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Critical Review of Human Element, Regulatory, and Safety Challenges in the Era of Maritime Autonomous Surface Ships (MASS)

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ABSTRACT

The advent of Maritime Autonomous Surface Ships (MASS) marks a transformative shift in the maritime domain, promising significant improvements in cost-efficiency, safety, and logistics optimization. However, the integration of autonomous systems presents new and complex challenges, particularly in terms of human element transformation, regulatory adaptation, and maritime safety management. This study critically analyzes these challenges based on the levels of autonomy defined by the International Maritime Organization (IMO), highlighting the gaps in existing frameworks such as the STCW Convention. We explore the evolving role and legal ambiguity of remote operators (ROs), training needs for future maritime personnel, and paradoxes introduced by high automation. Our key findings call for a redefinition of the seafarer's legal identity, urgent revision of the STCW Convention, and the development of customized training programs and human-machine collaborative interfaces. These recommendations serve as a roadmap for the safe, ethical, and effective integration of MASS into global maritime operations.

Keywords - Autonomous ships, Human element, MASS, Remote operator, STCW

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I. INTRODUCTION

The global maritime industry is undergoing an unprecedented transformation, driven by increasing demands for environmental sustainability, operational efficiency, and technological innovation. Among these transformative trends, Maritime Autonomous Surface Ships (MASS) have emerged as a pivotal innovation, poised to reshape international shipping, reduce human error, and optimize vessel operations. Initiatives to develop and deploy MASS are accelerating in technologically advanced countries such as Norway, South Korea, Japan, and China, underpinned by digitalization, decarbonization, and automation goals.

According to the International Maritime Organization (IMO), MASS are defined as 'ships which, to a varying degree, can operate independently of human interaction'[5]. The IMO has classified autonomy into four levels, ranging from crewed ships with automated decision support (Level 1) to fully autonomous ships (Level 4). Expectations for MASS include enhanced safety—with potential to reduce maritime accidents by up to 75% as well as cost savings in crew management and logistical gains through continuous operations [11].

Despite these promising developments, the integration of MASS presents profound challenges related to the human element, legal responsibilities, training standards, and compatibility with current international conventions such as the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). Traditional frameworks, built on the assumption of onboard human presence, now face critical misalignments when applied to remote or fully autonomous vessels. Furthermore, MASS does not entirely eliminate human error but shifts its locus—from onboard crew to shore-based remote operators—introducing new forms of risk, fatigue, and legal ambiguity.

This study addresses the urgent need for a critical examination of MASS from regulatory, operational, and human-centered perspectives. We argue that without the reevaluation of concepts such as 'seafarer', 'master', and 'command', and without updating training protocols and interface design, the promise of autonomous shipping may be undermined by emerging safety and liability concerns. The objective of this research is to analyze the key challenges posed by MASS and offer integrated recommendations for safe, ethical, and functional deployment in the global maritime framework.

This paper is organized as follows: Section 2 reviews the current academic and regulatory literature on MASS development and classification. Section 3 outlines the methodological approach adopted for this critical review. Section 4 presents key challenges categorized by levels of autonomy, followed by strategic discussions. Section 5 discusses the limitations of this study, and Section 6 concludes with concrete recommendations for regulatory reform, human-machine collaboration, and future research.

II. LITERATURE REVIEW

2.1 The development of Maritime Autonomous Surface Ships (MASS) has garnered growing attention from academia, industry, and international regulatory bodies. Initial discussions within the International Maritime Organization (IMO) date back to the 1960s, with formalized attention emerging in the 2018 Maritime Safety Committee (MSC) meeting. In MSC 99, the IMO introduced four levels of autonomy ranging from conventional ships with decision support tools to fully autonomous vessels without any human presence onboard [5].

Degree	Description
Degree 1	Ship with automated processes and decision support: Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control.
Degree 2	Remotely controlled ship with seafarers on board: The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.
Degree 3	Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.
Degree 4	Fully autonomous ship: The operating system of the ship is able to make decisions and determine actions by itself.

Table 1. IMO MASS autonomy degrees

Academic literature such as Chae et al. (2020) and Ji (2022) underscore the technological progression from automated navigational systems to artificial intelligence-driven control systems. Countries such as South Korea, Norway, and Japan have initiated experimental MASS projects like the AutoShip project (EU), MUNIN, and SMART-Navigation, which reveal not only the technical viability but also highlight the regulatory fragmentation.

