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A systematic literature review of Human-Machine Cooperation in Maritime Autonomous Surface Ships

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ABSTRACT

This study presents a systematic critical literature review examining the core technologies in Maritime Autonomous Surface Ships through the lens of Human-Machine Cooperation. Existing reviews primarily focus on technical performance, whereas this work emphasises how technological advancements are reshaping seafarer roles by shifting them from onboard operators and decision-makers to remote supervisors and collaborative partners. Furthermore, the review identifies key research gaps in current Human-Machine Cooperation practices, such as the lack of transparency, inadequate operator training, and limited human-centred design. To address these challenges, it proposes targeted recommendations and strategic insights. The findings contribute to a deeper understanding of human-autonomy interaction and offer strategic directions for designing future MASS systems that are both technologically advanced and human-aware.

1. Introduction

Since the beginning of the 21st century, the rapid development of innovative technologies such as Artificial Intelligence (AI), deep learning, and the Internet of Things (IoT) has propelled multiple industries, including manufacturing, healthcare, and transportation, into a new stage of intelligence and autonomy (Bathla et al., 2022). The shipping industry is also undergoing profound transformations driven by these advancing technologies, gradually evolving towards a more intelligent, efficient, safe, and sustainable future (Tijan et al., 2021).

Maritime Autonomous Surface Ships (MASS), as a representative of autonomy in the shipping industry, are reshaping traditional maritime navigation and management models through key technologies such as sensor fusion, autonomous collision avoidance, and remote control (Qiao et al., 2023; Xin et al., 2025; Zhao et al., 2025). In 2018, the International Maritime Organization (IMO) officially defined MASS and established the Levels of Autonomy (LoA) classification system. This system categorises autonomous ships into four levels ranging from human-operated ships (LoA 1) to fully autonomous navigation (LoA 4) (IMO, 2018), as illustrated in Fig. 1. DNV (2025) has also developed a classification system for autonomous ships and notes that decision support systems are currently the most common application of autonomous shipping. In the long term, however, the industry is expected to transition toward fully autonomous vessels, relying on advanced technologies, minimal onboard crew, and monitoring from Remote Operations Centres (ROCs). Furthermore, Lloyd's Register (2024) emphasises in one report that keeping humans central to autonomous systems helps ensure that

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new technologies support and strengthen their critical roles in analysis and decision-making.

The advancements in autonomous ship technologies are not limited to onboard autonomous systems but also extend to shore-based remote monitoring and control systems and ship-shore collaborative systems (Liu et al., 2024). As shown in Fig. 2, this ship-shore collaboration forms the backbone of data exchange between the MASS and ROC. In this framework, sensor data collected on board is transmitted to the ROC through a ship-shore communication link. This link is not a single channel but a composite communication infrastructure, for long-range connectivity, it primarily relies on satellite communications, while in coastal or port areas it may be supplemented by terrestrial channels such as Very High Frequency (VHF) radio, the Automatic Identification System (AIS), or 5G shore-based networks. The ROC then performs situational analysis, makes navigational or operational decisions, and transmits control commands back to the ship. Advanced onboard autonomous systems enhance the ship's ability to operate independently, reducing the need for human intervention (Ventikos et al., 2020). To ensure safe and effective operation, these autonomous systems require continuous human oversight provided through shore-based facilities. The rapid development of shore-based monitoring and control technologies enables operators to remotely perceive the ship's environment, monitor its operational status in real-time, and take control when necessary (Alsos et al., 2022; Wang et al., 2020). Continuous optimisation of ship-shore collaborative technologies ensures high-quality data transmission and information sharing between ships and shore-based centres, providing robust support for remote control and situational awareness (Alqurashi et al., 2022; Wei et al., 2021). Currently, several autonomous ships pilot projects worldwide, such as the Yara Birkeland and the Mayflower Autonomous Ship, have preliminarily demonstrated the feasibility and application potential of autonomous technologies in the maritime industry (Skredderberget, 2018; Soyer et al., 2022). While research on fully autonomous ships remains in its early stages, existing studies highlight numerous advantages of MASS, including improved operational efficiency, reduced environmental impact, and enhanced navigational safety (Kim and Schröder-Hinrichs, 2021; Negenborn et al., 2023). At present, LoA 1 ships, where autonomous technologies provide decision-support information for human operators, have already been deployed in real-world operations. However, fully autonomous (LoA 4) ships are unlikely to be realised in a short term (Alamoush et al., 2024). Current research on MASS primarily focuses on the development and industrial deployment of LoA 2 and LoA 3 technologies (Munim et al., 2025). Accordingly, this study also concentrates on autonomous ships operating at these two levels of autonomy.

Despite the progress in MASS technologies, challenges remain in the transition from research to practical applications. While autonomous systems have made significant advances in areas such as autonomous navigation (Alamoush and Olcer, 2025), collision avoidance (Zhu et al., 2024), risk analysis (Tao et al., 2024), and remote monitoring and control (Martelli et al., 2021), autonomous ships still encounters challenges. These include multi-objective cooperative collision avoidance, uncertainty in remote environmental awareness, and the intelligent modelling of the *International Regulations for Preventing Collisions at Sea* (COLREGs) (Akdağ et al., 2022; Kim et al., 2022; Palbar Misas et al., 2024; Rødseth et al., 2023). On the regulatory front, although the IMO has initiated the development of the MASS Code, with its mandatory adoption expected in 2032, challenges persist regarding the distribution of accident liability between human operators and autonomous systems, as well as the adaptation of international navigation regulations (Issa et al., 2022; Kim et al., 2020). Furthermore, as the LoA in autonomous ship increases, the role of human operators undergoes substantial changes compared to conventional ships, creating new challenges for effective Human-Machine Cooperation (HMC) (Liu et al., 2022a).

Existing studies have highlighted that the development of autonomous shipping can reduce human errors, which are traditionally deemed as one of the leading causes of maritime accidents (Hasanspahić et al., 2021). However, MASS is still far from being entirely independent of human intervention and supervision. In LoA 2 ships, although the ship is remotely controlled from another location, seafarers must remain on board to take control when needed and operate shipboard systems and functions. In LoA 3 ships, shore-based remote operators continuously monitor the ship's status and environment in real-time and intervene when necessary by assuming control. This "autonomous system + human supervision" model of HMC imposes high demands on the efficiency and stability of Human-Machine Interaction (HMI). Efficient HMC not only directly impacts the functional stability and operational transparency of autonomous systems but also plays a crucial role in ensuring the responsiveness and safety of remote operators when taking control of the ship (Song et al., 2024; Veitch and Alsos, 2022). Consequently, developing a reliable and effective HMC framework that ensures a Human-Centred Design (HCD) in autonomous ships is a key issue affecting the safety, economic viability, and sustainability of autonomous shipping (Li and Yuen, 2024; Veitch and Alsos, 2021).

Although recent research has started to address HMC issues in autonomous ships, particularly in areas such as operational safety, risk perception, system transparency, and trust, studies in this field remain in the early exploratory stage (Cheng et al., 2024; Huang et al., 2020b; Wu et al., 2021). Significant gaps remain in understanding how increasing levels of autonomy affect HMC and in

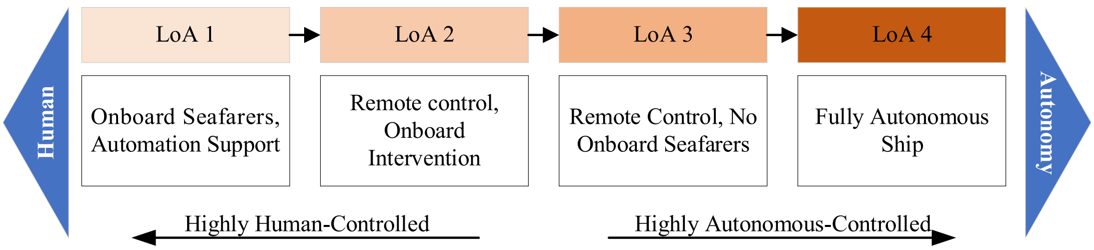

Fig. 1. The LoA of MASS.

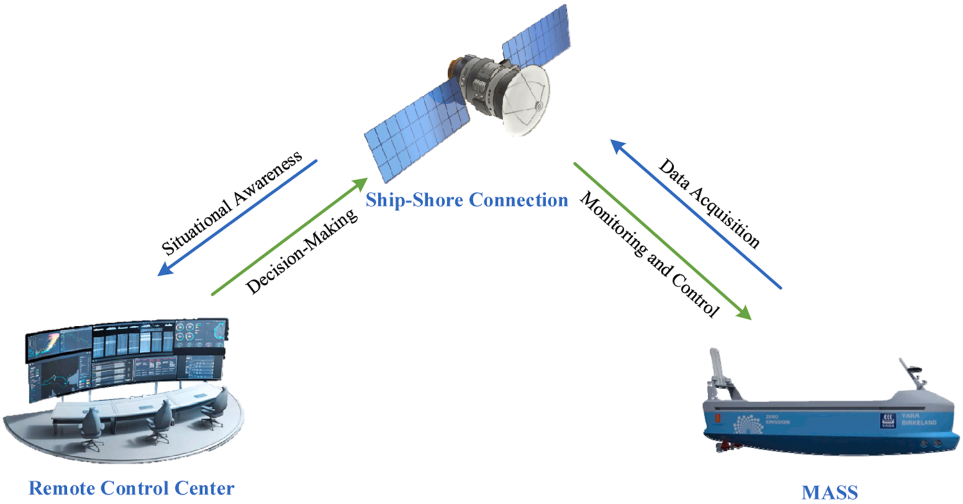

Fig. 2. Ship-shore communication framework for MASS.

examining the evolving roles and responsibilities of human operators in autonomous maritime systems. To our knowledge, this is the first systematic review that explicitly combines technological progress with an HMC perspective to examine the role transformation of human operators in MASS. Unlike previous research that treats technological development and HMI as separate domains, this study bridges both aspects through a unified analytical framework. In particular, this study applies the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to select relevant studies systematically. Then it uses bibliometric mapping to organise and visualise the research landscape, together with providing a clear and reliable evidence base for analysis. This approach enables a unified analysis of technological developments and HMI, offering insights into the relationship between MASS technologies, evolving HMC models, and shifting operator roles. Building on these insights, the review also identifies research gaps and proposes recommendations to support the practical implementation of autonomous ships. The main contributions of this research include:

(1) An integrative review of technologies and HMC in MASS.

