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ARTICLE

Safety challenges related to autonomous ships in mixed navigational environments

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Abstract

Digitalization and technological advancements have accelerated the development and emergence of autonomous and remotely controlled ships in the maritime transport sector. This type of vessels consists of highly intelligent and adaptive functionalities, equipped with a variety of external sensors and actuators to gain situation awareness, automated control and adaptive maneuvering for achieving more efficient and sustainable operations. There are, however, many safety and reliability assurance challenges in autonomous operational and navigation systems due to their complex, adaptive, and non-deterministic nature. The issue of a mixed navigational environment where conventionally manned, remotely controlled, and unmanned vessels are interacting at the same sea area can be considered as one of the major obstacles in adopting of autonomous ships. Vulnerabilities can increase due to the potential divergence of vessel state awareness between autonomous operational systems and humans in such situations. Little research to date has dealt with such safety issues that a mix of human-operated, remotely controlled, and autonomous vessels will bring. This study explores the potential safety challenges related to autonomous ship operations in a mixed navigational environment and discusses several possible ways to reduce the same issues related to the identified safety risks, while including a discussion for possible future practice and research interests in ship navigation.

Keywords Autonomous ship · MASS · Maritime safety · Remote control · Unmanned vessel

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1 Introduction

Recent technological advancements have accelerated the development and application of increasingly intelligent navigation systems in ship operations and given rise to the prospect of autonomous shipping. Despite the short time span since the concept of maritime autonomous surface ships (MASSs) has been introduced, there has been considerable research and development activities around the world and it is projected to bring a series of economic, environmental, and safety benefits as well as challenges, while opening up many unprecedented opportunities for the maritime industry (Kim and Schröder-Hinrichs 2021). Embracing automation technologies in commercial vessels is not new, as the discussions on automation in ships at the regulatory level can be traced back to 1964 during the 8th session of the Maritime Safety Committee of the Inter-Governmental Maritime Consultative Organization (IMCO) (former name of IMO) (EU 2020). However, the technological and regulatory developments of MASS have been accelerated in recent years with extensive R&D investments and interests from the maritime industry, academia, and regulators. The market of MASS is growing rapidly and projected to increase by 7% each year to $1.5 billion by 2025 (UNCTAD 2020).

Remotely controlled and autonomous navigation solutions in shipping hold the potentials to change the maritime transportation in many ways. The move towards greater autonomy at sea with reduced human operators on board has the potential to improve safety and reliability of ship operations, and offer a way to increase maritime transport capacity while reducing the road congestion and operating costs. As the majority of ship handling and maneuvering accidents are directly or indirectly contributed by human factors, reducing human tasks have the potential to reduce the frequency of human-related accidents onboard ship caused by fatigue, excessive workloads, violations, complacencies, miscommunication issues, etc. With few or no crews onboard, the risks of occupational accidents would also decrease, and the alternative shipboard organization and new ship design could also improve the fuel utilization to support maritime decarbonization and the reduction of greenhouse gas emission. In addition to safety, security, and environmental benefits, researchers have also analyzed the economic, human element, and social benefits of autonomous ship, as summarized in Table 1.

In terms of its wider impact for the maritime industry, researchers have noted that the adoption of autonomous shipping has the potential of addressing several humanitarian challenges the industry currently faces—such as crew change, stranded seafarers under pandemic situation, and the long-standing welfare issues of seagoing personnel (Kim et al. 2019). The adoption of remotely controlled and autonomous operational concept with shore-based ship monitoring and control has additional potential to bring societal values to increase the attractiveness of seafaring professions by moving bridge officers from the remote and hazardous working condition to a shore-based office environment.

However, although autonomous and remotely controlled ships are projected to be the future of maritime operations, their safety (Felski and Zwolak 2020), risk control (Utne et al. 2020), reliability (Abaei et al. 2021), legal (Ringbom et al.

