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Enabling the Future of Autonomous Shipping: Regulatory Challenges, Infrastructure Modernization and Pathways to Integration

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ABSTRACT: The widespread adoption of Maritime Autonomous Surface Ships (MASS) has the potential to transform global shipping by enhancing efficiency, safety and environmental sustainability. However, achieving this transformation requires strong support from governmental and maritime authorities to ensure the smooth and secure integration of these technologies into existing systems. This paper explores the crucial role of regulatory bodies in enabling the operational acceptance of MASS, focusing on regulatory frameworks, the modernization of port infrastructure and the need for standardization. It also examines key challenges such as cybersecurity risks, interoperability concerns and legal liabilities associated with MASS deployment. Finally, the paper offers recommendations for future actions to facilitate the effective implementation of autonomous shipping technologies

1 INTRODUCTION

Maritime Autonomous Surface Ships (MASS) represent a significant technological advancement in maritime logistics [1]. By increasing automation and artificial intelligence [2], [3], MASS offers promising enhancements in operation efficiency, cost saving, navigational safety and rules compliance. Nevertheless, their deployment presents a series of intricate challenges that span technical, regulatory and infrastructural dimensions [4]. As a result, the role of administrations is becoming increasingly critical acting as facilitators, ensuring that innovation is verified according to the applicable regulatory framework, making it more suitable as possible for MASS operations [5], [6]. This paper focuses on the contributions of administrations facilitating the acceptance and guaranteeing safe operation of MASS, highlighting also the necessity of harbor infrastructure upgrades and the establishment of global and regional standards.

The concept of smart ports [7], [8] is emerging as a crucial enabler for MASS, leveraging digitalization, IoT and AI- driven systems to ensure seamless integration with autonomous vessels [9], [10]. Ports need to adopt real-time traffic management systems, automated docking facilities and advanced cybersecurity measures to support MASS operations effectively [11], [12]. At the national level, regulations such as the U.S. Coast Guard’s Navigation and Vessel Inspection Circular (NVIC) 01-20 guide the oversight of autonomous and remotely operated vessels. Similarly, the Norwegian Maritime Authority (NMA) has developed a framework for testing and certifying autonomous ships, setting a precedent for national regulatory adaptation. The International Maritime Organization (IMO) has established a working group for MASS regulation aimed at developing a MASS Code [13]. However, the MASS Code should become mandatory not before 2032 and up to now the lack of an international framework has challenged the implementation of national policies and infrastructure improvements. Effective implementation will require collaboration between international bodies, national administrations and private stakeholders. This paper aims to provide a roadmap for administrations to address these challenges and enable the successful integration of MASS into modern maritime operations.

2 THE REGULATORY FRAMEWORK

2.1 *IMO Role*

Following a detailed scoping exercise that began in 2017, the IMO finalized its initial regulatory framework in 2021. This framework paved the way for the development of the MASS Code, which is expected to be finalized in its non- mandatory form during this year. This version will undergo an experience-building phase to gather feedback from the first projects and ensure practical applicability. The mandatory version of the MASS Code is scheduled to be completed by 2028, with adoption by 2030 and formal entry into force on January 1, 2032. Initially, the code will apply only to cargo ships, with the potential expansion to passenger vessels planned for a later phase.

The IMO has identified since the first steps four levels of autonomy, ranging from ships with automated processes and decision support to fully autonomous vessels. This tiered structure allows for incremental integration of MASS and its interconnected sub-systems into maritime operations (see Figure 1).

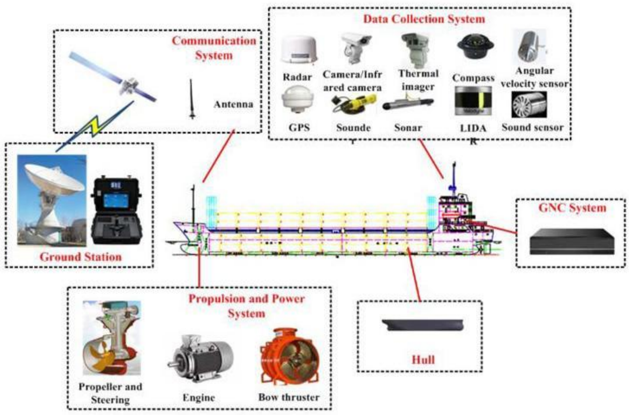

Figure 1. System composition of MASS [14].

