Challenges for the operation of autonomous and unmanned vessels in real-world environments: analysis of the current and future global regulatory framework

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Abstract

The development of autonomous and unmanned vessels has become a central focus of maritime research and innovation. The literature includes various studies related to the subsystems and algorithms for the autonomous operation of vessels. However, discussions surrounding the regulatory and normative framework appear to lag behind technological progress. Despite this, the debate cannot be considered null. Some authors have analyzed the operation of autonomous surface vessels (ASVs) and unmanned surface vehicles (USVs) considering the current regulatory framework. There are also reflections on the role of the human component and on the interaction with conventional vessels. On the other hand, the International Maritime Organization (IMO) and different entities have included the topic on their agendas, for which they have activated different mechanisms and scenarios for the development of the debate. Against this backdrop, this paper examines the regulatory and normative framework of the operation of autonomous vessels, trying to identify some of the facets that make up the current debate. The entry into operation of vessels in real-world contexts will be a reality soon and points of convergence between the technological aspect and the social component must emerge. Considering the potential impacts and advantages of integrating new technologies with conventional ones, it is expected that the social debate will develop in such a way that the regulations are timely and appropriate.

Key words: MASS, USV, regulatory framework.

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Introduction

The development of autonomous and unmanned vessels has become a a major focus of maritime research and development. The literature abounds with studies related to the various subsystems and algorithms required for autonomous navigation in the performance of tasks or missions in aquatic environments. However, the discussion of regulations for the operation of these vessels in real-world applications or contexts appears to be lagging behind. Searches in academic databases yield few results for articles that address the issue of autonomous vessels from a legal, political, ethical, or social perspective. This gap is consistent with broader trends observed in the naval, defense, and transportation sectors, where technological development has often advanced more rapidly than regulatory and governance frameworks *(Torres González et al., 2025)*.

As often happens with technological advancements, developments in autonomous and unmanned vessels have outpaced the discussions surrounding their regulatory frameworks. Clearly, technological advancements alone do not address all dimensions of this complex issue. Consequently, limitations and restrictions give rise to numerous needs, challenges, gaps, and unanswered questions. Compared to the abundance of literature on the development of autonomy, publications on the implications and requirements for operating these vessels in maritime, riverine, and lacustrine environments are significantly fewer. Nevertheless, the debate is not entirely absent; several definitions and guiding frameworks can be identified. Furthermore, recent literature highlights that maritime and riverine transportation systems face increasing pressures not only in terms of autonomy but also regarding environmental sustainability, emission reduction, and the integration of new propulsion and monitoring technologies. dimensions that intersect with autonomous vessel regulation and contribute to the complexity of the required normative frameworks *(Zapata Cortés et al., 2023)*.

This study focuses on the regulation and standardization of autonomous vessel operations, aiming to identify key aspects of the current discourse to foster a comprehensive understanding of the subject. This study identifies three primary perspectives: academic research, the role of the International Maritime Organization (IMO), and the role of standardization bodies. Academic research, while often tangential to the topic, has produced studies on collision avoidance algorithms that comply with the International Regulations for Preventing Collisions at Sea (COLREG). Other studies have analyzed the operation of autonomous surface vessels (ASVs) and unmanned surface vehicles (USVs) within the existing regulatory framework. Additionally, reflections on the evolving role of human operators and their interaction with conventional vessels can be found. To understand the current state of the regulatory and standardization framework for USVs, a preliminary review of Horne et al. (Horne et al., 2023) work was conducted. Based on this review, additional relevant articles were identified. Moreover, recent studies on inland waterway transport indicate that Industry 4.0 technologies such as machine learning, AIS-based analytics, and big-data-driven navigation tools are transforming vessel operations and may influence future regulatory models for autonomous and semi-autonomous navigation *(Restrepo-Arias et al., 2022).*

The IMO has also placed the issue on its agenda and has initiated various mechanisms and scenarios for its development. The IMO is leading global efforts to establish a robust regulatory framework for Maritime Autonomous Surface Ships (MASS). In response to rapid technological advancements in the maritime industry, the IMO has recognized the need to adapt existing regulations and develop new standards to ensure the safety and efficiency of these vessels. This institutional effort aligns with global initiatives aimed at reducing environmental impacts and fostering cleaner and more efficient maritime operations, as highlighted in studies addressing green technologies and sustainability transition frameworks *(Paipa-Sanabria et al., 2025)*.