Table 1 Envisioned benefits of autonomous shipping

Dimension	Potential benefits of MASS	Literature
Safety	•Reduce the number of maritime traffic accidents caused by human factors (e.g., fatigue, human errors, violations, improper maneuvering)	(de Vos, Hekkenberg et al. 2021; Li et al. 2021)
	•Reduce and reorganize the workload of human operators while decrease the risks of occupational accidents on board	(Kim and Mallam 2020; Kim and Schröder-Hinrichs 2021)
	•Decrease the number of human injuries and fatalities from maritime accidents	(DNV 2018; Utne et al. 2020)
Security	•Lessen risk due to the lack of crew to hold hostage	(Arnsdorf 2014; Hogg and Ghosh 2016)
Environment	•Reduce energy consumption through fuel saving measures and innovative ship design	(Blagovest 2019; Chen, Haseltalab et al.)
	•Support maritime decarbonization and reduction of greenhouse gas emissions	(Allal, Mansouri et al.)
Economy	•Reduce crew cost and proportionally higher cargo capacity due to absences of human-support facilities and systems on board	(DNV 2014; Kim and Schröder-Hinrichs 2021; Tam and Jones 2018)
	•Reduce operating costs and improved ship fuel efficiency lead to better economic profitability	(Akbar et al. 2021; Kretschmann et al. 2017)
Human element	•Move ship crew from the "24 h society" to shore-based office environment	(Kim and Schröder-Hinrichs 2021; Mallam et al. 2019)
	•Address several humanitarian challenges the industry currently faces, such as welfare issues, crew change, stranded seafarers under pandemic situation	(WMU 2019)
Societal influence	•Mitigate the shortage of seafarers	(Wróbel et al. 2017)
	•Increase the attractiveness of seafaring professions	(Kim and Mallam 2020)
	•Mitigate gender imbalance issues in the maritime industry	(Kim et al. 2019)

2020), qualification and watchkeeping requirements for remote control operators and seafarers (Sharma and Kim 2021), economic (Kretschmann et al. 2017), cyber security (Tam and Jones 2018) as well as many other challenges (Hogg and Ghosh 2016) have also been viewed as obstacles in transforming this concept into reality. Disruptive technologies promise new capabilities and solutions, but also bring new risk profile, quality assurance, and safety management challenges.

With higher level of autonomy, the unpredictability and uncertainties would become more significant, which creates new safety and reliability assurance challenges for MASS operations (Goerlandt 2020). Several studies as of present have assessed the risks involved in the operations of MASS (Bao et al. 2022; Chang et al. 2021; Fan et al. 2020; Huang and van Gelder 2020). However, there has been less discussion related to the risks and hazards involved in the mix-navigational scenarios.

Today there are more than 61,000 conventionally manned ships carrying more than 80% of world trade on the global oceans; it can be predicted that in near future, different degrees of MASS and conventional ships will share and operate at the same time in the same sea area, which means the autonomous ships will navigate in a mixed environment with potentially close-range encounters. The vessel interactions in such environments can complicate the decision-making process and compromise navigation safety since both humans and systems are making the respective decisions, specially in ship collision avoidance situations (Perera and Batalden 2019). The risk and safety issues under such navigation conditions should be considered and identified so that preventive measures could be designed during the current technological development phase. This study explores the potential safety challenges related to autonomous ship operations in a mixed navigational environment and provides an analysis regarding the safety factors to be considered for the interaction scenarios and how greater compatibility might be achieved within a mixed traffic environment.

2 Definitions and levels of autonomous ships

To cope with the industrial development and to ensure effective incorporation of new advanced technology in the international maritime regulatory framework, the Maritime Safety Committee (MSC) of the International Maritime Organizations (IMO) at 98th session in June 2017 has initiated an regulatory scoping exercise (RSE) for the use of MASS (MSC98/23 2017), and finalized the analysis of relevant ship safety treaties for regulating MASS at its 103rd session in May 2021. For this purpose, a MASS has been defined as "*a ship which, to a varying degree, can operate independent of human interaction*" (IMO 2018) and four degrees of autonomy has been articulated for the purpose of the RSE, as shown in Table 2. The RSE has been approached through two steps in which the first step reviewed the related legal instruments which are under the purview of MSC that could be affected by the adoption of autonomous ships at varying degree of automation, while the second step analyzed the most appropriate way of addressing the MASS operations under those instruments (Kim and Schröder-Hinrichs 2021). IMO considered four

Table 2 Categorization of ship autonomy based on MSC99/5/6 (2018, p 2–5)

