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Open User Interface Architecture for Digital Multivendor Ship Bridge Systems

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Abstract
Equipment found on ship bridges rarely offer consistent user interface design across the numerous systems that seafarers interact with. It is well documented in human-computer interaction research that consistency is an important aspect for reducing human error and increasing user ability to efficiently use digital systems. Current workplace regulations and design guidance do not provide a clear path towards interface consistency between different maritime vendors and equipment. Because of this, there is a need to develop new and consistent frameworks for the design of modern ship bridges and their systems. We approach such a problem by asking the following question: How can the organization of ship bridge systems enable consistent user interfaces for multivendor ship bridges? To answer this, we present work from an industry-driven project seeking to regulate the relationships between ship bridge (i) integrators and (ii) system vendors. This paper presents a user interface architecture that systematically distinguishes between system integrators and system vendors. This user interface architecture then applies web development processes and methods that, we argue, establish a framework for increased design consistency. Furthermore, this architecture presents a new path for ship bridge user interface development that adapts current state-of-the-art user interface methodologies to a maritime context. We argue that by implementing the proposed architecture framework the industry can capitalize by saving costs, increasing innovation and improve the quality of ship bridges, thereby optimizing the work environment for seafarers and overall ship safety.

Keywords: Interface Design, Navigation, Human-Machine Interfaces, Maritime Design System

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Equipment found on ship bridges rarely offer consistent user interface design across the numerous systems that seafarers interact with. It is well documented in human-computer interaction research that consistency is an important aspect for reducing human error and increasing user ability to efficiently use digital systems. Current workplace regulations and design guidance do not provide a clear path towards interface consistency between different maritime vendors and equipment. Because of this, there is a need to develop new and consistent frameworks for the design of modern ship bridges and their systems. This problem is approached by asking the following question: How can the organization of ship bridge systems enable consistent user interfaces for multivendor ship bridges? This article presents work developed from an industry-driven project seeking to regulate the relationships between ship bridge (i) integrators and (ii) system vendors. This user interface architecture then applies web development processes and methods that establish a framework for increased design consistency. Furthermore, this architecture presents a new path for ship bridge user interface development that adapts current state-of-the-art user interface methodologies to a maritime context. By implementing the proposed architecture framework the industry can capitalize by saving costs, increasing innovation and improve the quality of ship bridges, thereby optimizing the work environment for seafarers and overall ship safety.

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1. Introduction

Ship bridges are complex workplaces where seafarers collaborate in carrying out work in constantly variable environmental, organizational and operational conditions. Because of these challenges it is critical that maritime workplaces are well designed. Yet, observational studies onboard ships regularly report ergonomic and user problems with various workspaces and equipment, including the bridge (Lützhöft and Nyce 2008; Meck et al. 2009). This has been traditionally addressed through anthropometric analysis and optimization of the work environment related to physical ergonomic issues of equipment design and layout (American Bureau of Shipping 2003; 2014; Germanischer Lloyd SE 2012; International Maritime Organization 2000; Mallam et al. 2015). However, these approaches generally do not address the increasing digitalization of modern ship bridges. The most current supporting document is the LR Ship Control Centre Guidance, with revised versions of ISO 8468:2007 and IMO Circ. 265 currently under development.

Various digital systems and requisite operations onboard a ship's bridge are cognitively demanding (Grech et al. 2008). Lack of consistent or sub-optimal user interface design across the various equipment of ship bridges can also negatively impact system safety and efficiency. User interface design consistency across equipment and software is a central principle for developing systems that reduce human error, while also increasing efficiency and user satisfaction (Nielsen 2014).

Ships are typically delivered with multivendor ship bridge systems (MBS) that, as opposed to integrated ship bridge systems (IBS), are made up of equipment delivered by multiple system vendors. It is not uncommon to find up to 30 brands on a single bridge (Oltedal and Lützhöft 2018). The user experiences of MBS are defined by the sum of their equipment, where there is little or no coordinated development of user interfaces. This creates fragmented user experiences with MBS, forcing users to adapt to multiple differing design languages on a single bridge (Lützhöft 2004).

Human error is often identified as a major contributor to maritime accidents, with suboptimal human-machine interactions and equipment design identified in contributing to negative outcomes (Grech et al. 2008; Hetherington et al. 2006; Kataria et al. 2015). In conducting a systematic literature review of maritime design regulations and guidelines, a lack of support that *effectively* supports design of user interface design consistently across all systems on a ships bridge was found (Mallam and Nordby 2018). Most current user interface design guidelines address generic principles of design, such as general workstation and equipment layout, readability, visual contrast or consistent use of symbols. However, there is limited support that may enable design consistency and guidance for entire user interfaces across all systems of MBS.

The industry is aware of the issues related to inconsistent design and the International Maritime Organization (IMO) is addressing the issues through initiatives such as E-Navigation and S-Mode (Lee et al. 2015). In an effort to improve current deficiencies in design, several companies delivering MBS have moved towards installing common digital workstations. Instead of installing the physical equipment in consoles on the bridge, most equipment is mediated through multifunction screens. The rationale for digital integration of MBS is to reduce production cost through sharing of hardware resources amongst MBS (such as screens, servers and interaction technologies). In addition, the companies argue the digitally integrated workplaces offer improved ergonomics for users.

New ship build projects require large capital investments, thus are intended to have long operational lifecycles (i.e. several decades) in order to recoup initial expenses and derive profit. As a ship ages, it requires periodic retrofitting, refurbishment and updating. In the past, this has created a patchwork effect within a ship's work environments, equipment, control systems and user interfaces. As newer generations of technologies and equipment are installed, 10, 20 or 30 years after a ship is originally built, this patchwork of differing, and often unintegrated interfaces, can have negative impacts on seafarers and operations. Thus, by moving forward with increasingly digital interface interactions, the development of consistent design guidelines will facilitate the success of inter-generational technology and IBS frameworks.