An integrative review is conducted that connects the development of core technologies in MASS, such as situational awareness, autonomous control, and remote operation, with their impact on HMC. By analysing technology and human factors together, it provides a more holistic understanding of the evolution of maritime autonomy. It addresses a gap in the existing literature in which technical and human aspects are often treated separately, and offers new perspectives for identifying and advancing research on HMC in autonomous ship operations.

(2) Analysing the evolving role of human operators in MASS.

How advancements in MASS technologies are reshaping the roles of human operators is reviewed. It identifies a transition from traditional onboard operators and decision-making to roles as remote supervisors and collaborative decision partners. By linking these role shifts to technological developments, this study underscores the critical role of HMC in enhancing situational awareness, facilitating decision processes, and ensuring safe remote control within autonomous maritime systems. This contribution advances understanding of seafarers' role transformation in the era of autonomy and offers practical insights for designing future training programmes tailored to MASS operations.

(3) Identifying key challenges and future research in MASS.

Key challenges in HMC stemming from implementing autonomous technologies in MASS are pinpointed, including increased cognitive workload, trust in automation, the need for updated HMC models, and competency gaps among seafarers. It highlights the ongoing tension between human expertise and AI-driven autonomy, and offers recommendations to improve HMC design, enhance system transparency, safety, and reliability, and advance seafarer training. These insights provide a strategic foundation for future research and development towards safer and more efficient maritime autonomy.

The rest of this paper is structured as follows: Section 2 outlines the methodology for collecting and analysing relevant literature. Section 3 presents both qualitative and quantitative analyses of the selected studies. Section 4 identifies current challenges in the development and application of MASS and proposes recommendations for future research. Finally, Section 5 summarises the key findings and conclusions of the study.

2. Methodology

The selection of data sources and analytical methods is critically important in systematically reviewing state-of-the-art research in MASS that integrates technological development and human-machine collaboration. To ensure methodological transparency and minimise selection bias, this study employs the PRISMA framework (Page et al., 2021). PRISMA has been validated in existing literature as an efficient tool for enhancing transparency, traceability, and reproducibility in systematic reviews, making it especially valuable for synthesising evidence across diverse and fragmented domains (Akdağ et al., 2022; Hsieh et al., 2024). Guided by this framework, the present study conducts a systematic analysis to identify current trends, technological advancements, and key HMC issues in the context of MASS.

2.1. *Review strategy and framework*

The review steps employed in this study are illustrated in Fig. 3. It consists of three key steps: Literature Search, Data Refinement, and Bibliometric Analysis and Visualisation. This framework ensures a comprehensive, systematic, and rigorous approach to identifying, refining, and analysing relevant research on technologies and HMC in the context of MASS.

In the first step, Literature Search, relevant articles are identified through systematic search across major academic databases, including Web of Science (WOS) and Scopus. A structured search strategy, detailed in Section 2.2, uses carefully selected keywords to ensure broad coverage of relevant literature. Initial search results are screened based on criteria such as language, publication year, and document type, yielding a refined set of records for further processing.

The second stage, Data Refinement, applied the PRISMA framework to systematically filter and process the retrieved literature, ensuring both relevance and methodological rigour. By adopting PRISMA, the study establishes a transparent and traceable procedure that mitigates selection bias and strengthens reproducibility. Predefined inclusion and exclusion criteria were applied to select studies directly addressing technological developments, human factors, and HMC in the MASS domain. The selection includes primarily peer-reviewed journal articles and conference proceedings. Following this, duplicate records are removed, and the data is integrated and cleaned, including the harmonisation of keywords to ensure consistency. A manual data screening process is then conducted, during which authors independently evaluate the abstracts and research focus of the shortlisted articles. This stage produces a curated, high-quality dataset for subsequent bibliometric analysis.

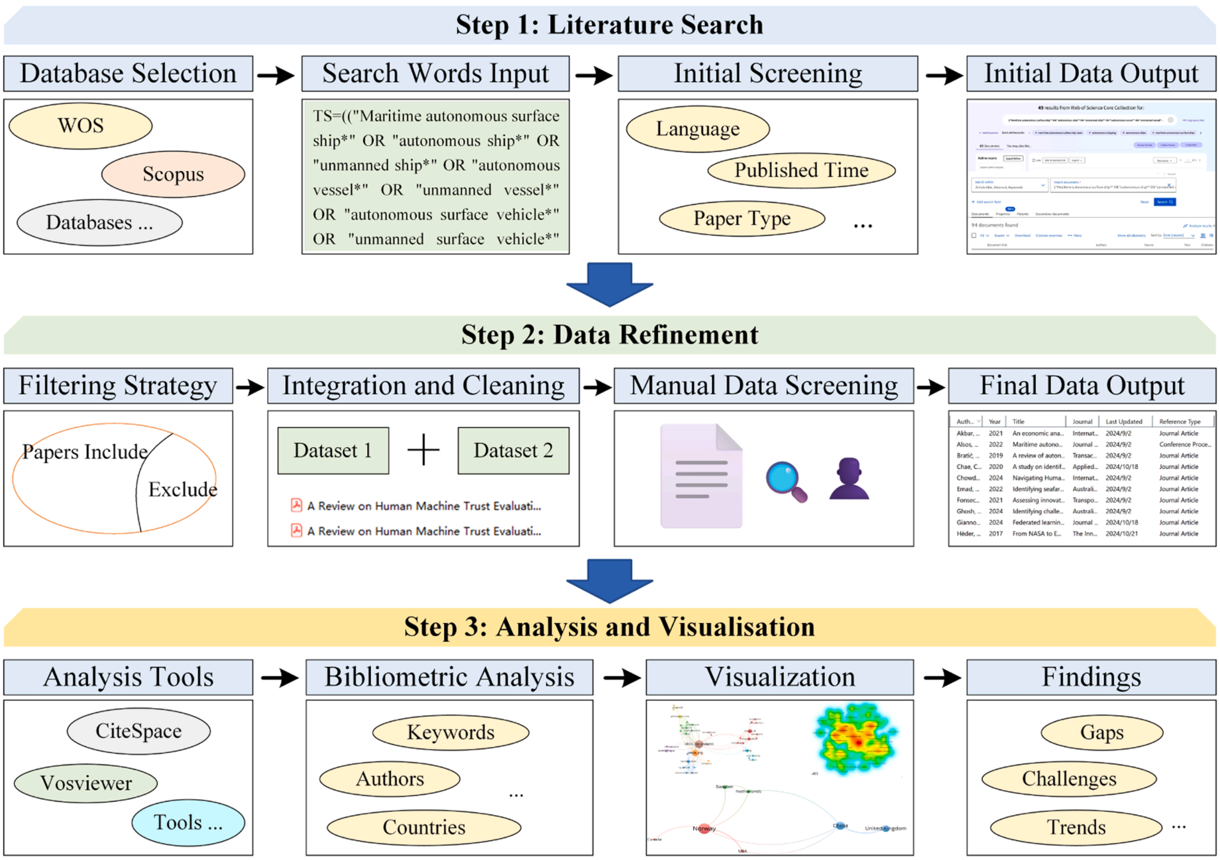

Fig. 3. The framework for the bibliometric review.

In the final stage, Analysis and Visualisation, quantitative and qualitative techniques are applied to explore the characteristics of the selected literature. Tools such as VOSviewer and CiteSpace (Ding and Yang, 2022) are used to identify key trends, including frequently occurring keywords, influential authors, research institutions, and geographic distribution of publications. Following this, visualisation techniques are employed to generate co-authorship networks, keyword co-occurrence maps, and thematic clusters, offering a structured overview of the research landscape. Additionally, content analysis is used to extract more profound insights into emerging research themes, particularly those related to the development of autonomous navigation technologies and HMC in the context of MASS. The findings are summarised by identifying existing research gaps, key development trends, and challenges in the field.

2.2. Literature search and selection outcomes

This section outlines the details of the review process, while the selected literature analysis will be presented in Section 3. The search strategy uses a combination of relevant keywords and Boolean operators to ensure that the retrieved papers address both technological and HMC aspects of MASS. The search string used in WOS (with similar logic applied in Scopus) was:

TS=(("Maritime autonomous surface ship*" OR "autonomous ship*" OR "unmanned ship*" OR "autonomous vessel*" OR "unmanned vessel*" OR "autonomous surface vehicle*" OR "unmanned surface vehicle*" OR "autonomous surface ship*" OR "unmanned surface ship*" OR "intelligent ship" OR "smart ship") AND (technology* OR technique* OR innovation* OR progress* OR develop* OR advancement*) AND ("human machine*" OR "human automation*" OR "human centered*" OR "human centred*" OR "human technology*" OR "human system interaction*" OR "human computer interaction*")).

Fig. 4 presents the results of each step in the literature search and screening process, following the PRISMA 2020 framework. The initial search yielded 49 records from WoS and 94 records from Scopus. The review scope is set from 2012 to February 2025, as research on MASS is relatively recent, with the MUNIN project (2012–2015) widely regarded as the first major initiative in MASS development. The search is limited to English-language publications and includes journal articles and conference proceedings. After applying the initial screening criteria, which filtered results by language, document type, and publication year, the dataset was narrowed down to 43 records from WoS and 76 records from Scopus.

