

Design Principles for Human–Autonomy Interaction in the Maritime Domain: Transition From Onboard to Remote Operations

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ABSTRACT

As the maritime industry transitions toward highly automated and autonomous operations, the roles of human operators, remote control centers, and decision-support technologies are evolving rapidly. In this changing context, particularly from onboard operation to remote operation of multiple autonomous vessels, ensuring safety, usability, and resilience in safety-critical systems requires the effective application of human factors (HF) and human-centered design (HCD) principles. This paper presents a literature review in the maritime sector to identify key design principles that integrate human factors into highly automated operations. The aim is to explore how HF and HCD principles can support the transition from traditional onboard maritime operations to remote operation systems, ensuring safety through successful design strategies. The review draws on eight academic publications (years 2013–2025) that were systematically filtered to include empirical studies addressing HF and HCD applications in maritime automation, with particular attention to Maritime Autonomous Surface Ships (MASS), remote operation centers, and integrated decision-support systems. These publications were selected based on clearly defined inclusion criteria and screened for HF and HCD principles, outcomes, gaps, and implications. The results show that current practices address a range of micro-, meso-, and macro-level HF principles and design implications. It was found that both research and practical application remain limited and lag behind the rapid technological developments within AI and automation. Across the literature, consistent gaps remain in the study of HF and HCD for MASS and remote operations. These gaps highlight the complexity of transitioning from onboard to shore-based operations and underscore the need for a sociotechnical perspective that spans individual, team, and system coordination, as well as organizational and ecological contexts.

Keywords: Human factors, Human-centred design, Maritime autonomous surface ships, Remote operation centre, Human-autonomy interaction

INTRODUCTION

Over the past decades, advanced technologies have been integrated into maritime navigation to support onboard operators by clarifying cues, enhancing situational awareness, and predicting near-future contexts (Conceição, 2018). However, accidents and near misses continue to occur (AGCS, 2021; Pilatis et al., 2024).

A key reason lies in the inherent complexity of navigation (Baldauf et al., 2025; Xue et al., 2023). Operators must simultaneously interpret multiple sources of information, such as vessel trajectories, environmental forces, ship characteristics, navigational aids, and communications under varying visibility and workload conditions (Grech et al., 2008).

The emergence of Maritime Autonomous Surface Ships (MASS) and remote operation centers introduces a new layer of complexity. Human operators are moving from ship bridges to shore-based control centers, losing direct sensory perception and instead relying on transmitted data from vessels (Porathe et al., 2014; Kari & Steinert, 2021). This shift may introduce new challenges, as systems and agents that previously collaborated effectively may not function as intended in the new context and ecology. Beyond changes in the workplace, established practices of perceiving, interpreting, comprehending, and executing tasks may no longer apply in the same way. Furthermore, the rules of conduct, regulations, and responsibilities will inevitably be affected. This requires a reconsideration and reorganization of accountability, communication, and regulatory frameworks based on the new and remote work environment.

In this regard, early adoption of HCD and HF engineering is necessary for successful design. Addressing these aspects from the early stages of system design not only enables the assessment of user interaction with specific systems but also allows for the examination of their broader ecological impact, including communication with other agents and adaptation to the surrounding operational context. Therefore, in this paper, we aim to investigate what HF and HCD applications are currently employed, what improvements need to be made, and which gaps need to be addressed. This work aims to shed light on what is needed for a safer and smoother transition from onboard to offshore operations, as well as the transition of shipboard crew to shore-based operators.