1.1. The Need for Developing a Framework for Design Consistency

The reduction of user interface hardware is in itself an improvement, since current ship bridges may have a large number of redundant user interface devices cluttering the workspace. However, there are several hurdles for achieving the full benefits of digital integration. Presently, there is no framework for system vendors to deliver applications in a consistent manner to MBS integrators. Furthermore, there is no common framework for digital integration of user interfaces, thereby making it necessary for system integrators to make individual adaptations for each system integrator. The lack of a coordinating framework results in several problems:

1. Custom applications must be delivered by system vendors to multiple ship bridge vendors. This increases the threshold for delivering systems to multiple MBS providers, as well as limit new actors' ability to deliver to MBS.
2. A variety of different applications delivered by multiple vendors (often with inconsistent designed interfaces) must be integrated into a single bridge working environment by the system integrators. This raises costs, potentially reduces quality and limits the number of optional systems that integrators may offer to customers of the MBS.
3. MBS customers (e.g. ship owners) and users (e.g. seafarers) get poorly integrated workplaces, which may lead to reduced efficiency and performance, while increasing the possibility of errors and accidents (Oltedal and Lützhöft 2018).

1.2. Purpose

For the industry to move towards consistent user experiences for MBS, while allowing for innovation and branding, there is a need to better organize the development of MBS user interfaces. We argue that this can be achieved by re-conceptualizing MBS as an open user interface platform for system developers' applications. In such a model we separate between the companies delivering full ship bridges (ship bridge integrators) and the companies delivering individual systems to a ship's bridge (system vendors). Figure 1 (*left*) presents the current climate of MBS where applications (b) are integrated towards individual MBS system (a). New vendors (c) have limited access to MBS development. Figure 1 (*right*) shows an open user interface architecture as a layer between the integrator (a) and the applications (b, c). Each application can be adapted to the architecture in order to access all MBS.

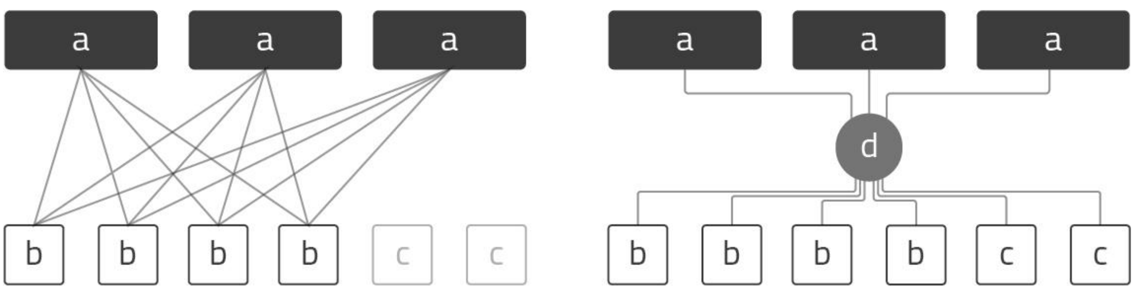


Figure 1. a. MBS system vendors; b. Applications; c. New vendors; d. Open User Interface Architecture.

This article presents a framework supporting digitalization of MBS with the purpose of realizing consistent user experiences, as well as improved maritime workplaces. This research is part of the industry-driven research project OpenBridge. The project has 15 partners from academia, ship bridge vendors, integrators and regulatory authorities (http://www.openbridge.no/). The OpenBridge project as a whole addresses user interfaces, technical integration and system approval processes; however, this article focuses specifically on aspects relating to user interfaces.

A user interface platform is not a full operating system, such as Android or Windows. Rather, it is a layer on top of such operating systems that manages the infrastructure that makes a consistent user experience possible with MBS. Such a platform needs to manage and coordinate user interface resources, including screens and user interface software components, in order to make them available for system developer's applications. This work supports a move towards MBS as an open platform by offering a conceptual framework describing the components related to a user interface that together constitute MBS as a user interface platform. The conceptual framework is referred to as *user interface architecture* that we argue is useful as a foundation for developing new design guidelines, rules and other design support that can help realize consistent user interfaces for MBS. In order to develop such a model we ask the following question: *How can the components that constitute ship bridge systems be modelled to better facilitate a transition towards consistent design of multivendor ship bridges?*

2. Frameworks and Approaches for User Interface Design

Maritime user interface development is largely driven by domain-specific regulations and guidelines. In general, maritime guidelines have a tendency to focus on minimum requirements and generalized goal-based instructions, offering few examples of best practices that are suitable for guiding modern user interface design. Although the guidelines do include some support of designing user interfaces, they do not offer tools enabling realization of consistent design. Issues such as effective use of interaction components (e.g. toggle buttons or menus) or how to structure applications are seldom covered (American Bureau of Shipping 2014; International Maritime Organization 2000).

Previously, there have been attempts to develop guidelines for consistent user interface design. The most notable current example is by the IMO's E-Navigation and S-Mode initiative (The Maritime Executive 2017; The Nautical Institute 2008), which seeks to develop a standardized design process with design guidance for navigational equipment across all ships. This approach focuses on creating the foundation for design consistency for all user interfaces in a ship's bridge, with less focus on the specific functions mediated through them.

Due to the current lack of effective maritime design frameworks, it is of interest to transfer technological concepts and knowledge from other fields. In particularly, methods and technologies related to web development are utilized. In this field, there are well-developed user interface technologies and methods, such as cascading Style Sheets 3 (CSS3), HTML5 and responsive design (Marcotte 2010). These are powerful and ubiquitous approaches that can streamline user interface development, as well as enable applications to scale across a large variety of compatible user interface devices. This makes it possible to create applications that can scale to a large number of ship bridge form factors, as well as mobile devices and personal computers.