The code emphasizes safety equivalency, requiring that autonomous vessels achieve safety standards comparable to those of conventional ships. Other critical areas addressed include cybersecurity measures to protect against operational risks, environmental compliance to meet international sustainability goals and operational protocols for Remote Operations Centers (ROCs). The IMO's goal-based Code will provide a flexible framework for shipowners and manufacturers to innovate while maintaining high safety and environmental standards. However, the successful implementation of these regulations requires close collaboration among all stakeholders, including national administrations, classification societies and designers. The IMO has also established joint working groups (MSC-LEG- FAL group) to address key legal and operational challenges, including liability, command transitions between remote and onboard crews and jurisdictional issues. These ongoing efforts are critical for ensuring that MASS operations are reliable and safe.

2.2 *National Administration Role*

National administrations play an indispensable role in ratifying international conventions and making regional laws to follow to assess the safety of Autonomous Navigation. Due to their role, the Administration is responsible for the mechanisms that enable the certification and licensing of MASS operations, supervising the establishment of Remote Operations Centers, and coordinating with private and public stakeholders to ensure compliance with safety and environmental standards. For example, Norway's progressive approach to the Yara Birkeland project and the United Kingdom's Code of Practice for MASS demonstrate the effectiveness of the process. Administrations also face the challenge of addressing jurisdictional issues, especially in the case of MASS operating on international routes. International operations will require harmonization of national laws with international conventions. Harbor infrastructure must be adapted to accommodate MASS, including the integration of automated mooring systems, enhanced VTS (Vessel Traffic Services) for remote monitoring, and digital communication frameworks that facilitate seamless interaction between advanced fast response (see Figure 2) and autonomous vessels and port authorities. Investments in cybersecurity and AI-driven traffic management will also be necessary to ensure safe port operations and prevent potential disruptions.

Figure 2. General Arrangement of a high-speed maritime vessel - a Search and Rescue (SAR) craft. These types of vessels are typically designed for rapid response to emergencies at sea and equipped with advanced intelligent navigation and communication systems to perform rescue operations.

From a regulatory perspective, frameworks such as the EU's Strategic Research Agenda for Smart and Autonomous Sea Transport and Singapore's Maritime Autonomous Surface Ships regulatory sandbox provide structured approaches for national administrations to develop legal frameworks that align with emerging international guidelines. Additionally, the International Convention for the Safety of Life at Sea (SOLAS) and the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) are being adapted to address the unique challenges posed by autonomous navigation.

2.3 *Classification Society Role*

Some Classification Societies, to anticipate the mandatory IMO MASS code entry into force, have developed a set of rules to provide a service to "forward-thinking" shipowners and shipyards. Among these, RINA and China Classification Society (CCS) offer contrasting approaches. RINA's guidelines [15] focus on integrating MASS technologies into traditional maritime practices through a goal-based approach, through a complete risk assessment keeping into account the operational design domains and the concept of operation of the MASS. CCS [16], on the other hand, provides a more prescriptive approach to some technical aspects of the Rules for Intelligent Ships, offering specific functional notations to describe the level of autonomy. A key difference lies in their methodologies. RINA emphasizes flexibility and tailored solutions for diverse MASS scenarios, requiring detailed risk analyses and performance validation. CCS adopts a structured approach, with predefined criteria for system design and functionality, emphasizing redundancy and fault tolerance. Additionally, RINA prioritizes collaboration between stakeholders to define testing procedures, while CCS incorporates detailed documentation requirements into its certification process. These differences reflect varying philosophies but collectively contribute to the advancement of safe and reliable autonomous shipping. During this phase, Class societies, acting as Recognized Organizations (RO), are actively supporting many Flags in the development of their national requirements for assessing the safety of the MASS and obtaining authorization to operate in national waters in the first phase.

