The Journal of Navigation (2025), 1–30
doi:10.1017/S0373463324000237

RESEARCH ARTICLE

Exploring the MASS-DoA2 control-switching mechanism: Results from the autonomous ship guidelines review and expert survey

Wenjun Zhang,[1,2]* Congrui Mu,[1,2] Yu Wang,[1,2] Xue Yang,[1,2] Xiangyu Zhou,[1,2]
Xiangkun Meng,[1,2] and Lianbo Li[1,2]

[1]Navigation College, Dalian Maritime University, Dalian, China
[2]Dalian Key Laboratory of Safety & Security Technology for Autonomous Shipping, Dalian, China.
*Corresponding author: Wenjun Zhang; Email: wenjunzhang@dlmu.edu.cn

Received: 12 December 2023; **Revised:** 22 March 2024; **Accepted:** 11 June 2024

Keywords: maritime autonomous surface ship; control switching; autonomous ship guideline; expert survey

Abstract

The development of Maritime Autonomous Surface Ship (MASS) is progressing rapidly within the maritime industry. Degree Two of MASS (MASS-DoA2), balancing human oversight and autonomous efficiency, will likely gain regulatory approval and industry acceptance. MASS-DoA2 possesses different control modes to adapt to various scenarios. However, the control-switching mechanisms among operators at shore control centres, autonomous navigation systems and number of seafarers onboard remain ambiguous, which poses a new risk that may significantly influence navigation safety. This study focuses on MASS-DoA2 and carries out a systematic review of autonomous ship guidelines. A questionnaire was designed based on the review findings, and a survey was carried out among captains and researchers in related fields. The review identified 11 control-switching scenarios with suggested takeover agents and the switching process and outlined the priority relationship between various takeover agents. Finally, a control-switching framework for MASS – DoA2 is proposed. It can serve as a theoretical framework for research on MASS's dynamic degree of autonomy and provide a reference for maritime regulatory authorities in establishing MASS – DoA2 control-switching mechanisms.

1. Introduction

The advent of the Industry 4.0 era has further accelerated the application of autonomous technologies in the transportation sector. Among these technologies, the Maritime Autonomous Surface Ship (MASS) guidance, as representative of autonomous applications in the maritime industry, is emerging as an inevitable trend for future developments (Zhou et al., 2021). The International Maritime Organisation (IMO) has categorised MASS into four degrees of autonomy (DoA) (Maritime Safety Committee (MSC), 2021): DoA1 – with automated processes and decision support (MASS-DoA1); DoA2 – remotely controlled ship with seafarers on board (MASS-DoA2); DoA3 – remotely controlled ship without seafarers on board (MASS-DoA3); and DoA4 – fully autonomous ship (MASS-DoA4). MASS shows significant potential in cutting operational costs and reducing human errors (Felski and Zwolak, 2020; Luo et al., 2022). In recent years, extensive research and exploration have resulted in numerous achievements and advancements. In the last years, several autonomous ships have been put into sea trials and operational testing, as listed in Table 1.

Notably, these MASS trials possess different control modes, ranging from autonomous, remote and manual control (Table 1). These control modes correspond to different DoA (Ludvigsen and Sørensen,

Table 1. *Delivered MASS for sea trials and their operational modes.*

Ship name	Ship type	Manufacturer	Control modes	Year
Yara Birkeland (Yara International, 2021)	Container	Kongsberg & Yara	Autonomous, Remote, Manual	2020
Zhi Fei Hao (Luo et al., 2022; Xing and Zhu, 2023)	Container	Brinav & Qingdao Shipyard Co., Ltd.	Autonomous, Remote, Manual	2022
Sunflower Shiretoko (Mitsui, 2022)	Ferry	TOKYO-Mitsui O.S.K. Lines, Ltd.	Autonomous, Manual	2022
Eidsvaag Pioneer (Marine in Sight, 2023)	Cargo	Kongsberg & Eidsvaag shipping company	Autonomous, Remote, Manual	2023
Zulu 4 (KONGSBERG, 2023)	Barge	Kongsberg & Blue Line Logistics NV	Autonomous, Remote	2023
HL Nambu 2 (Hyundai Samho Heavy Industries, 2023)	Bulk	HD Hyundai & H-LINE shipping	Autonomous, Manual	2023
Hokuren Maru No.2 (Japan Radio Co. Ltd, 2023)	Ferry	Nippon Foundation	Autonomous, Manual	2023
Pos Singapore (Marine in Sight, 2024)	Container	Hyundai Mip Dockyard Co.	Autonomous, Manual	2024

2016), which are designed to adapt to specific requirements and operational contexts. Among these autonomous ships, MASS-DoA2 has the most complex control-switching mechanisms (Liu et al., 2022a). For instance, as a MASS-DoA2 enters open waters, it can operate in autonomous mode under the control of the Autonomous Navigation System (ANS). However, in an operational context of collision avoidance, if the decision by ANS is considered as unsuitable, the control may switch to remote control mode, signifying a decrease in DoA. When navigating into a port with heavy traffic, a lower DoA with human onboard control is typically employed. This changes of DoAs is referred to as 'dynamic autonomy' (Sheridan, 2011; Burmeister et al., 2014; Ramos et al., 2019; Yang et al., 2020; Wu et al., 2022), which brings extra navigational safety and regulatory challenges for operations of MASS (Zhou et al., 2020a; Zhang et al., 2022a; Li et al., 2023a).

Researchers have analysed the impact of dynamic DoA and employed diverse methods to evaluate associated risks, primarily concentrating on remotely controlled ship without seafarers on board (MASS-DoA3) that operates at autonomous control mode (ACM), or remote control mode (RCM). Ramos et al. (2020a) conducted research on dynamic DoA changes and the human involvement in collision avoidance within MASS-DoA3 using hierarchical task analysis (HTA), and further introduced a human–system interaction in autonomy (H–SIA) method, combining event sequence diagrams (ESD) and concurrent task analysis (CoTA), to model and compare safety aspects across different DoA in MASS (Ramos et al., 2020b). Yang et al. (2024) proposed a three-phase framework to identify failure scenarios during the control-switching, integrating systems–theoretic process analysis (STPA), state machines, and sequentially timed events plotting (STEP) diagram, offering solutions to address significant challenges posed by the dynamic DoA for the MASS safe navigation. Zhang et al. (2020) used a combination of the technique for human error rate prediction (THERP) and Bayesian networks (BNs) to develop a probabilistic model assessing the likelihood of human errors by Shore Control Centre (SCC) operators during emergency takeovers from autonomous to remote control. Bačkalov (2020) explored the adaptability of the European inland waterway shipping regulatory framework concerning the takeover of autonomous inland vessels (AIVs) by SCC operators. Kari and Steinert (2021) reviewed more than 50 articles, identifying 13 human factors that impact the supervision and remote-control performance of SCC operators. Wang et al. (2022) proposed a trust management scheme between the SCC operator and MASS to ensure cyber security during takeover. Guo and Utne (2022) carried out a risk assessment to offer decision support for SCC operators and establish safe takeover operational procedures. In the investigation of potential risks and causality in MASS, Li et al. (2023b) discovered that the timely takeover of the vessel by SCC operators could effectively avoid collisions.

Compared to MASS-DoA3, MASS-DoA2 introduces an additional control agent: the seafarers onboard. This integration transfers control between the seafarers onboard and either the autonomous system or the SCC operator. Such dynamics increase the complexity and potential instability during control switching (Veitch and Alsos, 2022; Cheng et al., 2023). The continuous involvement of both seafarers onboard and SCC operators in the control loop means that the risk of human errors persists (Zhang et al., 2022b; Yang et al., 2023). Without preventive measures for human errors and standardised procedures for human operations, there is an increased risk of accidents. Fan et al. (2022) developed a risk-based framework to compare the risks associated with the different control modes that involve three controllers of MASS in certain situations. Nonetheless, there have been few efforts to address these risks, particularly the gap in understanding control-switching mechanisms, in terms of operational details and underlying principles (Zhang et al., 2020; Cheng et al., 2023). This gap hinders effective modelling and risk analysis of control switching and presents challenges for maritime regulatory authorities in establishing standards and overseeing MASS navigation.

Therefore, the objective of this paper is to bridge this gap by proposing a framework for a MASS-DoA2 control-switching mechanism. This is achieved by reviewing relevant provisions regarding control switching within autonomous ship guidelines (ASGs) from various classification societies and implementing expert surveys among captains and researchers in related field. The paper contributes to a deep understanding of the MASS-DoA2 control-switching mechanism, and provides insights to regulatory authorities, designers and operators to ensure navigational safety.

The rest of the paper is structured as follows. Section 2 introduces the research process, the autonomous ships guidelines and expert survey methodology used in this research. Section 3 and Section 4 present the control-switching mechanisms extracted from the guidelines and findings from the questionnaires and expert interviews. Section 5 provides a discussion related to the key findings and their implications. Conclusions and the limitations of the current study are presented in Section 6.

2. Methods

2.1. *Guidelines for autonomous ships*

Autonomous shipping is a relatively new and rapidly developing field. IMO has been actively working on frameworks to integrate MASS into existing regulations (IMO, 2018; Goerlandt, 2020). The MASS is required to achieve a safety level equivalent to conventional ships, without compromising the safety of people, property or the environment (Bureau Veritas (BV), 2019; Maritime Safety Committee (MSC), 2019; European Union, 2020; Det Norske Veritas, 2021). To address this, classification societies have developed and issued their respective ASGs. These guidelines aim to provide designers, manufacturers, shipowners and administrations with recommendations for designing, constructing, testing, certifying and operating MASS across different countries (Rødseth and Nordahl, 2017; ClassNK, 2020; Russian Maritime Register of Shipping (RS), 2020; American Bureau of Shipping (ABS), 2022). They address the challenges of effectively integrating autonomous technologies into MASS development. Furthermore, they assist authorities in the supervision and legislation of MASS, helping to establish a statutory framework for its application.

Control switching, essential in MASS operations, is recommended to follow the relevant provisions in the guidelines to ensure safety and reliability (Goerlandt, 2020). These provisions not only guide the current operations of MASS but also influence upcoming legislative and regulatory changes in this sector (Issa et al., 2022; Li and Seta, 2022). Thus, a systematic review of the provisions explores recommended control modes in various scenarios, laying the groundwork for developing a control-switching mechanism. For this purpose, the study has collected 15 ASGs from IMO, the Maritime Safety Administration of the People's Republic of China (China MSA) and eight international classification societies (Table 2), and investigated in-depth for provisions related to control switching, focusing on the following questions:

1. In what scenarios is human intervention required to take over the MASS during the voyage?
2. Which takeover agent should control the MASS in different scenarios?
3. What process should be followed when switching control between different takeover agents?
4. What is the priority of each takeover agent in controlling the MASS directly under any scenario?

