Human Factors in Transportation, Vol. 95, 2023, 730–739
https://doi.org/10.54941/ahfe1003858

Human-Machine Interaction Challenges for Bridge Operations in Large Passenger Ships and Future Improvements from The Deck Officers' Perspective

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ABSTRACT

Technological bridge solutions have been implemented to improve safety and efficiency, but deck officers still face challenges in their daily use of these tools. Prior maritime human factors research has primarily focused on investigating issues such as workload, stress, teamwork, and situation awareness in ship operations, with limited attention given to the integration work, dynamic context, and factors on the system design level. Through interviews with maritime experts and field studies on two large Baltic passenger ships, this study examines the human-machine interaction challenges in today's bridge operations and identified areas for improvement. The results do not only explore the integration challenges imposed on the mariners, but also identify several contextual and system factors that contribute to these challenging bridge operations: dynamic situations and uncertainties, potentially conflicting goals, trust issues, lack of tool support and standardization. Suggestions for future improvements to bridge systems from the deck officers' perspective are also presented, with a focus on supporting proactivity, trust, context-awareness, and system integration. A few system design reflections were also made to fathom the challenges and inform potential future design directions. The study provides a thorough understanding of human-machine interaction challenges in bridge operations, which sets a foundation for future design and deployment of human-centered integrated bridge systems.

Keywords: Maritime, Human factors, Human-machine interaction challenges, Bridge operations, Integration, Usability, Proactivity, Context, Trust, Standardization, Safety

INTRODUCTION

Maritime navigation can be seen as a complex socio-technical system (Grech 2008) involving automation systems which are capable of sensing, producing and storing large amounts of data. Increasing automation solutions in turn pose challenges to navigators' situation awareness and workload (Sarter and Woods 1995, Grech, Horberry et al. 2002, Lützhöft and Dekker 2002). In an analysis of 192 marine occurrences reported to Transportation Safety Board of Canada (TSB) between 1998-2018, interface design as well as non-standardized system layout were found to be prominent contributing factors to accidents (Gauthier, Kruithof et al. 2019). As a result of technological advancements, the role of maritime navigators is shifted towards monitoring and planning, while surveillance and execution are in many cases offloaded to automated systems (Conceição, Carmo et al. 2018). Although bridge systems do have an increased ability to integrate information (Jurdzinski 2018), the integration may not fully address the new role's demands. Prior studies suggest that navigators can involve themselves into integration work (Lützhöft and Nyce 2008). In order to design future human-centered bridge systems, it is crucial to comprehend the underlying challenges of Human-Machine Interaction (HMI) on ship bridges, as well as the specific requirements and limitations of the users and the technology within the navigational context.

RELATED WORK

Prior research in the maritime human factors domain looks closely at various challenges that seafarers face onboard ships, including issues related to workload, fatigue, stress, ship operations, ill-designed systems, teamwork, and communication (Hetherington, Flin et al. 2006, Grech 2008, Shanahan 2010). A crucial aspect to consider is the interaction between humans and technology, which has been extensively studied with diverse research (Endsley 1988, Lee and See 2004, Hollnagel 2011, Hancock, Jagacinski et al. 2013) that can be applied to the maritime domain. Examples include using concepts such as human error (Lützhöft and Dekker 2002), situation awareness (Man, Weber et al. 2018, Pazouki, Forbes et al. 2018), trust (Aylward, Weber et al. 2020), system resilience (Praetorius, Hollnagel et al. 2015) etc.

Human-system integration is a critical aspect of human-technology interaction research, yet there is limited research that focuses on the integration challenges faced by deck officers in their daily practices, including the underlying contextual and system factors. The study from Lützhöft and Nyce (2008) have highlighted that modern bridge technologies require mariners to perform some sort of integration work, as machines cannot communicate in ways that officers find useful (Lützhöft 2004). Other recent studies point out the issues with non-standardized design (Gauthier, Kruithof et al. 2019, Nordby, Gernez et al. 2022). However, these studies have only partially examined the contextual or system factors that contribute to these challenges. Additionally, they have not sufficiently included the needs and perspectives of the end users regarding potential future improvements of bridge systems. This paper aims to address these gaps and set a foundation for human-centered design of future bridge systems.