3 FLAG REQUIREMENTS FOR MASS OPERATIONS

To establish a regulatory pathway for the authorization of MASS by flag states, it is essential to formulate an approach that supports the issuance of "flag state approval" and ensures compliance and equivalence with applicable safety standards. This approach must align with the overarching principle of achieving equivalency in safety levels between autonomous and traditional manned vessels. The evaluation of risks associated with MASS operations requires consideration of parameters such as the vessel's operational area, traffic density, level of autonomy, and momentum (as a product of the speed and its mass). As these risks increase, the certification requirements become stricter, demanding an assessment tailored to each scenario. For traditional vessels, flag administrations or RO typically assess the main safety aspects such as hull integrity, buoyancy, stability, propulsion and steering, electrical generation, etc. In the context of MASS, additional checks are required for autonomous capabilities, including navigation, communication, and automation system integration, to ensure this meets or exceeds safety benchmarks established for manned configurations. To propose a solution to the above-mentioned problem, a high- level regulatory framework is proposed to address varying levels of operational risk:

- Low-risk scenarios: A risk analysis has to demonstrate that the operational risks of the autonomous configuration are mitigated to an As Low As Reasonably Practicable (ALARP) level.
- Medium-risk scenarios: Beyond risk analysis, the design must undergo specific evaluations and operational testing to verify seaworthiness for the intended Concept of Operations (ConOps). Successful prototypes may receive type approval, with subsequent vessels eligible for manufacturing certification.
- High-risk scenarios: The flag state should require certification from an RO, with additional class notations for autonomous capabilities tailored to the vessel's degree of autonomy. Compliance with international safety conventions and land-based crew training standards must also be verified.

This structured framework provides the necessary legal and technical foundation to accommodate the unique challenges of MASS, ensuring that safety, reliability, and regulatory integrity remain paramount in their deployment.

4 FUTURE CHALLENGES

The next challenges in establishing effective certification schemes depend on the rapidly evolving legal and operational intricacies linked to autonomous and remote operations. A particularly pressing issue is the redefinition of roles and responsibilities for both traditional onboard crew and "remote crew" stationed at Remote Operations Centres. While the IMO has asserted that the master's responsibilities remain the same as on conventional vessels (IMO, MSC 107, 2024) [17], MASS operations introduce unique complexities that demand a reevaluation of what constitutes "command" and "control." These complexities include scenarios where the master may not be physically present on board and whether one master can oversee multiple MASS, particularly in environments characterized by high density of traffic.

A MASS could be managed by several ROCs across multiple territorial jurisdictions during a single voyage and that highlights the importance of a unified international regulatory framework. Adhering to international conventions such as UNCLOS while addressing jurisdictional conflicts and ensuring a seamless transfer of operational control between ROCs will necessitate innovative regulatory approaches. Furthermore, the master's role within the ROC hierarchy, particularly in scenarios involving the delegation of responsibilities to multiple remote operators, underscores the need for detailed procedural guidelines to ensure accountability and safety. The deployment of MASS within naval operations adds a layer of complexity. In current practice, many Naval MASS are considered extensions of their mother vessels, with its master ultimately having the responsibility for USV's operation. As autonomous naval systems continue their development, it becomes increasingly important to clearly define liability, operational command, and responsibility delegation. An accurate certification framework will need to address the distinct requirements of both civilian and military operations, ensuring clear guidelines for their safe and effective implementation.

Standardizing port infrastructure to support autonomous navigation is a crucial aspect of MASS implementation. Ports where MASS are permitted to operate must be equipped with advanced and reliable communication systems, including robust V2I (vessel-to-infrastructure) protocols, to enable seamless interaction between vessels and port authorities. These communication networks will facilitate safe navigation, berthing, and cargo handling for autonomous vessels. To achieve high-precision navigation and docking, Real-Time Kinematic (RTK) positioning and Differential GPS (DGPS) are essential. RTK enhances positioning accuracy by providing real-time corrections to GPS signals, achieving centimeter-level precision crucial for autonomous ship maneuvering in confined port areas. Similarly, DGPS improves positional reliability by correcting satellite signal errors, ensuring precise localization, and reducing navigational risks [18]. These technologies play a vital role in enabling automated docking, optimized traffic flow, and collision avoidance [19], [20], [21], thereby enhancing the overall efficiency and safety of MASS operations.