2.2. *Expert surveys*

After thoroughly examining ASGs, it became evident that the existing guidelines merely outline recommended practices without clarifying their underlying principles. This lack of explanation makes it difficult to explore the essential working mechanisms of the control mode switch. Additionally, ASGs vary in their recommendations for control modes in identical operational situations, leading to potential confusion among practitioners. To address these discrepancies, this paper utilised expert surveys, a widely recognised method for investigating unresolved questions (Rindermann et al., 2016; Rindermann et al., 2017; Lehtola et al., 2020; Rindermann et al., 2020). These surveys were conducted in a semi-structured manner, combining questionnaires and interviews. The questionnaires initially collected experts' opinions on the outcomes of the ASGs review. Then, interviews were conducted to delve deeper into control-switching specifics, seeking to establish a consensus on the MASS-DoA2 control-switching mechanism. The insights gained from these surveys contribute to refining the control switching for MASS-DoA2.

Table 2. *Autonomous ship guidelines reviewed in this study.*

ID	Title	Classification societies	Relevance introduction	First publication year
1	*Rules for Intelligent Ships* 2024 (China Classification Society (CCS), 2023)	CCS	Some provisions present normative requirements and specifications for various aspects of control-switching.	2015
2	*Digital Ships* (Lloyd's Register (LR), 2017a)	LR	Describing the 'seafarers' in MASS, but not specifically addressing the issue of 'control-switching' in MASS.	2016
3	*Code for Unmanned Marine Systems* (Lloyd's Register (LR), 2017b)	LR	Mentioning the necessity of manual takeover without specifying further details.	2017
4	*Guidelines for Autonomous Shipping* (Bureau Veritas (BV), 2019)	BV	In the comprehensive requirements for the design and operation of MASS, standards for control-switching are included.	2017
5	*Guidelines for Concept Design of Automated Operation/Autonomous Operation of Ships* (ClassNK, 2020)	Class NK	The primary focus is on technical standards and does not address operational standards for MASS control-switching.	2018
6	*Autonomous and Remotely Operated Ships* (Det Norske Veritas, 2021)	DNV	Relevant provisions explain the human intervention in MASS and propose the requirements for MASS control-switching.	2018
7	*Guidelines for Autonomous Cargo Ships* (China Classification Society (CCS), 2018)	CCS	Some provisions point out the principles to consider for control-switching functionality.	2018
8	*Guidance for Autonomous Ships* (Korean Register (KR), 2022)	KR	Several provisions specify MASS control-switching, outlining operational standards to meet from a safety perspective.	2019

Table 2. *Continued.*

ID	Title	Classification societies	Relevance introduction	First publication year
9	*Interim Guidelines for Mass Trials* (Maritime Safety Committee (MSC), 2019)	IMO	The primary objective is to ensure the safety of autonomous ship trials, without specifying detailed requirements for control-switching.	2019
10	*Regulations for Classification of Maritime Autonomous and Remotely Controlled Surface Ships (MASS)* (Russian Maritime Register of Shipping (RS), 2020)	RS	Relevant provisions impose requirements for the standards associated with the MASS control-switching.	2020
11	*Requirements for Autonomous and Remote Control Functions* (American Bureau of Shipping (ABS), 2022)	ABS	Defining human supervision responsibilities within autonomous systems, but lacking specific details about MASS control-switching.	2021
12	*Competence of Remote Control Centre Operators* (Det Norske Veritas (DNV), 2022a)	DNV	Introduces the responsibilities of personnel within the MASS system but does not specify operational standards for control-switching.	2021
13	*Certification Scheme for Remote Control Centre Operators* (Det Norske Veritas (DNV), 2022b)		This recommended practice describes a framework for certifying SCC operators, but with no provisions related to control-switching.	2021
14	*Management Systems for Auto-Remote Operations* (Det Norske Veritas (DNV), 2022c)		Aims to establish a standardised operational management system for MASS, taking into account factors related to transferring control, but does not provide specific details regarding control-switching.	2022
15	*Provisional rules for the trial technology and inspection of autonomous navigation of ships* (Maritime Safety Administration of the People's Republic of China (China MSA), 2023)	China MSA	This document primarily addresses trials of autonomous navigation and remote control for Chinese-flagged vessels, providing regulations for control and switching during trials, SCC and risk analysis of control transfer.	2023

Table 3. *Statistics of expert information.*

Option	Explanation	Value
Strongly Disagree	Indicates strong disagreement, with no doubt or opposition.	−1
Disagree	Indicates disagreement, but perhaps with hesitation or reservation.	−0 · 5
Agree	Indicates agreement, but perhaps with hesitation or reservation.	0 · 5
Strongly Agree	Indicates strong agreement, with no doubt or opposition.	1

Table 4. *Evaluation factors for experts' proficiency and weights of their impact on experts' judgement.*

	Impact on experts' judgement		
Evaluation factors	Significant	Moderate	Minor
Theoretical knowledge	0 · 3	0 · 2	0 · 1
Professional experience	0 · 5	0 · 4	0 · 3
Literature	0 · 1	0 · 1	0 · 1
Experts' intuition	0 · 1	0 · 1	0 · 1

Table 5. *The values of Cs upon degrees of familiarity.*

Degree	Unfamiliar	Slightly familiar	Moderately familiar	Fairly familiar	Highly familiar
Value	0	0 · 3	0 · 5	0 · 8	1

The questionnaire assumed a MASS-DoA2 with three operational modes: manual control mode (MCM), RCM and ACM. The control process involved three controllers: the seafarer onboard, the remote operator at the SCC and the onboard autonomous navigation controller (ANC). The questionnaire used a four-level scoring system to reflect the strength of the experts' opinions: 'Strongly Disagree', 'Disagree', 'Agree', and 'Strongly Agree' (Schrum et al., 2020; Botes et al., 2023). These options were assigned numerical values of −1, −0 · 5, 0 · 5, and 1 to enhance the visualisation of overall expert opinions. Aggregating these values allowed for calculating the mean, offering a clear representation of the central tendency of expert opinions, as elaborated in reference (Göb et al., 2007). The detailed explanations are provided in Table 3.

Prior to analysing the results, the expertise was also assessed by considering the experts' knowledge and experience in the relevant fields (Trevelyan and Robinson, 2015; Shang, 2023). The expertise level of each expert, denoted as Cr, was calculated by the arithmetic mean of two factors: their proficiency and judgement basis for content evaluation (Ca) and their familiarity with the specific issue under consideration (Cs). Ca encompasses four dimensions: theoretical knowledge, professional experience, literature and intuition. These dimensions were assessed based on their impact and classified as significant, moderate, or minor. The Ca value was calculated as the sum of the weight indices provided in Table 4 (Zeng, 1996). And values of Cs are detailed in Table 5. The calculation formula for Cr is: Cr = (Ca + Cs)/2, where a Cr value of 0 · 7 or higher is considered a satisfactory level of expertise (Zeng, 1996).

The questionnaire revealed that experts struggle to interpret MASS provisions without comprehensively understanding the context. Meanwhile, practitioners, especially captains of convention vessels, hold different views on specific provisions regarding control switching. To address these dependencies, interviews were conducted, aiming to delve into the reasoning behind the experts' opinions. In the interview, ambiguities of related provisions were thoroughly discussed with the interviewer for experts'

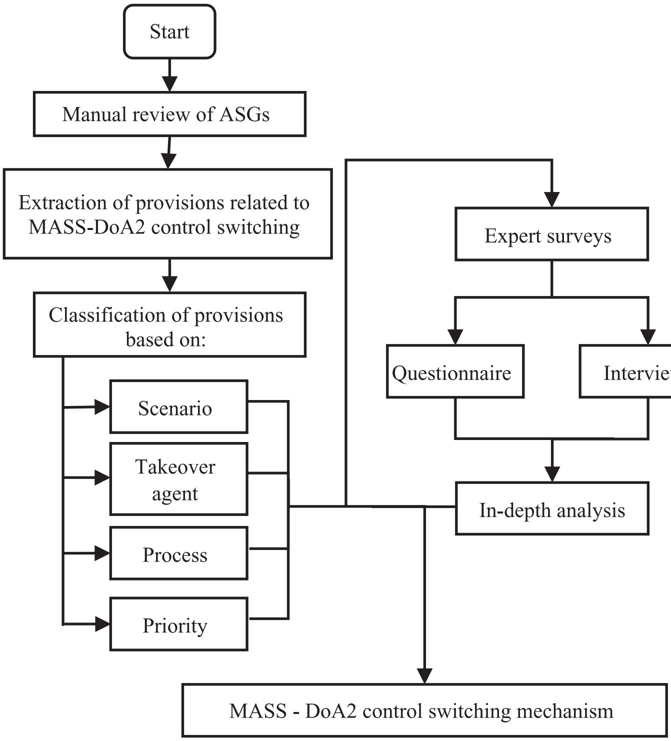

Figure 1. *Flowchart of the research.*

insights and clarification. In addition, the rationale behind expert judgements was further explored. These insights also constitute a part of the essential findings in this study.

2.3. The research process

This study begins with a review of ASGs from IMO and various influential classification societies to collect and categorise provisions related to control switching among three controllers of MASS-DoA2, namely ANS, SCC operator and seafarer onboard, followed by a survey including both questionnaires and interviews to gather further insights and reasoning behind. The review and survey cover four main aspects: scenario, takeover agent, process and priority. By synthesising findings from the systematic review and expert surveys, a framework for MASS-DoA2 control-switching mechanism is developed. The detailed research process is shown in Figure 1.

3. Results from review of MASS – DoA2 control-switching provisions

3.1. Provisions for the control-switching scenarios

The term ‘control-switching scenario’ in this paper refers to the conditions that trigger control switching for MASS-DoA2. It encompasses situations ranging from standard navigation situations to exceptional circumstances affecting MASS’s navigation safety. Changes in these scenarios may increase the complexity of navigation tasks, and pose challenges to the MASS’s ability to manage complex tasks or maintain safety of MASS-DoA2 operations. Therefore, identifying scenarios requiring manual intervention, either from SCC operators or seafarers onboard, is crucial to understanding the control-switching mechanism and lays the groundwork for further exploration of related issues.

Analysis identified a total of 21 provisions related to control-switching scenarios (Table 6). Some provisions use broad term such as ‘when necessary’, suggesting that the scenarios may extend beyond the specific scenarios explicitly mentioned in the guidelines. The identified provisions address 11 different scenarios for MASS-DoA2 control switching, including entering/leaving port, berthing/unberthing, anchoring, navigating in a narrow channel, operating in extreme environments, deviating from course, encountering unidentified obstacles on course, autonomous collision avoidance violating COLREGs (International Regulations for Preventing Collisions at Sea) and dealing with system failures related to it (i.e. ANC, remote control system and engine failures).

