navigation tasks	HMD
(35)	Augmented reality for precision navigation: Enhancing performance in high-stress operations	Unspecified navigation tasks	HUD
(7)	AR voyage information display system	Collision and grounding avoidance	HUD
(5)	Augmented reality as part of a man-machine interface in e-navigation	Collision and grounding avoidance	HMD

(4)	Using augmented reality to improve collision avoidance and resolution	Collision and grounding avoidance	HMD
(36)	Advanced navigation aids system based on augmented reality	Navigation in busy waterways	HUD
(37)	Smart glasses to support maritime pilots in harbor maneuvers	Navigation in busy waterways	HMD
(8)	Rolls Royce Intelligent Awareness System for vessels	Navigation in busy waterways	HUD
(6)	Impacts of wearable augmented reality displays on operator performance, situation awareness, and communication in safety-critical systems	Navigation in busy waterways	HMD
(38)	Applying the navigation brain system to inland ferries	Navigation in busy waterways	HUD
(20)	Exploring designs of augmented reality systems for ship bridges in arctic waters	Ice navigation	HMD

Table 2. Overview of references for other types of use cases

Ref.	Title	Type of use case
(39)	Simulations, virtual and augmented reality technologies for ship life-cycle engineering	Support to shipyard floor worker
(40)	Augmented reality for the retrofit of ships	Support to shipyard floor worker
(41)	Augmented reality supported information gathering in one-of-a-kind production	Support to shipyard floor worker
(42)	Augmented reality assistance for outfitting works in shipbuilding	Support to shipyard floor worker
(43)	Introduction of AR applications for shop floor in shipbuilding	Support to shipyard floor worker
(44)	Application of AR technologies to sheet metal forming in shipbuilding	Support to shipyard floor worker
(45)	Augmented reality pipe layout planning in the shipbuilding industry	Support to shipyard floor worker
(11)	Maritime applications of augmented reality–experiences and challenges	Support to shipyard floor worker

(46)	Content first: A concept for industrial augmented reality maintenance applications using mobile devices	Remote inspection and maintenance
(47)	Benefits achieved by applying augmented reality technology in the marine industry	Remote inspection and maintenance
(48)	AR-based ship design information supporting system for pipe maintenance	Remote inspection and maintenance
(49)	Modular authoring of augmented reality-based service instructions	Remote inspection and maintenance
(50)	AR spatial intelligence	Remote inspection and maintenance
(51)	Wärtsilä successfully tests remote guidance service capabilities	Remote inspection and maintenance
(11)	Maritime applications of augmented reality – Experiences and challenges	Marketing and sales support
(52)	Evaluating evacuation simulation results in a virtual reality environment	Video overlay for simulation verification
(11)	Maritime applications of augmented reality – Experiences and challenges	Video overlay for simulation verification
(53)	Interaction and ergonomics issues in immersive design review environments	Visualisation at early design process stage
(54)	Efficient use of virtual and mixed reality in the conceptual design of maritime workplaces	Visualisation at early design process stage
(55)	Potential benefits of augmented reality in the smart ship	Visualisation at early design process stage
(56)	Virtual and augmented reality for the maritime sector – Applications and requirements	Visualisation at early design process stage

Table 3. Maritime functions rendered in AR.

Reference	Ship Traffic	Manoeu-vring	Charting	Depth monitoring	Radar	Other
(37)	1		1	1	1	
(6)		1				1
(36)	1		1	1		1
(8)	1		1		1	
(38)	1		1	1	1	1
(5)		1	1			1
(4)		1	1		1	
(7)	1		1		1	1
(20)	1	1	1			
(33)		1	1			
(28)						1
(27)		1				
(34)	1	1				
(29)		1	1	1		
(35)	1		1		1	1
(30)		1				
(17)			1		1	1
(31)			1			
(32)	1	1	1			
Total	9	10	15	4	7	8