METHOD

This paper is a review of recent literature on the design principles that contribute to successful automation and remote operation, as part of the Meaningful Human Control (MAS) project that conducted a literature review on this topic (years 2013–2023), and complemented with further scoping of relevant articles (years 2023–2025). In November 2022, searches were conducted across the Web of Science, Scopus, Dimensions, Compendex, and IEEE databases. Search terms and strings were developed using the PICO framework and refined through an iterative process, with extensive testing and modification prior to the final search. Following the established protocol, 404 articles were selected for further analysis. After screening, a total of

223 articles in the period of 2013 to 2023 remained, and they were further sorted by sector. There were 15 articles within the maritime sector that met the inclusion criteria. Full-text reviews were initially conducted on these 15 papers. This paper builds on this previous work by extending it to more recent literature. To capture more recent publications, an additional search was carried out using the same search strings and databases, but with the publication period extended to 2025. In this round, two additional groups of search strings were introduced, themed around maritime and empirical, each containing several relevant keywords. Based on title and abstract screening, an additional 11 papers were selected for full-text review.

In total, 26 papers underwent full-text review. At this stage, the focus was on filtering papers that satisfied the following three criteria: (1) The study reported empirical research; (2) HF or HCD principles were considered; and (3) The study was relevant to the maritime domain. Only papers meeting all three conditions were retained for further analysis. After applying these criteria, eight papers remained, as presented in Table 1. Analysis of the screened articles focused on understanding which HF and HCD principles have been employed and why. By doing so, an overview of the research and practice within HF and HCD principles with advancing technologies within the maritime sector will be presented, and the research gaps and implications for the future will be identified.

Table 1: Summary of articles selected for analysis in chronological order.

Reference	Article Title	Method
Man et al., 2018	Human factor issues during remote ship monitoring tasks: An ecological lesson for system design in a distributed context	Mixed
Aylward et al., 2020	An evaluation of low-level automation navigation functions upon vessel traffic services work practices	Mixed
Veitch et al., 2021	Design for resilient human-system interaction in autonomy: The case of a shore control centre for unmanned ships	Qualitative
Alsos et al., 2022	Maritime autonomous surface ships: Automation transparency for nearby vessels	Quantitative
Veitch et al., 2024	Human factor influences on supervisory control of remotely operated and autonomous vessels	Quantitative
Li et al., 2025	Mental workload-performance relationships in maritime autonomous surface ship remote control scenarios	Mixed
Madsen et al., 2025	Improving decision transparency in autonomous maritime collision avoidance	Mixed
Westin and Lundberg, 2025	A survey on Swedish maritime pilots' trust, training, understanding, and use of the portable pilot unit's predictor automation	Mixed

RESULTS

The Overview of HF and HCD Principles Explored

In the reviewed studies, several HF and HCD principles were identified, which can be organized across micro, meso, and macro levels. At the micro level, which focuses on individual cognition and performance, key concepts include situation awareness (SA), mental workload, trust in automation, and skill or experience level. The meso level, concerned with teaming and system coordination, encompasses shared SA, interface integration and usability, transparency and explainability, adaptive automation, error prevention and support systems, and resilient interaction design. The necessity and quality of training can also be situated at this level. At the macro level, which reflects the organizational and ecological context of broader system design, principles such as human-centred, ecological, and context-aware design approaches are emphasized. It should be noted that although these principles are presented along a micro-meso-macro spectrum, the boundaries between levels are not discrete; rather, they are interdependent and collectively shape human performance in maritime autonomous systems.

The Application of Micro-, Meso-, and Macro-Level HF Principles and HCD

On the micro level, HF and design considerations are the work of Li et al. (2025), which focused on the relationship between mental workload (MWL) and operator performance in Remote Operation Centers (ROC) for MASS. The authors conducted a controlled experiment where a single operator managed two vessels under varying task difficulty, time of day, and operator experience. The authors focused on MWL, human-in-the-loop reliability, task allocation, and performance optimization. Both subjective (NASA-TLX) and objective (physiological) measures were used to inform a Human Performance Model (HPM), integrating cognitive workload considerations into ROC design. The findings showed that operator experience and time of day significantly influenced performance and MWL, while task difficulty had minimal impact. Experienced operators reported lower MWL but took longer, reflecting a cautious strategy. Results confirmed an inverted U-shaped relationship between MWL and performance (Yerkes-Dodson Law), with optimal mid-range workload supporting best task execution. The results imply that ROC design and task allocation systems should account for operator experience, time-of-day effects, and workload dynamics. Iterative testing across multiple conditions is essential to optimize human-in-the-loop performance, balancing cognitive workload with safety and efficiency in multi-ship operations.