3.2. Provisions for control takeover agent

In control-switching scenarios for MASS-DoA2, the control takeover agent is crucial as the command recipient within the control loop. The takeover agent must promptly recognise their responsibilities and execute the takeover in a timely and safe manner. This includes not only ‘accurately assum[ing] control in dynamic traffic scenarios (SAE International, 2014)’, but also managing subsequent tasks across different scenarios. For MASS – DoA2, potential takeover agents include the ANS, SCC operators and seafarers onboard.

The control switching is a primary form of human intervention in MASS autonomous navigation, highlighting the significance of human input within the MASS system. This study specifically targets scenarios identified by ASGs requiring control switching, which involves complex navigational conditions, challenging tasks and stringent safety requirements. These circumstances exceed the capabilities of MASS, leading to the need for manual intervention. Therefore, this section mainly explores the roles of SCC operators and seafarers onboard as takeover agents.

Altogether, 17 provisions related to takeover agents are summarised in Table 7. The table presents details from these provisions and outlines the roles of takeover agents in various control-switching scenarios. According to these guidelines, seafarers onboard are responsible for taking control in situations such as entering/leaving port, berthing/unberthing, anchoring, navigating in narrow channels, and in case of falure of autonomous systems, remote systems and engines. SCC operators, on the other hand, are expected to take over control in scenarios such as deviation from course, encountering unidentified obstacles on course, autonomous system failure and engine failure. However, these provisions lack specific guidelines for takeover agents in scenarios of ‘operating in extreme environment’ and ‘autonomous collision avoidance violating COLREGs’.

3.3. Provisions for control-switching process

The process of control switching involves the flow of command among different takeover agents. It constitutes the operational standards that both human operators and the MASS must adhere to for a successful transfer of control. This aspect is critical as it directly affects ship control and is a key component of human–system interaction within the MASS-DoA2 framework. Therefore, establishing standardised processes for MASS control switching is essential for ensuring operational safety. This includes facilitating a smooth transition of control and reducing the likelihood of human errors.

Table 8 outlines eight provisions related to the control-switching process as derived from ASGs. However, these provisions only provide a general outline of the process, without providing detailed insights into specific procedures or steps involved in the process.

3.4. Provisions for takeover priority

In the context of MASS-DoA2, takeover priority acts as a critical safeguard in the control-switching mechanism. It defines the precedence given to takeover agents to assert control over the ship under various circumstances. Given the immature and somewhat limited application of MASS technology, complex or unexpected scenarios may arise, leading to uncertainty about which agent should assume

Table 6. *Relevant provisions (extract from (China Classification Society (CCS), 2018; Bureau Veritas (BV), 2019; Russian Maritime Register of Shipping (RS), 2020; Det Norske Veritas, 2021; Korean Register (KR), 2022; China Classification Society (CCS), 2023) for MASS – DoA2 control-switching scenario.*

Provision ID	Provision	Guideline ID	Scenario
1.1.1	8.4.2.1.4 – The ship is generally to be provided with necessary equipment operation and management personnel who can take over the operation and control of the equipment as required by safe operation of the ship (e.g. **entering and leaving port** or **berthing and unberthing**) or in an emergency.	1	Entering/Leaving port; Berthing/Unberthing; Anchoring; Narrow channel
1.1.2	9.1.3 – Functional notation: AI – The ship can realise autonomous operation from anchorage to anchorage, with remote control and monitoring. When necessary, the remote control station can remotely control the ship. The ship is operated by crew and/or pilots when **entering and leaving the port** and **during berthing**.		
1.1.3	9.2.11.1-(8) – In complex operation scenarios such as **entering and leaving ports**, **narrow waterways**, and **berthing and unberthing**, the navigation operation is completed by onboard personnel by means of crew members or piloting.		
1.1.4	Section 3, 2.2.4 – **The docking, undocking, mooring, unmooring** and **anchoring operations**, as well as the **harbour navigation** or **port approach** and the assistance in distress situations should be controlled or remotely supervised in case the degree of automation does not allow a full automation for these operations.	4	
1.1.5	3.4.1 (1) – The ship can be designed with autonomous operation or remote control or both functions during **berthing and unberthing** or **entering and leaving port**.	7	
1.1.6	Chapter 2, Section2, 202.2(6) – In the case of no complete autonomous operation of the navigation and **berthing/leaving** within the port, control shall be transferable to the onboard operator or the operator in off-board support system	8	
1.1.7	9.3.1.1 – Human control using ship means at **entering the port/departing from the port** and **mooring**, accidents at sea	10	
1.1.8	9.3.2.2 – MASS may be so designed that **mooring operations** and **movement in port waters**, as well as **entrance to the port and departing from the port** are performed autonomously or by remote control or using both.		

Table 6. *Continued.*

Provision ID	Provision	Guideline ID	Scenario
1.2.1	Chapter 2, Section 2, 202.2(8) – Navigation plans shall be established to avoid **extreme environments** when equipped with an economic navigation system and a track control system, since safe operation of ship may be difficult by the system in the event of heavy weather.	8	Extreme environments
1.3.1	Section 3, 2.4.5 – Depending on the degree of automation, the NAS (Navigating Automation System) should be able to notify the Remote Control Centre (RCC) each time the ship is **deviating from the planned course** and **should send an alarm** when the deviation is out of specified margins.	4	Deviating from course
1.3.2	Chapter 2, Section2, 202.2(4) – If the ship is equipped with a track control system, it shall notify the operator of any **departure from the planned route**, and an alarm shall be issued when the deviation exceeds the specified limits.	8	
1.4.1	2.3.4 – When any **unidentified floating object is detected in the navigation direction** by the ship, **an alarm message is to be sent** to the remote operation centre so as to obtain the operational instruction from the centre.	7	Encountering unidentified obstacles on course
1.5.1	Chapter 2, Section 2, 202.2(7) – Automatic avoidance technique, **based on navigational regulations** (COLREG, etc.) applicable to existing ships for all identified ships in the vicinity and appropriate ship manoeuvring, shall be applied to autonomous navigation systems equipped with collision avoidance module based on maritime regulations.	8	Autonomous collision avoidance violating COLREGs
1.6.1	2.4.1.8 – When the failure of the situation awareness system or the autonomous navigation system finally leads to the **damage of autonomous navigation capability of the ship**, an alarm is to be activated and the personnel onboard are to intervene and take over the operation of navigation of the ship.	1	System failures related to ANC

Table 6. Continued.

Provision ID	Provision	Guideline ID	Scenario
1.6.2	9.3.2.6 – Navigation control system shall be designed and constructed so that it is capable of performing autonomous navigation and switching to remote control from RCC **in case of failure**.	10	
1.7.1	8.4.1.2.6 – When **the remote control function is affected** due to the failure of the ship or failure of system of the remote control station, the ship's personnel are to transfer control from the remote control station to the ship's control station.	1	System failures related to remote control system
1.7.2	8.4.2 .2.6 – When **the remote control system of the remote control station cannot achieve the intended function**, an alarm is to be given to notify the ship's personnel, and means are to be provided to ensure the changeover to onboard control is conducted in a timely manner.		
1.7.3	Section3 8.1.6 – In case the connection between ship and RCC or between ship and shore is unavailable for a period of time, **the ship should enter into a fail-safe sequence** to be defined depending on the degree of automation.	4	
1.7.4	9.3.2.2 – During the remote operation, when the **communication does not meet the requirements**, the ship shall automatically switch to autonomous navigation.	10	
1.8.1	Section 5, 4.2.6 – The engineering watch in RCC should be provided with sufficient monitoring, alerts, diagnostic functions and controls to intervene **in case of unexpected events and failures** which are not safely handled by the automatic control functions.	6	General system failures and unexpected events
1.8.2	9.3.2.13 – The RCC personnel shall control the parameters and, **if necessary**, intervene in the MASS technological processes.	10	

Table 7. *Relevant provisions (extract from (China Classification Society (CCS), 2018; Bureau Veritas (BV), 2019; Russian Maritime Register of Shipping (RS), 2020; Korean Register (KR), 2022; China Classification Society (CCS), 2023; Maritime Safety Administration of the People's Republic of China (China MSA), 2023) for MASS – DoA2 control-switching takeover agent.*

Provision ID	Scenario	Provision	Guideline ID	Suggested takeover agent
2.1.1	Entering/Leaving port; Berthing/Unberthing; Anchoring; Narrow channel	9.1.3 – The ship can realise autonomous operation from anchorage to anchorage, with remote control and monitoring. When necessary, the remote control station can remotely control the ship. The ship is operated by **crew and/or pilots** when entering and leaving the port and during berthing.	1	Seafarer onboard
2.1.2		9.2.1.1.1 (8) – A navigation control station is to be provided on the ship. In complex operation scenarios such as entering and leaving ports, narrow waterways, and berthing and unberthing, the navigation operation is completed by **onboard personnel** by means of crew members or piloting.		
2.1.3		Chapter 2, Section2, 202.2(6) – In the case of no complete autonomous operation of the navigation and berthing/leaving within the port, control shall be transferable to the **onboard operator** or the operator in off-board support system.	8	
2.2.1	Deviating from course	Section 3, 2.4.5 – Depending on the degree of automation, the NAS (navigating automation system) should be able to notify the **RCC** each time the ship is deviating from the planned course and should send an alarm when the deviation is out of specified margins.	4	SCC operator
2.2.2		Chapter 2, Section2, 202.2(4) – If the ship is equipped with a track control system, it shall notify the operator of any departure from the planned route, and an alarm shall be issued when the deviation exceeds the specified limits.	8	
2.3.1	Encountering unidentified obstacles on course	2.3.4 – When any unidentified floating object is detected in the navigation direction by the ship, an alarm message is to be sent to the remote operation centre so as to obtain the operational instruction from the centre.	7	SCC operator

Table 7. *Continued.*

Provision ID	Scenario	Provision	Guideline ID	Suggested takeover agent
2.4.1	System failures related to ANC	2.4.1.8 – When the failure of the situation awareness system or the ANS finally leads to the damage of autonomous navigation capability of the ship, an alarm is to be activated and the personnel onboard are to intervene and take over the operation of navigation of the ship.	1	Seafarer onboard
2.4.2		3.6.2 – In the event of failure in ANS or RCC functions, visual and auditory alarms should be immediately issued at relevant control stations, allowing for prompt manual takeover by seafarer onboard or implementation of other effective measures to prevent loss of control.	15	
2.4.3		9.3.2.6 – Navigation control system shall be designed and constructed so that it is capable of performing autonomous navigation and switching to remote control from RCC in case of failure.	10	SCC operator
2.5.1	System failures related to remote control system	8.4.1.2.6 – When the remote control function is affected due to the failure of the ship or failure of system of the remote control station, the ship’s personnel are to transfer control from the remote control station to the ship’s control station.	1	Seafarer onboard
2.5.2		8.4.2.2.6 – When the remote control system of the remote control station cannot achieve the intended function, an alarm is to be given to notify the ship’s personnel, and means are to be provided to ensure the changeover to onboard control is conducted in a timely manner.		
2.5.3		3.6.2 – In the event of failure in autonomous navigation or remote control functions, visual and auditory alarms should be immediately issued at relevant control stations, allowing for prompt manual takeover by seafarer onboard or implementation of other effective measures to prevent loss of control.	15	

Table 7. *Continued.*

Provision ID	Scenario	Provision	Guideline ID	Suggested takeover agent
2.5.4		3.4.1(2) – During the process of remote control, if the communication fails to meet the requirements for remote control, the ship will automatically switch back to autonomous navigation;	7	ANS
2.5.5		9.3.2.2 – During the remote operation, when the communication does not meet the requirements, the ship shall automatically switch to autonomous navigation.	10	
2.6.1	General system failures and unexpected events	8.4.2.1.4 – The ship is generally to be provided with necessary equipment operation and management personnel, who can take over the operation and control of the equipment as required by safe operation of the ship (e.g. entering and leaving port or berthing and unberthing) or in an emergency.	1	Seafarer onboard
2.6.2		9.3.2.13 – The RCC personnel shall control the parameters and, if necessary, intervene in the MASS technological processes.	10	SCC operator
2.6.3		9.3.2.14 – It shall be possible to manually intervene in the control of propulsion units and thrusters from RCC.		