Organization	Level of automation					
	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6
IMO	D1: Ship with automated processes and decision support: seafarers are on board to operate and control. Some operations may be automated	D2: Remotely controlled ship with seafarers on board: the ship is controlled and operated from another location. Seafarers are available on board to take control	D3: Remotely controlled ship without seafarers on board: the ship is controlled and operated from another location. There are no seafarers on board	D4: Fully autonomous ship: the operating system of the ship is able to make decisions and determine actions by itself		
Bureau Veritas	Level 0 Human operated—automated or manual operations are under human control. The human makes all decisions and controls all functions	Level 1 Human directed—decision support, human makes decisions and actions. The system suggests actions; human makes decisions and actions	Level 2 Human delegated—human must confirm decisions. The system invokes functions; human can reject decisions during a certain time	Level 3 Human supervised—system is not expecting confirmation; human is always informed of the decisions and actions. The system invokes functions without waiting for human reaction	Level 4 Fully autonomous—system is not expecting confirmation; human is informed only in case of emergency. The system invokes functions without informing the human	
Lloyd's Register	Level 0 No cyber access—no assessment—no descriptive note—included for information only	Level 1 Manual cyber access—no assessment—no descriptive note—included for information only	Level 2 Cyber access for autonomous/remote monitoring	Level 3 Cyber access for autonomous/remote monitoring and control (onboard permission is required, onboard override is possible)	Level 4 Cyber access for autonomous/remote monitoring and control (onboard permission is not required, onboard override is possible)	Level 5 Cyber access for autonomous/remote monitoring and control (onboard permission is not required, onboard override is not possible)

Table 2 (continued)

Organization	Level of automation					
	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6
Norwegian Forum for Autonomous Ships (NFAS)	Decision support—decision support and advice to crew on bridge, crew decides	Automatic bridge—automated operation, but under continuous supervision by crew	Remote control—unmanned continuously monitored and direct control from shore	Automatic ship—unmanned under automatic control, supervised by shore	Constrained autonomous—unmanned, partly autonomous, supervised by shore	Fully autonomous—unmanned and without supervision
Rolls-Royce	Level 0 No autonomy—all aspects of operational tasks performed by human operator, even when enhanced with warning or intervention system. The human operator safely operates the system at all times	Level 1 Partial autonomy—the targeted operational tasks performed by human operator but can transfer control of specific sub-tasks to the system. The human operator has overall control of the system and safely operates the system at all times	Level 2 Conditional autonomy—the targeted operational tasks performed by automated system without human interaction and human operator performs remaining tasks. The human operator is responsible for its safe operation	Level 3 High autonomy—the targeted operational tasks performed by automated system without human interaction and human operator performs remaining tasks. The system is responsible for its safe operation	Level 4 Full autonomy—all operational tasks performed by an automated system under all defined conditions	

Table 2 (continued)

Organization	Level of automation					
	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6
UK Marine Industries Alliance	Level 0 Manned—ship/craft is controlled by operators aboard	Level 1 Operated—under operated control all cognitive functionality is within the human operator. The operator has direct contact with the unmanned ship over, for example, continuous radio (R/C) and/or cable (e.g., tethered UUVs and ROVs). The operator makes all decisions, directs, and controls all vehicle and mission functions	Level 2 Directed—under directed control some degree of reasoning and ability to respond is implemented into the unmanned ship. It may sense the environment, report its state, and suggest one or several actions. It may also suggest possible actions to the operator, such as prompting the operator for information or decisions. However, the authority to make decisions is with the operator. The unmanned ship will act only if commanded and/or permitted to do so	Level 3 Delegated—the unmanned ship is now authorized to execute some functions. It may sense environment, report its state and define actions, and report its intention. The operator has the option to object to (veto) intentions declared by the unmanned ship during a certain time, after which the unmanned ship will act. The initiative emanates from the unmanned ship and decision-making is shared between the operator and the unmanned ship	Level 4 Monitored—the unmanned ship will sense environment and report its state. The unmanned ship defines actions, decides, acts, and reports its action. The operator may monitor the events	Level 5 Autonomous—the unmanned ship will sense environment, define possible actions, decide, and act. The unmanned ship is afforded a maximum degree of independence and self-determination within the context of the system's capabilities and limitations. Autonomous functions are invoked by the onboard systems at occasions decided by the same, without notifying any external units or operators