Similar functionality would be useful in the maritime domain because applications need to scale to many integrator platforms with different user interface hardware. As maritime equipment and systems move from physical analogue interactive inputs (e.g. physical buttons, levers, dials, etc.) to increasingly digital interfaces, a standardized approach for interface integration is of high value. There are a range of design guidelines and frameworks supporting these technologies which are useful in informing the development of maritime user interface architecture. Three different types of frameworks are presented which address design consistency: (i) design guidelines for application platforms, (ii) front-end web application tools, and (iii) design systems frameworks.

2.1. Design Guidelines for Application Platforms

The major global actors of the web industry are currently the leading providers of systematic digital design guidelines. These frameworks are delivered by platform owners to ensure their product offerings are desirable for both users and developers. By making effective guidelines and tools for developing applications with common user interface traits, these frameworks seek to harmonize user experiences on their platform despite applications being delivered by a multitude of commercial companies and individuals.

iOS from Apple (Apple 2018a), Mac OS from Apple (Apple 2018b), Material Design from Google (Google 2018b) and Windows Universal Platform from Microsoft (Microsoft 2018) offer well-designed online guidelines for application design. The guidelines follow much of the same structure across the four frameworks but use slightly different terminology. Three of the frameworks include user interface adaptation techniques, such as responsive design. The notable exception is Mac OS, which is limited to personal computer-style screen sizes. The Windows Universal Platform goes beyond responsive design and offers methods for user interface scaling that include new form factors, such as mixed reality and advanced support for multimodal interaction.

All four design guidelines offer very detailed specifications and offer suggestions for best practice interaction design. Although it is possible to vary interaction design within the guidelines, following them will result in applications with a high level of design consistency. The clear examples also offer some efficiency benefits, thereby making it easier to obtain an adequate design.

2.2. Front-End Web Application Tools

The user interface design guidelines are tightly connected to user interface technologies. However, they only show how to design for such technologies. Front-end web application frameworks go further by offering software tools for implementing user interfaces. They provide reusable software components for implementation of web-based cross-platform user interfaces. There are a number of such frameworks such as React (Facebook Inc. 2018), Angular (Google 2018a), Bootstrap (team 2018) and Polymer (Polymer 2018). Many of these are open source and some are promoted by large internet companies, such as Facebook (React) and Google (Angular). Several of the frameworks are also specifically linked to design guidelines, such as Material Design (Google 2018b).

The front-end web application frameworks support both design consistency and design efficiency by offering ready-to-use code for user interface implementation. A well-maintained framework may significantly improve development speed and increase developers' ability to upgrade and maintain user interfaces. It is increasingly common to base new user interfaces on such frameworks.

2.3. Design Systems Frameworks

In the web industry, large corporations have struggled with an increasing number of applications and rising user interface development costs. In order to reduce costs of application development, as well as establish design consistency, there has been a growing trend to embrace systemic approaches to user interface design. Such approaches have recently been popularized through concepts, such as Atomic Design and design systems (Frost 2016). A design system combines traditional design style guides, user interface design guidelines and front-end application frameworks into a single system. Such an approach is not new in user interface development (Nielsen 2014), but has recently been revitalized.

In design systems, the focus is to develop simple user interface components that can be assembled into increasingly complex and larger components. The library of components can be used as a resource across applications in order to create consistency. A design system can be presented as a product that is maintained by a company and under continuous redesign, much like a product or service (Nathan 2016). Design systems have the benefit of representing both the design practice tradition (through design guidelines) and software development tradition (through front-end frameworks). As such, they represent design consistency and efficiency, both from developer and design perspectives.

3. Building a Maritime Design System

3.1. Approach

The maritime user interface architecture has been developed in a participatory and iterative framework involving the multidisciplinary project team with participants from industry, regulatory bodies and academia. This has been performed through: (i) review of state-of-the-art design frameworks in maritime sectors and other industries; (ii) review of current MBS workstations and interface design; (iii) ongoing development of a common design system for MBS applications. Two main categories of state-of-the-art design frameworks are investigated. First, the current maritime regulations in relation to workplace and user interface design frameworks were reviewed. Second, four design frameworks from the PC, web and mobile industries were reviewed.

The review of current systems are based on the systems and practices of the project consortium partners. The project consortium consists of four partners that deliver complete ship bridges, referred to as *ship bridge integrators*, since they are responsible for integrating systems from multiple vendors into a complete ship bridge. Six partners are referred to as *system vendors*, which deliver equipment that are to be integrated into the ships bridge. The existing system review comprises of six physical MBS workstations. In addition, the digital user interfaces of ten systems typically installed in MBS workstations were analysed. The selected examples of MBS workstations and digital user interfaces were taken from the project partners current product portfolios. Existing system review is commonly the first step in developing user interface systems across an organization (Curtis 2010).

To develop a new domain-specific model for ship bridge user interface architecture, the components identified in the current systems were used to construct a new model within the framework of modern design systems from the web industry (e.g. Google Material Design guidelines), but altered to fit domain-specific attributes. Examples of such attributes are maritime symbols and icons or the components in the physical workstations (American Bureau of Shipping 2014), as well as integration system elements including physical hardware. Such components are not documented in web-based standards.

This architecture has been co-evolved with a design process performed on behalf of the industrial partners that demonstrated component-based user interface design in practice. The user interface architecture has been presented and modified after input from industry partners in the OpenBridge project. During the course of the project four workshops were organized with between 15-20 industry representatives and user interface experts from academia. The workshops included participatory design activities to elicit knowledge mobilization between the participants with and common discussions revolving around shared boundary objects, such as architecture models and sketches. In addition to the workshops individual meetings with industry actors were arranged in-person and over video conference where design proposals were evaluated and discussed. The industry actors offered input on the functionality of their current systems and added to the discussion on how it could be structured in the new architecture. This resulted in changes the structure and the content of the new architecture.