Also on the micro-level HF spectrum is the work of Westin and Lundberg (2025). These authors surveyed 69 Swedish maritime pilots to investigate their experiences with a course predictor automation tool on Portable Pilot Units (PPUs), used to support navigation in confined waters. The research examined training, understanding, use, and trust in the automation. Design principles emphasized improving transparency, providing clear information about sensor inputs, data processing, underlying models, uncertainty, and

prediction reliability. The findings showed that pilots frequently used and valued the predictor but often lacked formal training, relying instead on self-learning. They struggled with sensor error detection and understanding how the system works. Trust varied with age and experience, with younger or less experienced pilots showing higher trust and usage.

Veitch et al. (2024) examined human factors in remote supervisory control of autonomous ships through simulated intervention scenarios, involving 32 participants performing handover and takeover tasks under varying conditions of skillset, monitoring time, number of vessels, available time, and decision support system (DSS) availability. The authors' findings show that skillset (gamers vs. navigators) had little effect, while longer monitoring increased boredom but minimally affected performance. Supervising multiple vessels, low time availability to react, and the absence of DSS reduced performance, highlighting the impact of workload, vigilance, and stress on remote supervisory control.

Madsen et al. (2025) explored human–AI interaction in MASS, focusing on AI-based collision avoidance systems. Simulator experiments involved nautical students and licensed navigators to evaluate how transparency layers could support SA and decision-making. A HCD approach was used to create transparency layers that visualize AI reasoning through labels, diagrams, and simulations. The design focused on enhancing SA across perception, comprehension, and projection, while avoiding cognitive overload. The findings show that transparency layers improved SA, particularly at Level 3, and increased user satisfaction. However, excessive transparency sometimes led to passive decision-making, indicating that too much information can reduce operator engagement. The implication of this work is for designers to balance information presentation to foster active human oversight, prevent cognitive overload, and avoid over-trust. Adaptive transparency guidelines are needed to optimize human–AI compatibility and maintain critical operator involvement in safety-critical maritime decisions.

Focusing on the meso-level HF and design considerations, the work of Alsos et al. (2022) examined embedding human navigational practices into automation. The authors focused on the design of unmanned autonomous ships. The research focused on concepts of SA, perception of other ships' signals, and adapting existing maritime practices into automation. Findings revealed the challenges in transferring human navigational practices to autonomous systems.

The study by Veitch et al. (2021) examined MASS and its operation from a Shore Control Centre (SCC), where human operators provide backup control during system failures. This work included micro-, meso-, and macro-level considerations. The research focuses on human–system interaction in autonomy, treating humans as a source of resilience. A HCD approach, guided by ISO 9421-210, was applied to develop resilient interactions between operators and autonomous systems. It can be concluded that resilience in this context of design can be understood through redundancy, adaptive interfaces, error recovery support, and effective communication protocols. The application of resilient design enhances human oversight and error management, creating safer and more effective MASS operations.

The study by Man et al. (2018) also focuses on the meso level, with implications for macro-level HF principles. The authors focused on the remote monitoring of six cargo ships. The study addressed SA, psychophysical and perceptual limitations, decision-making latency, automation bias, and socio-technical system design. It applied ecological and human-centered approaches to interface and system design to support operators in distributed contexts. It was found that conventional navigational tools (ECDIS, radar, CCTV) without adaptation for shore-based operation reduced SA, slowed decision-making, and increased automation bias. Participants faced difficulties in verifying information, and the absence of specific regulations led to varied interpretations of safety. Even mature onboard technologies can cause errors when used remotely without contextual adaptation. Safe and effective remote ship operations require interfaces and system designs that account for ecological, cognitive, and work-domain constraints.

