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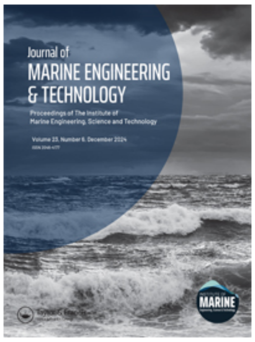

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REVIEW ARTICLE

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Safety and efficiency of human-MASS interactions: towards an integrated framework

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ABSTRACT
Maritime Autonomous Surface Ships (MASS) have gained much attention as a safer and more efficient mode of transportation and a potential solution to reduce the workload of seafarers. Despite the highly sophisticated autonomous systems that enable MASS to make independent decisions, the presence of humans on board or in the loop of safety management highlights the need for effective human-machine interaction. However, a potentially systematic review of critical aspects of human-MASS interaction has not yet been conducted. In this paper, we aim to fill this gap by reviewing the literature related to human-MASS interaction from four crucial perspectives: the state of the art of human-MASS interaction, situational awareness for MASS, collision avoidance methods for MASS within a mixed waterborne transport system (MWTS), and human trust in MASS. Our review reveals that human-MASS interaction for safety and efficiency mainly focuses on four key aspects: (i) human factors, (ii) available technologies supporting the autonomy of MASS, (iii) system analysis and design for human-MASS interaction, and (iv) potential requirements regarding regulations. Moreover, we provide a detailed discussion of the three fundamental factors that influence human-MASS interaction, including situational awareness, decision-making for MASS in a mixed waterborne transport system, and human trust in the autonomous system of MASS. Finally, based on our analysis, we propose an integrated framework of human-MASS interaction in which these human factors are taken into account. We anticipate that these factors and their interaction will receive more attention to improve the safety and efficiency of MASS.

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KEYWORDS
Human-MASS interaction; situational awareness; collision avoidance for MASS; MWTS; human trust in MASS

1. Introduction

1.1. Background

In recent years, the maritime industry has faced great challenges, including a shortage of skilled seafarers (Kim et al. 2020) and the severe consequences of traffic accidents in waterborne transport systems (WTS) (Levander 2017; Bakdi et al. 2020). Maritime Autonomous Surface Ships (MASS) have emerged as a promising solution (Cheng and Ouyang 2021) to mitigate these issues by reducing human errors, which account for a large proportion of maritime accidents. Over the years, more and more projects on MASS have been initiated. A survey on MASS prototypes was conducted by (Schiaretti et al. 2017) with the autonomy levels of MASS, including MUNIN (Rødseth et al. 2013), AAWA (Carey 2017), and NOVIMAR projects (Haseltalab et al. 2019). It is expected that the advent of autonomous ships could reduce the number of human errors that account for a major part of the accidents in WTS (Song et al. 2022b).

To ensure the effective integration of MASS into existing maritime frameworks, the International Maritime Organisation (IMO) has classified MASS into four levels of autonomy, as shown in Table 1, ranging from ships with automated processes and decision support to fully autonomous ships capable of making independent decisions. Additionally, to meet specific needs, a more detailed Level of Autonomy for MASS (Lloyds Register 2016) and a new classification for autonomous surface vessels (Schiaretti et al. 2017) regarding the overall system and sub-systems were proposed, including decision, action, exception handling, and cooperation. These classifications underscore the necessity of understanding how these varying degrees of autonomy interact with human operators to ensure safety and operational efficiency.

Importantly, the level of autonomy of a MASS may change during different phases of its journey (Lynch et al. 2024). For instance, an open sea transit may be fully automated, requiring minimal human intervention, while complex traffic situations during a port approach could necessitate significant human oversight. This variability also highlights the need for targeted research into the specific aspects of human-MASS interaction across different operational contexts.

1.2. Importance of key research aspects

- Situational Awareness

Situational awareness is crucial for the safe navigation of MASS, involving the comprehensive capability construction of both human seafarers and autonomous systems to perceive, understand, and predict the maritime environment. Effective situational awareness requires not only sensors on board but also integrating domain knowledge and expertise of seafarers to build a reliable understanding of the navigational context. In this way, MASS can make timely decisions across various navigational scenarios.

- Collaborative Collision Avoidance

Collision avoidance is another critical area where human-MASS interaction plays a key role. Autonomous systems should be capable

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Table 1. Classification of the autonomy degree of Maritime autonomous surface ships by IMO.

Degree in Maritime Autonomous Surface Ships		Description
1	Ship with automated processes and decision support	Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated.
2	Remotely controlled ship with seafarers on board	The ship is controlled and operated from another location, but seafarers are on board.
3	Remotely controlled ship without seafarers on board	The ship is controlled and operated from another location. There are no seafarers on board.
4	Fully autonomous ship	The ship's operating system is able to make decisions and determine actions by itself.

of collaborating with conventional ships and the MASS with different levels of autonomy to navigate safely. This requires sophisticated algorithms and real-time data processing to make informed decisions. The integration of seaman skills in these systems is vital to handle various circumstances and ensure safe and efficient navigation.

- Human Trust

Humantrust in MASS affects how operators interact with autonomous systems (Misas et al. 2022), particularly in risky scenarios (e.g. performing collision avoidance tasks). Developing trust requires ensuring that MASS can reliably perform tasks such as situational awareness and decision-making under various conditions. Establishing and maintaining a proper level of trust is essential for achieving efficient and effective communication between human operators and autonomous systems. The interplay between trust and system performance requires in-depth investigation to optimise human-MASS interactions.

In view of the importance of situational awareness, collaborative collision avoidance, and human trust for the effective navigation of MASS, it is essential to conduct research in these areas. This study aims to investigate these critical aspects to ensure safe and efficient human-MASS interaction, thereby facilitating the integration of MASS into a mixed waterborne transport system (MWTS).

The objective of this paper is to review and discuss several key issues related to the safety and efficiency of MASS and the importance of carefully considering them during both the design and operation phases. Among the key issues that need to be taken into account are the lack of situation awareness capability in MASS, the need for collaborative collision avoidance between MASS and conventional ships, and human trust in MASS.

For this purpose, we start by introducing the following definitions based on the knowledge available in the literature:

- Definitions 1: Safety in maritime navigation is a mandatory requirement encompassing, but not limited to, navigational safety, mechanical and structural integrity, safety from fire, safety training for crew members, emergency preparedness, and security measures against potential threats. Hereinafter refers specifically to navigational safety, e.g. preventing collisions.
- Definitions 2: Efficiency in maritime navigation refers to the optimal utilisation of resources to achieve voyage objectives with minimal environmental impact and operational cost. It entails not only the reduction of travel time and fuel consumption but also the strategic planning of routes and the adoption of technologies that enhance fuel efficiency.
- Definitions 3: Situational awareness refers to the capability (of the human seafarer or the autonomous agent) of perceiving, understanding, and predicting the situation that the ship encounters within a certain time/distance.
- Definitions 4: Human trust in MASS is the belief that the human holds to the autonomous system capability of situational awareness and appropriate task implementation.

Table 2. Research questions related to human-MASS interaction.

Questions	Section
What is the state of the art on the safety and efficiency of human-MASS interaction?	3.1
How can situational awareness be applied to MASS safe navigation, and how can it be measured?	3.2
How can MASS make decisions to avoid collision with manned ships or ships with different degrees of autonomy?	3.3
What factors could influence human trust in MASS, and how can trust be measured?	3.4

In this paper, we aim to conduct a comprehensive review of the existing research on human-MASS interaction, with a focus on key factors that impact the safety and efficiency of MASS. To guide our review, we formulate four research questions, which are detailed in Table 2.

1.3. Contributions & outline

This paper contributes to the field of human-MASS interaction by conducting a comprehensive review of the existing research, with a focus on key factors that impact the safety and efficiency of MASS. The aim of this review is to provide insights and highlight important avenues for future research in this field.

The contributions of our study are summarised as follows:

(1) A comprehensive and up-to-date review of existing research on this topic is provided, in which the key features of different earlier works are identified, and the gaps in knowledge that need to be addressed in future research are highlighted.
(2) The scope of earlier review/survey papers on autonomous ships is significantly extended by providing a more detailed and systematic analysis of the research on critical human factors of human-MASS interaction safety. Specifically, the three aspects that affect human-MASS interaction for safety and efficiency are examined: situational awareness, collision avoidance for MASS and human trust in MASS.
(3) Future scenarios in which autonomous ships and humans will need to work together are identified. This is particularly important given the rapid pace of technological development in this field and the potential for great changes in the way in which humans and autonomous systems interact in the future.
(4) An integrated conceptual framework for human-MASS interaction is proposed to support the safe and efficient navigation of MASS, by incorporating situational awareness and human trust into the process of decision-making.

The paper is organised as follows. In Section 2, we describe our review methodology, which includes a systematic search of relevant literature in several databases. In Section 3, we present the results of our review, which cover four main aspects of human-MASS interaction research. In Section 4 and Section 5, we discuss and conclude the review outcomes, respectively.

2. Methodology

2.1. Review scoping

The process of literature review, as depicted in Figure 1, was conducted systematically to ensure a comprehensive and focused analysis of relevant studies. Initially, a detailed search was carried out across two databases, including Scopus and Web of Science, using carefully selected keywords that align with the research themes, as detailed in Table 3. This search, conducted up to May 2024, yielded a total of 209 English records (85 from Web of Science and 124 from Scopus).

An eligibility assessment was then performed on the remaining records, which led to the exclusion of 22 studies due to reasons such as their falling outside the core research areas, not discussing relevant MASS safety mechanisms, or not addressing key aspects like trust or human-MASS interaction.

To ensure the breadth of the literature covered, a snowballing technique was employed, which identified 12 additional studies that were not captured during the initial database searches. Ultimately, this process resulted in the selection of 105 studies for detailed analysis. These included both empirical studies and 12 key reports, which were then examined to address the research questions. The results of this screening process, including the number of papers related to each topic, are summarised in Table 4.

2.2. Structure of review

To provide a clear picture of the interplay between these topics and human-MASS interaction, we first present an in-depth overview of situational awareness, decision-making strategies, and human trust in MASS as they relate to safety and efficiency in an MWTS. Through this approach, we aim to uncover the connections among these themes and highlight their significance.

Additionally, we perform a detailed analysis of the relationships between the three sub-research topics and human-MASS interaction, specifically in the context of safety and efficiency. This analysis provides insights into the relationship between individual research themes in human-ship interaction and their correspondence to the broader themes of safety and efficiency.

The bibliometric approach is used here to investigate the relationships between key concepts in the literature on human interaction with MASS using the term co-occurrence analysis method. The visualisations presented in Figures 2 and 3 demonstrate the connections between various research themes.