Enhanced cybersecurity measures are also essential to ensure the safe integration of MASS within existing maritime operations [22], [23]. Autonomous vessels and smart port systems are vulnerable to cyber threats, requiring robust encryption, intrusion detection systems, and continuous monitoring of communication networks [24]. In this regard, the new IACS Unified Requirements (UR) E26 and E27— which focus on cybersecurity and software integrity in ship operations—must be further extended to cover MASS operations comprehensively. Collaborative efforts, such as those led by the IMO and global port authorities, aim to establish standardized autonomous shipping corridors and harmonized port operation protocols. These initiatives are essential for developing a cohesive international framework and fostering confidence in MASS deployment across the maritime industry. Additionally, automated docking systems and real-time traffic management solutions must be integrated into port infrastructures. These systems utilize AI-driven navigation, automated mooring technologies, and dynamic route optimization to facilitate efficient and secure MASS movements within ports. As automation advances, continuous innovation in port technologies will be pivotal to ensuring seamless MASS integration into modern maritime logistics.

5 CONCLUSION

The integration of MASS into global shipping operations holds the potential to revolutionize the maritime industry, offering enhanced efficiency, improved safety, and greater environmental sustainability. However, the realization of these benefits requires a comprehensive approach that addresses regulatory, infrastructural, and operational challenges. Central to this transformation is the role of administrations in creating the conditions necessary for the effective deployment of MASS. Existing frameworks, SOLAS and COLREG, were developed with traditional, crewed vessels in mind and are insufficient to govern autonomous operations. To integrate MASS seamlessly, these frameworks must be revised and expanded to address the unique requirements of autonomous technologies. Administrations must lead efforts to establish comprehensive guidelines for the certification, inspection, and operational approval of MASS, ensuring these systems meet rigorous safety and reliability standards. Additionally, these updates must address cybersecurity and remote monitoring protocols, safeguarding vessels against emerging technological vulnerabilities. The successful deployment of MASS is heavily reliant on the modernization of port infrastructure. Autonomous ships require advanced facilities such as automated docking systems, enhanced sensor networks, and robust communication platforms to operate efficiently. Transitioning to "smart ports" equipped with real-time data- sharing capabilities will optimize logistical processes and reduce operational inefficiencies. Furthermore, the digital infrastructure supporting these operations must prioritize cybersecurity to protect against potential cyber threats, ensuring the uninterrupted functionality of both port operations and autonomous systems.

The adoption of MASS introduces several operational challenges. Safety remains a primary concern, particularly in maritime environments where traditional crewed vessels and autonomous ships coexist. Standardized communication protocols and interaction frameworks are essential to prevent collisions and ensure safe navigation. Interoperability between MASS and existing maritime systems is another critical issue that requires the development of universal standards for communication, data exchange, and system integration. Without these, operational inefficiencies and conflicts are likely to arise. Collaboration among stakeholders is indispensable in addressing these challenges. Governments, technology developers, maritime operators, and international organizations must work together to ensure a unified approach to the integration of MASS. This collaboration will facilitate the pooling of resources, expertise, and insights, accelerating the adoption of autonomous technologies while mitigating risks. By addressing these challenges, administrations can create an environment that fosters the successful integration of MASS into global shipping operations. The recommendations outlined in this paper provide a roadmap for enabling this transformation, emphasizing the need for proactive governance, infrastructure modernization, and collaborative efforts among stakeholders. With the right strategies and partnerships in place, the maritime industry can unlock the full potential of MASS, reshaping global logistics and positioning itself as a leader in technological innovation.

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