Table 8. *Relevant provisions (extract from (China Classification Society (CCS), 2018; Bureau Veritas (BV), 2019; China Classification Society (CCS), 2023; Maritime Safety Administration of the People's Republic of China (China MSA), 2023) for MASS – DoA2 control-switching process.*

Provision ID	Provision	Guideline ID
3.1	8.4.1.2.5 – The transfer of control right is only to be carried out at the onboard control position and after acknowledgement at the remote control station.	1
3.2	8.4.2.2.3 – Transfer of control between the remote control station and onboard control station can only be carried out at the onboard control station.	
3.3	8.4.2.2.6 – When the remote control system of the remote control station cannot achieve the intended function, an alarm is to be given to notify the ship's personnel, and means are to be provided to ensure the changeover to onboard control is conducted in a timely manner.	
3.4	Section 1, 2.7.5 – Before taking control of a ship from the RCC, remote operators should first ensure that they have an accurate situational awareness and that all devices to control the ship remotely are available and operational.	4
3.5	Section 1, 2.10.2 – The ergonomics of monitoring and control systems should take into account the human vigilance that could be reduced during extended periods of remote control or when several ships which are in different situations are managed by only one operator.	
3.6	Section l, 2.10.3 – The remote operators should be aware of the latency due to the communication that cause a delay between his/her action and the actual ship reaction. The latency should be continuously displayed during the operations (e.g. manoeuvring) and a warning should be issued when the latency is over pre-defined limits.	
3.7	3 4.1(3) – where the ship is provided with a navigation control station, it can obtain the control right of ship subject to approval by the remote operation centre. After the completion of control, the control right needs to be transferred back to the remote operation centre.	7
3.8	3.6.3 – Control-switching between the SCC and the ship's bridge should occur at the bridge, and it should be performed only after acknowledgment confirmation from the SCC.	15

control. Moreover, in cases of failures, the transfer of control might deviate from standard procedures. Therefore, it is imperative to assign clear priorities to each takeover agent, ensuring they can take immediate control of the MASS when necessary.

This study has identified and analysed nine provisions related to the prioritisation in control switching (Table 9). Although these provisions vary in content, they collectively highlight consistent viewpoints among various classification societies regarding the priority among different takeover agents. Specifically, the consensus indicates that the priority of seafarers onboard supersedes SCC operators and autonomous systems, with SCC operators holding a higher priority than ANS.

Table 9. *Relevant provisions (extract from (China Classification Society (CCS), 2018; Bureau Veritas (BV), 2019; Russian Maritime Register of Shipping (RS), 2020; Det Norske Veritas, 2021; Korean Register (KR), 2022; China Classification Society (CCS), 2023; Maritime Safety Administration of the People's Republic of China (China MSA), 2023) for MASS – DoA2 control-switching priority.*

Provision ID	Provision	Guideline ID	Priority
4.1.1	Section 1, 2.2.3 – The possibility for the crew or remote operators to regain control of a ship in case of emergency or system failure should always be present.	4	Seafarer onboard/SCC operator > ANS
4.1.2	3.4.1 – The main propulsion and steering systems of the MASS should be capable of automatic operation and control according to instructions from the ANS or SCC, with the ability to switch to seafarers at any time.	15	
4.2.1	Section 1, 2.2.5 – When a ship is operated remotely, the crew should always be able to regain control of the ship in priority to the remote operator.	4	Seafarer on board > SCC operator
4.2.2	Section 5, 6.4.4 – Only one location (on board/RCC) should possess the privilege for control of a vessel function or an Equipment Under Control (EUC) at any time and means for transfer of control should be arranged. The two control locations may not have the same capabilities, but if justified by document concept of operation, it should be possible to override or perform emergency control on board the ship.	6	
4.3.1	2.4.1.1 – The ship is capable of autonomous navigation in open water. During such period, onboard personnel will supervise the navigational operation of the ship and can intervene at any time where necessary to obtain the control of navigation and manoeuvre the ship.	1	Seafarer onboard > ANS
4.4.1	12.3.1 – The remote operation centre is at least to have the following functions: (4) overriding the autonomous navigation of autonomous ships as necessary, remotely operating the ships and systems.	7	SCC operator > ANS
4.4.2	Chapter 2, Section 2, 202.2(2) – The operator shall be able to control the autonomous navigation system at any time.	8	
4.4.3	9.4.7.2.1 – Under normal operating conditions, the authority of RCC has the highest level, and the authority of artificial intelligence system is under its control.	10	
4.4.4	10.3.2.4 – The RCC shall perform cancellation of autonomous mode of navigation and switching to remote control mode of MASS and its systems, if necessary.		

3.5. Summary

Based on the thorough review of relevant provisions in the ASGs, a preliminary framework for the control-switching mechanism was developed. Current guidelines, constrained by the present development of MASS, do not provide extensive details on the control-switching processes. Nevertheless,

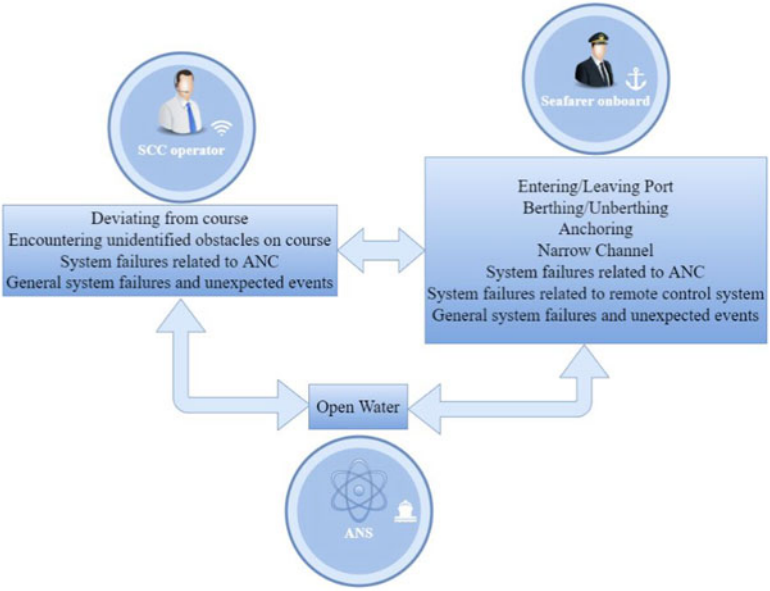

Figure 2. *MASS – DoA2 control switching schematic.*

there is a widely recognised consensus on the hierarchy of priority among different takeover agents. Figure 2 illustrates the interplay between various scenarios and the corresponding takeover agents. This visualisation forms the foundational reference for further expert surveys and discussions.

A particular provision (ID 2.5.4) recommends transferring control to the ANS in case of remote failure. This is significant as remote control system failures can surpass the capabilities of autonomous navigation. In this context, this paper proposes that seafarers onboard should be the designated takeover agents in remote failure scenarios, ensuring continuity and safety of navigation.

Notably, current provisions do not specifically identify takeover agents for scenarios involving ‘extreme environment’ and ‘autonomous collision avoidance violating COLREGs’. Additionally, notable discrepancies exist among various ASGs concerning the designated takeover agents for scenarios such as ‘System failures related to ANC’, ‘System failures related to remote control system’ and ‘General system failures and unexpected events’. These gaps and inconsistencies in the guidelines highlight areas that require further exploration and clarification. These issues, along with their implications for the control-switching mechanism in MASS-DoA2, will be addressed and analysed in detail in the expert survey, which is thoroughly discussed in Section 4 of this paper.

4. Expert survey for MASS – DoA2 control switching mechanism

4.1. Questionnaire results

The questionnaire designed for this study gathered insights from experts on the selection of takeover agents in 11 distinct control-switching scenarios as outlined in the ASGs. We received responses from 14 experts who have relevant expertise in this field. Their detailed opinions on the specified questions, along with comprehensive discussions about their individual perspectives, are presented in the interview section of this paper. This section offers an in-depth analysis of expert viewpoints, contributing valuable insights to the understanding of control-switching mechanisms in MASS-DoA2. Table 10 lists the background information of each expert, and Table 11 lists the expertise level of the respondents on this subject.

The expertise level serves as a metric to assess the proficiency of the respondents in the surveyed field, along with the reliability and applicability of their contributions. The analysis of the data in Table 11

Table 10. *Statistics of expert information.*

Information	Classification	Amount
Title/Office	Professor	3
	Associate Professor	5
	PhD Candidate	3
	Captain	2
	Chief Officer	1
Research field	Safety Engineering	4
	Autonomous Ship	7
	Maritime Safety and Security	3
Years of research experience in relevant field	Less than 3 years	6
	3–5 years	4
	5–7 years	2
	More than 7 years	2

Table 11. *The expertise level of the respondents.*

	Expert$_1$	Expert$_2$	Expert$_3$	Expert$_4$	Expert$_5$	Expert$_6$	Expert$_7$
C_r	0.8	0·75	0·85	0·7	0·7	0·8	0·85
	Expert$_8$	Expert$_9$	Expert$_{10}$	Expert$_{11}$	Expert$_{12}$	Expert$_{13}$	Expert$_{14}$
C_r	0·8	0·8	0·7	0·7	0·9	0·8	0·75

yields an average credibility rating of $\bar{Cr} = 0\cdot 78 \pm 0\cdot 06$ .The rating satisfies the criteria $Cr \geq 0\cdot 7$, both from a collective and individual standpoint, indicating a satisfactory level of expertise. Consequently, the expertise levels in this survey are in line with the set requirements, providing a substantial degree of confidence in the reliability of the experts' opinions.