In the second stage, initial screening is conducted by reviewing the titles of the retrieved records, and only articles directly related to MASS technologies and HMC are retained. A total of 8 irrelevant publications are excluded based on their lack of relevance to the review scope. Subsequently, the datasets from WoS and Scopus are merged, and 26 duplicate entries are merged to ensure data consistency and accuracy. Following this, a manual screening of the remaining records is performed to assess the relevance and quality of each publication, resulting in the removal of 4 records. As a result, a final dataset of 81 literature records is compiled for subsequent analysis. At the end of this process, a refined and curated set of publications is established for further bibliometric and content analysis in Section 4.

3. Development trends and comparative analysis

This section presents quantitative and qualitative analyses of the selected literature to explore development trends, and research

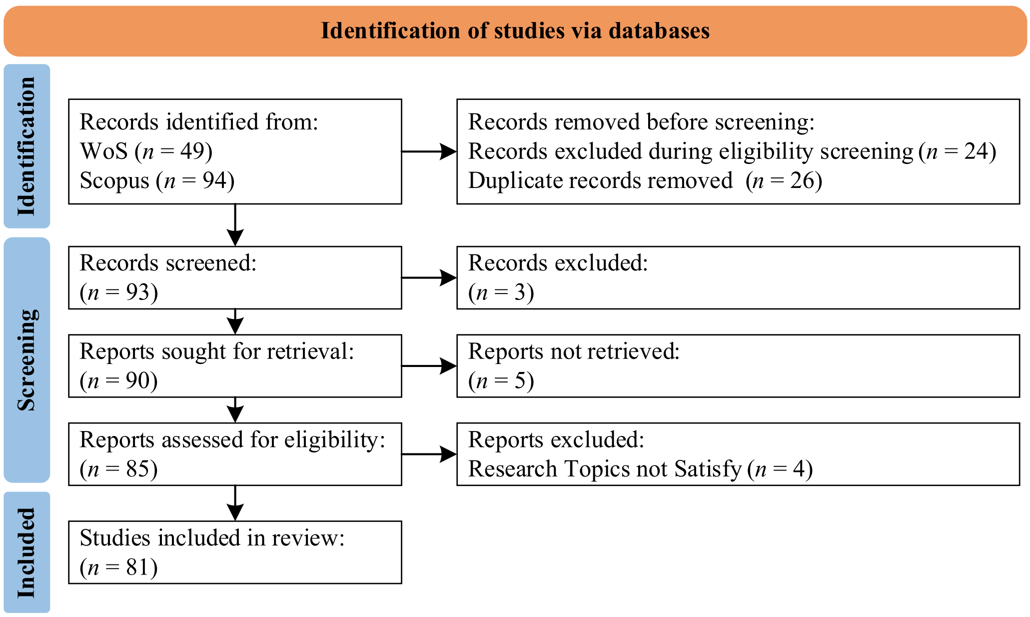

Fig. 4. PRISMA 2020 flow diagram for systematic reviews (Page et al., 2021).

focuses on autonomous ship technologies and HMC. Initially, statistical data and visualisations are employed to illustrate key research trends and the field's current state. A more in-depth analysis follows this to provide insights into technological and HMC-related developments in the context of MASS.

3.1. Publication statistics and trend

This section provides an in-depth review of the basic characteristics of the selected literature, including publication year, country of origin, affiliated institutions, and research hotspots. Firstly, the literature was analysed to determine the annual number of journal articles and conference papers published. The results of this analysis are presented in the form of visualisations, as shown in Fig. 5.

The data indicate that 2018 represents a significant milestone, as the number of publications in both research categories remained only one article per year before this point. Since 2018, the volume of publications has exhibited an upward trend, and has maintained a high level of research interest in the following years. Notably, research articles reached their highest point, with 18 publications in 2022. This trend can be attributed to the Maritime Safety Committee (MSC)'s approval of MASS definitions, autonomy levels, and a structured work plan during its 99th and 100th sessions in 2018, which played a pivotal role in stimulating academic interest in MASS development. Previous studies have also noted this observation (Chaal et al., 2023; Munim and Haralambides, 2022).

The collected literature was categorised and analysed based on the number of publications from each country to examine the research status of different countries in this field. The dataset includes contributions from 17 countries, with the top five contributors in terms of publication volume presented in Table 1.

The distribution of research articles across different countries and the corresponding average citations per article are summarised and visualised, as shown in Fig. 6(a). Norway, China, and the United Kingdom emerged as the top contributors in the number of publications, with Norway leading the list with 24 articles. However, despite having only six publications in this field, the Netherlands exhibits the highest research impact, with an average citation count of 55.33 per article, indicating significant academic influence.

Fig. 6(b) illustrates the collaboration network between countries in the research of technologies and HMC in MASS. Unlike Fig. 6 (a), which lists all countries involved, Fig. 6(b) displays only those countries with established collaboration links; countries without connections are therefore not shown. In the collaboration network, the relative size of nodes and thickness of connecting edges suggest that Norway, China, and the United Kingdom serve as central hubs in advancing research and fostering global partnerships. Norway appears to have the strongest international connections, engaging closely with multiple countries. Additionally, China and the United Kingdom exhibit frequent research collaboration, as indicated by the thickness of the connecting edge between their nodes. This suggests that these countries are central in advancing research and fostering international partnerships in this domain.

To investigate the research contributions and collaboration networks of institutions in the field of Technologies-HMC related to MASS, the collected literature was categorised and analysed based on institutional affiliations. Fig. 7(a) shows how many papers each institution has published and how often those papers have been cited, including only institutions with more than one publication. As shown in this figure, the Norwegian University of Science and Technology (NTNU) has published the most papers in this field, with 17 publications, followed closely by Wuhan University of Technology (WUT), which has published 8 papers. This trend is consistent with the earlier analysis of publications by countries, further confirming the important roles of Norway and China in this research area. It is also worth noting that despite contributing only to 2 publications, Delft University of Technology has achieved a total citation count of 328, far exceeding other institutions. This indicates that the studies conducted by this institution generate high impact and contribute to the key technological innovations or theoretical breakthroughs in the field.

In addition, Fig. 7(b) visualises the collaborative network among institutions. Still, unlike Fig. 7(a), it displays only the main institutions within each cluster to more clearly show the cluster structure of the network. The network structure shows that the Norwegian University of Science and Technology (NTNU) and Wuhan University of Technology (WUT) are the most productive institutions and act as central hubs for international collaboration, forming two primary clusters. Furthermore, NTNU collaborates

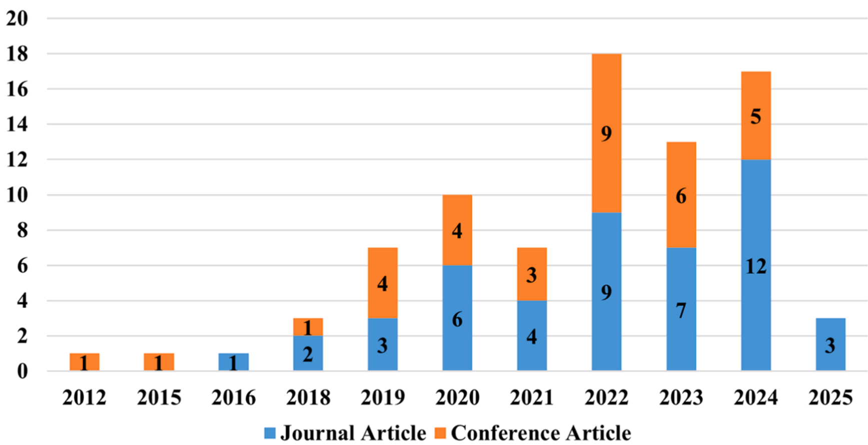

Fig. 5. Annual distribution of journal and conference publications.

Table 1
Top 5 countries in the publications.

Country	Article Numbers	Total Citations	Ave. Citations
Norway	24	289	12.04
China	17	132	7.76
United Kingdom	14	117	8.36
Sweden	7	39	5.57
Netherlands	6	332	55.33

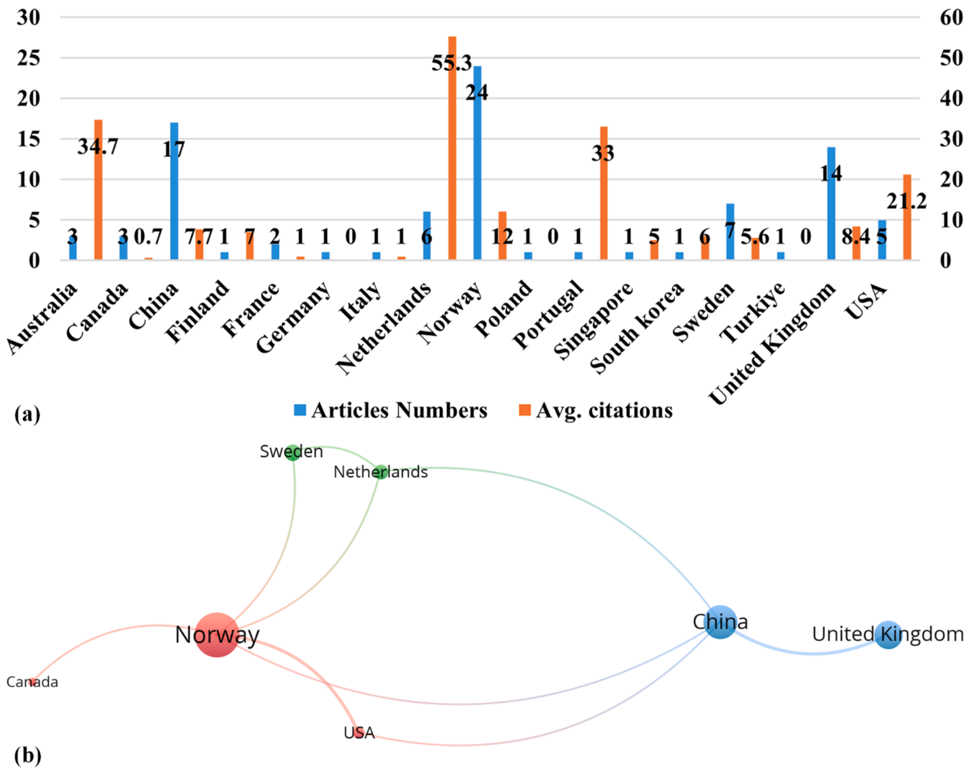

Fig. 6. Country contributions and collaborations in collected literature.

closely with institutions such as the University of South-Eastern Norway and the University of California, Los Angeles, while WUT has also established partnerships with several international universities.