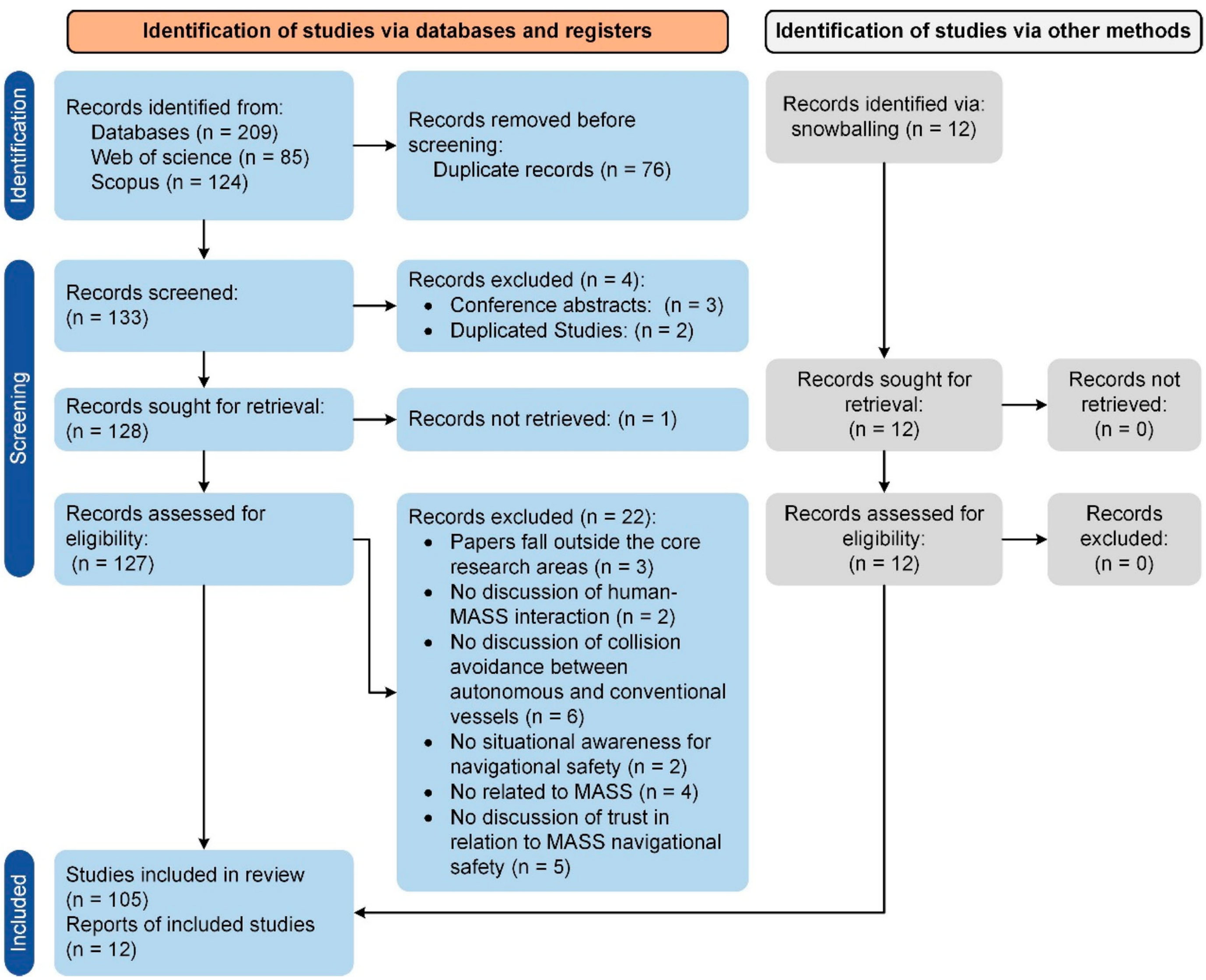

Figure 1. The flow diagram of the literature screening process.

Table 3. Keywords corresponding to each research question.

No.	Keywords	Scopus	Web of Science
1	TS = ('Human' AND ('autonomous ship∗' OR 'maritime autonomous surface ship∗' OR 'autonomous vessel∗' OR 'maritime autonomous surface vessel∗') AND ('interact∗ OR 'cooperat∗')' AND ('safety' OR 'efficiency'))	46	29
2	TS = ('Situation∗ awareness' AND 'human' AND ('autonomous ship∗' OR 'maritime autonomous surface ship∗' OR 'autonomous vessel∗' OR 'maritime autonomous surface vessel∗'))	41	30
3	TS = (('Autonomous ship∗' OR 'maritime autonomous surface ship∗' OR 'autonomous vessel∗' OR 'maritime autonomous surface vessel∗') AND ('manned ship∗' OR 'conventional ship∗' OR ' manned vessel∗' OR 'conventional vessel∗') AND 'collision avoidance')	25	28
4	TS = ('Trust' AND ('autonomous ship∗' OR 'maritime autonomous surface ship∗' OR 'autonomous vessel∗' OR 'maritime autonomous surface vessel∗'))	28	16

Figure 2 shows a network of colours where each colour stands for a different theme: green for safety, yellow for efficiency, purple for human-MASS interaction, red for situational awareness, teal for human trust, and brown for decision-making. The width of the lines connecting these themes indicates how often they are mentioned together in the literature; wider lines mean more frequent mentions.

Figure 3 zooms in on the interplay between safety and efficiency. The visual articulation, using the same colour coding, emphasises the substantial overlap between these directions. This intersection underscores a salient research trend: considerations of efficiency are rarely isolated from safety imperatives. The emergent pattern from this confluence indicates that safety considerations form the primary context within which efficiency is situated and discussed.

From these figures, we draw two main conclusions: firstly, safety is a major concern and is often discussed along with efficiency, reflecting a tendency to consider them jointly rather than separately. Secondly, there is a noticeable gap when it comes to human trust, especially in connection with safety and efficiency. This gap suggests that more research is needed to understand how trust in autonomous systems can affect the adoption and use of MASS.

3. Results

3.1. Human-MASS interaction for safety and efficiency

3.1.1. Human factors

The concept of human complementary in the maritime domain has gained much attention in recent years. It involves the collaboration between MASS and human operators to enhance safety, efficiency, and overall performance in water areas. The human factor is of paramount importance in the successful implementation of human-MASS interaction, particularly in ensuring safety. In this regard, extensive research has been conducted in this area to investigate the various facets of the human factor in the context of MASS operations.

- Frameworks for Human Involvement in MASS

Several studies have explored the integration of humans as an essential part of MASS operations. A framework involving humans as one element of the system was proposed by (Kari et al. 2018) to improve team performance, suggesting human monitoring will be diminished to exploit the potential of fully autonomous MASS as trust develops. Furthermore, In the study referenced by (Kari and Steinert 2021), it is highlighted that human factors, including cultural and social aspects, may impact the effectiveness of remote ship operations and the interactions between operators in shore control centres. Specifically, these factors affecting operators responsible for MASS at Remote Control Centres (RCC) are identified and organised into thirteen distinct categories.

- Changes in Operator Cognition & Situational Awareness

Operator cognition and situational awareness have been studied extensively, particularly in challenging environments. The study (Soper et al. 2023) discussed the challenges of using the digital system on the vessel in the Arctic environment and highlighted the considerations that need to be taken into account when designing maritime navigation systems. Additionally, the unmanned ship was focused on particularly to investigate possible human benefits and challenges regarding ship safety (Wahlstrm et al. 2015). In this study, situational awareness was discussed, indicating the importance of proactive communication between MASS and manned ships in an MWTS. Furthermore, Human takeover times during the operation of automated ships were analysed in (Shyshova et al. 2024). The study revealed that takeover times are often longer than expected, requiring situation-specific management strategies to ensure safe and autonomous operations.

- Trust, Decision-Making, and Human-System Interaction

Trust between human operators and autonomous systems has been identified as a critical factor for successful collaboration. In the study (Ahvenjrvi 2016), human elements were discussed in the MASS, which is remotely controlled. In this study, the author argued that it is critical to keep aware of the situation of human operators at RCC, which directly influences the safety and efficiency of the MASS. Moreover, it is stressed that the behaviour of MASS would influence the behaviour of the conventional ships in an MWTS. Human elements were analysed by (Mallam et al. 2019) and (Mallam et al. 2020) for future autonomy, where trust, situational awareness, and training were discussed based on interviews. In this study, the relationships among trust, situational awareness, and decision-making in the autonomous system were stressed. Moreover, the relationship between human trust in autonomy and professional commitment was investigated by (Aalberg 2024). The study finds that higher professional commitment correlates with lower trust in autonomy. This study highlights the importance of addressing human factors to foster trust in autonomous systems.

Additionally, challenges in designing the Shore Control Center (SCC) for MASS were addressed by (Dybvik et al. 2020), with a focus on human-machine interaction. The paper emphasised that optimising human-system interfaces is critical for operators to maintain situational awareness and make informed decisions in remote environments. Focusing on the mental health effects of humans involved in the MASS controlled remotely, (Tam et al. 2021) investigated in-depth human factors. It is found that the difference in situational awareness and trust discrepancy between human operators and the autonomous system could lead to high stress on humans and wrong decisions accordingly.

In order to identify potential risks in the scenario of collaborative human-MASS navigating, a method of scenario analysis was applied on a virtual remote manoeuvring platform for MASS (Hoem et al. 2022). With that method, human factors related to potential risks within human-MASS interaction can be found effectively by observing the reaction of participants. Accordingly, decision-making can be considered in the ship design phase in advance for remote-controlled MASS.

Table 4. The overview of the relevance between literature and research questions.