degrees of autonomy including manned ships with automated processes and decision support (D1); remotely controlled ships with seafarers on board (D2); remotely controlled ships without seafarers on board (D3); and fully autonomous ships (D4) (IMO 2018). Fully autonomous vessels can operate without any human control or monitoring. In addition to the widely adopted IMO's definition of MASS, there are also several other organizations (e.g., Lloyd's Register, Rolls-Royce, Bureau Veritas, Norwegian Forum for Autonomous Ships (NFAS), UK Marine Industries Alliance, Ramboll) that have proposed additional detailed classification methods for ship autonomy (MSC99/5/6 2018). A detailed overview of the MASS classifications is provided in Table 2. Different organizations have varied criteria when categorizing the ship autonomy.

Many of the issues raised with regard to adoption and operation activities of remotely controlled and autonomous ships are currently not addressed in the IMO conventions but left to the domestic member state's legal systems. The RSE outcomes highlighted a number of issues across several instruments, in particular under D3 and D4 operations where no seafarers on board. This represents a significant shift in the maritime domain with vessels being completely controlled from remote locations without the prospect of onboard crew taking over the control if needed.

Several key safety instruments such as the International Regulations for Preventing Collisions at Sea (COLREGs) indicate the vessel requirements rather than seafarer requirement. So that it is projected that the rules would not be necessary to be significantly altered for the purpose of MASS but the system algorithms shall be developed to address the requirement of the COLREGs as the rules of the road. However, as the COLREGs are primarily written for human operators without detailing the quantitative criteria for navigation actions, it create difficulties to be used to develop testing scenarios for MASS (Bolbot, Gkerekos et al.; Woerner et al. 2019). A goal-based MASS instrument, such as a "MASS code," has been envisioned as a way forward to address the gaps and themes identified across the treaties for safety assurance of MASS of the future.

It is noted that autonomous ships can be designed in a way that permits to switch between various degrees of automation during the single voyage. This also implies that the solutions to the legal barriers will also need to be dynamic and adaptive towards the autonomy level at which such ships are specifically operating. In this paper, we used the IMO's categorization of autonomous ships (i.e., D1, D2, D3, D4) as the basis for analysis.

3 Ship encountering scenarios

Vessel maneuvering in confined waters is a critical part of ship navigation since the difficulties, complexity, and risk of accidents increases significantly compared with open sea navigation. Efficient and safe ship navigation in congested situations is one of the many challenges faced by mariners, especially in terms of determining the maneuvers necessary to avoid a potential collision in compliance with the COLREGs (Perera and Soares 2015). Currently, collision avoidance at sea is conducted by seafarers on board. Seafarers keep a proper lookout, use navigation aids, and

communicate tools with other approaching vessel(s) to make an agreement regarding collision avoidance maneuvers.

Under autonomous ship operations, the COLREGs will need to be interpreted by both humans as well as systems during these ship encounters, making their own respective decisions in a mixed environment. Safe and automated decision-making will thus become a critical component of MASS (Sharma and Kim 2021). Future ship navigators need to communicate with not only shipboard operators, but also remote ship operators and/or with intelligent autonomous navigation systems directly for decision-making in close ship encounter situations. Many challenges can be anticipated with regard to understanding the vessel intention in such situations, predicting own ship behaviors as well as approaching ship's status and behaviors. It can also be a challenge to know what the types of vessels they are interacting with. This uncertainty may lead to increased stress levels in humans and systems in altered crossing decisions, which can lead to possible collision situations. There are many major safety challenges in autonomous ship operations in a mixed navigational environment as detailed in Table 3. These safety challenges would be relevant for all MASSs but at the different levels of severity.

A mixed environment would complicate the collision risk estimation and collision avoidance actions. To be able to operate remotely or autonomously in such environment, MASS should be able to replace human navigators to keep general lookout, generate safe and efficient trajectories in different maneuvering situations and different weather conditions, detect, track, classify navigational dangers and other vessels, manage the system and equipment failures as well as be able to handle emergency situations (e.g., fire, oil spill, robbery, illegal boarding). To ensure that autonomous ship operating systems should generate safe and efficient trajectories in different maneuvering situations and in unfavorable weather conditions would be a fundamental prerequisite for autonomous ship operations. The future ship navigation systems should be designed that could make instantaneous and effective decisions, which have been a continuing challenge for developers. A large body of research has been carried out on the collision avoidance aspect of autonomous ships (Abilio Ramos et al. 2019; Hedjar and Bounkhel 2020; Statheros et al. 2008) with many collision avoidance control algorithms available today that follows the COLREGs. However, many of these algorithms still face challenges in generating safe and optimal paths in complex navigational scenarios (Johansen et al. 2016).