A keyword analysis and visualisation were conducted based on the selected literature to analyse further and identify the research hotspots in this field. This analysis includes both the keywords provided by the authors and the high-frequency terms identified through text mining (this work can be done in VOSviewer), capturing the core concepts that appear repeatedly across the collected papers. This approach helps to systematically reveal the key research topics and thematic focus within the field of MASS Technologies-HMC.

Fig. 8 presents a visualisation of the keyword analysis and co-occurrence network based on the collected literature in MASS Technologies-HMC. In Fig. 8(a), the keyword cloud highlights the most frequently occurring terms in this research area. Key terms such as “automation”, “ships”, “risk assessment”, and “human factors” stand out, indicating that these topics are central to current research on Technologies-HMC in the context of MASS. By visualising the keyword co-occurrence network, as shown in Fig. 8(b)-(c), the analysis presents the frequency distribution of keywords, where larger nodes indicate higher frequency. It reveals that research in this field has gradually evolved into several key directions. These directions include autonomous navigation technologies (Green and Blue clusters), HMC (Red and Green clusters), and risk assessment (Purple and Yellow clusters). This analysis reflects the pressing technological innovation needs within MASS development. It highlights the increasing research focus on human factors, particularly the efficiency of HMC during the application of innovative technologies. It is worth noting that these different keyword clusters are not isolated. Instead, they are interconnected through core keywords such as “autonomous ship”, “human factor”, and “safety”, forming a closely linked network. The research in MASS Technologies-HMC requires attention to technological development, human factors, and system safety.

A co-authorship network analysis was conducted to gain further insights into the collaborative relationships among authors in the

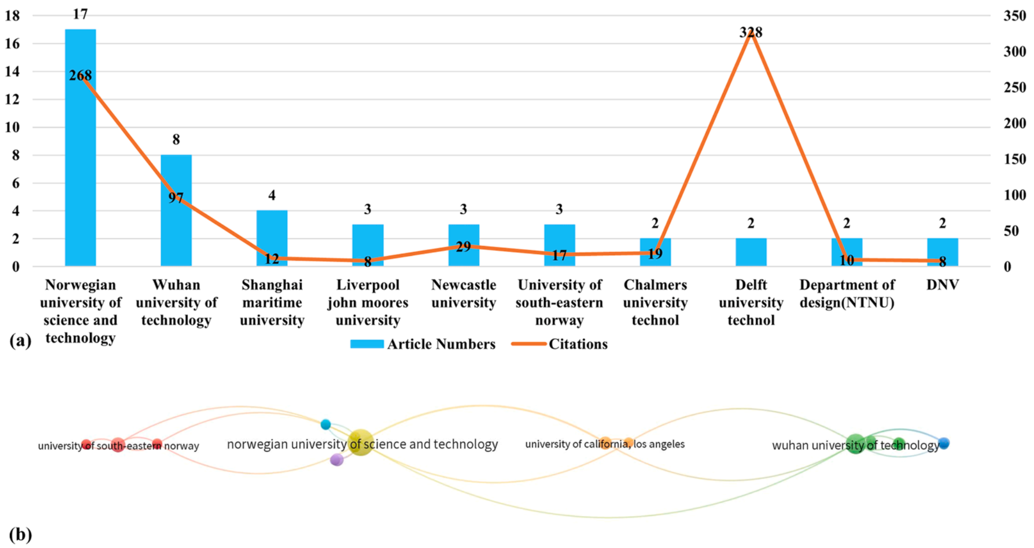

Fig. 7. Institutional contributions and collaborations in collected literature.

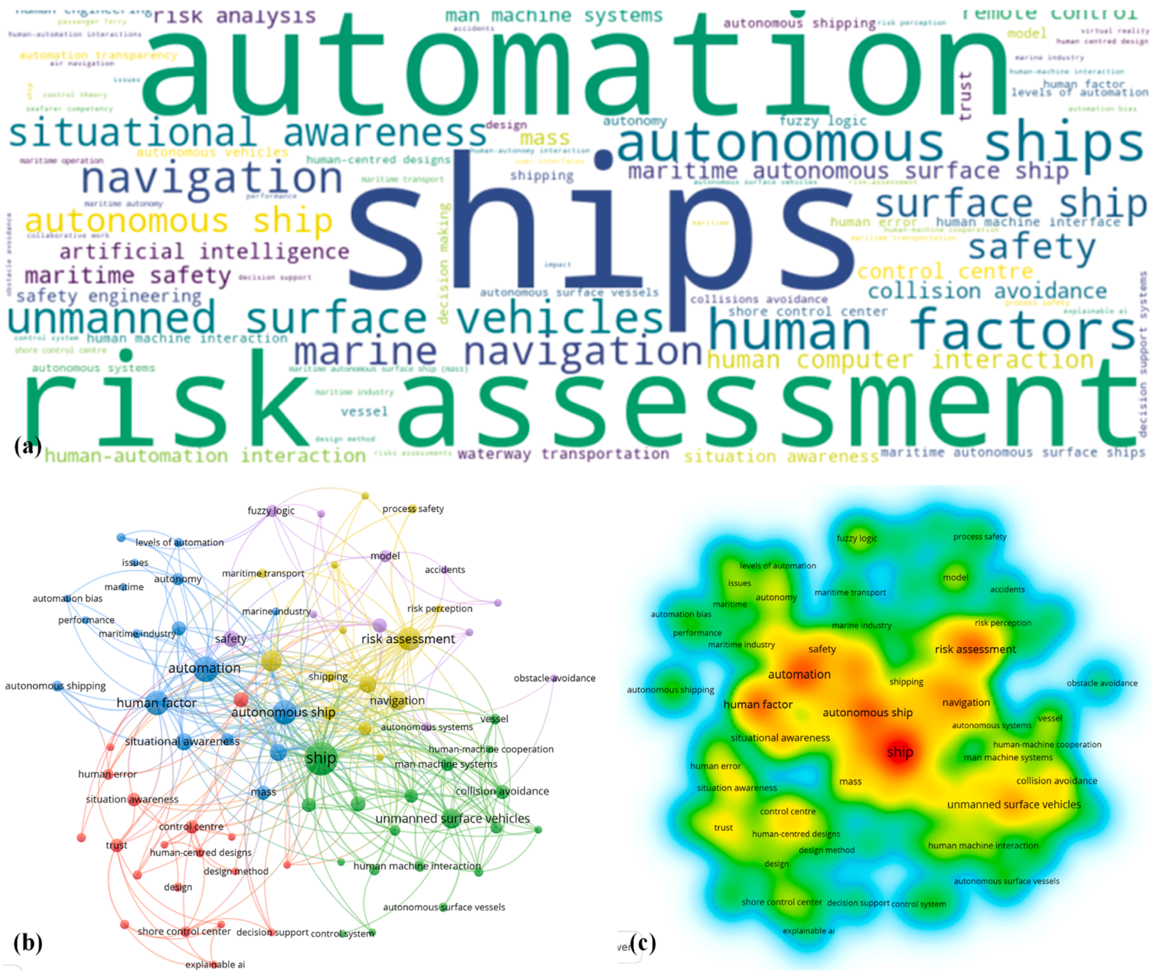

Fig. 8. Keyword analysis and research hotspots in collected literature.

collected literature, as shown in Fig. 9. This figure visualises the collaborative relationships between key researchers, where each node represents an author, and each edge indicates a co-authored publication. The network is colour-coded to represent distinct collaborative clusters, and node size reflects the number of co-authored papers contributed by each author. Fig. 9(a) illustrates the largest connected component within the author cooperation network. It can be observed that Alsos Ole Andreas and Veitch Erik occupy central positions in the network, indicating that both scholars maintain close collaboration with their respective research teams and actively engage in cross-cluster cooperation with researchers from other groups. This highlights their important bridging role in facilitating knowledge exchange between different research communities in MASS Technologies-HMC.

Additionally, the collaborative group led by Mosleh Ali and Breivik Morten exhibits high internal connectivity, indicating that these authors have formed a stable and cohesive research team focusing on specific technical or thematic areas related to MASS. Notably, the smaller collaborative clusters to which Porathe Thomas and Wu Bing belong still maintain clear collaborative ties with the core cluster centred around Alsos Ole Andreas. There are also independent clusters in the co-authorship network, as shown in Fig. 9(b)-(c). Such isolated clusters likely emerge because these research teams focus on specific subtopics within the broader field of MASS Technologies-HMC. The high density of internal connections within these clusters further indicates that frequent and close collaboration occurs among team members, fostering strong internal cohesion within these groups.

This co-authorship network also demonstrates that knowledge development in MASS Technologies-HMC is not limited to these independent research teams, but is driven by extensive cross-team academic collaboration. At the same time, some research groups focus on specialised subtopics, such as autonomous navigation (Huang et al., 2020b), human factors in remote control (Fan et al., 2025b), and risk management in autonomous ships (Chaal et al., 2023), and their targeted contributions collectively enrich and advance the overall development of the field.