On the macro-level, HF principles were studied by Aylward et al. (2020). This study focused on Sea Traffic Management (STM), and the importance of design for shared situational awareness and information sharing between sea and shore was emphasized, showing the importance of considering the entire sociotechnical system. The study of the STM Validation Project highlights that integrating STM services—low-level automated tools for ship-shore information exchange—affects both communication patterns and the roles of Vessel Traffic Service Operators (VTSOs) and officers on the bridge. Results reveal a gap in understanding human-technology interactions, showing that usability and workload can vary depending on system implementation. Conflicting feedback between VTS operators and ship-bridge participants emphasizes the importance of HCD, where the broader work system and the people involved are also accounted for in the implementation of advanced technologies.

The Overview of Identified Gaps

The current literature on human factors and design for MASS reveals several research gaps that span the micro-, meso-, and macro-levels of human–system interaction. At the micro level, studies highlight unresolved issues in understanding and managing individual operator performance and cognitive processes. Li et al. (2025) identify a limited understanding of the dynamic relationship between workload and performance in a remote operation center. Similarly, Westin and Lundberg (2025) point to problems of understanding and interaction with automation as they struggled with sensor error detection and lacked proper training. This points to the need for enhanced transparency and training. Madsen et al. (2025) further emphasize that while transparency is essential for trust and oversight, excessive or poorly structured transparency can overload operators cognitively and promote complacency. This emphasizes the need to understand how to balance information presentation at any given time to the operator to avoid undesired workload variations. Veitch et al. (2021, 2024) point to an underdeveloped understanding of resilience and supervisory control, noting that empirical

research on workload, trust, and adaptive control in remote supervision remains scarce. Furthermore, their research shows the need to focus on the issues of workload deviation and boredom, as well as the importance of well-designed decision support systems, and this can be extrapolated to the need to research the operator-vessel supervision ratio.

At the meso level, research underscores the need for improved coordination and communication within human–automation teams. Alsos et al. (2022) identify persistent gaps in communication and interaction with MASS, emphasizing that current autonomous systems cannot adequately perceive or interpret other vessels' states. They argue that dedicated communication systems and conversational interfaces are crucial to improving interaction amongst ships.

Finally, at the macro level, broader organizational and contextual design challenges persist. Aylward et al. (2020) discuss regulatory and operational variability, highlighting the absence of standardized VTS guidelines and the inconsistent operational roles across jurisdictions, which can lead to unnecessary cognitive burden without corresponding gains in utility. Man et al. (2018) extend this critique to the realm of ecological and contextual design, arguing that the migration of maritime operations from ship to shore often fails to account for critical ecological and contextual shifts. This, in turn, undermines system performance, safety, and adaptability. Together, these studies reveal that while technical progress in maritime autonomy is advancing, human factors research still lags across all levels of system design. Addressing these gaps is essential for a safer transition from onboard to offshore maritime operations.

DISCUSSION AND CONCLUSION

The transition from onboard ships to remote operation centres and navigation and supervision of multiple autonomous vessels requires a thorough HF and HCD application. The aim of this review paper was to investigate how we can support the transition from onboard maritime operation to remote operation, using HF and HCD principles. The results showed that current practices focus on a range of micro-, meso-, and macro-level HF and HCD principles, but the research and application thereof are still limited and lagging compared to the pace of technology development within the field of AI and automation. The risk is to transition from onboard to offshore operation, carrying along the existing HF and design challenges into an even more complex and information-limited context that lacks ecological realism. While the aforementioned HF and HCD principles explored are necessary, the current gaps need to be addressed as well.

Across the reviewed literature, human factors principles in maritime autonomous systems span the micro–meso–macro spectrum, with a predominance of micro- and meso-level focus. Four studies—Westin and Lundberg (2025), Li et al. (2025), Veitch et al. (2024), and Madsen et al. (2025)—primarily address micro-level human factors, examining individual cognition, situation awareness, workload, trust, and decision-making in interaction with automation or AI. Three studies—Alsos et al. (2022),

Veitch et al. (2021), and Man et al. (2018)—focus on meso-level factors, highlighting human–system coordination, integration of human expertise into automation, interface design, and resilient interaction within socio-technical systems, occasionally touching on macro-level implications. Only Aylward et al. (2020) is situated at the macro level, emphasizing Sea Traffic Management as a systemic, organizational, and sociotechnical framework that shapes safety, communication, and operational roles. Collectively, these studies illustrate that effective maritime autonomy research must integrate cognitive, interactional, and systemic perspectives to capture the full complexity of human factors. The consistent theme is that automation and AI alone cannot ensure safety. Successful implementation requires systems that adapt to human capabilities, maintain engagement, and account for socio-technical constraints.