METHODS

The majority of the study subjects were either on-duty master mariners working on board two Ro-Ro (roll on - roll off) passenger ferries in the Baltic Sea ($n = 13$, all men), or actively working in the maritime domain on-shore as nautical instructors or in shipbuilding management ($n = 4$, all men). All master mariners were interviewed and observed during active duty on the ship bridges. The prepared semi-structured interview protocol involved topics such as maneuvering, monitoring, harboring, and administrative tasks, by covering current practices, challenges, and future perspectives. Observations of the master mariners were also carried out on the bridges to observe how they interact with different technological tools. The produced field study data was investigated in an inductive thematic analysis (Clarke 2006) by initially transcribing and coding the material in MAXQDA 2020[1] after which codes were extracted to a shared digital workspace to categorize the data into various themes.

RESULTS AND DISCUSSION

Human-Machine-Interaction Challenges and Contextual Factors

Integrating Synthesizing and Prediction in a Dynamic Environment

An evident interaction challenge onboard ships was found in dynamic environments where there are multiple vessels in close proximity to each other. If a vessel changes its speed or heading unexpectedly, it can show another intention and thus affect the trajectory and potential collision course of the other vessel. In these situations, deck officers must monitor the actions of the surrounding vessels, predict the development of the situation based on various information, as well as their experience and navigation regulations in order to avoid a collision or other safety hazard. In congested waters this may require a high level of cognitive resources such as mental effort and attention. The presence of leisure boats in the archipelago areas, which are more unpredictable in their movements and actions according to the deck officers, adds an additional layer of complexity and make situation even more stressful.

Another crucial factor that can characterize the dynamic environments is the effect of wind on navigation, which can affect the speed, heading, stability and trajectory of the vessel. Deck officers talked that they often closely monitor wind direction and strength and use their own experience to make decisions about how to compensate the wind's impact on the vessel's movement. This is essential in archipelago and harbor areas where there is limited maneuvering space and thus requires the deck officers responsive to fast changing conditions.

Topography is another indispensable factor that contributes to the dynamics and complicate navigators' decision-making processes. For example, navigating through an archipelago can present some unique challenges due to the presence of multiple islands and waterways. The islands in the archipelago area can block the view of the navigator, leading to limited visibility. The narrow channels that the vessels must navigate through requires precise steering and maneuvering. Additionally, the water depth can vary significantly. When the vessel is navigating in shallow water, it must use more energy to maintain its speed due to increased drag on the hull, therefore speed adjustment becomes necessary for energy efficient navigation.

An officer needs to prioritize safety by slowing down the vessel or changing course to avoid a potential collision, but this may also impact the time schedule and increase energy consumption. Balancing the potentially conflicting goals of safety, punctuality, and energy efficiency can be challenging in such a dynamic environment. It was observed that these trade-offs are not

[1] MAXQDA software for content analysis: https://www.maxqda.com/content-analysis

always easy to navigate sometimes, nevertheless it is crucial for the officers to get support in understanding and synthesizing all these factors so that they can plan and act early (such as adjusting the vessel's course or speed to take advantage of favorable wind conditions or avoiding shallow water and collision where possible).

However, the study reveals that when the officers are synthesizing a large amount of information from various sources, it is a cognitively demanding process without getting sufficient proactive decision support from the current integrated bridge systems. The dynamic nature makes conventional prediction support like plotting the vectors for surrounding vessels less reliable for indicating their intention. In an archipelago and a harbor area, the wind can be affected by the presence of land masses, which can create local wind patterns that can change quickly and are difficult to be picked up by onboard sensors in advance. Overall, the observed bridge systems have limited ability to accurately consider and account for the constantly changing context and conditions that impact a vessel's safety and energy efficiency. This leaves deck officers responsible for manually integrating, synthesizing and predicting information in order to make informed maneuvering decisions.

Distractive Work Environment With Fragmented Information and Controls

Alarms can be an important source of information for deck officers, but they are also distractive by nature. The officers mentioned that some alarms communicate information that they already know (e.g., Closest Point of Approach alarms) or the annoying alarms that arenot relevant at the operating stage that they are in. One additional challenge is that infrequent alarms can be difficult for officers to comprehend and identify the origin of, which can further divert their attention from their primary navigational duties. During the field study, the authors observed a scenario in which the entire bridge crew came together to locate a false sprinkler alarm on board.