Ref.	State of the art					
	HMI†	Safety	Efficiency	*SA*†	*CA*†	*HT*†
Zhang et al. (2019)			✓		✓	
Bakdi and Vanem (2022)			✓	✓	✓	
Wei and Kuo (2022), Zhai et al. (2022)		✓			✓	
Wahlstrm et al. (2015), Papageorgiou et al. (2022)		✓		✓		
Song et al. (2022a), Wei and Kuo (2022)		✓		✓	✓	
Thombre et al. (2022)		✓	✓	✓		✓
Wu et al. (2022), Carrara (2022), Poornikoo and vergrd (2022)	✓					
Wang et al. (2022)	✓					✓
Huang et al. (2020b)	✓				✓	
Thieme and Utne (2017)	✓				✓	✓
Lyu and Yin (2019), Huang et al. (2020b)	✓			✓		
Lynch et al. (2023), Dybvik et al. (2020)	✓			✓	✓	
Gregor et al. (2023)	✓			✓		✓
Mallam et al. (2019), Han et al. (2022)	✓			✓	✓	✓
Venverloo et al. (2021)	✓		✓			✓
Costanzi et al. (2020)	✓		✓		✓	
Ramos et al. (2018b), Ventikos and Louzis (2023), Veitch and Alsos (2022), Chang et al. (2021), Vakil (2021), Pedersen et al. (2022), Adnan et al. (2024), Hynnekleiv et al. (2020), Thieme et al. (2018), Vagale et al. (2022a), Bakdi et al. (2021)	✓	✓				
Veitch et al. (2022), Ramos et al. (2020b), Ahvenjrvi (2016), Hoem et al. (2022), Abilio Ramos et al. (2019), Zhang and Furusho (2016), Zhang et al. (2020), Wróbel et al. (2020), Heiberg et al. (2022), Dreyer (2023), Aylward et al. (2022), Namgung et al. (2020)	✓	✓			✓	
Ventikos et al. (2020), Fjørtoft and Mørkrid (2021), Kim et al. (2022), Liu et al. (2022), Wielgosz and Pietrzykowski (2022), Cheng et al. (2024), -lawski et al. (2022), Zhou et al. (2020b), Porathe (2021), Alsos et al. (2022), Shyshova et al. (2024)	✓	✓		✓		
Perera and Murray (2019), Vagale et al. (2022b), Yoshida et al. (2020), Namgung et al. (2018), Ramos et al. (2020a), Zheng et al. (2023)	✓	✓		✓	✓	
Mallam et al. (2020)	✓	✓		✓	✓	✓
Veitch et al. (2021; Veitch et al. 2024b), Geng et al. (2019), Kari et al. (2018, 2019)	✓	✓	✓			
Porathe and Rødseth (2019), Li and Fung (2019), Porathe (2020), Man et al. (2018), Veitch et al. (2024a)	✓	✓	✓	✓		
Endsley (1995)	✓	✓	✓	✓		✓
Porathe (2019), Martelli et al. (2021), Dittmann et al. (2021b), Wu et al. (2021), Akda et al. (2022)	✓	✓	✓	✓	✓	
Tam et al. (2021), Kari and Steinert (2021)	✓	✓	✓	✓	✓	✓

SA† implies Situational Awareness for MASS.
CA† implies Collision Avoidance between MASS and Manned Ships.
HT† implies Human Trust in MASS.
HMI† implies Human-MASS Interaction.

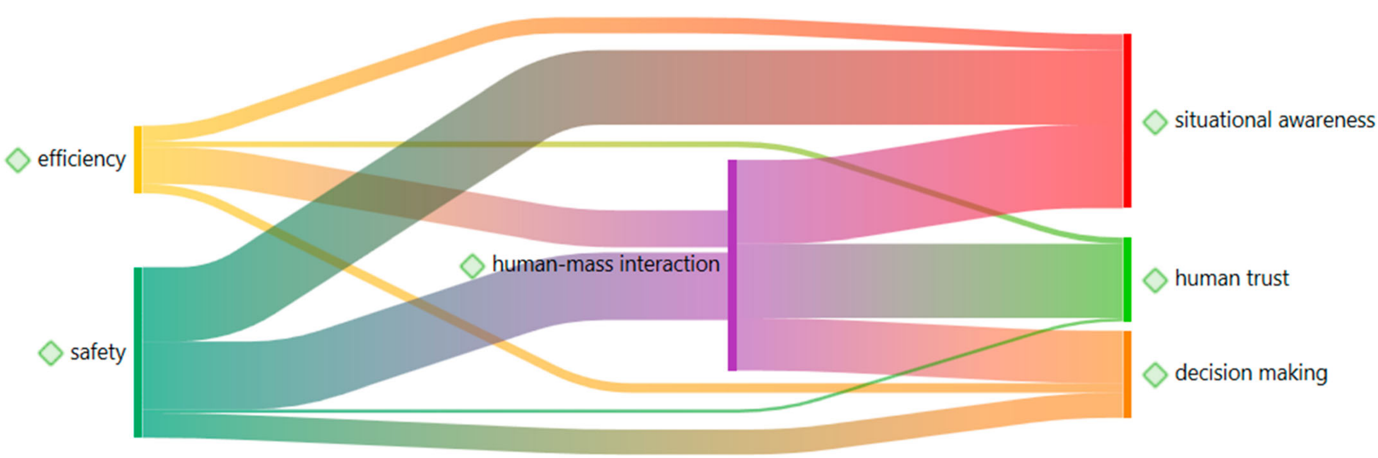

Figure 2. The visualisation of overall co-occurrence analysis of various research themes.

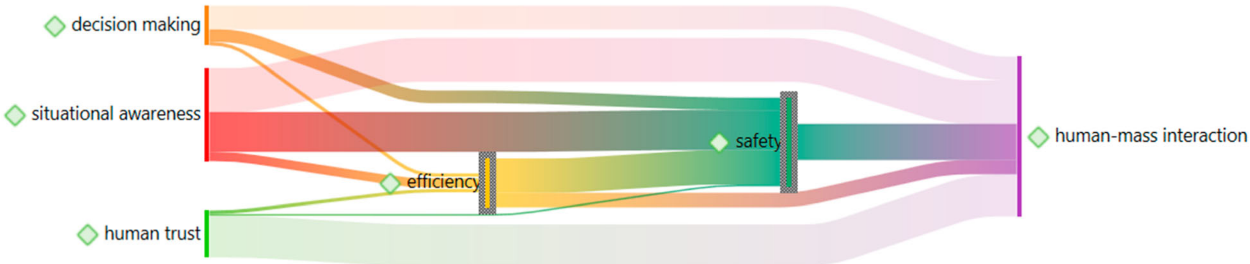

Figure 3. The visualisation of co-occurrence among three directions and human-MASS interaction considering safety and efficiency.

- Risk Assessment and Operator Error Analysis

Risk assessment and operator error analysis are critical for enhancing the safety and reliability of MASS. Numerous studies have explored the two aspects, aiming to develop models and methods that mitigate the risk of human error and improve system performance.

In terms of risk assessment, several studies have utilised advanced analytical methods to evaluate the risks associated with human factors in MASS operations. For instance, The study by (Khan et al. 2023) applied a Bayesian network method, identifying that human factors interactions and operator issues are the main factors leading to accidents. Similarly, By using Evidential Reasoning and a Rule-based Bayesian Network, risk levels of main hazards on MASS were assessed for MASS by (Chang et al. 2021). It is stressed that the risk from the interactions for MASS within an MWTS and human failure on MASS should receive more attention. Additionally, the study by (Thieme et al. 2018) evaluated the applicability of the existing 64 risk models for MASS, revealing that none of them are fully suitable for direct use. This study highlights the need for new models that incorporate multiple considerations like software performance, control algorithms, and human-machine interaction, as mentioned in the study, to ensure the safety of autonomous vessels.

When examining operator error analysis, several studies have focused on the vulnerabilities and potential failures in human interactions. For example, the study by (Ramos et al. 2018b) explored potential human failure events within RCC operations, revealing that human errors can occur due to system alert failures, remote operations, and ship takeover processes. Furthermore, to investigate potential human failures in MASS during collision avoidance scenarios, (Abilio Ramos et al. 2019) employed a task analysis methodology complemented by a cognitive model to outline collision avoidance procedures facilitated by human operators. This study illustrates how the integration of human interventions with autonomous system capabilities can navigate threats effectively, emphasising the critical role of human oversight in emergency situations. Moreover, the potential human failures were also discussed by (Ramos et al. 2020a) with a method of Fault Trees, where failure events that occurred in human-MASS interaction could be identified and predicted.

Additionally, the study by (Liu et al. 2022) utilised an approach of the Success Likelihood Index Method under interval type-2 fuzzy sets to identify the possible errors of human-MASS interaction with the human operator remotely and MASS. The results of the study provide insights into the human factors (i.e. Stress, task difficulty, level of preparation (preparation), experience level (experience), fatigue, event-related factors (event factors), etc.) that can contribute to operational errors in autonomous ships. Furthermore, techniques and challenges of human and organisational factors in the maritime domain were analysed by (Wu et al. 2022). In this study, it is stressed that human factors that may influence ship safety would also widely exist in future transport. For example, the possible high stress of human operators could be caused by the remote supervision of multiple vessels at a time and the failure of the collaboration between conventional ships and MASS with different degrees of autonomy.

Similarly, the critical role of the human element in autonomous maritime navigation was explored in the study (Veitch et al. 2022). The work underscores the persistence of human errors not just operationally but also in the design and remote control of both unmanned and manned vessels, highlighting the potential for autonomous ships to alter seafarer behaviour on manned ships, posing additional risks. Furthermore, the research by (Cheng et al. 2024) examined human errors in human-autonomy collaboration in autonomous ships, particularly in collision avoidance scenarios. Using the human reliability analysis method and virtual experiments, the study identifies key performance-shaping factors influencing human errors. It contributes to understanding human factors in MASS operations, which is crucial for improving safety and efficiency.

- Technologies for Improving Operator's Situational Awareness

Various technologies have been employed to enhance operator situational awareness. It is pointed out by (Endsley 1995) that the transparency of dynamic systems varies with the levels of situational awareness, arguing that human trust in an autonomous system should be calibrated to reach efficient cooperation. In addition, in the study by (Venverloo et al. 2021), an Immersive Virtual Reality method was used to evaluate the human experience on a MASS and a manned ship. In this study, the factors of trust, stress, and perceptual risk from human operators were measured under various scenarios regarding environmental settings by means of a post-hoc questionnaire for a comparison between the MASS and manned ships. Similarly, in the study by (Vakil 2021), Augmented reality and Virtual reality were explored as a means of training seafarers for the remote operation of autonomous ships. The study highlighted the importance of equipping operators with the necessary skills to manage complex systems remotely, suggesting that these training methods could improve safety and operational efficiency in the autonomous maritime environment.

Research on human factors has highlighted the essential role of human oversight in MASS operations. This encompasses the collaboration between MASS and human operators to bolster safety and performance. Studies emphasise that while automation is advancing, human situational awareness and the establishment of trust are critical for safety. The research spans various dimensions, including cultural and social aspects affecting remote operations and emphasises the need for effective communication strategies. A key point is the calibration of human trust in autonomous systems, which aligns with the enhancement of situational awareness and underscores the importance of incorporating human factors in the design phase to mitigate potential errors and stress-induced decisions. These findings highlight the critical nature of human oversight and the interplay between human operators and MASS.