The results of the data analysis are listed in Table 12, and Figure 3 presents the overall stance of expert opinions. In this representation, positive values signify a general consensus among the experts, indicating agreement on the topics discussed. Conversely, negative values denote a divergence of opinions, pointing to disagreement. The absolute value, whether positive or negative, indicates the strength of this agreement or disagreement. Essentially, the larger the magnitude of the value, the more pronounced the level of concordance or discordance in the overall expert opinion.

The analysis of expert's opinion leads to the following conclusions:

1) There is a broad consensus among experts that, across various control-switching scenarios, seafarers onboard are capable of assuming control of MASS.
2) Experts generally agree that SCC operators are also capable of taking over control of MASS in most scenarios, with the exceptions of remote system failure and anchoring operation. However, the level of agreement for SCC operators taking over is lower compared to that for seafarers onboard.
3) The majority of experts believe that, in almost all the 11 control-switching scenarios outlined by ASGs – with the exceptions being the berthing/unberthing and extreme environment scenarios – it is essential to shift to human control of the MASS.

4.2. Results from the interview

The questionnaire, grounded in ASGs, yielded results that primarily reflect the collective perspectives of the experts. To provide more detailed and valuable theoretical contributions to the research on the

Table 12. Descriptive statistical analysis of the expert questionnaire results.

	Entering/ Leaving port	Berthing/ Unberthing	Anchoring	Narrow channel	Extreme environment	Deviating from course	Encountering unidentified obstacles on course	Autonomous collision avoidance violating COLREGs	System failures related to ANC	System failures related to remote control system	General system failures and unexpected events
Seafarer onboard	0·93	0·86	0·75	0·82	0·5	0·39	0·43	0·61	0·86	0·93	0·68
SCC operator	0·46	0·43	–0·16	0·5	0·29	0·5	0·71	0·64	0·75	–0·64	0·16
ANS	–0·5	0·07	–0·21	–0·21	0·07	–0·11	–0·21	–0·54	–0·82	–0·18	–0·57

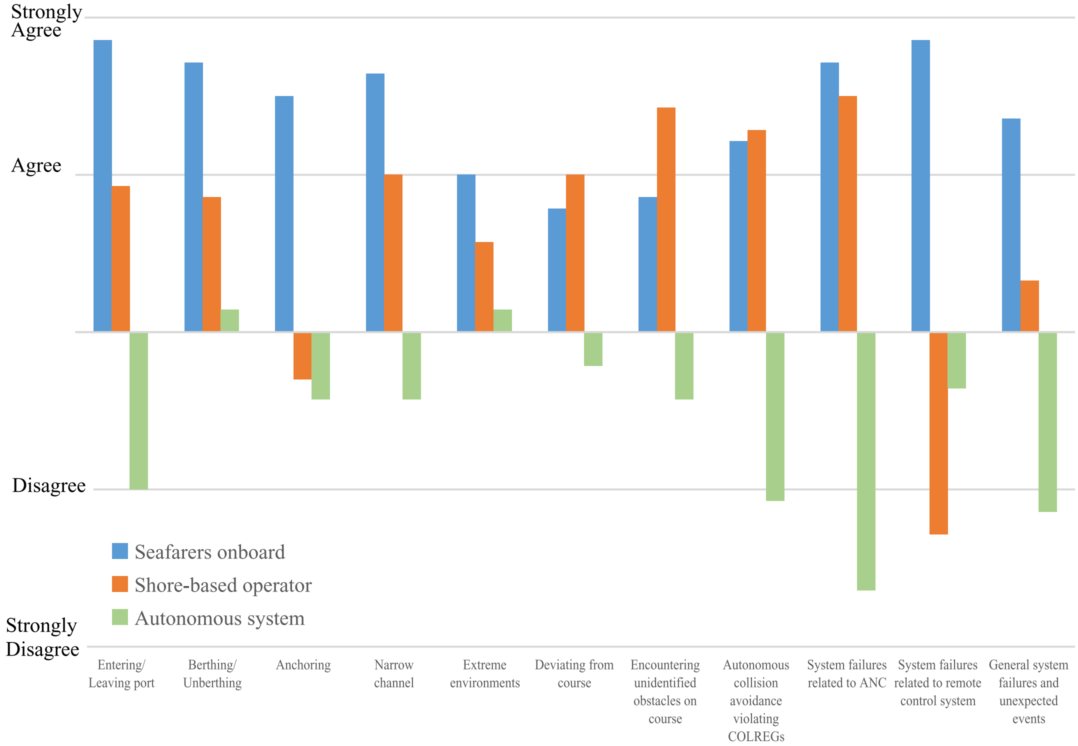

Figure 3. *Agreement and disagreement in expert views.*

MASS-DoA2 control-switching mechanism, this paper organised the insights proposed by the experts during the interviews. These insights, directly relevant to the core research areas of this study, serve as a basis for refining the framework of the control-switching mechanism.

1) Entering/leaving port – ASGs commonly state that MASS–DoA2 should have seafarers onboard responsible for navigation tasks when entering or leaving port. However, the overall consensus suggests that some experts believe that ship control can also be taken over by SCC operators during entering or leaving port. A professor with seafaring experience noted *(anonymised quotes from the experts are part of results)*:

> Entering and leaving port involves considerations such as port channel configurations, traffic flow conditions, local navigation rules and complying with VTS (vessel traffic systems) dispatch. With the support of electronic navigation information, remote control and communication technology, SCC operators may also be capable of remotely controlling MASS entering or leaving ports.

   This perspective aligns with the provisions in ASGs concerning control switching for 'uncrewed' MASS. As MASS evolves, the responsibilities of seafarers onboard are not eliminated as ships become less manned or unmanned; instead, they are gradually shifted to SCC operators (Zhang et al., 2020). However, this viewpoint does not specifically address MASS-DoA2, and the performance of SCC operators in terms of the 'equivalent safety principle' (de Vos et al., 2020; Zhou et al., 2020a) also remains unverified.

2) Berthing/unberthing – The responses revealed a range of opinions among experts about the capability of MASS-DoA2 to autonomously accomplish safe berthing and unberthing. Despite the diversity in viewpoints, there is a general trend toward agreement on this capability. To shed light on this perspective, a professor with extensive experience and captain qualifications provided an insightful explanation *(specific comments from experts are anonymised for this study)*:

> Some actual MASS, even though they are still in the testing and trail stages, are already capable of autonomously berthing and unberthing. Therefore, MASS–DoA2 with autonomous berthing and unberthing capabilities can perform these manoeuvres autonomously, instead of transferring the control to human operators.

Indeed, as this expert stated, MASS has made substantial progress in the field of autonomous berthing and unberthing (Tran and Im, 2012; Mizuno and Kuboshima, 2019; Nguyen, 2019; Piao et al., 2019). This advancement also paves the way for further research into the mechanisms of MASS control switching. In the subsequent sections, we delve deeper into the nuances of identifying appropriate takeover agents for berthing and unberthing scenarios, further elaborating on this aspect within the broader context of MASS control switching.

3) Anchoring – The results highlighted divergent expert opinions on the role of SCC operators as the takeover agent in the 'anchoring' scenario. The general trend among these responses leans towards disagreement with the idea of SCC operators managing the anchoring process. To provide context to this perspective, a chief officer with significant maritime practical experience shared his viewpoint *(the expert's comments are anonymised as part of the study's confidentiality protocol)*:

> After a vessel is anchored, it would experience swaying due to wind, current and seabed condition. Local VTS often requires an appropriate safety distance between anchored vessels. However, in ports with heavy traffic, the distance between anchored vessels during swaying can be less than 2 nautical miles. If a vessel drags anchor, the situation becomes extremely urgent. There is a need for further validation regarding the emergency response capabilities and reaction times of SCC operators, particularly in their ability to effectively handle scenarios such as anchoring.

The scenario described by this expert, though unique, raises important considerations. The expert's viewpoint indirectly reflects the necessity of takeover by seafarers onboard during anchoring, while also providing analytical insights for the functional design and operational management of the MASS anchoring process. This input is instrumental in shaping the approach towards enhancing MASS capabilities in complex maritime operations.

4) Extreme environment – The provision (Provision ID 1.2.1) addresses extreme environment scenarios on the autonomous functionality. It points out that such influences might result in the autonomous system being unable to ensure safe navigation (Korean Register (KR), 2022). During interviews, five experts highlighted that 'extreme environment' covers a range of situations, each requiring consideration of its specific context. One particularly notable viewpoint among these was as follows:

> Extreme environment encompasses various situations. For example, during heavy winds and waves, crew members might be prone to human errors, implying that crew control may not be more stable than autonomous control. In cases of poor visibility, the performance of perception sensors might be compromised, leading to an incomplete perception of the situation. With seafarers onboard, additional measures such as adding lookouts or auditory watch can be employed to ensure safety. Hence, the control switching under various extreme environments must be categorically explored.

This focused analysis is vital to ensure that the control mechanisms in MASS are robust and reliable under a wide spectrum of challenging conditions. Indeed, extreme environments comprise various conditions, and their implications for control switching should be individually assessed rather than generalised. As highlighted by the expert, conditions such as 'poor visibility' can be seen as a representation of the adverse effects of environments on autonomous functionality. Furthermore, the situational awareness of the SCC operator also relies on performance of onboard equipment (Liu et al., 2022b; Li et al., 2023c). When the relevant functions of the autonomous system are restrained in adverse environments, the operation of the SCC operator may also be constrained. Therefore, in extreme environment scenarios that may impact the autonomy functionality of MASS-DoA2, it become necessary for seafarers onboard to take control of the ship.

5) Autonomous collision avoidance violating COLREGs – During the interviews, it was observed that not just the interviewed captains and chief officer but also other experts with navigation experience pointed out that executing avoidance manoeuvres that deviate from COLREGs is a frequent and common occurrence in practical navigation. This insight sheds light on the complexities of real-world navigation, where strict adherence to COLREGs might not always be feasible or optimal. One of the experts provided the following explanation:

   > Whether it concerns traditional vessels or MASS, it is vital to distinguish between deviating from the COLREGs and outright violating them. This distinction is crucial for both types of vessels that operate under the guidance of COLREGs.

   'Deviating from rule' refers to situations where vessels take evasive manoeuvres that deviate from COLREGs in special circumstances to ensure navigational safety. In such cases, deviating from the specific stipulations of COLREGs can paradoxically be seen as an adherence to their overarching principle. These deviations are often necessary to ensure safety and are made in the spirit of the COLREGs, which fundamentally aim to prevent collisions and promote safe navigation. On the other hand, 'violating the rule' refers to situations where vessels intentionally disregard COLREGs without any valid justification. This is not permitted by the COLREGs and constitutes a violation of maritime regulations. This distinction between necessary deviations and outright violations is critical, particularly for the operational protocols of MASS, where adherence to maritime safety standards is paramount.