In addition to the distracting alarm issues, the bridge also faces a challenge of interoperability. The trend of being inundated with information that is increasingly dispersed and fragmented was observed during the field study. The environment is overwhelmed with many systems and equipment from different manufacturers that provide isolated information that is relevant to the operation of the vessel. One example is that various means, including meteorological reports, onboard sensors, navigation charts and maps, radio communication and visual lookout, can provide essential navigational information regarding weather and topography. Integrating these fragmented pieces of information can be a challenging task for the officers, particularly for those who are lessexperienced, when they need to prioritize targets or tasks within a short timeframe. At present, there is a lack of supportive tool on board ships that would make this integration process easier.

The field study also discovered that information and controls being distributed across multiple bridge systems often require the officers to move from one location to another to "make it work". For instance, some operations were observed to be performed in specific positions or in specific ways because not all the information or assistive tools are integrated or within reach. As Fig. 1 shows, an officer is using a calculator to plan cargo, writing

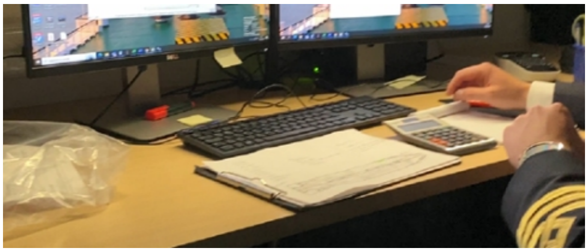

Figure 1: In the back bridge area, an officer is using a calculator to calculate stability for cargo planning.

the numbers on a piece of paper, and then manually transferring them to a different computer to calculate stability.

While some officers mentioned the lack of standardization in controls and displays can lead to an increase in the amount of training needed, the study also identified that they are very flexible in developing their own workarounds to bridge the gap between the systems. One example observed is the use of a cardboard label as a reminder for the officers to remember to deactivate the stabilizing fins when they are not needed (see Fig. 2). This workaround is necessary because the fin control system is positioned further away from the more accessible navigational systems and they are not integrated, as they are from different manufacturers. As a result, the officers must "manually integrate" the systems by constructing a physical representation within their sight. The lack of interoperability between the systems is making information more distributed and fragmented, creating additional cognitive and physical demands for the users. This illustrates how even stacking isolated human-cantered design systems can be a hindrance to system safety, efficiency, or user experience. Although local adaptation may solve the issues, it might actually increase the risk of a larger system failure (Dekker 2011).

Figure 2: Use of a cardboard label as a reminder for remembering to deactivate the stabilizing fins.

Trust Issues

Trust issues were also identified to be a pain point on the ship bridges, leading to reduced usage or reliance on certain systems. During mooring a captain was observed to verbally communication with another deck officer (essentially counting down the markings on the quay) to confirm the distance to the right docking position.When asked if it would be acceptable to deploy an automation system to literally read the meters, he expressed concern that the machine may fail at some point even though the probability is low. These trust related phenomenon are commonly seen in the shipping industry (Lützhöft and Dekker 2002) and in this case it is about the user's confidence in the system's capabilities and reliability.

Usability Issues

The field study also concluded that the officers have difficulties using the bridge systems at times due to various usability issues. In addition to its connection to standardization, the system design was observed as lacking interaction design considerations. One example is the systems can require specific interactions that are cumbersome to perform frequently, such as changing course requires using a trackball on a screen rather than physical buttons, and switching between autopilot, manual, and tandem modes requires more interactions than the navigators are accustomed to. Another factor is software glitches, e.g., when a user clicks and drags the ECDIS/Radar screen to view a different area, the contents in the field of view frequently automatically reset back to the ship center.

User Suggestions

The deck officers' suggestions on future improvement of the bridge systems were also collected and they resonated with the forementioned issues. An emerging theme is about getting more proactive decision-making support from the digital systems. Today, the officers rely more on their own capabilities to understand the dynamic environment, estimate how the situations will develop and navigate the ship accordingly. Many conventional navigational tools are used for tactical purposes, such as assisting maneuvering in close-quarter situations. The mariners expect to have more proactive decision-making support tools that allow for strategic maneuvering early. As an officer mentioned, "*making very subtle change in speed or course very early on so the situation did not even develop to COLREG (Convention on the International Regulations for Preventing Collisions at Sea) situation at all*". By anticipating potential issues with proactive support, the officers would have improved situation awareness and alleviate the stress and uncertainty that can come with navigating a ship in challenging conditions.