3.1.2. Available techniques supporting the autonomy of MASS

The development of autonomous systems for MASS relies on a range of techniques to ensure efficient decision-making and collision avoidance. The available techniques can be broadly classified into two categories: sensor integration and communication for situational awareness and collision avoidance algorithms. Each plays a crucial role in enhancing the situational awareness, operational safety, and autonomy of MASS.

- Sensor Integration and Communication for Situational Awareness

Advances in sensor technology form the backbone of MASS situational awareness, providing essential data for navigation and operational safety. The sensors that are available for situational awareness of MASS were reviewed by (Thombre et al. 2022), where how to fuse sensor data using AI technologies was discussed. Additionally, rule-based approaches represent another important way to improve situational awareness and further collision avoidance (Huang et al. 2020a; Zhang et al. 2021). Furthermore, The study by (Zhang et al. 2023) focused on a rule-based method to analyse maritime traffic, which can enhance situational awareness among traffic service operators. Another specific method to enhance situational awareness is the ship domain model, which helps define safe operational spaces for vessels. The study by (Wielgosz and Pietrzykowski 2022) introduced a model where the declarative domain represents a theoretically safe area, while the effective domain reflects real-time human decisions based on situational factors.

Communication systems are vital to enhancing situational awareness, especially in an MWTS. For example, an efficient procedure of intent exchange between MASS and conventional ships in an MWTS was given by (Namgung et al. 2018). This paper argued that communication is necessary for situational awareness of ships for a clear and rule-compliant interaction when the collision risk is higher than the predetermined threshold that is set for triggering information exchange. Additionally, the study by (Namgung et al. 2020) introduced a process map for collision avoidance based on information exchange between autonomous vessels and manned ships. The study found that autonomous ships can avoid collisions more safely by exchanging navigational intentions with other vessels rather than acting independently.

Moreover, e-Navigation is another critical technology for enhancing situational awareness. e-Navigation is the integration of navigation systems, information exchange, and communication technologies. The principles of e-Navigation include safety, efficiency, interoperability, and so on. In the study (Porathe 2020), e-Navigation is suggested as a way to solve the interaction between MASS and conventional ships in an MWTS. A novel concept of Moving Havens was introduced in that paper to enhance traffic safety. Besides, the study conducted by (Akda et al. 2022) suggested applying e-Navigation to improve the collaboration performance of ships, especially for collaborative collision avoidance. Based on the analysis of the benefits of e-Navigation for conventional ships and the feature of collision avoidance between MASS, an innovative strategy was proposed, that is, combining those two to improve traffic safety.

- Collision Avoidance Algorithms

Various computational models and algorithms have been developed to ensure that MASS can autonomously avoid collisions in real-time. One of the foundational approaches to collision avoidance in MASS relies on traditional rule-based systems, which are often grounded in established maritime regulations such as COLREGs. These algorithms typically focus on ensuring compliance with navigational rules by encoding expert knowledge into decision-making processes. For instance, the study by (Zhang and Furusho 2016) proposed a ship decision-making model for collision avoidance by integrating expert experience and prior knowledge with a Bayesian Network, ensuring reliable navigation safety. Similarly, as noted by (Wang et al. 2023), the refinement of rule-based methods enables MASS to dynamically interpret traffic conditions, improving decision-making in real-time and supporting safer autonomous operations.

To further emulate human-like decision-making, the study by (Bakdi and Vanem 2022) employed a Fuzzy Logic approach to evaluate compliance with COLREGs. This method allows MASS to process navigational situations through a human lens, enabling more flexible interpretations of the rules and ensuring safer navigation in complex environments. These approaches, while effective in structured and rule-defined scenarios, often face challenges when dealing with highly dynamic or multi-vessel environments. Furthermore, to investigate how human navigators interpret the term 'safe speed' in the COLREGs, a study was conducted by (Dreyer 2023). This study stresses that navigators assess speed based on situational control rather than fixed metrics. This dynamic interpretation presents a challenge for autonomous ships, which must be programmed to understand and apply human-like decision-making to comply with maritime regulations and operate safely alongside conventional vessels.

In contrast to rule-based methods, data-driven and adaptive learning approaches focus on the ability of MASS to learn from the environment and continuously adapt their decision-making processes. Machine learning, particularly deep reinforcement learning, plays a key role in these techniques. For example, the work by (Zhang et al. 2019) introduced an Artificial Potential Fields (APF)-Deep Reinforcement Learning (DRL) method for collision avoidance. This approach combines APF with an ontology-based system for classifying encounter scenarios, allowing MASS to optimise decision-making while remaining compliant with COLREGs. Expanding on the APF methodology, the study conducted by (Lyu and Yin 2019) used a method of modified APF for MASS. It was demonstrated how the algorithms performed in the scenario of encountering a single target ship, as well as multiple target ships, considering a COLREGs-constrained strategy and a reactive avoidance strategy in case of a violation from the target ship. Similarly, (Wei and Kuo 2022) applied a DRL model to multi-ship collision avoidance. The study divided encounter situations into four regions based on COLREGs, transforming navigational goals into corresponding rewards, such as collision avoidance and path following. This method allows MASS to navigate safely in environments with multiple vessels, further highlighting the capabilities of adaptive learning systems in complex and multi-agent scenarios.

Hybrid optimisation and predictive approaches combine the strengths of traditional rule-based methods with advanced computational techniques to enhance decision-making in uncertain environments. These approaches often involve optimisation algorithms and predictive models that allow MASS to handle dynamic obstacles and multi-target scenarios more effectively. For instance, a greedy interval-based motion planning model was proposed by (Geng et al. 2019) based on the Velocity Obstacle method. This method enables MASS to navigate efficiently while predicting the movements of surrounding vessels, making it an effective solution for avoiding both stationary and dynamic obstacles in maritime traffic systems.

In terms of risk-based decision-making, a risk-aware approach by incorporating a risk evaluation model was introduced into a DRL framework by (Heiberg et al. 2022). This method enables MASS to balance between path-following and collision avoidance behaviours dynamically, adapting to the level of risk present in real-time maritime scenarios. The study showed great improvements in decision-making capabilities when navigating complex environments, particularly in high-risk situations. Additionally, to address the uncertainties present in mixed-obstacle environments, the study (Zheng et al. 2023) introduced a decision-making model that combines a Partially Observable Markov Decision Process (POMDP) with Proximal Policy Optimization (PPO). This hybrid approach proved to be more effective than conventional algorithms in enhancing navigational safety, as it allows MASS to make more accurate decisions in uncertain and partially observable environments.

Another hybrid approach was developed by (Wu et al. 2021), who proposed a proactive decision-making model that integrates human risk preferences into the navigation process. In this model, human preferences for risk, such as aggressive, neutral, or cautious approaches, can override autonomous decisions. This allows MASS to make flexible and adaptive decisions based on the risk tolerance of the human operator, ensuring that navigation is both safe and efficient under varying conditions. Furthermore, in scenarios where MASS operates alongside manned vessels, human-machine interaction becomes a key area of focus. Human-machine integration approaches aim to combine human judgment and preferences with the autonomous capabilities of MASS. For example, A study utilising a maritime simulator to evaluate the available algorithms was carried out by (Vagale et al. 2022b), where the decisions made by human navigators and the autonomous navigator driven by algorithms were compared. The scenarios in this study considered the interaction between MASS and manned ships, providing a potential approach for future research and testing on the interaction in an MWTS with different competencies of human operators.

Additionally, the work by (Dreyer 2023) explored the challenges of programming MASS to interpret and apply the concept of safe speed in the context of COLREGs. The study highlighted that human navigators assess speed based on situational control rather than fixed metrics, which presents a challenge for autonomous ships. MASS must be able to replicate this dynamic decision-making process to operate safely alongside conventional vessels. Moreover, a Double Deep Q Network (DDQN) that integrates human experience with COLREGs was developed by (Zhai et al. 2022) for collision avoidance. This system allows MASS to learn from human navigational practices, enabling rule-compliant and efficient decision-making. The DDQN model helps improve safety by learning how human operators react in real-world environments and applying similar decision-making strategies autonomously. In order to improve the capability of collision avoidance of MASS, the study conducted by (Hwang et al. 2024) provides adaptive collision avoidance systems (CAS) to enable the MASS to avoid collisions with manned ships in an MWTS. By focusing on the target ship's manoeuvring behaviours, particularly the manned ships, a simulator-based method was used to collect the navigational data that would be used to adjust the sensitivity of CAS collision avoidance.

Investigations into MASS autonomy have concentrated on the development of sensor integration, communication systems for situational awareness, and collision avoidance algorithms. These tools are crucial for maintaining situational awareness and executing collision avoidance strategies. The analysis indicates a focus on designing algorithms that not only comply with maritime regulations such as COLREGs but also incorporate human operation practice in decision-making processes. The emerging theme is a concerted effort toward systems that balance autonomy with human-like responsiveness, emphasising the need for seamless human-machine interaction.

3.1.3. System analysis and design for human-MASS interaction

This section reviews the frameworks and methodologies proposed in the literature aimed at developing systems for human-MASS interaction. The approaches discussed cover various requirements of the MASS system, as well as the implementation of system designs that ensure both operational safety and efficiency.

- Systems Analysis of MASS

Research on the systems analysis of MASS has focused on constructing frameworks for human-MASS interaction. Two kinds of design in human-robot interaction (HRI) serve as the basis for developing frameworks for human-MASS collaboration: Human Emulation and Human Complementary (Fong et al. 2003). While human emulation focuses on mimicking human decision-making processes, human complementary approaches combine and utilise both human and computer abilities. MASS, regarded as a robot for executing different procedural tasks, is closer to the human complement (Huang et al. 2020b). There has also been some work with the human emulation approach, such as a human-like knowledge base for the autonomous ship on the basis of expert experience for autonomous ships (Bachari-Lafteh and Harati-Mokhtari 2021; Kooij 2021; Kooij and Hekkenberg 2021). It was concluded that both kinds of approaches are feasible for MASS.

Several studies have explored these frameworks in detail. For instance, the study (Veitch et al. 2024b) used field study observations, semi-structured interviews, and theoretical sampling to investigate a design of collaboration work in the control room by advocating for a collaborative approach that leverages the strengths of both human and AI components. This study suggests that training and certification programmes are necessary to equip navigators with the skills required for human-AI collaboration. Similarly, the study by (Bakdi et al. 2021) developed a data-driven method to create realistic test scenarios for testing MASS. By using large-scale traffic data from AIS, digital maps, and vessel registries, the study constructs complex navigation scenarios that simulate real-world conditions such as collisions, grounding risks, and vessel-to-vessel interactions.