The various frameworks supporting design reveal a variation of different approaches for supporting user interface development that supplement each other. A design guideline can coexist with front-end development framework and a design system may include both a development framework and design guidelines. Overall, it is likely useful to combine all four categories into a new maritime design system. However, developing a maritime design system needs to be done in progressive stages. A user interface architecture is proposed as a useful first step and fundamental in developing a comprehensive design framework. Such architecture will establish the overarching structure of the system, thereby making it possible to incrementally plan the various elements of design support.

3.2. MBS Workplace Hardware

Mapping the components that constitute current MBS workplaces is an important step in the process of developing the user interface architecture. Although modern applications can scale to many device types (e.g. mobile phones, tablets and computers), there is no certainty that such technology can be applied directly to MBS workplace hardware. The workplace hardware of an MBS system is very different than most web-enabled devices, and includes many screens and various types of input devices.

Physical workstations include interaction technologies that not only serve as central conditions for digital user interface design, but are also meant to support interactions with internal and external variables (e.g. communication between bridge crew or unobstructed vision of the ship's bow). In order to review the individual systems, the components in each workstation that support generic applications were identified, categorized and illustrated in a common graphical format for easier comparison. The components that constitute the workplace are divided into three categories:

- Generic Interaction Mechanisms (e.g. mouse and touch screens)
- Direct Interaction Mechanisms (e.g. physical buttons and levers)
- Display Technologies (e.g. different types of screens)

3.2.1. Generic Interaction Mechanisms

The physical design of each MBS varies widely between ship bridge integrators and a mix of digitally integrated systems (Figure 2). In identifying the generic components found on each MBS, three main sub-categories of generic interaction were found: (i) cursor-based methods, such as mouse or rollerballs, (ii) direct touch screens, and (iii) smaller touch screens, which offer condensed access to applications that are presented on screens located further away from the user(s). The generic interaction schemes found in the consoles are compatible with each other (e.g. pointer-based methods) and it is already common to design hybrid interfaces that support both pointer and touch. It is also possible to scale interfaces according to input type, where touch interfaces in general require larger hit areas and optional components for features, such as tooltips. Second screen control of applications is an addition that can be applied to any interface without removing support for touch or pointer-based interactions.

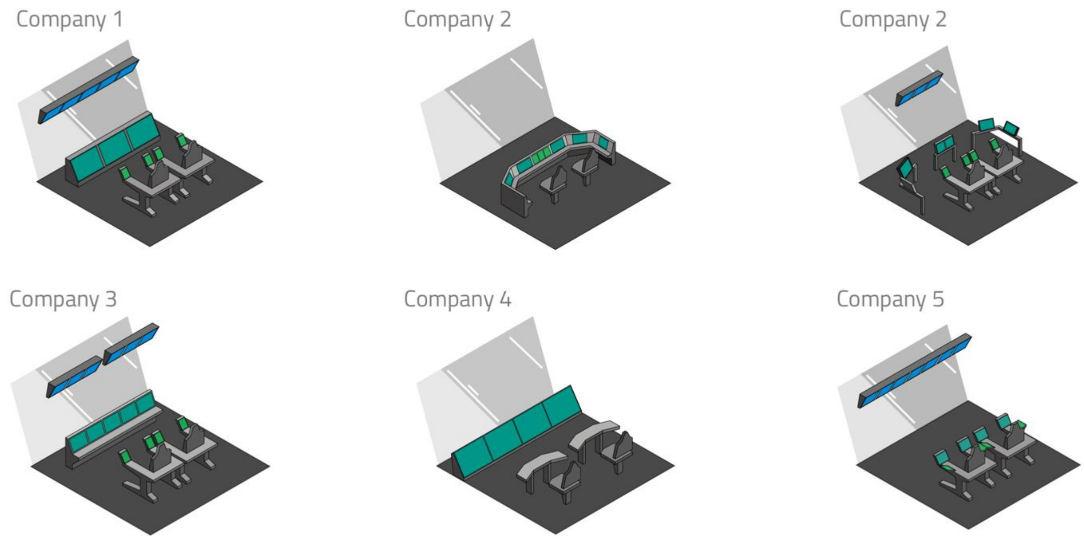


Figure 2. Physical workstations redrawn in a common format for comparison. Two of the workstations came from company 2.

3.2.2. Direct Interaction Mechanisms

Direct interaction related to manoeuvring is handled similarly across the various consoles analysed. However, some of the MBS offer digital user interfaces for buttons that were previously physical. The direct interaction predominantly uses standard components. The difference between the systems are limited to the look and feel of a few established interaction device types (e.g. buttons, levers, etc.). The inconsistencies are mostly related to whether a function is mediated physically or virtually on a screen. From a user interface perspective, such differences can be addressed by offering digital access to all buttons, but with physical representation as possible additions when desired.

3.2.3. Display Technologies

Three main categories of screens were identified: (i) large screens, used for full applications, (ii) smaller screens, used predominantly for displaying information, and (iii) smaller touch panels, located in close proximity to the user. The placement of the two former screen types varies in different ship bridge layouts, whiles screens for full applications are generally touch panels when close to the user.

The variations found in this analysis lie within the already established concepts of user interface scaling established in responsive design methods (Gardner 2011). Although the numbers, placement and size of screens vary (e.g. Figure 2), it is possible to develop applications that can scale to all screen sizes, placements or resolutions found in the sample. Applications following general guidelines from web and mobile responsive design will be able to scale to all the consoles reviewed and adapt to the local interaction scheme in each console.

3.3. Application User Interfaces

Ten applications from ten different developers in order to map the differences among current applications user interfaces. This includes both system developers and ship bridge integrators applications. The layout structure, menu systems, design of user interface components and overall style guide were compared. In deconstructing the interfaces, the components of each interface were categorized and redrawn in a common style guide for more effective comparisons.