One of the major obstacles to the adoption of autonomous ships is its operation in a mixed navigational environment where conventionally manned, remotely controlled, and unmanned vessels are interacting at the same sea areas. There are a total 11 possible interaction scenarios as shown in Table 4, creating mixed traffic situations with relevant vessels with different navigation levels and types of automation systems are interacting with each other.

Please note that this study does not include the cases for the same type of vessels interacting with each other (e.g., D1 vs D1, D3 vs D3 vs D3) due to the reason that when the same vessels are interacting with each other their intentions can be communicated and understood by each other better and/or the risk profiles would be somehow similar with mixed scenarios. However, future studies should expand on the scope of the analysis to consider more interaction scenarios.

Table 3 Major safety challenges in ship operations in mixed environment

Categorization	Safety challenges
S1: Navigational safety	S1.1. Collision
	S1.2. Grounding
	S1.3. Erroneous navigation data (AIS data anomalies)
	S1.4. Visualization, object identification failure, and sensory issues
	S1.5. CORLEG interpretation issues when multiple ships are approaching
	S1.6. Unpredicted behavior of the approaching vessels
S2: Ship system safety	S2.1. Autonomous navigation system failure and malfunction
	S2.2. Navigation systems and sensor failure
	S2.3. Communication and information transmission failure
	S2.4. Electrical system breakdown
S3: Ship structural safety	S3.1. Hull damage
	S3.2. Ship stability
S4: Personnel safety	S4.1. Operational safety violations
	S4.2. Loss of situation awareness
	S4.3. Fatigue
	S4.4. Onboard miscommunication
	S4.5. Occupational injuries
	S4.6. Man overboard
	S4.7. Human health issues
	S4.8. Complacency and automation overreliance
S5: Equipment safety	S5.1. Engine and propulsion system failure
	S5.2. IT structure failure
	S5.3. Other related equipment failure
S6: Security	S6.1. Piracy
	S6.2. Cyberattacks (malware, information theft)
	S6.3. Illegal boarding and robbery
S7: Cargo safety	S7.1. Cargo loss
	S7.2. Cargo stowage and securing failure
S8: Onboard emergency management	S8.1. Fire extinguishing
	S8.2. Chemical and biological issues
	S8.3. Emergency evacuation

4 Safety challenge analysis

The respective safety challenges, as presented in Table 3, are screened according to their likelihood and consequence for MASS at each degree of automation and presented in Table 5. The consequences associated with each safety challenge can often be projected, the knowledge of their likelihood is generally uncertain, and the likelihood and consequence associated with the safety risk could differ due to human interventions. For instance, in a cargo fire situation, if the crew is available on board,

Table 4 Ship encounter scenarios

Scenario	Type of ships interacting				Description
Scenario 1	D1	D2			Situation involving conventional vessel and manned remotely controlled vessel
Scenario 2	D1	D3			Situation involving conventional vessel and remotely controlled vessel without human onboard
Scenario 3	D1	D4			Situation involving conventional vessel interacts with fully autonomous vessel
Scenario 4	D2	D3			Situation involving two remotely controlled vessels interact with each other
Scenario 5	D2	D4			Situation involving remotely controlled vessel with human onboard interacts with fully autonomous vessel
Scenario 6	D3	D4			Situation involving remotely controlled vessel without human onboard interacts with fully autonomous vessel
Scenario 7	D1	D2	D3		Situation involving conventional vessel interacts with two remotely controlled vessels
Scenario 8	D1	D2	D4		Situation involving conventional vessel interacts with both manned remotely controlled vessel and fully autonomous vessel
Scenario 9	D1	D3	D4		Situation involving conventional vessel interacts with both fully remotely controlled vessel and fully autonomous vessel
Scenario 10	D2	D3	D4		Situation involving manned remotely controlled vessel interacts with both fully remotely controlled vessel and fully autonomous vessel
Scenario 11	D1	D2	D3	D4	Situation involving all four types of autonomous vessels interact at the same sea area