It is worth noting that transparency is an important factor that has been the focus of various studies on the framework of human-MASS interaction. A framework for human-automation interaction was presented in (Porathe 2021), focusing on automation transparency. The study proposed interface designs that allow operators to quickly regain situational awareness in emergencies, ensuring timely intervention and enhancing overall safety. Besides, Automation transparency was also examined by (Alsos et al. 2022), where the authors proposed methods for MASS to communicate their state and intentions to nearby vessels and stakeholders. The research concluded that improving transparency is key to ensuring safe navigation and interaction between autonomous and manned vessels. Additionally, a framework for human-automation interaction was presented by (Porathe 2021), focusing on automation transparency. The study proposed interface designs that allow operators to quickly regain situational awareness in emergencies, ensuring timely intervention and enhancing overall safety. Moreover, focusing on improving human supervision of autonomous collision avoidance systems by enhancing agent transparency, the study by (van de Merwe et al. 2024) identified specific situational awareness requirements and cognitive activities needed to verify agent performance.

Furthermore, safety concerns are important in autonomous system designs. In the study (Dittmann et al. 2021b), a sovereign-based control system design integrates human supervision, where decision-making starts with situational awareness and ends with actions executed by the human operator. Other studies, such as (Kim et al.

2022), explored safety challenges for MASS related to the interaction between MASS and conventional ships with varying degrees of autonomy. For example, Technical challenges (malfunction, communication interference, cyber threats, as noted by (Carrara 2022; Longo et al. 2023), environmental challenges (adverse weather, limited visibility, dynamic navigational conditions), and human-related challenges (responsibility confusion, human competence, human error), can all pose safety risks for autonomous ships in mixed navigational environments. The safety of interactions between humans and systems was analysed by (Cheng et al. 2023) for the MASS controlled or supervised by the operator at the shore control centre. The study proposed an approach that integrates the human cognitive model and system theoretic process analysis to identify safety risks.

With respect to the system analysis of ship collision avoidance, the study by (Huang et al. 2020a) reviewed the methods of collision avoidance for ships, where the strategy discrepancy of collision avoidance was pointed out. It is suggested to enable the MASS to be user-friendly for human operators by exploring the functions in conventional vessels. In addition, a decision-making framework of collaborative collision avoidance for MASS and manned ships was proposed by (Akda et al. 2022). The study takes advantage of the communication and cooperation between ships and the shore control centre to accurately predict and avoid collisions, utilising real-time data from various sources, including ship sensors and global navigation satellite systems, to provide a comprehensive view of the navigational environment. Furthermore, the paper by (Kim 2023) provided a methodology for legally correcting collision avoidance actions according to COLREGs by utilising a decision-making tree and quantitative analysis methods for COLREGs. It offers a framework for legal compliance in collision avoidance between autonomous and manned ships. Besides, considering the issues of information acquisition and situational awareness that may arise in an MWTS, several potential proposals were discussed by (Rødseth et al. 2023) in relation to Vessel traffic management, Traffic separation schemes, etc.

In addition, several other approaches have also been employed for the autonomous system of MASS. In (Poornikoo and vergrd 2022), a fuzzy logic approach was introduced to define levels of automation in MASS. The study aimed to address the imprecision in the current level of automation taxonomies and proposed a clearer framework to improve the interaction between human operators and autonomous systems. Furthermore, in the work by (Ramos et al. 2020b), the authors argued that the tasks of humans and the system are changeable, with the level of autonomy of the MASS being different. Using the human-system interaction in autonomy method, tasks involving monitoring ship status and surroundings and evaluating potential risks were examined for human-MASS collaboration in collision avoidance scenarios. Additionally, a System Theoretic Process Analysis was applied by (Ventikos et al. 2020) to determine the relationship between the hazards and the degree of autonomy of MASS. A key finding of this study is that situational awareness could fail due to the failure of the sensors, which supports that the design of humans in the loop and redundant sensors for situational awareness are necessary for MASS. Additionally, the resilience of MASS was discussed in (Fjørtoft and Mørkrid 2021), where human-MASS interaction was included. It is highlighted that the situational awareness of MASS contains several types: navigational awareness for safe navigation, operational awareness for information sharing, and distributed situational awareness for collaborative navigating on a remote-controlled ship. Moreover, a Bayesian belief network was applied in (Thieme and Utne 2017) to assess human-automation collaboration performance on unmanned underwater vehicles. In this study, the capability of situational awareness and the reliability of the autonomous system are suggested to support a smooth collaboration.

Additionally, a human-machine model was given by (Fan and Yang 2023) to evaluate seafarer competencies in automated systems. It emphasises the importance of training and assessing human factors to ensure safety in maritime operations. Functional requirements for Onshore Operation Centres supporting autonomous ships were outlined in (Adnan et al. 2024). The study discussed the technological, navigational, and operational needs of Onshore Operation Centres, concluding that robust communication technologies and real-time monitoring are essential for supporting safe and efficient vessel operations.

Moreover, risk assessment frameworks were also proposed for MASS. In (Pedersen et al. 2022), a high-level risk analysis of autonomous vessels was conducted, combining simulation-based testing with safety assessments. The study demonstrated that systematic testing is vital to mitigate potential risks before full-scale deployment, ensuring the safety and reliability of ship automation systems. A framework for analysing risk coupling in different operational modes of MASS was proposed by (Fan et al. 2024), focusing on the interaction with the environment and internal and external systems related to MASS. The study identified that 15 common failure modes could be classified into the risk factors related to humans, organisations, ships, environments, and technology, with the example of grounding accidents.

- Implementation of System Design

Human-centred design methods prioritise human needs and capabilities in the design of MASS systems. For instance, the study conducted by (Veitch et al. 2021) outlines a process that includes user analysis, requirements specification, system design, and evaluation, ensuring that the designs align with operator expectations and capabilities. Another innovative approach was the introduction of the 'ship immune system' proposed by (Ventikos and Louzis 2023), which highlights adaptive risk management strategies that anticipate and mitigate potential risks in real time, supporting the safety of MASS operations. Additionally, integrating AI in marine navigation is key to improving human-MASS collaboration. The study conducted by (Veitch et al. 2024c) investigated the integration of AI in marine navigation, underscoring the discrepancy between designers' and navigators' perspectives on human-AI collaboration. It suggests designing AI systems that incorporate social cues that articulate human work and that visualise computational activities to better support human cooperation.

In the realm of collision avoidance, various systems have been developed by integrating human and machine intelligence. A collision avoidance system was designed by (Huang et al. 2020a), where human operators playing various roles within different navigational scenarios were discussed in detail. This system supports the MASS in making correct and reliable decisions for cooperative MASS navigation. In (Martelli et al. 2021), a decision-making system was also designed for safe and efficient navigation of MASS, consisting of five components: real-time data collection and processing, decision-making algorithms, human-in-the-loop decision-making, communication and information exchange, and human-AI collaboration.

Literature on system design and analysis points to the importance of integrating human insights and advanced technology to ensure safety and efficiency. It focuses on enhancing transparency and situational awareness within autonomous maritime systems through the development of collaborative frameworks that balance human and machine capabilities. These systems are crucial for enabling effective communication and decision-making between manned and autonomous vessels, emphasising the need for adaptive risk management strategies and human-centred designs to address the dynamic complexities of the MWTS.

3.1.4. Potential requirements for human-MASS interaction regarding regulations

The successful implementation of MASS within existing maritime operations hinges not only on technological advancements but also on regulatory and human competency adaptations.

- Regulatory Framework Development

In recent years, IMO has been exploring the amendment of IMO standards for MASS based on the current standards. That means MASS not only pursues high efficiency and lower risks of navigation but should also comply with existing regulations at least as successfully as the conventional ship. Therefore, safety and efficiency (Thombre et al. 2022) are the primary goals for MASS.

Regarding compliance with regulatory standards, the study by (Misas et al. 2024) emphasises the regulatory requirements to ensure safe and secure MASS operations.

With respect to the amendment of COLREGs, the study by (Porathe 2019) emphasises the ambiguity in terminologies within COLREGs, which may lead to discrepancies in communication between MASS and traditional vessels. Possible solutions, namely increasing the transparency of actions, were discussed, as well as improving safety and efficiency.

- Human Competency and Skill Development

Incorporating MASS into maritime operations also requires a shift in the skills and competencies of human operators, particularly those working in Remote Control Centres. Several studies highlight the need for continuous development in human oversight skills as automation becomes more integral to maritime navigation.

The study (Hynnekleiv et al. 2020) emphasised the importance of human factors in MASS operations, identifying key skill sets required for operators managing highly automated systems. The research concluded that the continuous development of human competencies is essential for the successful integration of autonomous technologies in maritime operations. With a systematic literature review, several findings came up in (Veitch and Alsos 2022). In particular, the human operator plays the role of more than a backup regarding MASS safety, and new competency requirements need to be improved for human operators at RCC to deal with emerging issues.

Furthermore, a study analysed and explored possible competency requirements for remote operators at RCC by (Yoshida et al. 2020). By conducting an interview, potential threats were found, and thus, additional requirements were suggested to be satisfied by operators for safety-critical supervision of MASS. For example, the ability to recognise necessary information from a display of equipment and other items at RCC under restricted conditions and the ability to confirm the accuracy of the information obtained from restricted ship sense, radar display and other items.

The successful integration of MASS into maritime operations depends on a multi-faceted approach that encompasses regulatory framework development, human competency enhancement, and improving transparency in autonomous systems. Research shows that updating international regulations, such as COLREGs, is crucial to ensuring the safe operation of MASS. Equally important is the ongoing training and development of human operators, who play a central role in overseeing autonomous systems. In parallel, fostering transparency in MASS operations, particularly in high-risk scenarios like collision avoidance, is essential for preventing misunderstandings and ensuring cooperative interactions between autonomous and manned vessels.

Research in human-MASS interaction focuses on four domains: human factors, support for MASS autonomy through technological advancements, system analysis and design for human-MASS interaction, and potential regulatory requirements. These studies highlight the necessity of enhancing interactions between MASS and human operators from various perspectives. Collectively, these studies reveal a critical perspective: ***It is essential to ensure safe and efficient collaboration between humans and autonomous systems***. A detailed analysis of the research is given in Section 4.1.

3.2. Focusing on situational awareness of MASS

Ensuring safety is a primary objective in the maritime industry, particularly important across various operational states such as underway, anchoring, or mooring. The underway state, in particular, requires detailed attention due to its dynamic and complex navigational challenges.

Situational awareness is fundamental to maintaining safety under these conditions. The concept was proposed by (Endsley 1995) to describe what is happening, what it means, and what might happen next. This framework includes perception, comprehension, and projection as its core components.