Several of the ship bridge integrator systems reviewed offer software frameworks in which many of the ship bridge functions can be reached through a unified interface. They offer the means to open and close applications, and also offer ways for applications to display information on the available screens. This can be considered to be similar to the user interface frameworks offered by Android or iOS platforms. These platforms offer global functionality and manage how applications may take advantage of user interface hardware and software services available on mobile phones. However, unlike iOS or Android, ship bridge integration systems do not normally offer system developers tools or methods that allow them to deliver finished user interfaces to their platform.

Several of the system developers in the project consortium already deliver user interfaces that can be installed into an integration system. However, since there are no common frameworks for how these interfaces are to be integrated in the MBS, neither the system integrators nor system developers need to customize the applications to fit each individual MBS. This review reveals that the user interface design differs in all four categories of the analysis. Although many of the interfaces deal with similar types of information and functions (such as presenting alarms and providing global menus), they are structured in different ways. Most of the applications are custom designed for specific screens with a given resolution.

Menu systems are designed using multiple user interface component types, such as tab menus, flow-out menus or hamburger menus. There is no common design philosophy for when to use specific menu user interface components, where to place them on the screen or how to structure content within them. Figure 3 shows how four different interfaces use different user interface structures. There is a surprising variation in the design of common user interface components, such as buttons and sliders. For instance all applications use very different toggle button designs and several of the designs are lacking in their ability to clearly signify the toggle button status or their function in the system.

Figure 3. Variations of toggle buttons. The bottom row shows actual buttons found in the analysis, and the top row shows our interpretation in a common format.

The visual style of the applications varies strongly with different use of colours, lines, spacing and fonts, even though they may be used within the same workplace and by the same users. Although text size is used to signify critical information in most of the applications, there is no overarching consensus in how to use size consistently across applications. This lack of consistency also stretches to use of fonts and spacing between interface elements as a means to structure information to enhance readability and interaction.

Overall, it emerged that all the applications analysed use the same basic type of user interface components, such as toggles and buttons. Most use a central navigation menu, have setting pages and similar needs to clearly communicate labelled numerical datasets to the users. Despite the similarities in functional requirements for user interface design, there is a difference in how varying companies realise these functions through their design. These differences range through the categories reviewed: design of applications structure, menu systems, user interface components and style.

Our review reveals that the systems analysed are far from offering design consistency across equipment for MBS ship bridges. However, since the applications requirements for user interface functionality are similar amongst the applications, there are opportunities for developing design frameworks that may lead to consistent user interface design across ship bridge systems (Figure 4).

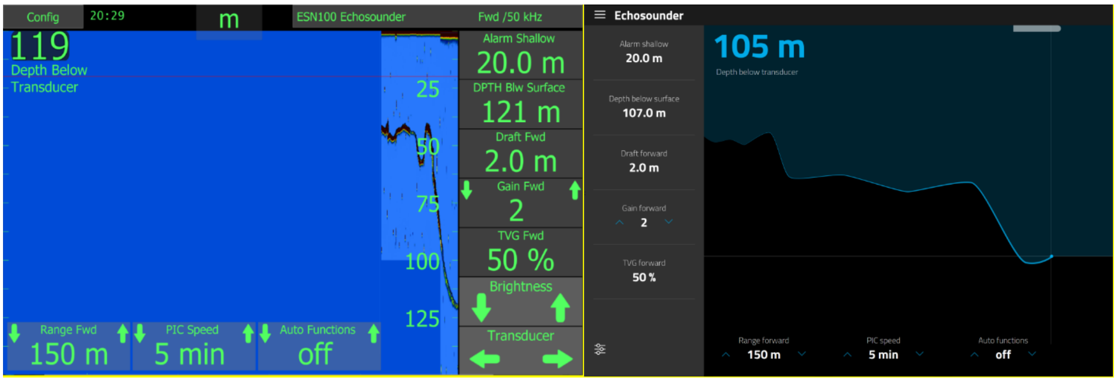


Figure 4. Example of a user interface test where an existing user interface (left) has been redesigned using standardized user interface components (right).

4. Proposed MBS User Interface Architecture

This section presents the proposed user interface architecture for MBS workstations. The architecture can be used to develop new tools (such as design guidelines and pattern libraries) that may enable a better organization of MBS design processes. The architecture is created from a user interface design perspective and does not describe technical implementation.

4.1. Applications, Integrator System and Workplace Components

Design frameworks, such as design guidelines, design systems or front-end applications frameworks, can be used to improve current workplaces. However, maritime workplaces have additional domain-specific requirements, particularly connected to physical interaction and multi-screen use that are not supported in such frameworks. Therefore, user interface architecture for maritime workplaces should extend beyond digital user interfaces to the physical properties of an entire workplace. In addition, an architecture needs to acknowledge the difference between integrators and applications developers to clarify the boundary between these different actors in the design process. This differs significantly from the web-based frameworks presented earlier (Apple 2018a; Google 2018b). Therefore, a MBS can be divided into three main categories: (i) workplace hardware, (ii) applications, and (iii) integration system (see Figure 5).