3.2. *Technologies' development from HMC perspective*

The autonomous development of MASS encompasses the process from environmental perception and autonomous decision-making to the execution of navigation tasks, relying on the coordinated advancement of multiple innovative technologies. Although some studies have reviewed the development of MASS technologies (Chae et al., 2020; Tao et al., 2024; Wang et al., 2020; Yang et al., 2024), most focus on a single aspect of technological advancement and lack an in-depth exploration of the interaction between technological progress and HMC. Therefore, this study builds upon existing reviews of MASS technologies by incorporating an HMC perspective to systematically analyse technological development across three key dimensions: environmental awareness, decision-making and control, and remote monitoring and control. These dimensions align with the key interfaces through which human operators interact with, monitor, and intervene in autonomous systems. Similar analyses from these dimensions can also be found in research across other fields (Zhou et al., 2024a).

3.2.1. *Environmental awareness technologies*

MASS environmental perception and situational awareness technologies primarily involve sensor data fusion for target recognition and the real-time perception of dynamic environments (Thombre et al., 2020). Related research in this area can be grouped into three streams: sensor fusion approaches, advanced modelling and risk-assessment frameworks, and applied USV platforms. The sensor fusion

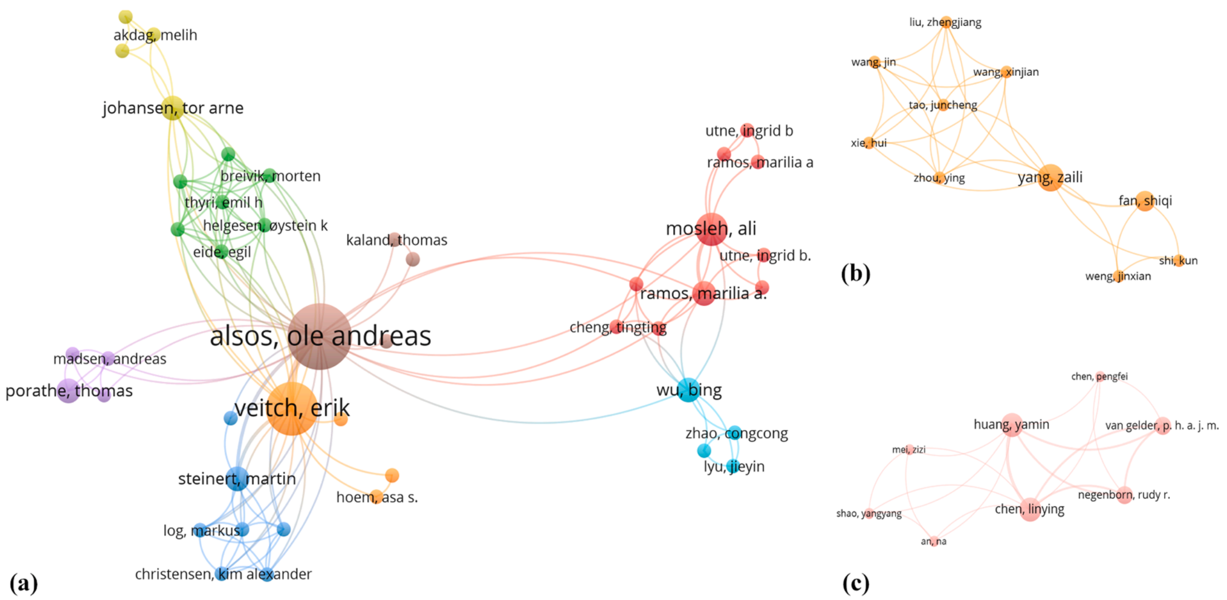

Fig. 9. Co-authorship network and independent collaborative clusters network.

approaches have established the basic feasibility of combining multiple data sources to enhance navigational awareness. Early efforts by Perera et al. (2012) designed and implemented real-time multi-sensor data fusion, integrating GPS and wireless communication technologies into an autonomous ship navigation and control platform. Liu et al. (2022b) and Lu et al. (2025) advanced this line of work by integrating multiple sensors to improve vision-based detection and berthing capabilities, thereby enhancing the operational efficiency and safety of MASS. The second part covers advanced modelling and risk-assessment frameworks, which extend basic data fusion by integrating diverse sensor inputs and providing outputs that support operator decision-making. Wang et al. (2022) examined the perception requirements of intelligent ships, identifying five key aspects: vision, ARPA radar, AIS, HMI and electronic chart systems that highlight the need for heterogeneous data integration. Zhao et al. (2023) constructed a system based on geometric encounter modelling and fuzzy inference, enabling real-time assessment of a ship's relative position, heading, speed, and collision risk. This system also incorporates a graphical user interface (GUI) to display the surrounding environmental conditions visually. Fruzzetti and Martelli (2023) proposed a target-tracking control method for unmanned surface vehicles (USVs), testing their navigation capabilities in unknown target motion environments and optimising tracking efficiency. Beyond technological advancements, researchers have also focused on the practical applications of sensor fusion in unmanned surface vehicles (USVs). Chang et al. (2021) and Wu et al. (2022) designed USV platforms based on multi-sensor data fusion, enabling real-time environmental perception. These platforms integrate target recognition technologies to support autonomous obstacle avoidance, water quality monitoring, and floating debris removal. These applications highlight the feasibility of sensor fusion in real-world tasks, although questions remain regarding their scalability and robustness when transferred to operations. Table 2 presents statistics on the relevant literature concerning the technologies used for environmental awareness and their application objectives.

However, from an HMC perspective, while most seafarers recognise the potential of automation in situation awareness, there is a growing tendency to over-rely on autonomous systems, which can lead to the out-of-the-loop problem and diminish their proactive situational awareness. (Chan et al., 2023; Lynch et al., 2024; Praetorius et al., 2019). Currently, MASS can leverage advanced technologies to achieve real-time perception of dynamic environments, and these technologies are gradually being applied in real-world scenarios. Nevertheless, ensuring that remote operators maintain real-time situational awareness of an autonomous ship's navigation environment through effective HMC remains a critical challenge.

3.2.2. *Decision-Making and control technologies*

Environmental awareness forms the foundation for autonomous decision-making and control in MASS. Several studies have explored the technologies that enable this domain. Wu et al. (2021) addressed the limitations of autonomous collision avoidance systems that overlook human operational experience and risk appetite to enhance decision-making reliability. They proposed an optimised risk-appetite collision avoidance decision-making system. Transparency emerged as a recurring theme in recent research. Zhao et al. (2023) improved operator trust by designing a visual interface to display collision scenarios and avoidance suggestions. Madsen et al. (2025) further examined how transparent decision support tools can strengthen operator confidence. Beyond visualisation, Van Den Broek and Van Der Waa (2022) and Woerner and Benjamin (2018) introduced frameworks that quantitatively assess COLREGs compliance, extending the concept of decision support to multi-ship coordination scenarios. In the area of Decision Support Systems (DSS) and path planning, Brandsæter et al. (2020) proposed a data-driven decision support function that ensures the safety and reliability of DSS in ship navigation, and Akdag et al. (2024) explored multi-objective optimisation and multi-criteria decision-making methods to establish a dynamic balance between shore-based remote supervision and autonomous ship decision-making, thereby enhancing the autonomy of MASS in path planning and HMC decision-making.

Despite the aforementioned advancements, human-machine cooperative collision avoidance in MASS still faces challenges. Aylward et al. (2022) highlighted that, although autonomous ship operators recognise the advantages of the advanced intelligent manoeuvring system in enhancing traffic situational awareness, they remain sceptical about the reliability and transparency of its

Table 2
Overview of research on environmental awareness technologies.

Papers	Technology Used	Application Objective	Awareness Type		
			Sensor Fusion	Target Recognition	Situation Awareness
Perera et al. (2012)	GPS, Wireless Comm., Multi-Sensor Fusion	Autonomous Navigation and Control Platform	√		√
Liu et al. (2022b)	Camera, AIS, YOLOX-s, Edge computing	AR-based situational awareness	√	√	√
Lu et al. (2025)	LiDAR, Inertial Measurement Unit, Real-Time Kinematic	MASS Berthing Navigation Perception	√		√
Wang et al. (2022)	Vision, ARPA Radar, AIS, ECDIS, HMI	Intelligent Ship Awareness Framework	√		√
Zhao et al. (2023)	GUI	Collision Risk Estimation and GUI			√
Fruzzetti and Martelli (2023)	Real-Time Tracking Control	Unmanned Target Tracking		√	√
Chang et al. (2021)	Ultrasonic, Visual, Sensor Fusion	Obstacle Avoidance, Water Monitoring and Cleaning	√	√	
Wu et al. (2022)	GPS, Ultrasonic, Camera	Path Tracking of USV for Water Monitoring	√		

recommendations. Huang et al. (2020a) identified several critical challenges in this field, including sensor uncertainty in complex dynamic environments, intelligent modelling of COLREGs compliance, and the effectiveness of multi-ship cooperative collision avoidance strategies. Table 3 summarises the reviewed literature's key research themes and main contributions.

3.2.3. Remote monitoring and control technologies

As the LoA of autonomous ships increases, seafarers can monitor and control ships remotely from Shore-based Control Centres (SCCs) (Størkersen, 2021). This shift in roles increases the demands on remote monitoring and control technologies in MASS. Remote operation is not merely a shift in technical control but a process that reshapes ship operators' information filtering, risk assessment, and situational awareness (Kari et al., 2018). Veitch et al. (2021) and Hoem et al. (2022) emphasised that remote control in MASS is not simply a task transfer but a dynamic human-machine adaptation process that varies across different autonomy levels. Within this process, operators' situational awareness, information acquisition, decision support, and fault-handling capabilities are crucial in ensuring system stability.