In the maritime domain, research related to situational awareness has focused on four topics, as presented in Table 5: Architecture development of SA, Investigation of SA requirements for MASS, Enhancement of SA comprehension and projection capabilities, and Quantification of SA. Three types of methods have been employed to explore those topics, including literature reviews, algorithm-based approaches, and mathematical models.

Recent research has increasingly focused on the situational awareness challenges in human-MASS interactions, especially as human operators transition to supervisory roles over autonomous vessels. The study (Misas et al. 2024) investigated the challenges of the SA of MASS through a questionnaire that gauged seafarers' experiences across different human operational modes. Focusing on a similar problem, the research (van de Merwe et al. 2024) explored potential solutions to enhance human operators' understanding of autonomous systems, advocating for greater transparency in autonomous behaviours to facilitate adaptation to supervisory roles.

The studies conducted by (Lynch et al. 2023, 2024) highlighted the importance of SA of MASS by drawing parallels between challenges in MASS and uncrewed aerial vehicles, suggesting that lessons learned in aviation could inform maritime operations. A distributed situation awareness framework for a mixed waterborne transport system was proposed by (Song et al. 2023), suggesting improvements through the integration of service information, which could lead to a more interconnected navigational environment. Additionally, a study examining the impact of the immersion levels on SA and human trust was conducted by (Gregor et al. 2023) using virtual reality, revealing how immersion of instruments influences human operators' perception and decision-making process.

Despite extensive research into SA for both conventional and autonomous maritime vessels, there is a gap in foundational studies that specifically address the SA principles necessary for MASS operation within an MWTS. These principles are essential for the development of decision-support systems that support the navigational needs of MASS, including (1) Perception of elements in the environment within a volume of time and space, (2) Comprehension of their meaning for supporting MASS' navigation, and (3) Projection of the situation for MASS in the context of MWTS. The need to develop comprehensive models that integrate all elements of situation awareness is critical for creating reliable and transparent systems that can support calibrated trust levels among human operators, MASS, and services. This issue, along with proposed solutions to bridge the gap, will be further discussed in Section 3.3.

Table 5. Current research on situational awareness in the maritime domain.

Ref	Architecture	Requirements	SA comprehension and projection	SA quantification	Literature review	Algorithm-based	Mathematical method
Endsley (1995), Glandrup (2013), Martelli et al. (2021), Hansen et al. (2022), Broek and Waa (2022)	✓						
Thieme and Utne (2017)	✓	✓					✓
Song et al. (2022a)	✓	✓	✓				
Dittmann et al. (2021b), Menges et al. (2023), Scarlat et al. (2023)	✓		✓				
Wahlstrm et al. (2015)	✓				✓		
Wielgosz and Pietrzykowski (2022), Brandster et al. (2020)		✓					✓
Thombre et al. (2022), Kim et al. (2022), Ventikos et al. (2020), Han et al. (2022), Porathe et al. (2014), Sharma et al. (2019), Tam et al. (2021), Kristoffersen (2020), Hannaford and Hassel (2021)		✓			✓		
Porathe (2019), Fjørtoft and Mørkrid (2021), Namgung et al. (2018), Porathe (2020), Misas et al. (2024), Song et al. (2023)		✓	✓				
Perera and Murray (2019)		✓	✓	✓			✓
Chan et al. (2023a; Chan et al. 2023b), Lynch et al. (2024), Dittmann et al. (2021a), Ramos et al. (2018a), Kennard et al. (2022)		✓					
Mallam et al. (2019; Mallam et al. 2020)		✓	✓	✓	✓		✓
Zhou et al. (2019), Gregor et al. (2023)				✓			✓
Papageorgiou et al. (2022), Chan et al. (2022), Murray and Perera (2021)			✓				
Huang et al. (2016), Du et al. (2020), Sui et al. (2020), van de Merwe et al. (2024), Son et al. (2023), Cafaro et al. (2023), Sandru et al. (2021)			✓			✓	

3.3. *Implications on decision-making for human-MASS collaborative collision avoidance*

Based on proper situational awareness, good decision-making can be obtained, as stated in (Endsley and Garland 2000). Many studies have investigated the fully autonomous MASS decision-making (Insaurralde et al. 2018; Burmeister and Constapel 2021), for example, path planning (Chen et al. 2016; Zheng et al. 2019; Zhou et al. 2020a), ship control (Liu et al. 2015; Haseltalab and Negenborn 2017; Zheng et al. 2017; Chen et al. 2020a), trajectory tracking g (Zheng et al. 2014; Liu et al. 2015; Haseltalab et al. 2020; Li et al. 2020), and multi-vessels cooperation (Chen et al. 2018; Chen et al. 2020b; Du et al. 2021a, 2021b). They promote the MASS to be more autonomous and further as a teammate of human operators in the human-MASS team to perform tasks independently or collaboratively.

In terms of collision avoidance decision-making for MASS within an MWTS, a summary of applications is given in Table 6. It can be found that most studies considered the COLREGs to force the MASS to avoid collision with manned ships. It is worth noting that the target ships set in their experiments are often regarded as vessels keeping their course and speed the same without combining the human experience, such as preference, which is unrealistic in practice.

For this reason, some studies consider human operators' navigational data to improve the capability of collision avoidance of MASS. For example, the research conducted by (Hwang et al. 2024) analysed and extracted seafarers' manoeuvres and tested the collision avoidance system of the unmanned vessel with the extraction results. The study of extracting navigational features of manned ships from AIS data was investigated by (Liu et al. 2023), the results of which were applied to train MASS through the reinforcement learning method. These studies have contributed to the enhancement of MASS's capability to avoid collisions in an MWTS.

In the field of human-robot interaction, many scholars tried to model human behaviour for robot inference and prediction (Gonzlez et al. 2018; Tsai and Oh 2020; Sripathy et al. 2021), which can be referenced in the context of the navigation of MASS in an MWTS. For example, search and rescue (Cacace et al. 2016; Williams 2020), human-multi-robots collaboration (Rosenfeld et al. 2017), and so on. Among them, the mainstream is the application of decision theory in economics on HRI (Kwon et al. 2020). Specifically, the focus is to obtain a suitable model to depict the human decision process, such as the noisily rational model (Kretzschmar et al. 2016) and the risk-aware model (Kwon et al. 2020; Jiang and Wang 2022). In terms of these models, there are several kinds of methods to solve, for example, inverse reinforcement learning (Gonzlez et al. 2018; Palan et al. 2019) and reinforcement learning (Liu and Nejat 2016; Sadigh et al. 2016; Sadigh et al. 2018; Zhang et al. 2022). A summary of the results of human models for decision-making is given in Table 7.

In conclusion, in current research, there is a noteworthy gap in addressing the navigational preferences of manned vessels within complicated maritime environments. Most studies tend to model target ships as operating on simulated trajectories and improve the capability from the perspective of evasive algorithms, which ensure navigational safety between manned ships and MASS. While the MASS is equipped with robust collision avoidance capabilities, the real challenge lies in proactive engagement during the avoidance phase. Proactive collision avoidance is key to maritime safety, as passive avoidance strategies may lead to misunderstandings of navigational intent, potentially resulting in new collision conflicts. Therefore, it is

Table 6. Review of approaches of collision avoidance in an MWTS.

Ref.	Method	COLREGs-considered		Human element-considered		Objects Setting	
		Own ship	Target ship	Own ship	Target ship	Dynamic	Stationary
Wei and Kuo (2022)	Reinforcement learning	✓	✓			✓	
Wu et al. (2021)	Risk appetite-considered	✓	✓		✓	✓	
Huang et al. (2020b)	HMI-CAS	✓		✓	✓	✓	
Zhai et al. (2022)	Reinforcement learning	✓		✓		✓	
Geng et al. (2019)	Velocity Obstacle algorithm					✓	
Lyu and Yin (2019)	APF	✓			✓	✓	
Zhang et al. (2019)	APF-Deep Reinforcement Learning	✓				✓	✓
Hwang et al. (2024)	Velocity obstacle algorithm	✓			✓	✓	
Chen et al. (2023)	Blockchain-based communication	✓	✓			✓	
Kim (2023)	Decision-making tree	✓			✓	✓	
Liu et al. (2023)	Deep reinforcement learning	✓			✓	✓	✓
Lazarowska (2023)	Firefly algorithm and ant colony optimisation	✓				✓	
Chen et al. (2024)	Scan-searching method combined with APF	✓			✓	✓	
Papadimitrakis et al. (2021)	Model predictive control and radial basis function	✓			✓	✓	

Table 7. Brief review of popular human decision models in HRI.

Ref.	Parameters	Method	Outputs	Setting	Type
Kwon et al. (2020)	Information amount of decisions, time, risks, and corresponding human actions	Cumulative Prospect Theory	The probability of behaviours anticipated	Human driver decision-making under uncertainty and risks	Risk-aware
Jiang and Wang (2022)	Subjective feeling to consequences; human detection cost	Regret theory	Risk awareness degree	Robots ordering in human-multi-robots task allocation	Risk-aware
Cacace et al. (2016)	Command, geometrical data, robot status, etc.	Dynamic Bayesian Network	The probability of being involved in the task	Multi-Robot Interaction in Search and Rescue Missions	Noisy rational
Sadigh et al. (2018; Sadigh et al. 2016)	Reward control and reward affect desired human actions	Reinforcement learning	Coordinated plans	Autonomous planning for autonomous vehicles coordinating with human-driven cars	Noisy rational
Christiano et al. (2017)	Human preference for trajectories	Reinforcement learning	The optimal strategy for action-taking	Human Preferences learning	Noisy rational
Gonzlez et al. (2018)	Driving behaviour features lane, Time-to-collision, Timeheadway, etc.	Inverse reinforcement learning	Reward cost function	Modelling driver behaviour	Noisy rational

essential to incorporate a model of human navigational preferences and decision-making processes. This would enable autonomous systems to predict and adapt to the manoeuvres of manned vessels more effectively, ensuring smoother and safer interactions.

3.4. *Trust in human-MASS collaborative navigating*

The introduction of MASS aims to augment maritime safety by minimising human error, a critical factor in maritime incidents. Nevertheless, this does not negate the essential role of human operators. Instead, it transforms it by positioning it as a critical overseer for autonomous operations. This model leverages human judgement alongside autonomous technology to strengthen safety protocols. Therefore, the efficacy of MASS hinges on human operators' trust in these systems' situational awareness and decision-making capabilities, ensuring they can intervene when unexpected challenges arise (Abilio Ramos et al. 2019; Zhu et al. 2019; Mansor 2022).