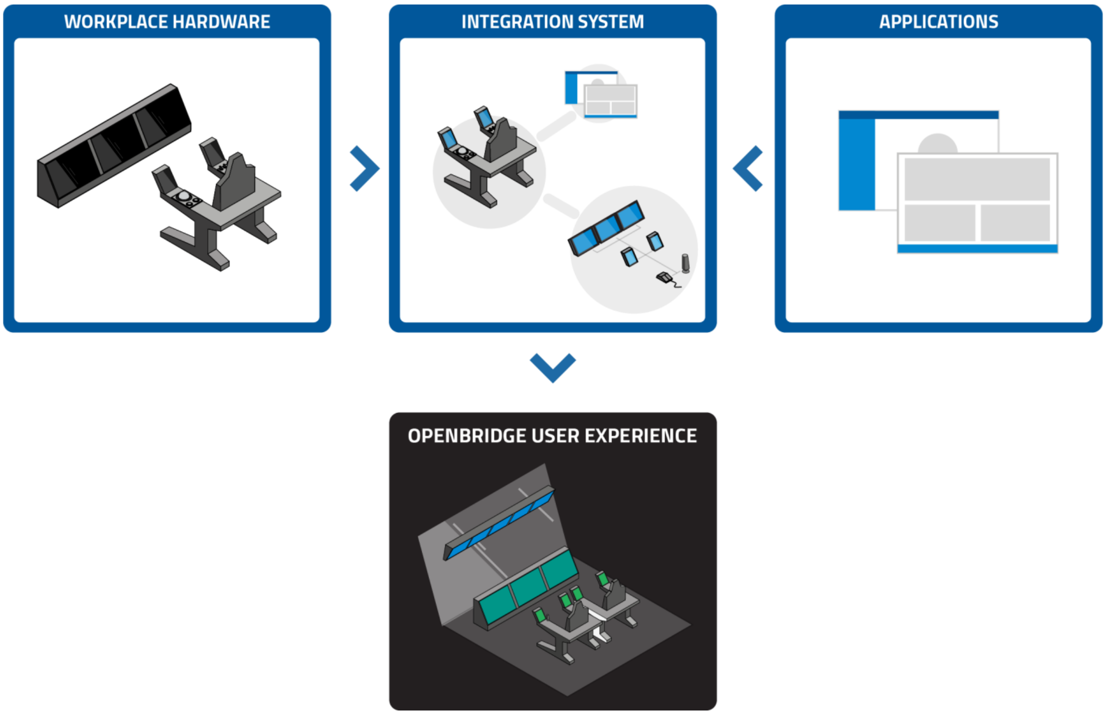


Figure 5. The three main levels of the user interface architecture and the components under each.

The three categories describe the MBS using the integration system as a bridge between applications and hardware. The architecture allows for focus on individual design support for each category with the aim of streamlining how the user interfaces of applications can be integrated into an MBS without any need to consider special requirements from individual MBS integrators.

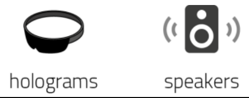
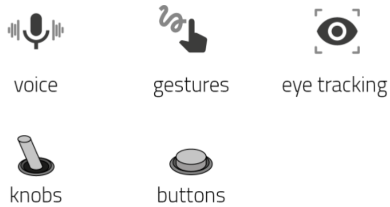
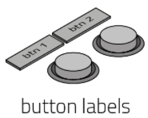
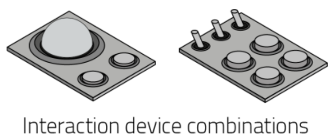
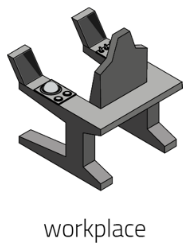
Our architecture mirrors how mobile apps are developed, where applications can scale to a range of different hardware platforms while taking advantage of the user interface resources on each platform. In order for such an architecture to function, it is necessary to develop clear specifications for how the integration system mediates between user interface hardware and applications, and how the integration system may regulate design consistency among applications.

4.1.1. Workplace Hardware

The workplace hardware taxonomy divides the physical workplaces into a range of components that together make up the physical workplace design (Table 1).

Table 1. Sub-categories of workplace hardware

Category	Description
Generic Input (Primary Input System)  roller ball touch mouse	Input technologies used for controlling screens. These comprise of pointing devices, such as mouse, rollerball and touch pads, as well as various types of touchscreens.
Screens (Primary Output System)  large screens touch screens far screens	This includes all screens that are available for ship bridge applications.

Additional Output Devices  	Alternative or extra output systems, such as speakers, leads or augmented reality systems.
Additional Input Devices  	Specialized input systems for applications, such as voice input, gesture or eye tracking. It also includes tangible input mechanisms such as buttons and knobs.
Maritime Input Devices  	Systems with direct mandatory functionality, such as levers controlling engines or emergency stop buttons.
Physical Workplace Labels and Graphics  	Non-digital signs and labels on equipment or workplace consoles. These can be logos, labels on buttons or labels showing the status of a lever.
Interaction Device Patterns  	Description of how to design specific assemblies of interaction components, such as placement of generic interaction options and clustering of buttons.
Workplace Layout  	Describes the overarching physical layout and elements of a workplace.

The architecture divides the workplace hardware into eight categories. Primary input and output signify the most important user interface hardware necessary for supporting generic applications in the MBS system. The additional input and output categories describe other interaction technologies that generic applications may take advantage of if they are present. Maritime input devices are predominantly tangible interaction devices that are directly connected to specific functions, such as propulsion levers and emergency stop buttons.

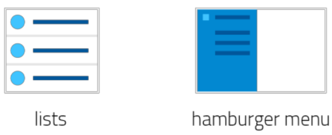
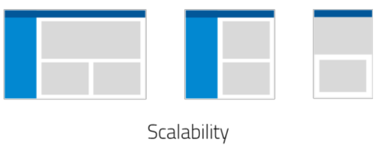
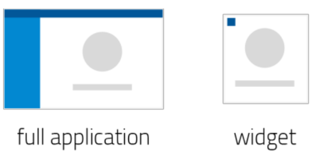
Although much of the traditional physical interaction in bridges are being moved to digital screen-based systems, this framework is open for linking both digital user interfaces and physical interaction of the bridge. Tangible interaction has advantages over generic interaction methods in that they are consistently available and offer distinctive feedback to users. Currently, many systems in MBS offer either tangible or generic interaction. Research shows that these interaction strategies could be combined in order to create more versatile interaction schemes for maritime workplaces (Nordby and Morrison 2016).

The architecture also makes room for extensive multimodal interaction capabilities. Interaction modalities such as voice, gesture and eye tracking are difficult to introduce in MBS since they need to be consistently implemented for all applications using them. This architecture creates a method to introduce such interaction mechanisms by offering them as optional functionality in MBS systems. This is important for maritime workplaces as shifting work conditions require multiple operational paradigms for users to interact with the system (Nordby and Lurås 2015).