Furthermore, Veitch et al. (2022) highlighted that to accommodate various LoA levels within SCCs, remote operators must develop advanced information processing and fault management skills. Additionally, Asplund and Ulfvengren (2022) explored the evolving role of ROC operators, suggesting a shift towards remote emergency intervention to enhance MASS emergency response systems. Chen et al. (2023) investigated the impact of communication quality, system performance, and traffic conditions on remote takeover decision-making and safety, aiming to improve the effectiveness and security of remote operations. Laso et al. (2019) developed a new human-computer interface (HCI) architecture to optimise remote operators' supervision and control of autonomous systems. Eide et al. (2025) further advanced the development of remote surveillance and control technologies for autonomous ships, promoting the continued evolution of MASS.

On the other hand, several studies have examined the potential negative impacts of remote control from a HMC perspective. Tam et al. (2021) explored the mental effects of remote monitoring and high-intensity operational demands, identifying cognitive overload, role anxiety, and trust erosion as potential risks for remote operators. Gregor et al. (2023) further validated these findings through experimental studies, demonstrating the negative effects of excessive information load on situational awareness and trust in remote control operations. Han et al. (2022) highlighted a lack of transparency, contributing to information gaps, situational awareness decline, trust deficits, and increased cognitive workload in remote operations. Cheng et al. (2024) identified reaction time, task complexity, and pre-warning information as key factors affecting the success rate of remote takeover operations. Additionally, van de Merwe et al. (2024) stressed that effective remote control requires more than just transparency in final decision outputs; full visibility into situational awareness, risk analysis, decision logic, and planned actions is necessary to establish decision transparency and collaborative trust. Table 4 summarises the reviewed literature's key research topics and thematic dimensions.

3.3. Exploring human role changes in MASS

Although autonomous technologies reduce human intervention in autonomous ships operations, human operators continue to play a critical role in decision-making, monitoring, and control, particularly in complex and dynamic navigation environments (Cheng et al., 2024). Additionally, the LoA of MASS is not static; it dynamically adjusts throughout the operation based on environmental conditions, mission requirements, and system capabilities (Poornikoo and Overgard, 2022). These dynamic adjustments directly influence the safety, reliability, and transparency of HMC in autonomous shipping, and they also drive a transition in the seafarer's role. Traditionally, seafarers functioned as onboard controllers and autonomous decision-makers, directly responsible for ship navigation and safety. While in MASS, the role of seafarer is evolving. Seafarers are expected to act as remote supervisors who monitor ship operations from shore-based control centres, and as collaborative decision partners with automated systems. This transition involves not only changes in operational tasks but also shifts in the responsibility, authority, and competencies of seafarers. Clearly defining human operators' role and influence on HMC is crucial for optimising collaboration mechanisms and facilitating the effective implementation and advancement of autonomous maritime technologies.

3.3.1. From decision maker to collaborative decision partner

In traditional shipping, seafarers rely on manual observation methods, such as visual inspection, radar, and nautical charts, to gather information and make navigational decisions based on their expertise and professional judgment. This decision-making process is relatively independent. However, in autonomous shipping, the integration of technologies such as Navigation Assistance Systems and DSS has enabled the real-time processing of environmental data, offering navigational recommendations and enhancing HMC (Mei et al., 2023). As a result, the role of seafarers has gradually shifted from independent decision-makers to collaborative decision

Table 3
Research themes and contributions on decision-making and control technologies in MASS.

Theme	Representative Studies	Main Contributions
Collision Avoidance Systems	Woerner and Benjamin (2018), Wu et al. (2021)	Risk-aware decision models; real-time COLREGs compliance tools
Transparency and Trust	Madsen et al. (2025), Zhao et al. (2023)	Visual/transparent interfaces; layered decision visualisation
Decision Support and Path Planning	Akdag et al. (2024), Aylward et al. (2022)	DSS assurance; optimisation for autonomy-supervision balance
Operator Support Concepts	Van Den Broek and Van Der Waa (2022)	Task allocation; risk assessment; progressive interfaces
Reviews of Methods	Huang et al. (2020a)	Survey of collision avoidance methods; key challenges identified

Table 4
Overview of research on remote monitoring and control technology.

Paper	Key Themes	Research Focus			HMC Aspect			
		SCC or HMI Design	Emergency Response	Risk Analysis	HCD	Transparency and Trust	Workload	HMC Control
Veitch et al. (2021)	Remote control across different LoAs	√				√		√
Hoem et al. (2022)	Human-centred approach to risk assessment	√		√	√		√	
Veitch et al. (2022)	Changing role of seafarers in ROC s			√		√	√	
Asplund and Ulfvengren (2022)	Emergency response via ROC		√	√	√			
Chen et al. (2023)	Remote takeover decision-making	√	√					√
Laso et al. (2019)	Human-computer interface (HCI) for MASS	√		√	√		√	√
Eide et al. (2025)	Surveillance and control technologies	√		√	√	√		
Tam et al. (2021)	Effects of remote control on seafarers' mental health			√	√	√	√	
Gregor et al. (2023)	Design of ROC and HMI	√				√	√	
Han et al. (2022)	Transparency and human factors challenges in SCCs	√				√	√	
Cheng et al. (2024)	Seafarer takeover of control in SCCs		√	√			√	
van de Merwe et al. (2024)	Information transparency requirements in MASS remote control		√	√		√		

partners.

As discussed in Section 3.2, advancements in situational awareness technologies have enhanced the intelligence of information acquisition in autonomous ships, providing a more comprehensive understanding of the operational environment. Consequently, human operators are no longer the sole analysers of information but instead act as information selectors and verifiers (Brandsæter et al., 2020). HMI design continues to be optimised to improve operator situational awareness, interaction transparency, and system trust in collaborative decision-making processes (Porathe, 2021). Tate and Cooke (2024) further argued that intelligent systems should provide stronger decision-support capabilities to empower operators in collaborative decision processes. Similarly, Cheng et al. (2024) pointed out that DSS must incorporate enhanced real-time computing and information integration capabilities to reduce the uncertainties associated with human-involved decision-making. The research themes and corresponding guidelines from the literature are presented in Table 5.

The shift in seafarers' roles from decision makers to collaborative decision partners, poses new challenges for HMC in autonomous shipping. Key factors, including decision-making, task demand, machine subsystems, and information transfer, may influence the effectiveness of HMC (Fan et al., 2025b). Additionally, Lynch et al. (2024) conducted a systematic literature review. They found that transparency and trust are crucial for collaborative decision-making, but challenges such as information overload and operator detachment from the decision-making loop may undermine system reliability. Tate et al. (2022) explored the role of networked AI in reducing operators' time pressure and cognitive workload. Still, it could also lead to reduced situational awareness and diminished trust in the system.

To further optimise HMC decision-making, Yu et al. (2023) proposed a Turing test-based intelligent navigation framework to improve automation transparency and minimise decision biases caused by information uncertainty. Dynamic transparency has been

Table 5
Themes and guidelines for research on collaborative decision partner.

Theme	Guidelines	Relevant References
Situational awareness and interface design	Enhancing operator awareness through HMI and visualisation systems for better decision context	Lutzhoft et al. (2019), Porathe (2021), Madsen et al. (2025)
Cognitive workload	Managing mental workload to prevent overload or underload in ROC	Tate et al. (2022), Lynch et al. (2024)
Transparency, trust and explainability	Designing systems that make decisions understandable, transparent, and trustworthy to human operators	van de Merwe et al. (2024), Yu et al. (2023)
Decision support systems	Systems that aid operator decision-making via real-time data processing, integration, and recommendations	Mei et al. (2023), Cheng et al. (2024), Tate and Cooke (2024)
Human factors in HMC	Studying human capabilities, roles, and limitations within HMC in MASS	Brandsæter et al. (2020), Fan et al. (2025b)

identified as a direction for improving MASS HMC, enabling information display to be adjusted based on operator needs, thereby reducing information overload and enhancing decision explainability (van de Merwe et al., 2024). Additionally, HCD principles were integrated, incorporating transparency layers to enhance situational awareness (SA Level 3), strengthen navigators' decision-making capabilities, and foster trust in autonomous systems (Lutzhoft et al., 2019; Madsen et al., 2025).

At LoA 2, human operators still play a critical role in the decision-making process of autonomous ships. At LoA 3, human roles shift to remote supervision, where operators intervene in decision-making only when necessary. In autonomous maritime operations, humans are no longer the sole decision makers but instead function as collaborative decision partners alongside the system. However, the transparency and explainability of autonomous systems' decisions significantly impact human-system trust relationships, ultimately influencing the efficiency of HMC.

3.3.2. From operator to remote supervisor

The application of automation technologies has optimised how seafarers acquire information. With the advancement of autonomous shipping and the increase of LoA, the role of seafarers is shifting from direct operators to remote supervisors and controllers (Veitch et al., 2024). As Veitch et al. (2022) highlighted in their earlier research, automation systems are gradually transforming the role of navigators from active controllers to "button pressers", shifting their primary responsibility from direct ship operation to system monitoring, with intervention required only in exceptional circumstances. Similarly, Li and Yuen (2024) highlighted that seafarers now monitor ship operations remotely through autonomous technologies, provide decision support, and intervene when necessary, taking on the role of a shore-based supervisor. However, in remote operation environments, the sensory information traditionally relied upon by seafarers, such as visual, auditory, and tactile cues, is replaced by screen-based visualisations, potentially leading to situational awareness loss (Kari et al., 2018; Kristoffersen, 2020). Table 6 summarises the reviewed studies' research focus and thematic contributions related to seafarer role transitions in remote operations.