Table 5 Safety challenge analysis of MASS at each degree of automation

Categorization	Safety challenges	D1		D2		D3		D4	
		L	C	L	C	L	C	L	C
S1: Navigational safety	S1.1. Collision	PO	SE	LI	SI	LI	SI	LI	SI
	S1.2. Grounding	PO	SI	PO	SI	PO	SI	PO	SI
	S1.3. Erroneous navigation data (AIS data anomalies)	UN	MI	PO	MO	PO	SI	PO	SI
	S1.4. Visualization, object identification failure, and issues (e.g., camera failure)	UN	MI	UN	MI	PO	SI	PO	SE
	S1.5. CORLEG interpretation issues when multiple ships are approaching	PO	MI	PO	MI	VL	SI	VL	SI
	S1.6. Unpredicted behavior of the approaching vessels	UN	SE	UN	SE	LI	SE	LI	SE
S2: Ship system safety	S2.1. Autonomous navigation system failure and malfunction	VU	NE	LI	MI	LI	SE	LI	SE
	S2.2. Navigation systems and sensor failure	UN	SI	PO	SI	PO	SI	PO	SI
	S2.3. Communication and information transmission failure	PO	MO	PO	MO	PO	SE	PO	SE
	S2.4. Electrical system breakdown	PO	MI	PO	MI	PO	SE	PO	SE
S3: Ship structural safety	S3.1. Hull damage	UN	MO	UN	MO	UN	SE	UN	SE
	S3.2. Ship stability	UN	SI	UN	SI	UN	SI	UN	SI
S4: Personnel safety	S4.1. Operational safety violations	PO	MO	PO	MO	UN	NE	VU	NE
	S4.2. Loss of situation awareness	UN	SI	UN	SI	PO	SI	PO	SI
	S4.3. Fatigue	PO	SI	PO	SI	UN	MI	VU	NE
	S4.4. Onboard miscommunication	PO	MO	PO	MO	PO	MO	VU	NE
	S4.5. Occupational injuries	LI	MO	LI	MO	VU	NE	–	NE
	S4.6. Man overboard	PO	SI	PO	SI	–	NE	–	NE
	S4.7. Human welfare issues	PO	MO	PO	MO	VU	NE	–	NE
	S4.8. Complacency and automation overreliance	PO	MO	PO	MO	PO	SI	VL	SI
S5: Equipment reliability	S5.1. Engine and propulsion system failure (automation system)	PO	MO	PO	MO	PO	SI	PO	SI
	S5.2. IT structure failure	LI	MO	LI	MO	PO	SI	PO	SI
	S5.3. Other related equipment failure	PO	MO	PO	MO	PO	SI	PO	SI

Table 5 (continued)

Categorization	Safety challenges	D1		D2		D3		D4	
		L	C	L	C	L	C	L	C
S6: Security	S6.1. Piracy	UN	SI	UN	SI	UN	MI	UN	MI
	S6.2. Cyberattacks (malware, information theft)	LI	MO	LI	MO	UN	SI	LI	SI
	S6.3. Illegal boarding and robbery	VU	MO	VU	MO	PO	MO	PO	MO
S7: Cargo safety	S7.1. Cargo loss	VU	MI	VU	MI	VU	MI	VU	MI
	S7.2. Cargo stowage and securing failure	VU	MI	VU	MI	VU	MO	VU	MO
S8: Onboard emergency management	S8.1. Fire extinguishing	PO	MI	PO	MI	PO	SI	PO	SI
	S8.2. Chemical and biological issues	VU	SE	VU	SE	VU	NE	VU	NE
	S8.3. Emergency evacuation	VU	MO	VU	MO	VU	NE	VU	NE

L, likelihood; *C*, consequences; *VL*, very likely; *LI*, likely; *PO*, possible; *UN*, unlikely; *VU*, very unlikely; *NE*, negligible; *MI*, minor; *MO*, moderate; *SI*, significant; *SE*, severe.

some fire extinguishing activities could be performed in the initial phase so that the consequences could be reduced. Therefore, mitigating actions could be taken appropriately by humans. On the other hand, systems may not have the flexibility and capability to constantly monitor and control the risks in all aspects of a ship at the initial stage of the MASS operations.