4.1.2. Applications

The applications categories describe the components of application user interfaces that may be installed in the MBS (Table 2). Most of the categories follow the structure of common design guidelines from the web domain. In addition, there are maritime specific categories due to unique requirements for maritime systems and operations.

Table 2. Sub-categories of applications

Category	Description
Style 	The style guide defines visual formatting of the elements in the user interface, such as fonts, lines and graphical elements. The visual formatting includes definition of colour palettes supporting shifting light conditions (night and day palettes). This includes naming conventions for elements, such as colour palettes, typography, grids and iconography. Styles include the definition of how to design for extended multimodal interface technologies, such as augmented reality and audio.
UI Components 	These include generic components, such as buttons, menus and labels which are the main building blocks for all interfaces. The components extend to multimodal capabilities beyond screen.
Maritime UI Components 	These encompass specific components that offer standardized information or functions in the user interface. It includes interactive components as well as non-interactive components, such as icons and graphics. Examples may be visualization of thruster, rate of turn or user interface components that display alarms. The components extend to multimodal capabilities beyond screens and differ from UI components in that they are connected to specific content.
UI Patterns 	These describe how to design specific sections of an application, such as navigation, settings and showing alarms. The components extend to multimodal capabilities beyond screen.
Layout 	Layout describes the structure of applications. These include responsive design that scale to available screen area and distance. It also covers design for various application categories and nesting of content that can be extracted from an application. The components extend to multimodal capabilities beyond screen.
Application Type 	Specification of the characteristics of the application, such as application group, connections to operation types, or whether the application needs permanent screen space. It also deals with special requirements for specific applications or application categories.
Documentation	Any digital data relating to the applications, such as help, system documentation, certificates or other documents.

Many of these categories are maritime-related versions of common design guidelines. However, there are three exceptions. The maritime user interface component category deals with user interface components that are connected to specific maritime content, such as thruster visualization. The application type describes any special requirements for categories of applications or specific application types. This is important since some applications may have special design requirements, particularly for applications that have special regulations or used by other systems (such as the bridge alert management system). The documentation category represents how to design any digital documentation that is associated with applications. This is not normally part of a design system, but it is useful to include it in a maritime system where consistent documentation is an important part of the user experience.

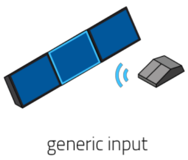
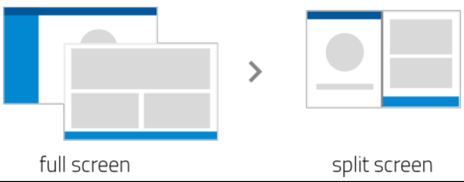
Our framework supports interaction technologies beyond the screen. Although such channels are not explicitly mentioned as categories, extensions for multimodal options are integrated within the existing categories are of value. Multimodal technologies are considered as an addition to screen-based interaction that app developers can take advantage of if available in individual MBS.

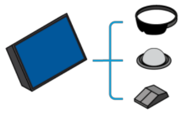
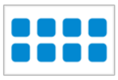
Since the framework separates style, it does support global change in style guides, making it possible for system integrators to globally change visual style. This is important since it will allow ship bridge integrators to adapt and integrate third party applications that visually fit into their integration system. The application layout category should include descriptions of responsive design of maritime applications. These should mostly follow current best practices from other domains. However, it is likely that they will have certain unique features, such as how to design for screen distance and size, including the ability to change layout according to whether a screen is within users' interaction reach. Responsive capabilities should make it possible for interfaces to scale to all MBS systems, as long as they offer screen space within the requirements of the workplace hardware category.

4.1.3. Integration System

A digital integration platform is not commonly identified as a separate system, detached from maritime applications. However, in reviewing current MBS, it is evident that such systems are emerging in the industry. There is a lack of design guidelines or regulations that directly manage the relationship between bridge user interface hardware and applications. The integration system category offers a framework of categories that formalizes how to design the user interface which manages the applications installed on the MBS (Table 3).

Table 3. Sub-categories of Integration Systems

Generic Input 	Collection of design patterns related to generic input. For example, screen selection and shifting of input device.
Screen Estate 	Collection of design patterns related to the manner in which screens are made available for applications. For example, characterizes what type of applications can access a screen, relationships between screens and applications areas within the screen space.
Secondary Input	Collection of design patterns for design of secondary input interfaces, such as screen representation of voice interface.

 voice interface  multiple input devices	
Secondary Output  haptic feedback	Collection of design patterns for design of secondary output interfaces, such as sound icons and haptic feedback.
Application Management  launch apps  arrange apps  close apps	Collection of design patterns that deal with the system design and enable users to manage applications. This includes identifying applications and opening and closing them.
Global Services  dimming  alerts	Description of services that can be accessed by applications, such as documentation system, alert system and dimming.

Harmonization of how applications are integrated in competing platforms are particularly important since this will streamline application development and enable a system vendor to deliver a single application that can be installed on multiple ship bridges. Harmonization will also reduce the need for system integrators to create their own version of applications user interfaces in order to make applications appear visually integrated in their MBS.

We have investigated the components of 6 workplaces in our study and found that there was limited variations in how screens were integrated in each system. We are therefore optimistic that it is possible to create a minimum compatible integration system, focusing on generic input and use of screens, with minimal formal requirements. However, secondary input and output modalities may require stricter regulation.

5. From UI Architecture to a Design System

This article introduces a user interface architecture that divides the current MBS into three main categories: workplace hardware, applications and integration system. This division is useful since it helps to separate what are essentially three very different approaches to design. The design of applications is very similar to any application design in other industries, with a few maritime-specific modifications and additions. Workplace hardware addresses only user interface hardware that supports applications. These are partially covered in existing maritime design guidelines. However, there is a lack specification of how workplace hardware should be designed in order to support interaction with applications. Finally, the integration system is defined as a user interface framework managing other applications. There is currently limited guidance of how to design such systems for maritime applications. This is a significant problem since the integration system is fundamental for creating open MBS systems.