   The results from the questionnaire reveal a preference among experts for SCC operators to take control in 'violating' scenarios. The design and operation of autonomous collision avoidance functions need to consider compatibility with COLREGs (Zhou et al., 2020b; Wróbel et al., 2022). Therefore, any decision by the MASS to violate COLREGs can be regarded as an autonomous system failure. The selection of the appropriate takeover agent in scenarios involving autonomous system failures in MASS will be further elaborated in the upcoming sections.

6) System failures related to ANC & general system failures and unexpected events – The guidance provided in ASGs regarding the appropriate takeover agents for scenarios involving these two types of failures shows variability. To shed light on this issue, one of the experts offered a perspective based on the DoA framework:

   > For MASS-DoA2, the primary responsibility should be with the SCC operator, while seafarers onboard are envisaged to play a supporting or backup role. This aligns with the development goals of 'less manned' and 'unmanned' MASS. In scenarios involving higher DoA, such as DoA 3 and 4, where there are no seafarers onboard, the SCC operators must be equipped with the necessary capabilities to address and manage any unexpected failures.

   Based on this perspective and in combination with the questionnaire results, we recommend that in autonomous system failure or engine failure scenarios, control should be transferred to SCC operators firstly, with seafarers onboard taking over if SCC operators are unable to manage.

7) Others – During the interview, experts shared numerous viewpoints based on their research backgrounds and practical experiences, which are also valuable for this study. For example, an associate professor specialising in autonomous ships pointed out:

   > The DoA forms the fundamental basis for control modes in MASS. It's one-sided to solely discuss control-switching mechanisms based on DoA. Instead, it is essential to consider the specific degrees of each autonomous function in different MASS and establish control-switching mechanisms that balance between common standards and the unique characteristics of each MASS system.

   In the viewpoint of this expert, the DoA does not fully represent the autonomous capabilities of MASS. However, by the DoA, it is possible to determine how many control modes the MASS possesses. For instance, the 'Zhifei Hao' has the capability for manual control, remote control and autonomous control. With seafarers onboard, based on the IMO's definition of DoA, it could be categorised as an MASS-DoA2. However, trial results have shown its ability to autonomously berth and unberth (Luo et al., 2022; Xing and Zhu, 2023). In scenarios like berthing and unberthing, the need for seafarers onboard, and consequently for control switching, may not be necessary. Therefore, the research on MASS–DoA2 control-switching mechanisms should extend beyond just the DoA and carefully examine the specific autonomous functions of each MASS-DoA2 system.

5. Discussion

In the foreseeable future, an increasing number of MASS will be deployed for trials or commercial operations (Zhang et al., 2020; Zhang et al., 2022a). This leads to a growing industry demand to establish regulations governing control switching in order to oversee MASS operations and to ensure navigational safety from a managerial perspective. Given the limited access to and the challenging nature of obtaining comprehensive MASS data for research purposes, this paper explores the control-switching mechanism through a review of ASGs and expert surveys. Consequently, it proposed a framework for the control-switching mechanism in MASS-DoA2, covering four key aspects: 'scenarios, takeover agents, processes, and priorities'.

Figure 4 presents the framework developed in this paper synthesising findings from the four aspects previously stated. This framework initiates control switching based on changes in scenarios, placing the scenarios as the primary triggers. Each scenario correlates with specific takeover agents, who are aligned with different control modes, thereby establishing control modes as the key reference points in the framework.

To facilitate real-time awareness of the control mode by humans and ensure that only one agent controls the ship, the process varies according to the scenario and agents involved. Different coloured narrow lines represent the various processes among different takeover agents, aiming to reflect relevant provisions from ASGs on 'processes', such as initiating, notifying, confirming and taking over. Notably, apart from the scenario indicated by ASGs, seafarer onboard may take over from the SCC operator in case of accidents or failures preventing remote control, serving as a safety barrier. This process is depicted in Figure 4 by red dashed lines. And 'Priority' within this framework is illustrated using black dashed arrows, bypassing intermediate steps to highlight its direct and overriding nature in the control-switching mechanism. This representation underscores the importance of quickly establishing which agent has control in various scenarios, ensuring clarity and efficiency in the operation of MASS-DoA2.

5.1. Interpretation of the findings

The research has identified 11 control-switching scenarios, while acknowledging that the list is not exhaustive. The MASS-DoA2 considered in this study poses three operational modes controlled by three distinct agents: the ANS, the SCC operator and the seafarer onboard. This is to be aligned with the current state of most delivered MASS-DoA2 deployed for sea trial today, and the expectation that MASS-DoA2 is a transition phase leading towards more advanced level, such as MASS-DoA3 and MASS-DoA4.

The primary goal of this study is to develop practical control-switching mechanisms that adequately reflect these diverse operational modes. Therefore, it's important to recognise that the autonomy capabilities of MASS-DoA2 may extend beyond 'open-water autonomous navigation'. Should MASS demonstrate proficiency in autonomously navigating in more intricate scenarios, it could necessitate revisions or more adaptable approaches within the ASGs.

The results of expert questionnaire consistently show a preference for seafarers onboard as the primary takeover agent. However, this consensus does not necessarily imply seafarers onboard should always be present and in control across all 11 identified scenarios. Rather, it reflects the experts' confidence in the ability of seafarers onboard to competently manage navigation tasks within these scenarios. Therefore,

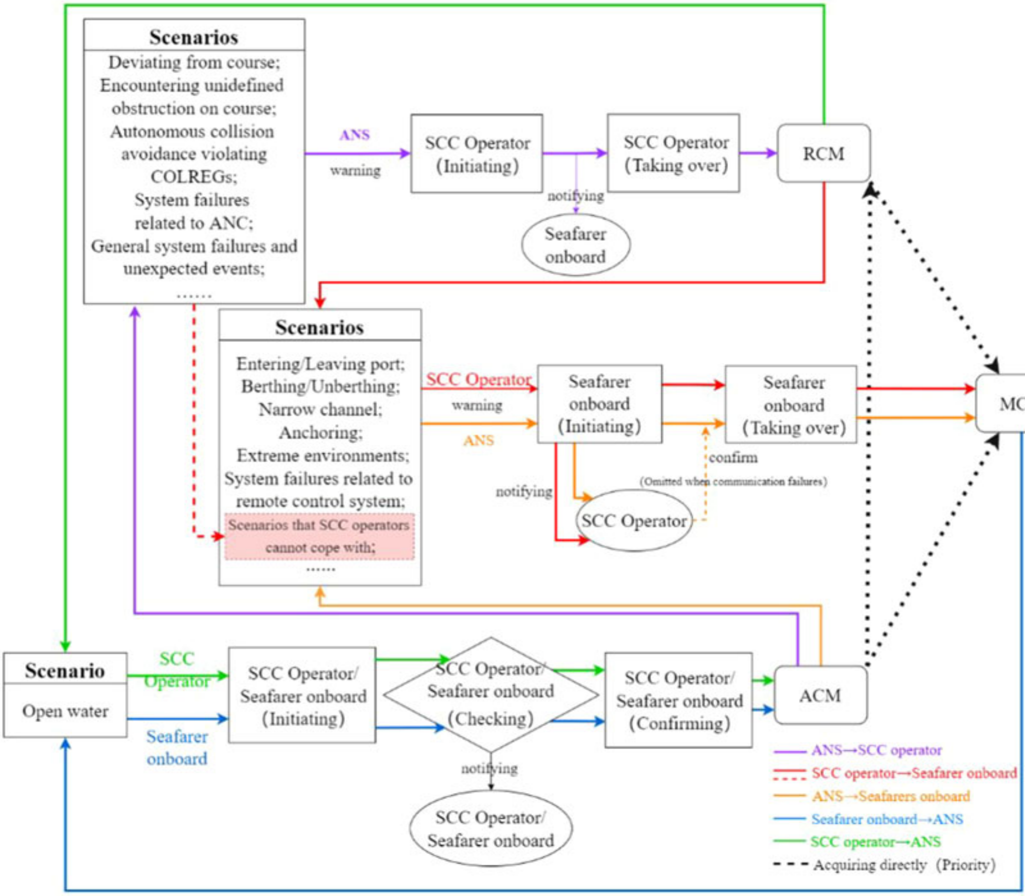

Figure 4. *MASS – DoA2 control-switching mechanism framework.*

this paper recommends adhering to the guidance provided by the ASGs to in determining the appropriate takeover agents. Additionally, when a SCC operator encounters difficulties in handling navigation tasks after assuming control, the control should be transferred to onboard seafarers onboard to ensure the safety of MASS navigation. This approach helps maintain a balance between utilising the capabilities of autonomous systems and ensuring safe navigation through human expertise when necessary.

The existing guidelines and expert surveys reveal a gap in specific guidance regarding the control-switching processes for MASS-DoA2. This lack of detailed description has limited our efforts to develop a comprehensive framework for the MASS-DoA2 control-switching mechanism. While we have endeavoured to incorporate the existing provisions from the ASGs, it is clear that establishing in-depth standards for these processes will require more practical experience and empirical data from the field of MASS operation.

The perspectives on the takeover priority of MASS-DoA2 show remarkable consistency between the ASGs and the results of expert interviews. This priority within the mechanism empowers both seafarers onboard and SCC operators with the ability to assume direct control of the MASS, ensuring timely intervention when necessary. The established consensus on this hierarchy is clear: ‘Seafarers Onboard > SCC Operator > ANS’. This prioritisation reflects a strategic approach to ensuring the safety and effectiveness of MASS operations, recognising the critical role of human oversight in autonomous maritime navigation.

5.2. *Implication of the framework*

The concept of dynamic DoA provides MASS-DoA2 with the flexibility and safety needed to adapt to a wide range of navigational scenarios. Despite the growing interest and recognition of the importance of dynamic DoA and safe control switching among control agents, a standard control-switching mechanism has not yet been established. The framework presented in this paper aims to support the establishment of related regulatory standards, improve the design of MASS systems and contribute to ongoing research on the safety of human–system interactions.

On the one hand, the framework offers valuable reference for maritime regulatory authorities in the development of control-switching mechanisms. ASGs provide both instruction and constraints for the design, construction, testing, deployment and regulation of MASS, aiming to enhance safety and facilitate regulatory oversight. MASS is encouraged to comply with the provisions specified by respective ASGs. This study consolidates the common control-switching requirements from various ASGs, integrates the variations in provisions through expert surveys and proposes a framework that aligns with established maritime practices. Consequently, the framework demonstrates wide applicability across diverse MASS system and can significantly contribute to the establishment of control-switching mechanisms for MASS.