An observation from the analysis is that the safety challenges increase with reduced human onboard and increased degree of automation. Despite the automated systems traditionally have performed repetitive tasks more reliable than human operators, it does not necessarily mean that they will perform the complex decision-making under novel ship encounters in a reliable manner compared to humans. In the event of multiple autonomous vessels interacting in the same sea area and must follow the COLREG rules in terms of giving way to vessel on starboard side, the vessels could enter into a loop if no adaptations are made. Human navigators would be more adaptive to overcome in this situation.

New types of autonomous systems and their related equipment and sensors would increase the system complexity and introduce new risk profiles, failure modes, system interdependencies, and unpredictable ship behaviors. In many cases with autonomous mode of operations, human operators will become relegated to a more supervisory role to the system. A passive role not conducive to maintaining situation assessment and attentional engagement, which could in turn create "out of the loop" issues and breed overreliance on the automation and causes human operators lose the situation awareness of the mode under which the system is operating (Alves et al. 2018). Therefore, increasing complexity of the system and automation levels could potentially lead to a system that is beyond human capacity to understand and control. This would in turn lead to poor awareness of the interaction between the state of the vessels and their environment and possibly hazardous decision-making processes.

Under mixed navigational scenarios, safety challenges also increase when the interaction involves MASSs with a higher degree of automation. Given the differences between autonomous system and human capability, mixed navigational scenarios are bound to involve significant communication, compatibility, and coordination issues. The initial risk matrix of mixed navigational scenarios is presented in Fig. 1.

Scenario	*Type of ships interacting*			
Scenario 1	D1	D2		
Scenario 2	D1	D3		
Scenario 3	D1	D4		
Scenario 4	D2	D3		
Scenario 5	D2	D4		
Scenario 6	D3	D4		
Scenario 7	D1	D2	D3	
Scenario 8	D1	D2	D4	
Scenario 9	D1	D3	D4	
Scenario 10	D2	D3	D4	
Scenario 11	D1	D2	D3	D4

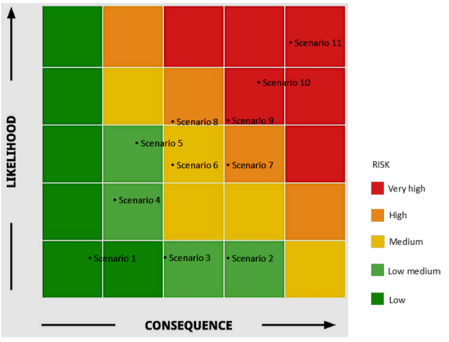

Fig. 1 Risk matrix of mixed navigational scenario

5 Discussion

Autonomous navigation systems can have the ability to communicate with similar systems using ship to ship information and communication technologies. System-based decision-making processes could be programmed based on a predefined set of rules so that these highly autonomous systems could participate in the traffic that abide strictly by rules and standard information transfer. These systems may not be able to communicate with human operators in the same way as other similar systems, and cannot predict the human behaviors on the same basis as autonomous systems. The autonomous navigation system may only be able to respond with predetermined decision criteria and logical sequence whereas a human operator can improvise. That will typically form their expectations regarding the approaching ship behaviors according to their own observations of the status and information provided by various equipment and sensors of the encountering vessels. The communication between autonomous systems and human operators would be indirect in nature. For manned ship to form expectations about the behavior of the remotely controlled or fully autonomous vessels, interpreting the information transmitted from the approaching vessels would be essential.

In the case of remotely controlled vessels under D2 and D3 operations, it is the vessel that is responsible for safe navigation and decision-making, not the remote-control operators that submitted the request. Various unpredictable motions relate to vessel status and maneuvering behavior can also be expected for vessels at sea due to ocean wind, wave, and current conditions. Any of the information channel or sensory failure would become a source of error propagation and could influence the accuracy of the decisions made by future vessels. This means, the communication and information exchange mechanisms between systems and humans would require more functionalities as well as the safety and security assurance in both manned and unmanned MASSs.