One of the earliest regulatory efforts addressing MASS was the Regulatory Scoping Exercise (RSE), conducted by IMO from 2018 to 2021. The RSE assessed current instruments such as SOLAS, MARPOL, COLREGs, and STCW for compatibility with MASS. Findings revealed that while some conventions are flexible enough for adaptation (e.g., MARPOL), others like the STCW face critical limitations—especially due to the spatially defined term 'seafarer' and the requirement for physical presence on board [6].

2.2 As Table 3 demonstrates, the STCW Convention is structurally incompatible with Levels 3 and 4 of MASS due to its reliance on shipboard training, manning requirements, and hierarchical authority structures. This leads to a central regulatory question: Should remote operators be considered 'seafarers'? If not, how should their roles, qualifications, and responsibilities be defined?

The Republic of Korean Seafarers' Act provides a unique precedent through the concept of 'preparatory personnel', where seafarer status is conferred based on job function rather than physical boarding. This national-level flexibility has inspired proposals to re-define seafaring status based on control and command rather than physical proximity [3].

Furthermore, new human factor challenges arise in MASS environments. Research by Yoshida et al. (2020) [14] and Yan et al. (2023) [13] demonstrate that remote operators face reduced situational awareness, information overload, and stress from multitasking. Automation paradoxes also emerge—while automation is meant to reduce human error, it introduces new risks in software design, human-computer interaction, and emergency override mechanisms [10].

2.3 Training frameworks must also evolve. Studies by Fan et al. (2020) [4] and Zhang et al. (2022) [15] suggest that MASS operators require proficiency not only in navigation, but also in data analysis, cybersecurity, and AI decision verification. Shanghai Maritime University has begun designing curricula aligned with these new competencies, emphasizing logic, leadership, and hybrid control systems. Table 2 summarizes the emerging skillset requirements for MASS operators [12].

Knowledge Classification	
Ability	Leadership & communication
	Obedience & execution
	Psychological stress resistance
Knowledge	Traditional nautical knowledge
	Network communication knowledge
	Automatic control knowledge
	Data mining knowledge
	Artificial intelligence knowledge
Technology	Autonomous navigation
	Fault diagnosis
	Remote control

Autonomy Level
-Vessel with process automation & decision support
- Remote-control vessels with crew onboard
- Remote-control vessels without crew
- Full autonomous vessels

Table 2. Summary of knowledge classification of practitioners on marine autonomous surface vessel

2.4 Recent initiatives by IMO such as the e-Navigation strategy and the e-Seafarer concept (IMO, 2023) [7] reflect growing consensus on the need for STCW revisions to address non-embarked personnel. Nevertheless, regulatory uncertainty continues to slow MASS investments, highlighting the urgent need for international alignment.

Despite the extensive discussions, literature gaps persist in three key areas: (1) long-term cognitive impacts of MASS operations on remote operators, (2) harmonization of international legal definitions of seafarer, and (3) standardized frameworks for human-automation collaboration at varying levels of autonomy. These gaps guide the analytical focus of this study.

Degree of Autonomy	The most appropriate way(s) of addressing MASS operations (I, II, III, IV)	Reasons for selecting the most appropriate way(s) of addressing MASS operations
Degree One	I and/or II	With seafarers serving on board, the Convention and Code in its entirety remains applicable to MASS. Some requirements may need to be amended based on the introduction of new technologies and/or automated processes. Changes can be made through the existing Convention processes and flexibilities-through authorized equivalencies or amendments to the codes or regulations.
Degree Two	I and/or II	Option 1 – Determination that "remote operator is a seafarer" .1 Changes to the Convention and Code to establish definitions and provisions to include the "remote operator" can be made through the existing Convention processes and other flexibilities – through authorized equivalencies or amendments to the codes or regulations. .2 Some requirements applicable to seafarers may need to be amended to: 1) introduce new technologies and/or automated processes; and 2) address the relationship of the "remote operator" with other seafarers serving on board. These changes can be made through the existing Convention processes and other flexibilities – through authorized equivalencies or amendments to the codes or regulations.
	I and/or II And or III	Option 2 – Determination that "remote operator is not a seafarer" .1 Provisions necessary to address the "remote operator" could be established through either:

		1) existing instrument(s) other than the STCW Convention and Code; or 2) a new instrument. .2 Some requirements applicable to seafarers may need to be amended to: 1) introduce new technologies and/or automated processes; and 2) address the relationship between the "remote operator" and other seafarers serving on board. These changes can be made through the existing Convention processes and other flexibilities – through authorized equivalencies or amendments to the codes or regulations.
Degree Three	I and/or II	Option 1 – Determination that "remote operator is a seafarer" .1 Changes to establish definitions and provisions to include the "remote operator" can be made through the existing Convention processes and other flexibilities – through authorized equivalencies or amendments to the codes or regulations. .2 There are no trained and qualified seafarers serving on board to perform the operational functions on board the vessel.
	III	Option 2 – Determination that "remote operator is not a seafarer" .1 Consistent with the first step assumptions, new provisions necessary to address the "remote operator" will need to be established through either: 1) existing instrument(s) other than the STCW Convention and Code; or 2) a new instrument. The provisions will need to include the relationship between seafarers on board and the "remote operator". However, this relationship will also need to be established in the STCW Convention through the existing processes and other flexibilities – through authorized equivalencies or amendments to the codes or regulations. .2 There are no trained and qualified seafarers serving on board to perform the operational functions on board the vessel. Article 3 (Application) of the STCW Convention stipulates that the Convention applies only to “Seafarers serving on board seagoing ships entitled to fly the flag of a Party…".
Degree Four		There are no trained and qualified seafarers serving on board to perform the operational functions on board the vessel.

Table 3. Results of the maritime autonomous surface ship (MASS) regulatory scoping exercise (RSE) Step 2 for STCW Convention.

III. METHODOLOGY

3.1 This study adopts a qualitative research approach, grounded in a comprehensive critical literature review and conceptual analysis. Rather than generating new empirical data through experiments or surveys, this research synthesizes and evaluates existing academic publications, regulatory frameworks, and organizational reports to examine the multifaceted challenges posed by the integration of MASS.

The primary sources of data include official IMO documentation from the RSE, technical reports on MASS pilot projects (such as MUNIN, AutoShip, and SMASS) [19], peer-reviewed academic articles from 2019 to 2025, and national maritime legislation from South Korea, Japan, and European Union member states. Key academic contributions were drawn from leading journals such as Ocean Engineering, Maritime Policy & Management, and the Journal of Marine Science and Engineering.

3.2 The analysis was conducted in three stages:
3.2.1. Document Selection and Extraction: The study first identified and collected relevant documents based on their significance to MASS autonomy, regulatory alignment, and the human element. Documents were filtered to include only those

addressing IMO MASS levels, remote operator training, and human-machine interface design.

3.2.2. Categorical Thematic Analysis: Collected data were categorized based on themes such as: (a) regulatory gaps by autonomy level, (b) evolving roles and legal ambiguities of remote operators, (c) safety and human risk factors, and (d) education and training requirements.

3.2.3. Critical Conceptual Analysis: A cross-sectional evaluation was conducted to highlight inconsistencies between technological capabilities, regulatory expectations, and human-system limitations. Special attention was paid to the paradox of automation, STCW interpretation, and risk migration from onboard crew to shore-based operators.

This approach enabled the formulation of an integrative framework that identifies key operational, legal, and human-centric challenges associated with different levels of autonomy in MASS. The outcomes of the methodology informed the development of targeted policy and training recommendations, discussed in the next section.

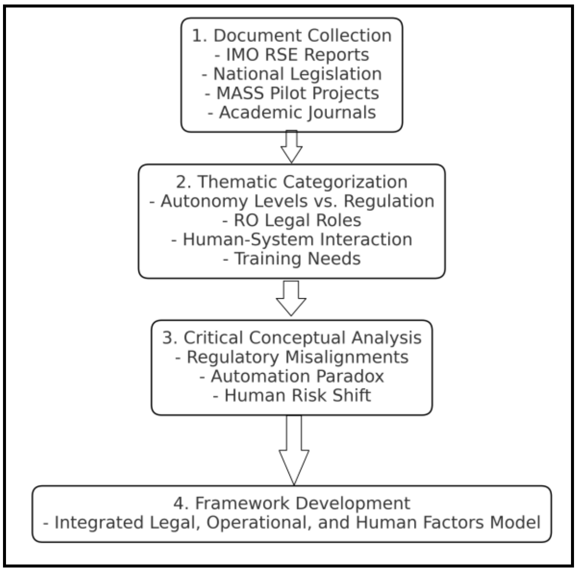

Figure 1. Methodological Framework for Critical Analysis of MASS Challenges.

IV. RESULTS AND DISCUSSION

This section presents the critical findings of the study by analyzing regulatory, human element, and training challenges across the four levels of autonomy defined by the IMO.

4.1 Regulatory and Legal Uncertainties Across Autonomy Levels

The STCW Convention presents a fundamental incompatibility with MASS Levels 3 and 4. These levels, characterized by the absence of onboard crew, contradict STCW Article III, which applies only to crewed vessels. Regulatory ambiguity is further compounded by the unclear status of Remote Operators (ROs). Should ROs be considered 'seafarers' under STCW? If not, no international certification system currently ensures their qualifications. This gap threatens the safety, interoperability, and accountability of MASS systems. The Korean Seafarers' Act (Choi & Lee, 2022) [3] offers a precedent in redefining legal status through the 'preparatory personnel' designation, but its application remains limited internationally.