The three categories help divide the functionality of the MBS, as well as the actors responsible for each element. The simple clarification of the MBS as an application platform and the sub-categories within each main category can now be used to plan methods and tools supporting design that would lead to the creation of compatible workplace hardware, applications and integration systems.

The sub-categories identified in the user interface architecture can be supported by a variety of methods, tools and processes. For example, the style category found under applications could both be supported by a design guideline and a front-end web application framework. Further, the category can also be associated with current maritime design regulations. Because of this, we suggest development of an open design system that includes all of these approaches. Such a framework mediates across design and development, thereby making it possible to increase development and design efficiency, while maintaining user interface consistency.

We address such a versatile framework for a *maritime design system* (Nordby et al. 2018). It is similar to design systems from other domains, but is adapted to maritime use cases and incorporates maritime regulations. The proposed user interface architecture provides a structure for this system. A maritime design system supports a radical change in how vendors design and develop MBS. Although many companies are currently adopting methods and technologies that the architecture is compatible with (such as web technologies), it is unlikely that all companies involved in MBS development can shift to a common approach in the short-term. It is therefore important to ensure that the architecture can be implemented in an incremental, evolutionary approach. An implementation of user interface guidelines for applications design would be an improvement over current MBS, even without changes to application implementation, workplace hardware or integration systems. It would improve design consistency and improve design process efficiency. The proposed architecture can be used to structure a gradual implementation process by allowing user interface development to be divided into items that industry can address systematically.

6. Design Freedom vs. Design Frameworks

How strictly a maritime design system will regulate the look and feel of an interface is not defined in the user interface architecture. However, it is likely that a maritime design system would affect the maritime industry's ability to use user interfaces to differentiate their products in the marketplace. There is precedence for such a limitation in existing competitive industries. All web-based frameworks advocate some restrictions on design freedom in order to increase and ensure a level of consistency. Most existing design systems offer more specific design solutions than maritime guidelines and regulation. There is room for company-specific design language, but the freedom of expression is mostly subordinate to platform design language. However, even though design systems from other domains are voluntary, a wide range of companies are embracing them, despite a potential limitation in user interface innovation. In doing so they benefit from well-established, consistent patterns in user interface design. The maritime domain is familiar with the standardization of various aspects of their industries, including standardized technical language, symbols and procedures; thus, a similar concept for bridge system design could prove successful from design, commercial and operational perspectives.

6.1. Implications for System Developers

The architecture may help realize applications that can scale to any compatible bridge system while maintaining design consistency. A consistent platform for applications deployment will lead to larger market access for existing system developers and make it easier for new system developers to offer their products to ship bridges. Finally, system developers will be able to reduce expenses on hardware, since they can now access ship bridge hardware through a standard integration platform. On the downside, the architecture may reduce the developer's freedom in user interface design and choice of development platform. This may be in conflict with the application developer's design and technology strategies, as well as their business strategy in striving for product differentiation in a competitive marketplace.

6.2. Implications for System Integrators

System integrators can offer their customers a larger selection of applications that all are integrated consistently in their design. They can potentially deliver the systems within their own visual profile since style and UI components can be changed and applied across all applications. They can save cost by reducing hardware investment and also reduce the number of ship bridge systems that they have to integrate manually. The workplace delivery will offer customers a consistent user-friendly design that is indistinguishable from single vendor integrated ship bridge systems. The threshold for implementing advanced interaction technologies, such as voice interaction, eye tracking and head-up displays, is lowered since the architecture allows for common guidelines, where applications can share such resources. This architecture does demand that system integrators support an open platform. This move will reduce the ability of system integrators to use a proprietary platform as a competitive tool.

6.3. Implications for Ship Owners

Ship owners will have access to user-friendly, highly customizable and affordable MBS. Since the ship bridge is constructed as an open platform, they can integrate new applications after installation and can potentially install their own systems directly into the ship bridge system. The modular design of ship bridge software makes it feasible for ship owners to compose new user interfaces supporting specific operations or ensure consistency across their entire fleet.

6.4. Implications for Users

Seafarers will benefit from the development of more consistent equipment interfaces and work environments across ship bridges. The unique nature of seafaring has created an environment where seafarers may frequently change ships and thus, have to learn and re-learn varied systems and operational procedures, depending on particular equipment specifications and combinations unique to each ship. Increasing the consistency of design across systems will improve the familiarization and training processes, thereby having a positive impact on user performance through increased efficiency and reduction of errors. The modular design can potentially enable personalization of interfaces according to each individual user and specific operational parameters (e.g. open sea vs. port navigation).

7. Conclusions

Inconsistent equipment design and high development costs are a pervasive issue for the maritime industry. Current approaches have not been able to adequately address these problems. This article argues that moving towards MBS as open application platforms is a possible pathway that can resolve many of the barriers to creating better maritime workplaces. In order to realize such open systems, a new user interface architecture is proposed for integrating consistent design across MBS based on proven models from web industries. We consider the proposed architecture an early stage model that will likely evolve further through the ongoing design and development work performed within the OpenBridge project.

The architecture described the structure and content of MBS in a manner which enables us to realize new methods, tools and processes supporting consistent and efficient user-friendly design. This can have positive effects on the industry, ranging from cost savings and increasing innovation to improving ship design, and therefore the efficiency and safety of ship operations. The presented user interface architecture represents a shift in how maritime industries can structure user interface development for advanced workplaces at sea by combining current maritime practices with best practices from other industries. Such architecture is a necessary first step towards a consistent maritime design system for MBS.

7.1. Further Research

The next stage in our work is to develop and demonstrate the first implementation of the user interface architecture in practice. Following this, we will describe the first iterations for design guidelines related to applications development, as well as initiate strategies for user testing.

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To be added

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