Previous studies have noted that the adoption of a higher degree of automation could bring benefits but also creates new error pathways and brings an additional set of safety challenges to the navigation system in shipping (Lützhöft and Dekker 2002; Porathe et al. 2018). Based on the observation of the risk analysis, the safety issues related to collision avoidance, cyberattacks, autonomous navigation system failure, and malfunction are more likely to happen with severe consequences for the ships with higher degree of autonomy. Human-related safety issues such as occupational injuries, man overboard, and human health issues onboard of ships will be reduced due to a higher degree of autonomy with the respective consequences being eliminated. Unpredicted behavior of approaching vessels would be a safety challenge for all vessels with severe consequences. Nevertheless, the likelihood to avoid this challenge is higher by onboard human operators in comparison to autonomous navigation systems, due to the lack of observations and information sharing and interpretation.

Realizing mixed maritime traffic conditions would be a fundamental requirement for achieving autonomy at sea. Autonomous vessels at D3 and D4 have to corporate with other manned vessels under complex scenarios. Insufficient communication

and information exchange could potentially increase the likelihood of failures in agreement seeking, status understanding, and intent sharing in close ship encounter situations. MASS at D3 and D4 must provide highly intelligent system capabilities to be able to perceive, understand, and predict its own ship status as well as understand approaching vessel's behaviors and respond in time commensurate with the activities in its environments. Their safety assurance must also address the nondeterministic behavior of these systems and vulnerabilities arising due to potential divergence of situation awareness between human operators and autonomous navigation systems.

6 Future research opportunities

This study leads to several future research avenues. Firstly, cooperative navigation between conventional vessels, manned or unmanned remotely controlled and fully autonomous vessels is a new research topic in the field of intelligent transportation systems, i.e., same applies to the automobile industry. Future research can explore how a MASS at D3 and D4 should cooperate with conventional ships and how to optimize decision-makings in mixed navigational situations. The projected complexity increase is associated with the future autonomous ship navigation systems; it is therefore likely that additional communication methods and safety assurance methods and technologies will be required. A sufficient and secured communication and information exchange approach is projected to be essential for increasing the availability of ship autonomy.

Secondly, a comprehensive safety analysis requires a thorough understanding regarding all sources of hazards involved in both system development and operations. The human–machine interactions would mean that the hazard profile could be different in comparison to the hazards recognized from the traditional ship system design and operations. Considering the scope of the hazard analysis, a more systemic thinking approach would be suited in order to obtain a thorough understanding regarding the sources of hazards. In this regard, the Systems Theoretic Process Analysis (STPA) method (Leveson 2011), a hazard analytic technique from System-Theoretic Accident Model and Processes (STAMP) model, would be particularly suited for this hazard analysis purpose.

In additional to the technical aspects, it would also be interesting to explore the MASS adoption issues from human, economic, and wider societal perspectives. Against the backdrop of a persistently weak global economy and challenging trade landscape, the outbreak of the COVID-19 pandemic has further affected maritime trade at an unprecedented scale and speed, and shone light on the vulnerabilities of the maritime transportation networks (UNCTAD 2020). Despite the downside of the pandemic, it has also led to an acceleration in automation and digital transformation of the shipping industry that has been underway for decades. Many maritime stakeholders, e.g., shipping companies, customs officials, port authorities, and freight forwarders, have adopted automated solutions and digital business models to maintain operations and reduce the manpower and operating expenses. Physical paper-based transactions and human to human contacts have now been digitalized

or automated; electronic freight trading and online freight forwarding—which have been around for some time—are now integrated to a greater extend. Future research can also explore how the COVID-19 pandemic would amplifying the opportunities and challenges from the digital transformation to further facilitate the industry in developing remotely controlled and autonomous ships to be operated in the post pandemic period.

7 Conclusion

The move towards greater autonomy at sea would be a natural evolution of the maritime transportation. To effectively leverage the advantages of the emerging automation technology and to unlock the long-term values of these new types of ships for the maritime industry, the forward path must be guided by extensive research collaborations and explorations to address the safety, legal, economic, and security challenges of MASS. One of the major issues to be considered is the safety issues related to MASS operation in a mixed navigational environment where conventionally manned, remotely controlled, and unmanned vessels are interacting at the same sea areas. The safety challenges highlighted in this paper hopefully shed light on further thoughts and research discussions for improving the design of future autonomous navigation systems.

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