Table 4. State of advancement

Code	Prototype built	Tested in simulator	Tested onboard ship If yes: specify	Users (in test)	Test method (surveys, etc)
(29)	Not specified	Not specified	Not specified	Not specified	Not specified
(7)	Not specified	Not specified	Not specified	Not specified	Not specified
(8)	Not specified	Not specified	Not specified	Not specified	Not specified
(27)	YES	YES	Not specified	4 male mariners with 20–30 years of experience	Learning phase, then control, then four different scenarios; measuring visual focus and heads down time
(28)	YES	Not specified	Not specified	Not specified	Not specified
(30)	YES	YES	Not specified	20+ students	Survey, with Likert-scale items and open questions
(17)	YES	Not specified	Not specified	Not specified	Not specified
(31)	YES	Not specified	Not specified	Not specified	Not specified
(32)	YES	Not specified	Not specified	Not specified	Not specified
(35)	YES	Not specified	Amphibious vehicle, on a beach (both land and sea)	Not specified	Comparing planned course with actual course with or without support of AR
(5)	YES	YES	Not specified	Not specified	Not specified
(4)	YES	Not specified	Not specified	Not specified	Not specified
(36)	YES	YES	Harbour entry/ departure	20 experienced ship officers	User surveys and one-on-one interviews
(37)	YES	Not specified	Not specified	Not specified	Interviews
(38)	YES	Not specified	Three inland river ferries	Not specified	Not specified

(20)	YES	VR simulator	Coast guard vessel in Ice navigation	Coast guard officers	Rapid prototyping and qualitative user testing in VR lab and/or field study
(33)	YES	Not specified	Not specified	Not specified	Not specified
(34)	Virtual prototype in Unity)	Not specified	Not specified	Not specified	Not specified
(6)	YES	30 min harbour entry/ departure scenarios	Not specified	Over 200 participants	Extensive set of qualitative and quantitative data before, during and after each transit scenario

Table 5. Rendering of information in AR.

Code	App display	Widget display	Annotation	Ocean overlay	AR map
(27)				1	
(28)		1	1		
(29)		1	1		
(30)			1	1	
(17)	1	1	1	1	1
(31)				1	
(32)		1			
(33)		1	1		
(34)	1	1	1	1	
(35)		1		1	
(7)		1	1	1	1
(5)		1	1	1	
(4)		1	1	1	1
(36)		1	1	1	
(37)		1	1	1	
(8)		1	1		
(6)			1		
(38)		1	1	1	
(20)		1	1	1	
Total	2	15	15	13	3

Table 6. Hardware and software used

Code	Technology: Hardware	Technology: Software
(27)	Not specified	Custom built
(28)	Augmentation camera, Fisheye camera, accelerometer sensor, binocular OLED display	Custom built
(29)	Head-up display by Afterguard; Hololens	Not specified
(30)	Projection on simulator screen	Custom built
(17)	LookSea system by Technology Systems Inc.	Custom built
(31)	Not specified - requires a video feed	OpenCV library (Intel Open Source Computer Vision)
(32)	Modified MG1 model from Laster	Custom built/presented in the publication
(33)	Custom built	Custom built
(34)	Not specified	Not specified
(35)	Custom built	Custom built
(7)	Not specified	Not specified
(5)	Not specified	Not specified
(4)	Not specified	Not specified
(36)	PTZ (Pan/Tilt/Zoom) camera, AHRS (Altitude and Heading Reference System), NMEA Combiner, and user console with an additional joystick device for camera control	Software system composed of a data manager module, user interface module, registration module, and augmented image rendering module (running with Unity)
(37)	'Smart Glasses' - Google Glass, Vuzix M100, or the EPSON BT200	Not specified
(8)	Not specified	Fusing sensor data with intelligent software for bridge systems
(6)	Google glass version 2 (2016)	GlassNav software developed at Le Moyne College
(38)	Not specified	Not specified
(20)	Hololens	Hololens and Openbridge libraries