On the other hand, the framework presented in this study also has significant implications for the design of autonomous systems. As control-switching is a crucial component of human–system interaction, and system design must enable MASS to achieve smooth and safe control-switching. A comprehensive understanding of the control-switching mechanism is essential for optimising this functionality from a design perspective, ensuring compliance with international convention standards, and realising its intended functionality.

Moreover, a review of relevant literature reveals that prior research, while addressing control-switching, has not extensively explored the specific events or behaviours during the transition. This gap is attributed to the lack of unified regulations, which makes it challenging to conduct detailed analyses of human intervention. The framework proposed in this paper addresses this gap to some extent, allowing for a more focused assessments of human–system interactions. This contribution is significant for advancing research in this field, offering a foundation for future studies to build upon and enhancing the overall understanding and development of human–sys dynamtemics in maritime operations.

6. Conclusions

The development and application of autonomous technologies have significantly advanced the evolution of MASS, but achieving complete independence of ships from human intervention remains a subject that necessitates further exploration and experimentation. During navigation, different control modes can be alternately employed to address tasks that are challenging for autonomous functions to execute. This requires humans to promptly take over the ship during supervision and complete the transition of control. However, the industry has yet to establish control-switching standards. Therefore, this paper conducted research on the MASS-DoA2 control-switching mechanism through ASGs and expert surveys, proposing a framework covering four key aspects: scenarios, takeover agents, processes and priorities. This framework could serve as the foundation for studies related to dynamic DoA, and provide insights for regulatory authorities in establishing such mechanisms.

Several limitations must be addressed in the future. Due to the constraints arising from the limited number of operational cases and data for MASS-DoA2, along with a scarcity of references, the proposed mechanism framework requires further verification and refinement if necessary. Firstly, the influence of diverse extreme weather conditions on control-switching remains unclear. Subsequently, integrating maritime practices with MASS technology could be pursued to investigate their impacts on MASS components and overall system performance. This would contribute to establish control-switching guidelines for varying conditions, thereby refining and improving the control-switching mechanism. Secondly, the control-switching process requires clearer specifications. In the future, human reliability analysis (HRA) methods could be introduced to evaluate the reliability of both the SCC operator and seafarers during the switching process, providing basis for establishing control-switching procedures and standardising human behaviour. Thirdly, the practicality of the control-switching mechanism is a key consideration. It is necessary to investigate the applicability of the proposed control-switching mechanism to maritime regulations and regulatory systems based on relevant shipping codes. This would be beneficial to enhance the practical application value of the proposed control transition mechanism framework.

While the proposed framework begins to bridge the current gaps in understanding control-switching mechanisms, further enhancements through theoretical research and validations within the MASS domain. This continued effort will contribute to developing a more robust and practical control-switching mechanism. In future research, the focus should be on modelling and analysing MASS-DoA2 control-switching through risk analysis models and case studies, thereby enriching the understanding and effectiveness of this crucial aspect of MASS operations.

Table of Acronyms/Glossary

ACM	Autonomous Control Mode
AIVs	Autonomous Inland Vessels
ANC	Autonomous Navigation Controller
ANS	Autonomous Navigation System
ASG	Autonomous Ship Guideline
BNs	Bayesian Networks
COLREG	International Regulations for Preventing Collisions at Sea
CoTA	Concurrent Task Analysis
DoA	Degree of Autonomy
ESD	Event Sequence Diagrams
HRA	Human Reliability Analysis
H – SIA	Human–System Interaction in Autonomy
HTA	Hierarchical Task Analysis
IMO	International Maritime Organisation
MASS	Maritime Autonomous Surface Ship
MCM	Manual Control Mode
RCM	Remote Control Mode
SCC	Shore Control Centre
THERP	Technique for Human Error Rate Prediction
VTS	Vessel Traffic Management Systems

Funding. This study was supported by the National Natural Science Foundation of China (NSFC) (Grant No. 52201408, No. 52301416), and National Key R&D Program of China (Grant No. 2023YFB4302300).

References

American Bureau of Shipping (ABS) (2022). *Requirements for Autonomous and Remote Control Functions*. TX: ABS.

Bačkalov, I. (2020). Safety of autonomous inland vessels: An analysis of regulatory barriers in the present technical standards in Europe. *Safety Science*, **128**, 104763. doi:10.1016/j.ssci.2020.104763

Botes, M., Bruce, J. and Cooke, R. (2023). Consensus-based recommendations for strengthening emergency care at primary health care level: A Delphi study. *Global Health Action*, **16**(1), 2156114. doi:10.1080/16549716.2022.2156114

Bureau Veritas (BV) (2019). *Guidelines for Autonomous Shipping*. Paris: BV.

Burmeister, H.-C., Bruhn, W., Rødseth, Ø. J. and Porathe, T. (2014). Autonomous unmanned merchant vessel and its contribution towards the e-navigation implementation: The MUNIN perspective. *International Journal of e-Navigation and Maritime Economy*, **1**, 1–13. doi:10.1016/j.enavi.2014.12.002

Chen, Q., Lau, Y.-y., Zhang, P., Dulebenets, M. A., Wang, N. and Wang, T.-n. (2023). From concept to practicality: Unmanned vessel research in China. *Heliyon*, **9**(4), e15182. doi:10.1016/j.heliyon.2023.e15182

Cheng, T., Utne, I. B., Wu, B. and Wu, Q. (2023). A novel system-theoretic approach for human-system collaboration safety: Case studies on two degrees of autonomy for autonomous ships. *Reliability Engineering & System Safety*, **237**, 109388. doi:10.1016/j.ress.2023.109388

China Classification Society (CCS) (2018). *Guidelines for Autonomous Cargo Ships 2018*. Beijing: CCS.

China Classification Society (CCS) (2023). *Rules for Intelligent Ships 2023*. Beijing: CCS.

ClassNK (2020). *Guidelines for Concept Design of Automated Operation/Autonomous Operation of Ships*. Tokyo: ClassNK.

Det Norske Veritas (DNV) (2021). *Autonomous and Remotely Operated Ships*. Oslo: DNV.

Det Norske Veritas (DNV) (2022a). *Competence of Remote Control Centre Operators*. Oslo: DNV.

Det Norske Veritas (DNV) (2022b). *Certification Scheme for Remote Control Centre Operators*. Oslo: DNV.

Det Norske Veritas (DNV) (2022c). *Management Systems for Auto-Remote Operations*. Oslo: DNV.

de Vos, J., Hekkenberg, R. G. and Koelman, H. J. (2020). Damage stability requirements for autonomous ships based on equivalent safety. *Safety Science*, **130**, 104865. doi:10.1016/j.ssci.2020.104865

European Union (2020). *EU Operational Guidelines for Safe, Secure and Sustainable Trials of Maritime Autonomous Surface Ships (MASS)*. Bruxelles: European Union.

Fan, C., Montewka, J. and Zhang, D. (2022). A risk comparison framework for autonomous ships navigation. *Reliability Engineering & System Safety*, **226**, 108709. doi:10.1016/j.ress.2022.108709

Felski, A. and Zwolak, K. (2020). The ocean-going autonomous ship – challenges and threats. *Journal of Marine Science and Engineering* **8**, 41. doi:10.3390/jmse8010041

Göb, R., McCollin, C. and Ramalhoto, M. F. (2007). Ordinal methodology in the analysis of Likert scales. *Quality Quantity*, **41**, 601–626. doi:10.1007/s11135-007-9089-z

Goerlandt, F. (2020). Maritime autonomous surface ships from a risk governance perspective: Interpretation and implications. *Safety Science*, **128**, 104758. doi:10.1016/j.ssci.2020.104758

Guo, C. and Utne, I. B. (2022). Development of risk indicators for losing navigational control of autonomous ships. *Ocean Engineering*, **266**(5), 113204. doi:10.1016/j.oceaneng.2022.113204

Hyundai Samho Heavy Industries (2023). Hyundai Samho Heavy Industries(HSHI) Building the World's First 'AI Engineer' Equipped ship. Available at https://www.hshi.co.kr/eng/bbs/news/view.do?n=142&pg=1 (accessed 7 October 2023).

IMO (2018). *Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-Making Process*. London: International Maritime Organization.

Issa, M., Ilinca, A., Ibrahim, H. and Rizk, P. (2022). Maritime autonomous surface ships: Problems and challenges facing the regulatory process. *Sustainability*, **14**, 15630. doi:10.3390/su142315630

Japan Radio Co. Ltd (2023). The Nippon Foundation MEGURI2040 Fully Autonomous Ship Project Demonstration Test of Autonomous Navigation System on Large RORO Cargo. Available at https://www.jrc.co.jp/en/news/2023/1128-1 (accessed 13 March 2024).

Kari, R. and Steinert, M. (2021). Human factor issues in remote ship operations: Lesson learned by studying different domains. *Journal of Marine Science and Engineering*, **9**, 385. doi:10.3390/jmse9040385

KONGSBERG (2023). KONGSBERG Successfully Demonstrates Autonomous Vessel Operations on Belgium's Inland Waterway Network. Available at https://www.kongsberg.com/maritime/about-us/news-and-media/news-archive/2023/trial-of-autonomous-shipping/ (accessed 13 March 2024).

Korean Register (KR) (2022). *Guidance for Autonomous Ships*. Busan: KR.

Lehtola, V., Montewka, J. and Salokannel, J. (2020). Sea captains' views on automated ship route optimization in ice-covered waters. *The Journal of Navigation*, **73**(2), 364–383. doi:10.1017/S0373463319000651.

Li, Z. and Seta, M. (2022). The expanding role of classification societies in conserving the marine environment: The case of the 2004 BWM convention. *Ocean Development & International Law*, **53**(4), 318–345. doi:10.1080/00908320.2022.2148793

Li, W., Chen, W., Hu, S., Xi, Y. and Guo, Y. (2023a). Risk evolution model of marine traffic via STPA method and MC simulation: A case of MASS along coastal setting. *Ocean Engineering*, **281**, 114673. doi:10.1016/j.oceaneng.2023.114673

Li, X., Oh, P., Zhou, Y. and Yuen, K. F. (2023b). Operational risk identification of maritime surface autonomous ship: A network analysis approach. *Transport Policy*, **130**, 1–14. doi:10.1016/j.tranpol.2022.10.012

Li, Z., Zhang, D., Han, B. and Wan, C. (2023c). Risk and reliability analysis for maritime autonomous surface ship: A bibliometric review of literature from 2015 to 2022. *Accident Analysis & Prevention*, **187**, 107090. doi:10.1016/j.aap.2023.107090

Liu, C., Chu, X., Wu, W., Li, S., He, Z., Zheng, M., Zhou, H. and Li, Z. (2022a). Human–machine cooperation research for navigation of maritime autonomous surface ships: A review and consideration. *Ocean Engineering*, **246**, 110555. doi:10.1016/j.oceaneng.2022.110555

Liu, J., Aydin, M., Akyuz, E., Arslan, O., Uflaz, E., Kurt, R. and Turan, O. (2022b). Prediction of human–machine interface (HMI) operational errors for maritime autonomous surface ships (MASS). *Journal of Marine Science and Technology*, **27**, 293–306. doi:10.1007/s00773-021-00834-w

Lloyd's Register (LR) (2017a). *Cyber-enabled Ships ShipRight Procedure Assignment for Cyber Descriptive Notes for Autonomous & Remote Access Ships*. London: LR.