To address the challenges associated with remote operations, Van Den Broek and Van Der Waa (2022) proposed an Intelligent Operator Support System, emphasising the need for efficient task allocation mechanisms and optimised cognitive workload management to prevent operators from becoming overly reliant on automation. Gregor et al. (2023) highlighted that the way remote operators interact with MASS using immersive technologies will directly impact the effectiveness of remote navigation supervision. On the other hand, minimising human errors in remote supervision and improving HMC remain critical challenges. Zhou et al. (2024b), Hodne et al. (2024), and Simic et al. (2023) investigated human errors in remote-controlled ship collision avoidance. They suggested that improving HCI could reduce operational errors and enhance the trust of remote supervisors in autonomous systems. Emad and Ghosh (2023) also emphasised the need to reform future seafarer training systems to support the transition from traditional operators to remote supervisors.

As the LoA in autonomous ships advances, the role of seafarers is shifting from direct ship operation to remote supervision and control. However, further research is required to explore how technological advancements, improvements in HMC, and training system reforms can enhance the efficiency, safety, and sustainability of remote supervision in autonomous shipping.

4. Challenges and recommendations in MASS

Despite the advancements in MASS technologies in recent years, the widespread adoption of MASS still faces challenges. These include seafarers' trust in automation systems, adjustments in HMC models, and the adaptability of seafarers' skills. This section explores the key challenges in developing MASS and proposes recommendations based on existing research to enhance its safety, implementation, and long-term sustainability.

Table 6
Studies on seafarer role transitions in remote operations.

Paper	Research Area	Key Themes				
		Role Transition	HMI Design	Risk Assessment	Training Needs	Workload and Fatigue
Veitch et al. (2024)	Operator experience and human factors	√	√			√
Li and Yuen (2024)	Seafarer skills and human factor risks	√		√	√	
Kari et al. (2018) Kristoffersen (2020)	Human systems integration	√	√			
Van Den Broek and Van Der Waa (2022)	Shore control system design		√	√		√
Emad and Ghosh (2023)	Seafarer training and competence	√	√		√	
Zhou et al. (2024b), Simic et al. (2023)	Risk assessment and cognitive workload			√		√
Gregor et al. (2023)	Immersive interfaces and remote HMI	√	√			√

4.1. Challenges

4.1.1. System stability and human trust

Safe and efficient operation of MASS relies on the reliability of sensor data, the ability to process information in complex environments, and the robustness of autonomous systems. However, in extreme weather conditions, complex navigational environments, or scenarios with limited communication, the performance of multi-source sensors can vary. For example, optical sensors are highly susceptible to interference in low-visibility conditions, while electromagnetic disturbances may affect GNSS signals. These data uncertainties can impair situational awareness, compromise system stability, and reduce operator trust in MASS operations.

Additionally, MASS relies on AI and IoT technologies for autonomous decision-making. However, the "black-box" nature of these technologies and algorithms often results in a lack of transparency, making it difficult for remote operators to comprehend the system's logic behind navigational strategies, collision avoidance decisions, or responses to unexpected failures (Lynch et al., 2024; van de Merwe et al., 2024). For instance, a collision avoidance system based on deep reinforcement learning (DRL) may adopt different evasive strategies in similar environments. Yet, operators may struggle to comprehend its reasoning quickly, reducing their trust in the system. The transparency of autonomous systems involves both the interpretability of decision-making processes and the clarity and intuitiveness of information presentation.

Furthermore, even if an autonomous system performs reliably in most cases, anomalous decisions can cause a sudden decline in operator trust, often much harder to restore than initially established. Therefore, enhancing the transparency and explainability of autonomous systems is a key challenge in developing MASS, as maintaining long-term operator trust and ensuring system stability are essential. The HMI serves as the primary interaction bridge between remote operators and MASS, playing a crucial role in improving system transparency and the efficiency of HMC (Ramos et al., 2020). However, current HMI designs still have a significant room for improvement (Hsieh et al., 2024).

4.1.2. Human-Machine cooperation changes

In future autonomous ships, as seafarers transition to collaborative decision participants, the role of HMC becomes increasingly critical. However, research on HMC in autonomous ships is still in its early stages, especially regarding how changes in HMC affect authority and responsibility allocation, for which no clear framework yet exists. This lack of a structured framework may result in two scenarios. One is over-reliance on autonomous systems, where operators cannot take over the system instantly in necessary situations. The other is that if there is a lack of confidence in the system, operators, may intervene excessively in autonomous operations, thereby reducing the effectiveness of autonomous systems.

In real-world operations, autonomous systems may generate mathematically optimal solutions that are impractical in actual execution. While human decisions tend to be more adaptable to real-world environments, they are also susceptible to cognitive biases. In complex maritime environments, especially under conditions involving multitasking, environmental uncertainty, or equipment failures, human judgment and response time can be affected at various points along the information chain. These differences in decision-making logic between humans and autonomous systems may reduce the overall efficiency of collaborative decision-making and introduce new risks in HMC. For instance, an autonomous system may select a theoretically optimal avoidance strategy based on navigation and collision avoidance algorithms in collision avoidance scenarios. However, in complex sea conditions or high-traffic areas, the practical applicability of this strategy may be limited. If operators frequently intervene, it may disrupt the coordination between human and autonomous decision-making, leading to an imbalance that creates new safety hazards. Therefore, establishing a well-defined HMC model and clearly delineating the boundaries of human and autonomous systems is crucial for optimising HMC in MASS.

Furthermore, MASS may dynamically switch between different LoA, such as transitioning from LoA 3 to LoA 2 with human intervention. Although some organisations have begun to propose frameworks for managing HMC transitions across autonomy levels, these efforts remain fragmented and lack international standardisation. Throughout this process, remote operators must quickly establish situational awareness within a limited timeframe and make timely and accurate decisions. However, delays in information transmission or limitations in HMI design may hinder operators from accessing critical decision-making information, potentially leading to delayed responses or decision errors. This aligns with the findings of Fan et al. (2025b), which emphasises that future MASS design and operator training should prioritise optimising task allocation and information flow to enhance maritime safety and system adaptability. If the autonomous system lacks an efficient HMC mechanism, this misalignment can increase operational risks, potentially resulting in safety incidents. Therefore, optimising information transmission efficiency and improving HMI design are crucial to enhancing the cooperation between human operators and autonomous systems.

4.1.3. Seafarer competencies gaps

With the advancement of technology, autonomous systems can now perform certain navigational decisions and operational tasks. However, seafarers continue to play a critical role in key areas such as decision-making, remote monitoring, and emergency intervention, ensuring the safe operation of autonomous ships. Despite this transition, the current maritime training system remains primarily designed for traditional ship operations and lacks adequate preparation for competencies required in autonomous shipping, such as understanding intelligent systems, remote monitoring, and data analysis (Fan and Yang, 2023; Ye, 2021). Sharma et al. (2019), in a survey of 82 officers evaluating 66 STCW competences, found that although STCW offers a baseline, revisions are needed to integrate MASS-specific skills such as remote supervision and AI oversight. Similarly, Emad and Ghosh (2023) identified a set of essential competencies for future operators, including digital skills, AI oversight, remote monitoring, and emergency management. A systematic review of 81 studies by Meštrović et al. (2024) further confirmed widespread competency gaps, reporting that both cadets and officers perceive current training as offering limited exposure to MASS, especially in areas of remote supervision, AI, and digital system management. This lag in training adaptation has widened seafarer competency gaps, leaving many with limited proficiency in key technologies, including AI, DSS, and situational awareness. Without these competencies, future seafarers may struggle to participate effectively in MASS's operation and decision-making processes. For instance, in SCCs, operators rely on HMI and intelligent interaction systems to access critical information and oversee autonomous system decisions. Table 7 summarises the roles of seafarers and autonomous systems and the seafarer competencies required at different LoA in MASS. Operators lacking sufficient training may encounter cognitive overload and reduced information-processing capacity during remote monitoring and decision-making. This reduces the efficiency of HMC in MASS and may also compromise overall system safety.

More critically, gaps in seafarer competencies may undermine emergency response capabilities in autonomous shipping. The current maritime training system does not adequately address emergency response strategies for autonomous ships, potentially hindering seafarers' ability to respond effectively and promptly to critical incidents, thereby increasing safety risks (Ceylan, 2025). In cases such as communication failures, system malfunctions, or extreme sea conditions, remote operators must quickly analyse complex ship scenarios and implement appropriate intervention measures within a limited timeframe. However, seafarer competency gaps may lead to inefficient emergency responses, posing a significant threat to the operational safety of MASS. Therefore, developing a training framework tailored to the needs of autonomous shipping, and enhancing operators' competencies in intelligent system cognition, remote monitoring, and emergency response is essential.

4.1.4. *Summary of challenges*

In this section, the main findings and challenges are synthesised from the preceding discussion. As shown in Table 8, the challenges identified across the three sub-sections are consolidated into four overarching areas: system stability and reliability, trust and transparency, role allocation and cooperation, and competency and training. Each theme integrates insights from different aspects of the review, highlighting both what is already established and where research gaps remain.

4.2. *Recommendations and future research*

4.2.1. *Advancing human-machine cooperation design*

To enhance MASS's transparency, safety, and operability, future research can focus on optimising the HMC mechanisms in the following key areas to improve effectiveness and reliability.

To increase the transparency of autonomous in MASS, explainable AI (XAI) can be introduced to enhance the interpretability of autonomous systems. XAI provides clear decision logic and reasoning pathways, allowing operators to understand the basis of system decisions, thereby reducing the cognitive burden caused by AI's "black-box" nature and improving operator trust and acceptance of autonomous decision-making.

Given that MASS operates under dynamic levels of autonomy, future remote information visualisation systems should incorporate a "dynamic transparency" mechanism, which adjusts information display on remote monitoring systems and visual interfaces based on real-time operator needs. This mechanism can mitigate decision delays or errors caused by information overload among remote operators, improving the adaptability and stability of HMC.