Another key recommendation is to design and develop more context-aware and intelligent bridge systems that have the capability to understand the current situation and provide dynamically updated information, so that the user can have access to the information they need at the exact moment. The system should be adaptive, taking into account different phases of navigation, such as port maneuver, pilotage, fully open waters and restricted waters. The officers have expressed appreciation for having simplified, relevant information provided to them, which also applies to alarm design. Context-aware systems would help reduce the cognitive load on the users, allowing them to focus on the most important task at hand. Some have even suggested that the bridge systems should have the ability to learn, follow up on what the user is using and provide information accordingly.

Regarding the issue of data being dispersed across multiple systems and the workaround practices being used, the officers have expressed a desire for more collaborative work from the manufacturers to standardize the systems in order to improve safety, efficiency, and user experience. Some have suggested that in order to increase interoperability, there is a need for the development of "a *standard of standards*" for equipment manufacturers to follow. Additionally, there have been suggestions for improvements to bridge layout design, such as having all equipment within reachable distances to make it easier to manage information and focus on tasks.

A few participants have emphasized the importance of trust and reliability in the design and implementation of bridge systems. With more automated solutions being introduced onboard, some have expressed the need for the bridge systems to have transparency and clarity to help users understand the limitations of automation. Examples of this include clear indicators of the automation's plans and defined operating limits for the ship's equipment.

System Design Reflections

An outstanding challenge identified from the field studies is the deck officers are performing integrating work in various ways to cope with dynamic situations on the bridge, where the contextual factors are complicated, needed information is fragmented, and technology is isolated at present. This is essentially human users "constructing a functioning whole out of parts" either mentally or using artefacts (Lützhöft and Nyce 2008). This effort can be demanding and may lead to new risks. For example, when there is a system failure, the users could focus on the technology rather than the task (Bødker 1996).

A theoretical framework that can be used to further understand the constituents of such HMI process and approach system design is distributed cognition, in which human operators constantly coodinate between internal cognitive resources and external structures in the environment (Hollan, Hutchins et al. 2000). It suggests that the design work should not just look at the cognitive demands and processes but also thoroughly consider the context in which technology is used. This implies:

1. A holistic perspective to understand the bridge socio-technical system to approach its future vision - who the operators are, what their roles and responsibilities are, what dynamic environmental factors make their work difficult, what products are in place, and how they are integrated with each other and how they are used in practice etc.

2. A human-centered approach where the user's experience, needs and contextual knowledge should drive the design and development of technology.

To ensure that the technology is useful and usable, it is important to consider the human, technical, and system aspects of integration readiness in system design. Endeavors in standardization (Man, Lundh et al. 2018, Gauthier, Kruithof et al. 2019, Nordby, Gernez et al. 2022) and system transparency (Aylward, Weber et al. 2022) are essential steppingstones.

From the practical perspective, Lützhöft and Nyce (2008) highlighted that the idea of having machines to be "situated" or "context-aware" is unrealistic. However, with the rapid advance in artificial intelligence (Kabir, Hoque et al. 2015, Rawson and Brito 2021, Palma, Godoy et al. 2022), we believe it is becoming increasingly feasible to design and develop such tools that are better able to understand and adapt to their context or pattern of use and provide more accurate predictive information.

CONCLUSION

The work has closely examined today's human-technology interaction challenges deck officers experience during bridge operations and gathered their suggestions for improvements. Field studies were conducted through observations and interviews with master mariners during active duty on two large passenger ships in the context of bridge operations. The main themes identified can be linked to the dynamic nature that characterizes the work on a bridge. The fragmented tool support currently available shows major shortcomings in handling the dynamics. The study also identifies the great potential for assistance with strategic and tactical tasks and hightlights the importance of integrated solutions. The usability issues make the officers' work unnecessarily difficult, and the use of standardization is suggested as an area for improvement.

This study provides a deeper understanding of interaction challenges and emphasizes the importance of a holistic perspective and a human-centered approach when designing future integrated bridge systems.

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