Trust in HRI is a priority topic that is gaining increasing attention in human-robot collaboration. With properly aligned trust, humans as supervisors can decide in time on the actions to be taken based on the belief in the robot. Trust is defined in (Kok and Soh 2020) as a multidimensional latent variable that mediates the relationship between events in the past and the former agent's subsequent choice of relying on the latter in an uncertain environment. Trust refers to the function of successful and proven operations that are assessed by human operators from the perspectives of social norms and technology acceptance in (Mallam et al. 2020). In that study, human trust is extracted through interviews about the potential impact of autonomous technologies, where 10 participants from both academia and industry were recruited to respond to questions related to their trust in autonomous ships.

Several studies indicated that the more human operators understand the robot's decision-making process, the more properly aligned trust they have in the robot (Yoshida et al. 2021). Therefore, better performance for MWTS can be obtained if each vessel within the current WTS can interact with one another to share its intentions to avoid misunderstandings. Properly aligned human trust in the autonomous system's true capabilities is the foundation of high-performance human-system teaming. Both over-trust and under-trust are undesirable in HRI, which may lead to poor collaboration performance (Kok and Soh 2020). In an MWTS, likewise, there will also be the collaboration between humans and MASS, such as MASS auto-docking at a conventional berth, collision avoidance for the conventional ship and the MASS, and so on, where trust is a critical factor to be considered affecting the collaboration performance (Veitch and Alsos 2022). An overall summary of the research results of human trust in the autonomous system of MASS is given in Table 8.

For the sake of ship safety, humans can generally take over control of the MASS in emergency situations that the MASS cannot handle. Due to cognitive differences, humans may diverge when encountering certain new situations. In addition, seafarers on board the ship and managers at RCC have differences in the level of trust in sensors (Wang et al. 2015), which may lead to a discrepancy in situational awareness. In order to obtain good and seamless collaboration and to further reduce the human workload, it is desirable that the

Table 8. Overview of human trust in the autonomous system of MASS.

Ref.	Methods	Parameters	Outputs	Setting
Venverloo et al. (2021)	Immersive virtual reality & post-session Questionnaires	Beliefs and observations of the robot's surroundings, goals, actions, etc.	Trust values	Evaluating human experience on a MASS and a manned ship
Veitch and Alsos (2022)	Literature review		The importance of trust in the human-autonomy interaction system	Human-autonomy collaboration performance
Costanzi et al. (2020)	Survey		The importance of trust in the human-autonomy interaction system	Interoperability of multiple Unmanned Marine Vehicles
Thieme and Utne (2017)	Bayesian belief network	Object status, reward function	Human interference rate	Assessing human-autonomy collaboration performance
Mallam et al. (2020, Mallam et al. 2019)	Interview		Potential effects of trust	Exploring the potential effects of MASS
Tam et al. (2021)	Survey		The impact of trust on human stress	Mental health effects on the MASS
Misas et al. (2024)	Questionnaires		Training needs	Maritime operations, remote operations
Aalberg (2024)	Questionnaires	Professional commitment, age of officers	Trust values	The relationship between Professional commitment and Trust in autonomy
Lynch et al. (2024)	Literature review	Decision-making factors	Design recommendations for MASS	Remote Control Centre operations
Lynch et al. (2023)	Interview		Key topics related to human trust in the decision-making process	The decision-making operation of the MASS investigation
Chan et al. (2023a)	Interview		Trust levels	The investigation of trust in autonomy
Gregor et al. (2023)	Simulated RCC interfaces, Virtual Reality	Levels of Immersion in HMI	Trust in systems	The effect of immersion on the trust level of RCC operators
Alsos et al. (2024)	Interview		Passenger trust in ferries	Trust in the use of autonomous urban ferries

MASS take reasonable and human-satisfactory actions. That is, the autonomous system of MASS is supposed to be safe, reliable, and trustworthy (Veitch and Alsos 2022).

Taking human trust into account, recent research has focused on the impact of human trust on the performance of the MASS system. As discussed in Section 3.2, (Lynch et al. 2023, 2024; Gregor et al. 2023; Misas et al. 2024) and (Aalberg 2024) highlighted the impact of human trust on the decision-making process of MASS and human operators, which should be considered carefully in the design of MASS and seafarers training. The research by (Chan et al. 2023a) investigated seafarers' trust in the autonomous system of unmanned vessels through interviews with 100 seafarers with varying navigational experiences. The results indicated that trust discrepancies existed among participants, with higher-ranking participants having similar perceptions of autonomy as those with less experience.

In conclusion, increasing attention is being given to the role of human trust in the context of human-MASS interaction, particularly regarding its integration into decision-making processes. However, this area of research has not yet been extensively developed and requires more focus. Effective integration of human trust is essential for ensuring safety and efficiency in the MWTS. Further research is necessary to understand and implement trust calibration within MASS operations, promoting better collaboration between human operators and autonomous systems.

4. Discussion

4.1. Synthesis and identified gaps

In the context of waterborne transport, the safety of the ship is of utmost importance and must be prioritised over any other objective. However, to meet the expectations of various stakeholders such as ship companies, seafarers, and other service providers, it is also crucial to improve the efficiency of the system.

It is noteworthy that various research topics that were previously studied independently must be considered in a more holistic manner in the MWTS. These include the situational awareness required to support the safe navigation of MASS, navigational preference-aware collision avoidance of MASS and conventional ships, and the assessment of human trust in the autonomous systems of MASS. All of these topics are interrelated.

There are still several findings and gaps in the existing state of the art, as well as gaps of knowledge:

4.1.1. Findings

Research in human-MASS interaction is broadly categorised into four main domains: human factors, technologies that support MASS autonomy, system analysis and design, and potential regulatory requirements for interactions. Key findings from each of these areas are outlined below:

- **Human Factors:** Studies indicate that human factors such as situational awareness and trust are important in MASS operations. Human errors, such as misjudgments caused by human errors or decreased situational awareness, can lead to operational failures. The establishment of trust between human operators and autonomous systems is critical for safe and efficient interaction, especially in remote control scenarios.
- **Technological Advancements:** There have been great developments in sensor integration and collision avoidance algorithms, enhancing the autonomous capabilities of MASS, especially in terms of situational awareness. These advancements support the independent operation of MASS but still necessitate human oversight.
- **System Analysis and Design:** There is a focus on designing human-machine frameworks or systems that enhance operator interaction with MASS. Clear and transparent system designs and well-defined human roles are crucial for maintaining operator situational awareness, particularly in emergency situations. Additionally, hybrid systems that integrate human decision-making with autonomous capabilities offer more reliable solutions for managing the complexities of the operational environment for MASS.
- **Regulatory Considerations:** As the roles of human operators shift from direct control to supervision, monitoring, and emergency response, there is a pressing need to update training and certification to align with these new responsibilities. Regulations, including COLREGs, must evolve to address the legal and

operational challenges posed by MASS, particularly in ensuring seamless collaboration between manned and autonomous vessels.

4.1.2. Gaps

Based on the review of current literature on human-MASS interaction within the contexts of safety, efficiency, and regulatory compliance, several gaps have been identified:

(1) **Situational Awareness Specific to MASS:** While situational awareness has been well-developed in maritime operations, specific applications to MASS require further development. Current models do not fully address the unique challenges of integrating MASS into mixed-traffic environments. There is a need for situational awareness models specifically tailored for MASS within an MWTS, which should incorporate the role of human operators during the human-MASS interaction process. This inclusion can enhance the reliability and clarity of MASS's decision-making processes. Furthermore, advanced situational awareness can also support human operators, assisting operators in managing complex situations. This serves as an intermediate step from manned operations to fully autonomous MASS, ensuring a smoother transition and improved safety.

(2) **Navigational Preference-aware Collision Avoidance in an MWTS:** There is a gap in research addressing the navigational preferences of manned vessels within complicated maritime traffic scenarios. Most existing studies simulate target ships on fixed trajectories and focus on enhancing the evasive algorithms of MASS. An evasive model involving the navigational preferences of manned ships in collision avoidance is crucial for ensuring navigational safety, which can provide proactive and mutually understandable navigation strategies within the MWTS.

(3) **Trust Calibration in Human-MASS Interaction:** Efficient collaboration between human operators and MASS relies on properly calibrated trust. Current research does not sufficiently cover trust calibration methodologies between human operators and MASS. Developing robust mechanisms for trust calibration is essential to ensure balanced human oversight and autonomous operation (neither under-trust nor over-trust), enhancing teamwork and safety in the MWTS.

4.1.3. Limitations

Despite the comprehensive literature review employed in this study, several limitations should be acknowledged, which may have impacted the findings and interpretations. Firstly, while a comprehensive keyword strategy was employed, there is always a possibility that the chosen keywords may have inadvertently excluded relevant studies due to variations in terminology. Secondly, subjectivity in the screening process, despite efforts to mitigate it through consensus and multiple reviewers, may have influenced study selection. Lastly, the eligibility criteria, such as restricting the review to English-language and peer-reviewed studies, may limit the generalisability of the findings. These limitations suggest that the results should be interpreted with caution, and future research should address these challenges.

4.2. Integrated framework for safety and efficiency of human-MASS interaction

In this section, taking the research gaps discussed above, we propose an integrated framework for human-MASS interaction, ensuring the safety and efficiency of MASS navigation. Firstly, we propose a taxonomy of interactions between humans and MASS within an MWTS by means of 11 future scenarios shown in Figure 4. Furthermore, in order to gain insight into these interactions, the scenarios are classified into four categories based on the participation status of different stakeholders: MASS, manned ships, services, and RCC, divided into mandatory and optional participation, as presented in Table 9.

The term 'services' in this context refers to various supportive entities that play crucial roles in maritime operations. These services include but are not limited to: Traffic Management Services, Pilotage Services, and Search and Rescue, see examples 1, 3, 5, 6, 8, 10, and 11 in Figure 4.

4.2.1. Module descriptions and functions

A diagram depicting the integrated framework for human-MASS interaction illustrates the critical components and their interrelationships, as shown in Figure 5. The framework is built on three key modules: situational awareness, navigation preferences of manned ships (hereafter referred to as 'navigation preferences') and human trust. Each module is adapted to the type of interaction specified in Table 9, with different scenarios determining the level of involvement of MASS, manned vessels, services and RCC.

It is evident that human trust has a direct impact on situational awareness and decision-making. Concurrently, situational awareness exerts an impact on navigational preference and decision-making modules. In turn, the outcomes of situational awareness and decision-making modules can influence human trust, creating a feedback loop that refines the performance of human-MASS interaction over time.

It is crucial to distinguish between 'impact', a direct and immediate effect on decision-making processes and 'influence', which refers to more gradual and subtle effects on the system's operations.