Standardization organizations are also contributing at various levels. This study identified international technical standards related to marine autonomous vehicles. By identifying these standards, the aim is to provide a national perspective on the standards that need to be adopted to meet these technical requirements. This effort seeks to serve as a foundation for the development of technical standards in Colombia, facilitating understanding of these technologies and the regulations governing their operation in maritime environments. National-level analyses further emphasize the relevance of aligning autonomous vessel regulations with broader strategic initiatives in riverine development, defense planning, and sustainable mobility, such as those documented in Colombia's river master plan and defense-sector technological agendas *(Paipa Sanabria & Murcia Fernández, 2020)*.

This paper is structured as follows. Section 2 presents a review of the state of the art in autonomous vessel regulation, identifying key trends. Section 3 delves into the current and future regulatory framework, with a particular focus on the advancements made by the IMO. Section 4 presents standardization activities applicable to autonomous vessels developed by standardization bodies at various levels. Section 5 discusses the challenges and opportunities presented by the current regulatory and standardization framework for the operation of autonomous vessels in real-world environments. Finally, the conclusions of the study are presented.

State of the art on the regulatory framework for autonomous vessels

In the review conducted by Horne *et al.* (2023), the authors present a preliminary chapter titled "Trust and Safety" by Devitt *et al*. *(Devitt et al., 2021)*, which is part of 'Robotics Roadmap for Australia', published in November 2021 *(Robotics Australia group, 2021)*. Their methodology combines academic and practical exploration, employing case studies of Australian legislation. Key topics addressed in *(Devitt et al., 2021)* regarding Australian legislation include safety and certification, emerging issues in regulating autonomous robots, regulations in the air, maritime, and land sectors, robotics standards, and new regulatory approaches. Although the resource offers limited coverage of PR1, it provides valuable insights into regulatory challenges for autonomous vessels in Australia and the challenges faced by the Australian Maritime Safety Authority (AMSA). The role of trust and certification in regulatory philosophy is also addressed by Horne in *(Horne et al., 2023)*. Key focus areas include general concepts of trust and explainability *(Bolster, 2017; Devitt et al., 2021; Glomsrud et al., 2020)*, the role of assurance in relation to trust *(Devitt et al., 2021; Glomsrud et al., 2020)*, and regulatory philosophy, including risk-based governance, adaptive regulation, and regulatory management *(Chesterman, 2021; Devitt et al., 2021; Johnsen et al., 2018)*. Additionally, Horne et al. develop an analysis of the international landscape regarding challenges in adopting regulations in *(Horne et al., 2023)*. Key topics include the legal treatment of autonomous vessels in national and international contexts, the definition of "vessel" in national laws (United Kingdom, Italy, Norway, Denmark, China, Germany, and the US), regulatory challenges, legal complexities, and ongoing organizational initiatives at the global level.

Expanding on the topics covered in the work of Horne *et al.*, subsequent authors have significantly deepened these initial concepts. Orzechowski *et al*. state that autonomous ships will need to comply with existing regulations, such as those for collision prevention, but new technical and construction requirements will also need to be established *(Orzechowski et al., 2024)*. In this review, the authors outline the main factors influencing these regulations in European inland navigation and categorize them into institutional, technological, regulatory, and socioeconomic preparedness. These categories provide clues about the aspects that will likely require regulatory intervention. Dean and Clack analyze UK law *(Dean & Clack, 2019)*, while Yoo et al. examine Canadian law *(Yoo et al., 2020)*, concluding that autonomous vessels can be considered "ships," although each country must define its own approach. This stance contrasts with the common belief that countries should await IMO determinations to ensure regulatory coherence.