4.2 Human Factors and Operational Risk Transfer

Human error accounts for over 75% of maritime accidents (BIMCO, 2020) [1]. While MASS aims to eliminate this, evidence suggests that automation merely shifts risks. Yoshida et al. (2020) [14] identify a loss of situational awareness, cognitive overload, and monitoring fatigue in shore-based operators. Additionally, MASS systems increase the risk of software malfunctions, cyberattacks, and delayed emergency responses, especially in Level 4 deployments. The automation paradox—where increased autonomy requires more skilled human oversight during anomalies is prominent.

4.3 Training and Competence Gaps

Current maritime education frameworks lack training programs for MASS operations. Studies by Fan et al. (2020) [4] and Zhang et al. (2022) [15] suggest that future RO personnel require a hybrid skill set including:

- AI-supported decision verification
- Autonomous system diagnostics
- Cybersecurity monitoring
- HMI and collaborative interface operation

Shanghai Maritime University's prototype training modules include scenario-based simulations for MASS remote control and critical thinking exercises, but global implementation remains sparse.

4.4 MASS-Specific Human–Machine Interaction (HMI)

Projects such as MUNIN have demonstrated the importance of ergonomic and information-centered dashboards for ROs. Poor interface design contributes to reduced cognitive mapping, slow responses, and error propagation. The human–machine interface should include [19]:

- Adaptive alerts
- Streamlined navigation data
- AI explanation systems

Effective HMI reduces mental strain and supports decision-making under uncertainty.

In summary, while MASS technology promises operational efficiency and safety, the transition raises profound questions about international law, human performance, and education systems. Without proper regulatory alignment and a redefined approach to maritime training, these ships may create new forms of systemic risk instead of solving existing ones.

V. LIMITATIONS

This study is subject to several limitations that must be acknowledged when interpreting its findings and implications.

First, the analysis relies heavily on existing literature and policy documents without conducting new empirical research. While this allows for a broad synthesis and conceptual critique, it limits the ability to incorporate real-world operational data or stakeholder perspectives from pilots, ship operators, and regulatory bodies.

Second, the rapid pace of technological and regulatory developments in the MASS domain may render some of the findings time sensitive. Changes in international agreements or national legislation occurring after the publication of this research may affect the validity or relevance of specific insights and recommendations.

Third, the focus of this paper is primarily on the regulatory and human elements of MASS integration. As such, it does not explore in depth other critical issues such as insurance liability, cyber risk modeling, ethical dimensions of decision automation, and public acceptance of autonomous vessels. These represent valuable areas for future investigation.

Despite these limitations, the study offers a robust foundation for understanding the multifaceted challenges of MASS and serves as a roadmap for future academic and regulatory research.

VI. CONCLUSION

This study has critically examined the regulatory, human, and operational challenges associated with the integration of Maritime Autonomous Surface Ships (MASS) into the existing maritime framework. Through a systematic analysis of the International Maritime Organization's (IMO) four levels of autonomy and the associated regulatory and human factor implications, several key insights have emerged.

First, there is a pressing need to revise the STCW Convention to reflect the rise of remote operations. The current definition of a 'seafarer' as someone physically on board is incompatible with MASS Levels 3 and 4. A globally accepted framework must redefine this term and establish legal accountability for Remote Operators (ROs). The Korean 'preparatory personnel' model offers a viable starting point for redefining maritime roles.

Second, while automation may reduce certain types of human error, it introduces new cognitive and technological vulnerabilities. The shift from shipboard crew to shore-based monitoring presents risks in communication latency, situational misinterpretation, and system complexity. These risks must be mitigated through enhanced Human–Machine Interface (HMI) design and collaborative control systems.

Third, training programs must evolve beyond traditional navigation skills. The future of maritime operations will require a fusion of maritime, technological, and cognitive expertise. New curriculums must address AI reasoning, cybersecurity, and decision-making under uncertainty. Institutions such as Shanghai Maritime University and the IMO's e-Seafarer initiative provide valuable blueprints for this transformation.

Ultimately, the promise of MASS lies not only in its technological innovation but in how the maritime industry adapts its regulatory, operational, and educational ecosystems. A proactive and integrative approach is needed—one that recognizes the complexity of autonomy and the centrality of the human element in ensuring safe and sustainable maritime futures.

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