(1) **Situational Awareness Module**: This module captures real-time data from MASS sensors and external sources to create a comprehensive view of the surrounding navigational environment. The accuracy of situational awareness relies not only on the sophistication of the sensors for perception but also on its capability of comprehension and projection to the situation correctly. It considers factors including the status of the own ship, proximity to nearby obstacles, weather/sea conditions, regulatory requirements, etc.

(2) **Navigational Preferences Module**: This module integrates learned preferences and historical patterns of manned vessels to predict the behaviours and preferences of manned ships in the vicinity, facilitating friendly and proactive evasive decision-making of MASS in an MWTS.

(3) **Human Trust Module**: This module is an essential component in human-MASS interaction to evaluate and adjust human trust, which could be captured by analysing the reactions of human operators to a calibrated level based on the interaction types classified in Table 9. For each type of interaction, whether involving direct operational collaboration or more autonomous functions, the module is dynamically adjusted. This ensures that MASS operates in accordance with human expectations and safety requirements. The trust settings are related to the participation of various stakeholders in each scenario, influencing the decision-making process of the autonomous system of MASS.

4.2.2. Decision-making process

The decision-making process within this framework is structured into three stages:

(1) In the first stage, human trust and situational awareness are involved in the decision-making of MASS. Data from various sources are processed to create a comprehensive understanding of the environment, which is used to assess the situation,

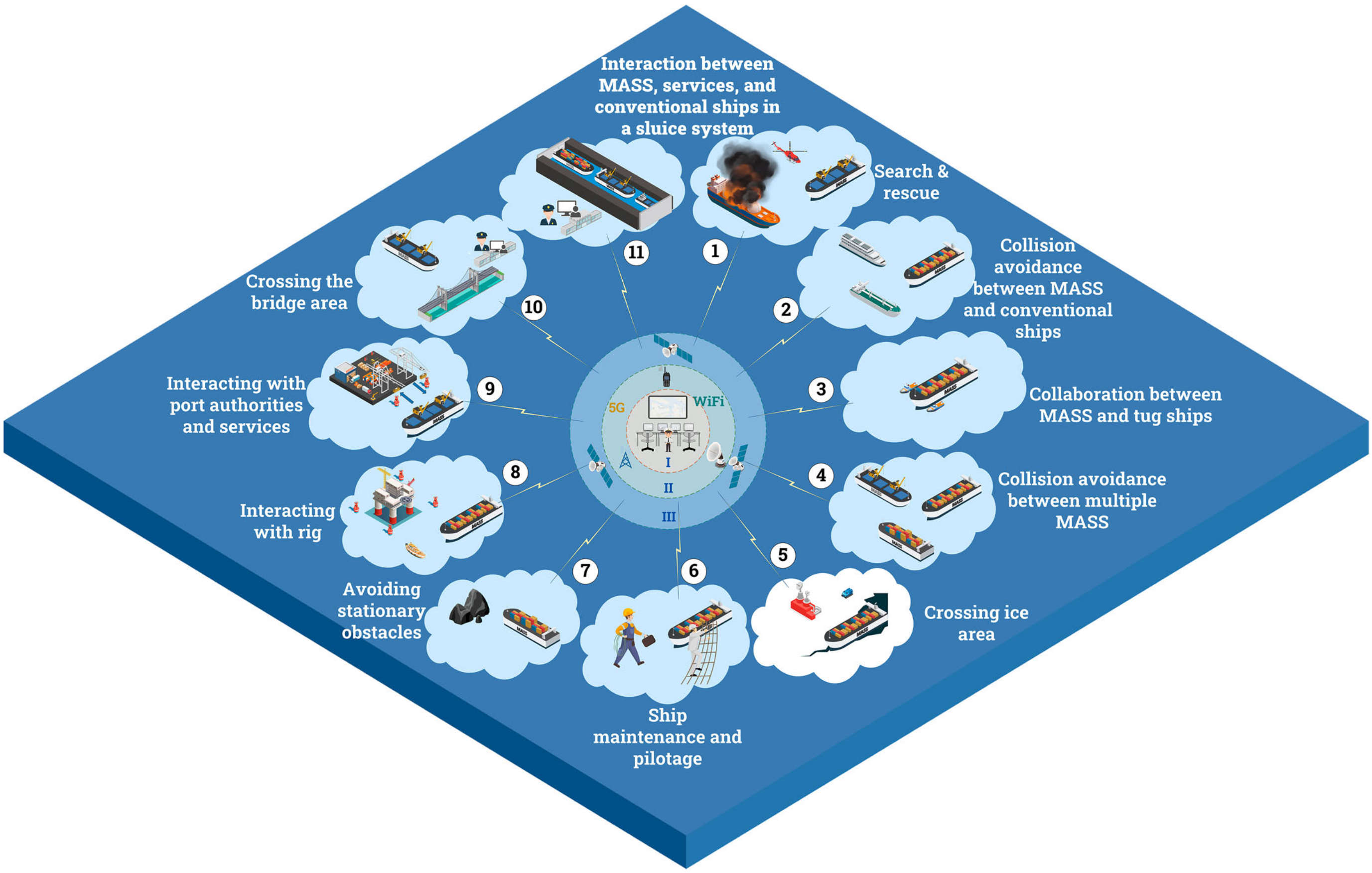

Figure 4. Taxonomy of scenarios of future interaction between humans and MASS.

Table 9. Keywords corresponding to each research question.

No.	Scenarios	MASS	Manned ships	Services	Remote control centre	Interaction types
1	The tasks of search and rescue	*	*	*	+	I
2	Collision avoidance between MASS and conventional ships	*	*	+	+	II
3	Collaboration between tug ships and MASS	*	*	+	+	II
4	Collision avoidance between multiple MASS	*	*	+	+	II
5	MASS crossing ice area	*	+	*	+	III
6	The task of maintenance for MASS by human operators	*	+	*	+	III
7	MASS avoiding stationary obstacles	*	+		+	IV
8	MASS interacting with rig	*	+	*	+	III
9	The interaction between MASS and port authorities and services	*	+	*	+	III
10	MASS being crossing bridge waterways	*	+	*	+	III
11	The collaboration between MASS, services, and conventional ships in a sluice system	*	*	*	+	I

Note: * indicates this attribute must be presented, whereas + means that this attribute is optional in this scenario.

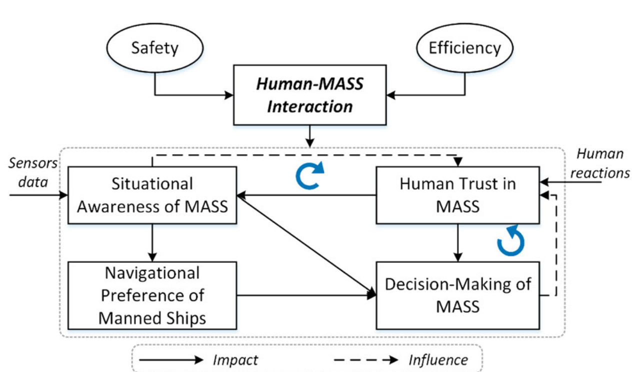

Figure 5. The diagram of human-MASS interaction for safe and efficient navigation.

determine the level of risk in the next step, and generate recommended actions to deal with it.

The situational awareness module integrates calibrated human trust for safe and reliable situational assessment. Human trust may affect the results of the situational awareness module due to the cognitive discrepancy, which may be caused by the human operator's experience and the degree of environmental awareness. The operator with high trust would give more autonomy to the vessel to be aware of the situation and plan further. On the contrary, humans check situational awareness from an autonomous system frequently and correct the results with low trust.

Regarding the method for investigating the impact of human trust on situational awareness in MASS, a method based on the combination of self-reported questionnaires, behavioural observations, and direct inquiry could be used, aiming to capture a comprehensive understanding of the relationship between human trust and situational awareness. More specifically, this method includes:

(i) Self-reported Questionnaires: Tailored to evaluate operators' trust towards the autonomous system's capabilities, these questionnaires should focus on eliciting responses that reflect trust levels in various operational scenarios.
(ii) Behavioural Observations: This involves monitoring operators' interactions with MASS systems under simulated conditions to identify behaviours that signify trust, such as the frequency of system overrides or reliance on autonomous decisions.
(iii) Direct Inquiry: This method allows participants, such as MASS operators or navigational personnel, to record their trust levels in real time based on their experiences or hypothetical scenarios involving autonomous systems.

(2) In the second stage, the navigational preference module participants when there is an obstacle in the vicinity, which may lead to potential collision conflict justified by the situational awareness module. The MASS makes decisions based on a comprehensive understanding of the situation, factoring in both situational awareness and the navigational preferences of nearby vessels. With the outcome of the situational awareness module as input, the module, along with the situational awareness module, provides evasive strategies to the decision-making module to make informed decisions in an MWTS.
(3) The final stage is to evaluate the performance of the MASS when considering the impact of human trust on its decision-making processes. In order to do that, the following steps should be considered: (i) selection of performance metrics for safety & efficiency; (ii) designing scenarios with varying levels of risk and uncertainty and across various interaction types categorised in Table 9; (iii) data collection from ship sensors and cameras, human reactions, and environmental conditions; (iv) data analysis for comparing MASS performance under different levels of human trust; (v) evaluating MASS performance using the selected performance metrics.

5. Conclusion

This study reviewed the state of the art in human-MASS interaction for safety and efficiency and focused on three aspects affecting it, i.e. situational awareness, collision avoidance for MASS in an MWTS, as well as human trust in the autonomous system of MASS. Our findings suggest that research in this domain is primarily focused on four areas: human factors, available technologies for the autonomous system of MASS, system design and test for human-MASS interaction, and potential amendment of legislation for MASS. These areas are intrinsically linked to the aforementioned aspects; for instance, advancements in technology and system design play a crucial role in enhancing situational awareness and collision avoidance, while legislative updates may influence the level of trust human operators place in MASS.

Finally, the integrated framework we have developed for human-MASS interaction prioritises safety and efficiency in supporting MASS navigation and is adaptable based on the categorised interaction types anticipated in future mixed waterborne transport systems. This framework holds potential as a paradigm for future human-MASS interactions across various scenarios with different interaction types. By incorporating situational awareness, navigational preferences of manned vessels, and calibrated human trust, it aims to facilitate a gradual evolution towards a system where human operators and autonomous systems can collaborate effectively and safely.

However, this study has certain limitations. Specifically, the research focused on 'Maritime Autonomous Surface Ships', providing a broad overview of the current research on human-MASS interactions. It did not delve into the detailed discussion on interactions between humans and autonomous ships with varying levels of autonomy. Future research should address this gap by conducting an in-depth investigation into these specific interactions.

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