Lloyd's Register (LR) (2017b). *LR Code for Unmanned Marine Systems*. London: LR.

Ludvigsen, M. and Sørensen, A. J. (2016). Towards integrated autonomous underwater operations for ocean mapping and monitoring. *Annual Reviews in Control*, **42**, 145–157. doi:10.1016/j.arcontrol.2016.09.013

Luo, J., Geng, X., Li, Y. and Yu, Q. (2022). Study on the risk model of the intelligent ship navigation. *Wireless Communications and Mobile Computing*, **2022**, 3437255. doi:10.1155/2022/3437255

Marine in Sight (2023). KONGSBERG Successfully Completes Autonomous Operation of Coastal Cargo Ship. Available at https://www.marineinsight.com/shipping-news/kongsberg-successfully-completes-autonomous-operation-of-coastal-cargo-ship/ (accessed 13 March 2024).

Marine in Sight (2024*)*. South Korea Launches 1st Container Ship Built for Autonomous Operations Available at https://www.marineinsight.com/shipping-news/south-korea-launches-1st-container-ship-built-for-autonomous-operations/ (accessed 13 March 2024).

Maritime Safety Administration of the People's Republic of China (China MSA) (2023). *Provisional Rules for the Trial Technology and Inspection of Autonomous Navigation of Ships*. Beijing: China MSA.

Maritime Safety Committee (MSC) (2019). *Interim Guidelines for MASS Trials*. London: IMO.

Maritime Safety Committee (MSC) (2021). *Outcome of the Regulatory Scoping Exercise for the use of Maritime Autonomous Surface Ships(MASS)*. London: IMO.

Mitsui, O. S. K. (2022). Lines, MOL and Partners Set World Records for Time and Distance in Autonomous Navigation with Sea Trial Using Large Commercial Car Ferry. Available at https://www.mol.co.jp/en/pr/2022/22017.html (accessed 13 March 2024).

Mizuno, N. and Kuboshima, R. (2019). Implementation and evaluation of non-linear optimal feedback control for ship's automatic berthing by recurrent neural network. *IFAC-PapersOnLine*, **52**(21), 91–96. doi:10.1016/j.ifacol.2019.12.289

Nguyen, V. S. (2019). Investigation on a novel support system for automatic ship berthing in marine practice. *Journal of Marine Science and Engineering*, **7**, 114. doi:10.3390/jmse7040114

Piao, Z., Guo, C. and Sun, S. (2019). Research into the automatic berthing of underactuated unmanned ships Under wind loads based on experiment and numerical analysis. *Journal of Marine Science and Engineering*, **7**, 300. doi:10.3390/jmse7090300

Ramos, M. A., Utne, I. B. and Mosleh, A. (2019). Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events. *Safety Science*, **116**, 33–44. doi:10.1016/j.ssci.2019.02.038

Ramos, M. A., Thieme, C. A., Utne, I. B. and Mosleh, A. (2020a). Human-system concurrent task analysis for maritime autonomous surface ship operation and safety. *Reliability Engineering & System Safety*, **195**, 106697. doi:10.1016/j.ress.2019.106697

Ramos, M. A., Thieme, C. A., Utne, I. B. and Mosleh, A. (2020b). A generic approach to analysing failures in human – system interaction in autonomy. *Safety Science*, **129**, 104808. doi:10.1016/j.ssci.2020.104808

Rindermann, H., Becker, D. and Coyle, T. R. (2016). Survey of expert opinion on intelligence: Causes of international differences in cognitive ability tests. *Frontiers in Psychology*, **399**(7), 1–9.

Rindermann, H., Becker, D. and Coyle, T. R. (2017). Survey of expert opinion on intelligence: The FLynn effect and the future of intelligence. *Personality and Individual Differences*, **106**, 242–247.

Rindermann, H., Becker, D. and Coyle, T. R. (2020). Survey of expert opinion on intelligence: Intelligence research, experts' background, controversial issues, and the media. *Intelligence*, **78**, 101406. doi:10.1016/j.intell.2019.101406

Rødseth, Ø.J. and Nordahl, H. (2017). *Definitions for Autonomous Merchant Ships*. Trondheim: Norwegian Forum for Autonomous Ships.

Russian Maritime Register of Shipping (RS) (2020). *Regulations for Classification of Maritime Autonomous and Remotely Controlled Surface Ships*. St. Petersburg: RS.

SAE International (2014). *Surface Vehicle Information Report: Taxonomy and Definitions for Terms Related to on-Road Motor Vehicle Automated Driving Systems*. New York: SAE International.

Schrum, M. L., Johnson, M., Ghuy, M. and Gombolay, M. C. (2020). Four Years in Review: Statistical Practices of Likert Scales in Human-Robot Interaction Studies. In *Companion of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (HRI '20)*. Association for Computing Machinery, New York, NY, USA, pp. 43–52. doi:10.1145/3371382.3380739.

Shang, Z. (2023). Use of delphi in health sciences research: A narrative review. *Medicine*, **102**, pe32829. doi: 10.1097/MD.0000000000032829

Sheridan, T. B. (2011). Adaptive automation, level of automation, allocation authority, supervisory control, and adaptive control: Distinctions and modes of adaptation. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, **41**, 662–667. doi: 10.1109/TSMCA.2010.2093888

Tran, V. L. and Im, N.-K. (2012). A study on ship automatic berthing with assistance of auxiliary devices. *International Journal of Naval Architecture and Ocean Engineering*, **4**(3), 199–210. doi:10.3744/jnaoe.2012.4.3.199

Trevelyan, E. G. and Robinson, P. N. (2015). Delphi methodology in health research: How to do it? *European Journal of Integrative Medicine*, **7**, 423–428. doi:10.1016/j.eujim.2015.07.002

Veitch, E. and Alsos, O. A. (2022). A systematic review of human-AI interaction in autonomous ship systems. *Safety Science*, **152**, 105778. doi:10.1016/j.ssci.2022.105778

Wang, Y., Chen, P., Wu, B., Wan, C. and Yang, Z. (2022). A trustable architecture over blockchain to facilitate maritime administration for MASS systems. *Reliability Engineering & System Safety*, **219**, 108246. doi:10.1016/j.ress.2021.108246

Wróbel, K., Gil, M., Huang, Y. and Wawruch, R. (2022). The vagueness of COLREG versus collision avoidance techniques—a discussion on the current state and future challenges concerning the operation of autonomous ships. *Sustainability*, **14**, 16516. doi:10.3390/su142416516

Wu, B., Yip, T. L., Yan, X. and Guedes Soares, C. (2022). Review of techniques and challenges of human and organizational factors analysis in maritime transportation. *Reliability Engineering & System Safety*, **219**, 108249. doi:10.1016/j.ress.2021.108249

Xing, W. and Zhu, L. (2023). Exploring legal gaps and barriers to the use of unmanned merchant ships in China. *Marine Policy*, **153**, 105662. doi:10.1016/j.marpol.2023.105662

Yang, X., Utne, I. B., Sandøy, S. S., Ramos, M. A. and Rokseth, B. (2020). A systems-theoretic approach to hazard identification of marine systems with dynamic autonomy. *Ocean Engineering*, **217**, 107930. doi:10.1016/j.oceaneng.2020.107930

Yang, X., Zhang, W. J., Lyu, H. G., Zhou, X. Y., Wang, Q. W. and Ramezani, R. (2023). Hybrid early-warning framework for unsafe crew acts detection and prediction. *Ocean & Coastal Management*, **231**, 106383. doi:10.1016/j.ocecoaman.2022.106383

Yang, X., Zhou, T., Zhou, X. Y., Zhang, W. J., Mu, C. R. and Xu, S. (2024). A framework to identify failure scenarios in the control mode transition process for autonomous ships with dynamic autonomy. *Ocean & Coastal Management*, **249**, 107003. doi:10.1016/j.ocecoaman.2023.107003

Yara International (2021). Yara to Start Operating the World's First Fully Emission-Free Container Ship. Available at https://www.yara.com/corporate-releases/yara-to-start-operating-the-worlds-first-fully-emission-free-container-ship (accessed 3 September 2023).

Zeng, G. (1996). *Modern Epidemiology: Methods and Applications*. Peking: Peking University Medical Press & Peking Union Medical College Press.

Zhang, M., Zhang, D., Yao, H. and Zhang, K. (2020). A probabilistic model of human error assessment for autonomous cargo ships focusing on human–autonomy collaboration. *Safety Science*, **130**, 104838. doi:10.1016/j.ssci.2020.104838

Zhang, D., Han, Z., Zhang, K., Zhang, J., Zhang, M. and Zhang, F. (2022a). Use of hybrid causal logic method for preliminary hazard analysis of maritime autonomous surface ships. *Journal of Marine Science and Engineering*, **10**, 725. doi:10.3390/jmse10060725

Zhang, W., Meng, X., Yang, X., Lyu, H., Zhou, X.-Y. and Wang, Q. (2022b). A practical risk-based model for early warning of seafarer errors using integrated Bayesian network and SPAR-H. *International Journal of Environmental Research and Public Health*, **19**, 10271. doi:10.3390/ijerph191610271

Zhou, X.-Y., Liu, Z.-J., Wang, F.-W., Wu, Z.-L. and Cui, R.-D. (2020a). Towards applicability evaluation of hazard analysis methods for autonomous ships. *Ocean Engineering*, **214**, 107773. doi:10.1016/j.oceaneng.2020.107773

Zhou, X., Huang, J., Wang, F., Wu, Z. and Liu, Z. (2020b). A study of the application barriers to the use of autonomous ships posed by the good seamanship requirement of COLREGs. *The Journal of Navigation*, **73**(3), 710–725.

Zhou, X.-Y., Liu, Z.-J., Wang, F.-W. and Wu, Z.-L. (2021). A system-theoretic approach to safety and security co-analysis of autonomous ships. *Ocean Engineering*, **222**, 108569. doi:10.1016/j.oceaneng.2021.108569

Cite this article: Zhang W, Mu C, Wang Y, Yang X, Zhou X, Meng X, Li L (2025). Exploring the MASS-DoA2 control-switching mechanism: Results from the autonomous ship guidelines review and expert survey. *The Journal of Navigation* 1–30. https://doi.org/10.1017/S0373463324000237