Clearly defining the roles and responsibilities of human operators and autonomous systems within MASS is also essential. Establishing systematic guidelines for authority distribution across different operational scenarios can improve both efficiency and safety while minimising uncertainties caused by unclear responsibilities. Such guidelines should specify when control remains with the system and when authority shifts to the human operator, particularly during transitions between levels of autonomy of the ships. They should also set criteria for intervention in emergency situations, outline procedures for conflict resolution between human and system decisions, and consider how responsibilities may differ between onboard and shore-based operators. Developing these guidelines will require a combination of simulation-based testing, human-in-the-loop experiments, and alignment with international regulatory frameworks, ensuring that authority distribution in MASS is both technically robust and operationally practical.

In HMI design, it is crucial to consider the situational awareness needs of remote operators. To improve the intuitiveness and immersion of remote operations, virtual reality (VR) technology can be integrated with traditional sensor data to develop advanced remote situational awareness systems. Operators can better understand complex sea conditions by providing a more immersive environmental perception experience, enhancing their situational awareness, emergency response capabilities, and overall operational

Table 7
Roles of seafarers and autonomous systems across LoAs.

LoA of MASS	Seafarer Roles	Autonomous Systems' Roles	Seafarer Skills Needed
1	Onboard operator and decision-maker	Supporting decision-making and performing simple autonomous functions	Traditional navigation, equipment handling, emergency response
2	Onboard supervisor with remote control support	Autonomous execution of basic functions; remote control enabled	Hybrid control, situational awareness, system oversight, decision support tools
3	Remote supervisor and decision supporter	Real-time navigation, environment perception, and collision avoidance	Remote monitoring, system reasoning, risk assessment, interface interaction
4	Remote supervisor and emergency intervention only	Full autonomy in navigation, planning, and decision-making	High-level system understanding, fault analysis, emergency control

Table 8
Summary of main findings and research gaps on HMC challenges in MASS.

Challenge Area	Main Findings	Research Gaps
System Stability and Reliability	Data and sensor uncertainty lowers system reliability	Need for robust assurance of AI in real-world maritime conditions
	Black-box AI produces unpredictable decisions	Lack of explainable methods to communicate system limitations to operators
Trust and Transparency	Transparent interfaces improve situational awareness and trust	No standardised transparency or explainability metrics for MASS
	Operators remain sceptical about DSS reliability	Limited longitudinal studies on trust evolution in operational contexts
Role Allocation and Cooperation	Autonomy shifts operator roles and responsibilities	Absence of HMC frameworks for authority handover
	LoA transitions can reduce SA and delay interventions	
	Conflicts arise between machine solutions and practical seafarer skills	Few validated HMIs for rapid SA recovery during takeovers
Competency and Training	Current training leaves gaps in AI oversight and remote monitoring	Lack of curricula for remote supervision and crisis management
	Emerging ROC roles require new skills in risk assessment and emergency handling	Limited research on workload and cognitive limits of ROC operators

efficiency. Additionally, HMI design should balance transparency and cognitive workload, preventing information overload that may impair operator decision-making and efficiency.

Recent advances in end-to-end large model technologies show considerable promise in autonomous driving (Chen et al., 2024). Such models can integrate perception, decision-making, and control into a unified framework, enabling ships to process multimodal inputs, including sensor data, navigational charts, and communication signals, while generating adaptive responses in real time. By reducing reliance on fragmented subsystems, large models can improve efficiency and robustness in complex operating environments. For example, autonomous navigation decisions can be continuously optimised from real-time data, helping operators avoid the influence of unnecessary intermediate outputs and maintain focus on ship supervision. Autonomous navigation can be continuously optimised from real-time data, reducing dependence on brittle intermediate module outputs and allowing operators to focus on supervision. End-to-end models can also enhance safety by producing timely, adaptive responses to changing conditions, supporting earlier hazard recognition and collision-risk assessment. From a reliability standpoint, an integrated architecture reduces the risk of subsystem failures, improving the efficiency and stability of autonomous navigation in complex conditions. For HMC, end-to-end large model also offer to enhance transparency and operator trust by providing interpretable decision rationales, supporting safer and more reliable MASS deployment.

As autonomous ships evolve, it is essential to adopt a HCD approach to ensure alignment with the cognitive capabilities and operational needs of seafarers. Functional near-infrared spectroscopy (fNIRS) offers a promising means to support this alignment by enabling monitoring of cognitive states such as workload, stress, and attention during remote operations (Fan et al., 2025a, 2021). This neurophysiological solution could provide objective measures on human performance and hence useful insights into how operators interact with autonomous systems, informing the implementation of emerging technologies, improving seafarer training, and optimising HMI design.

Furthermore, fNIRS aligns with the functional approach that could be formalised against the Regulatory Scoping Exercise conducted by the IMO (IMO, 2021). This approach emphasises that key safety and operational functions must be performed effectively, regardless of whether they are executed by humans or machines. By integrating fNIRS into both the implementation of emerging technologies and the development of seafarers' competencies, it is possible to enhance HMC in autonomous ships, increase system adaptability, and support the safe and effective deployment of MASS. Table 9 provides an overview of methods for advancing HMC design in MASS, outlining their advantages and disadvantages to highlight both their potential and current limitations.

4.2.2. Designing effective training for seafarers for MASS

Future seafarers will take on the roles of collaborative decision partners and remote operators. However, the growing disparity between traditional seafarers' skill sets and MASS's operational demands is becoming evident. To bridge this gap, a systematic, forward-looking, and targeted training framework must be established to develop future seafarers' competencies in remote operations, intelligent system monitoring, and data analysis. The future training framework should be developed in alignment with MASS operational requirements and integrated with the existing training standards set by the IMO. A specialised training system for MASS remote operators should be formulated, complementing traditional training programs with additional courses on autonomous system monitoring, multi-source data analysis, remote operation, and intelligent ship management. These additions will enable seafarers to efficiently execute tasks in an autonomous shipping environment and effectively intervene in autonomous system operations under complex navigational conditions, ensuring that ship operators meet autonomous ships' safety and operational requirements.

Effective training methods must also be tailored to different LoA in MASS. At LoA 1, existing STCW-based training already covers core competencies such as navigation, emergency response, and radar operation; additional training should reinforce the effective use of decision-support tools, best delivered through simulator exercises. At LoA 2, where ships are partially controlled from remote centres while crew remain onboard, training should focus on hybrid operations, combining onboard and remote practice through VR-based situational awareness systems and collaborative ship-shore exercises. At LoA 3, where ships are supervised remotely without

Table 9
Comparison of different methods for advancing HMC design.

Method	Advantages				Disadvantages			
	Improved Transparency	Better SA	Higher Efficiency	Human Supports	Lack of Standards	Information Overload	High Cost	Limited Validation
XAI	√				√			
Dynamic Transparency	√					√		
VR-based HMI		√				√	√	
End-to-End Large models	√		√		√		√	
fNIRS				√			√	

crew onboard, immersive ROC simulations and crisis drills are essential to prepare operators for anomaly detection, handover, and emergency intervention. At LoA 4, where operators may supervise multiple ships simultaneously, training should emphasise competencies in fleet oversight, AI governance, and system auditing, supported by digital twin environments and advanced certification schemes.

To maximise effectiveness across all levels, advanced visualisation technologies should be leveraged to enhance training effectiveness and create high-fidelity simulation environments that replicate real-world operational conditions. By simulating authentic navigational scenarios, seafarers can gain a highly immersive training experience, enabling them better to understand autonomous system logic and remote operations.

As MASS represents a significant shift toward autonomous shipping, it offers improved navigational efficiency and safety. It also introduces challenges related to system trust, HMC model changes, and seafarer competency structure adjustments. Therefore, future research on MASS should further explore key issues such as optimising HMC, enhancing trust in autonomous systems, and developing the competency needed for effective human oversight and control of autonomous ships.

5. Conclusion

With the implementation of LoA 2 MASS projects and significant technological advancements accelerating the development of LoA 3 systems, research efforts are increasingly put forward to address the risks, challenges, and human factors associated with autonomous ship operations. This review work examined core enabling technologies in MASS, specifically environmental perception, decision-making and control, and remote monitoring and operation, through the lens of HMC. While these technologies have considerably enhanced the functional capabilities of autonomous systems, they also introduce new challenges in HMC, particularly regarding system transparency, operator cognitive workload, and trust in automation.

A key insight from this review study is the evolving role of human operators, transitioning from traditional onboard decision-makers to remote supervisors and collaborative decision partners. This transformation necessitates a rethinking of interaction models, operational workflows, and the competency frameworks required for future maritime professionals. In particular, it calls for the design of adaptive, human-centred training programmes that equip seafarers to interact effectively with increasingly intelligent and autonomous systems. Despite substantial technological progress, the full-scale implementation of MASS remains hindered by several unresolved challenges. These include the limited transparency and stability of autonomous decision-making, the absence of mature and flexible HMC frameworks, and a growing skills gap among seafarers. To overcome these barriers, future research should prioritise developing explainable AI, refining HMI and cooperation models, and establishing targeted training and certification systems that reflect the evolving demands of MASS operations.

Ultimately, the future of maritime autonomy lies not in replacing humans, but in fostering a synergistic relationship between human operators and autonomous systems. Aligning technological innovation with human capabilities is essential to achieving safe, efficient, and sustainable autonomous shipping. Continued interdisciplinary research bridging automation design and human factors will be critical to ensuring that human oversight remains a pillar of trust and resilience in the maritime domain.

CRediT authorship contribution statement

Jiale Xiang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Eddie Blanco-Davis:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Formal analysis. **Xuri Xin:** Writing – review & editing, Validation, Supervision, Software, Methodology, Conceptualization. **Huanhuan Li:** Writing – review & editing, Validation, Supervision, Methodology. **Nabile Hifi:** Writing – review & editing, Supervision, Data curation. **Jin Wang:** Writing – review & editing, Supervision. **Zaili Yang:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nabile Hifi is currently employed by BAE Systems Maritime - Naval Ships. The author Jin Wang is an Associate Editor for

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