Over time, HF and HCD principles in maritime automation have evolved from supporting onboard operators with basic interface usability and SA, toward enabling humans to act as resilient supervisors in distributed and autonomous systems. Early work focused on skill, training, trust, and the integration of primary information sources, while assuming a centralized bridge context. As operations shifted to shore-based control and multi-ship scenarios, considerations expanded to include workload, vigilance, cognitive limits, and ecological/contextual factors, with design emphasizing socio-technical and adaptive interfaces. In the current phase, with AI-driven MASS and collision avoidance systems, human-centered and resilient interaction design, transparency, explainability, and human-in-the-loop reliability dominate. These elements ensure operators can maintain oversight, make adaptive decisions, and manage error, highlighting that automation alone cannot guarantee safety without context-aware, user-focused design.

Across the literature, several consistent gaps emerge in the study of HF and HCD for MASS and remote operations. First, there is a clear need for dedicated MASS communication systems that allow both autonomous vessels and crewed ships to perceive and interact with each other effectively, supporting automation transparency (Alsos et al., 2022). Regulatory and operational variability further complicates information exchange, as current VTS practices lack standardized guidelines, and high-frequency communication tools may increase cognitive workload rather than support decision-making (Aylward et al., 2020). The migration of operations from ship to shore introduces ecological and contextual challenges, where failing to account for changed work demands can exacerbate mismatches between operator capabilities and system requirements (Man et al., 2018). Empirical research applying resilience engineering principles to maritime autonomy remains limited, particularly in supervisory control contexts, and there is insufficient data on how workload and trust dynamics affect remote operators (Veitch et al., 2021; Veitch et al., 2024). Transparency design also presents gaps: excessive or poorly structured transparency can foster complacency and passive reliance on automation, yet models for balancing transparency against cognitive load are underdeveloped and under-tested in critical scenarios like collision avoidance (Madsen et al., 2025). Similarly, understanding dynamic workload-performance

relationships in RCC operations is limited, and linking subjective and objective measures of workload to operator performance remains challenging (Li et al., 2025). Finally, reliance on subjective self-reported data in surveys introduces bias, limiting insights into operators' understanding of automation tools (Westin & Lundberg, 2025). Collectively, these gaps highlight the need for empirically validated, context-aware, and human-centered design frameworks that integrate communication, transparency, workload management, and resilience principles in MASS and remote supervisory operations.

These findings suggest several important directions for future research. One key area is investigating optimal levels of information display and interface design for remote operation centers, including whether two-dimensional or three-dimensional formats better convey distance and depth. Another direction is exploring the role of immersive technologies in compensating for reduced realism when operators work offshore rather than onboard a ship. Research is also needed on the integration of decision support systems (DSS) and AI in resilient operational design, focusing on how to present operators with the right amount of critical and relevant information to support timely intervention. Additionally, studies should examine how dynamic systems can adapt to the psychophysiological state of operators in ways that are safe, ethical, and effective. It is also important to investigate whether DSS design should accommodate different levels of operator experience or be grounded in the mental models of highly experienced operators to capture covert cognitive processes and decision-making strategies.

Collectively, these research directions underscore the complexity of transitioning from onboard to offshore maritime operations. They highlight the necessity of adopting a sociotechnical perspective that extends from individual operators to interfaces and operational systems, and further to shared situational awareness within teams and coordination with other vessels and traffic management operators. Addressing these areas will help advance both the theoretical understanding and practical design of remote maritime operations.

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