Kim *et al*. (2020) delve into technical aspects, detailing the need for specific physical sensors such as GPS, LiDAR, and RADAR, and emphasizing the importance of cybersecurity and big data analytics *(Kim et al., 2020)*. Vagale et al. also focuses on technical challenges, particularly in adapting safety conventions like the COLREGs for autonomous vessels *(Vagale et al., 2021)*. Meanwhile, Mallam *et al.* (2020) state that autonomy represents a highly disruptive technology in a traditionally conservative industry, where the primary obstacles are not so much technological as they are related to human-technology aspects and new operational paradigms *(Mallam et al., 2020)*. Similarly, Aymelek (n.d.) the development of autonomous ships and artificial intelligence in the maritime sector, considering the existence of a gap related to the human element that must be addressed (Aymelek, n.d.). The IMO, in its regulatory scope study, should consider that the current conventions' "human on board" considerations are limited in addressing the needs of autonomous vessels. Askari & Hossain argue that autonomous ships are a strategy that allows the maritime industry to join Industry 4.0 and provide solutions to crises such as the COVID-19 pandemic and other maritime sector needs *(Askari & Hossain, 2022)*. However, the transition should not be disruptive but gradual, considering challenges and difficulties as an opportunity to develop strategies based on strengths and opportunities.

From a legal perspective, Parlov examines the compatibility of autonomous vessels with the United Nations Convention on the Law of the Sea (UNCLOS). The author highlights that remotely controlled vessels do not present major compatibility issues, although debates persist regarding fully autonomous ones *(Parlov, 2023).* Ringbom (2019) criticizes the limitations of the IMO's 'Scope Exercise', noting that it does not adequately address fundamental elements such as automated surveillance or machine-based decision-making *(Ringbom, 2019)*. Veal *et al.* provides a practical perspective on risk management and self-regulation, proposing a tailored approach for different types and sizes of operations *(Veal et al., 2019)*.

Lynch *et al*. study decision-making processes and operations, with a particular focus on analyzing the Perceptual Cycle Model (PCM) *(Lynch et al., 2023)*. The application area centers on unmanned maritime systems and remote control centers (RCC), specifically human-machine interaction and the decision-making processes of remote operators. Similarly, Lynch delves deeper into human-machine interaction, identifying seven key themes for Human-Machine Teams (HMTs): Decision Support Systems, trust, transparency, teams, task/role allocation, responsibility, and situational awareness *(Lynch et al., 2024)*. This analysis complements the trust aspects discussed in the initial questions of the previous work.

Regarding personnel training, the specific requirements for Remote Control Center (RCC) operators, emphasizing the need for multidisciplinary training that includes both technical aspects and general competencies, are detailed in *(Bachari-Lafteh & Harati-Mokhtari, 2021; Emad et al., 2022)*. The development of requirements and certifications for autonomous controllers in US Navy vessels, particularly for collision avoidance tasks on transoceanic voyages, is studied in *(Costello & Xu, 2023)*. The research presents certification artifacts for an autonomous controller that must comply with COLREGs, emphasizing the need for a robust certification process involving simulation and modeling (M&S), specific test plans, and future developments for emergency situations. The authors suggest that without these mature certification tools, authorization of autonomous controllers will remain limited in scope and real-world application. Their contributions significantly expand the initial focus on regulation and certification. Meanwhile, Choi and Lee argues that remote operators of autonomous vessels should be granted legal status equivalent to traditional crew members: for level R vessels (remotely controlled with a crew), operators should be considered "shore-based seafarers," while for level RU and A vessels (fully autonomous), they should be recognized as "remote captains" with command authority over vessel operations *(Choi & Lee, 2022)*.

The role of the IMO in the definition of the regulatory framework

Technological advancements in the maritime industry pose regulatory challenges, particularly with the emergence of technologies for developing autonomous vessels, which require guidelines to ensure operational safety. In this regard, the IMO has been working to create an appropriate regulatory framework, seeking to adapt existing regulatory tools for application to vessels with varying levels of automation. This effort is based on a thorough evaluation of the benefits and challenges posed by the emergence of autonomous ships.

As part of this process, the IMO has organized international seminars and symposia since 2022. These events bring together various stakeholders to discuss the implications surrounding the regulation of Maritime Autonomous Surface Ships (MASS). The 2022 seminar focused on the challenges and approaches for developing the regulatory framework for MASS. The 2023 seminar addressed legal aspects related to MASS, including UNCLOS. The 2024 seminar focused on understanding the implications, challenges, and opportunities related to MASS, ports, and public authorities. The symposium held in May 2024 in conjunction with the Republic of Korea aimed to support the IMO for the development of a flexible, non-mandatory MASS Code. At this event, experts shared their knowledge on the latest advancements in autonomous maritime systems and the results of successful trials.

Additionally, the Maritime Safety Committee (MSC), Legal Committee (LEG), and Facilitation Committee (FAL) have undertaken actions aimed at developing the regulatory framework for MASS. In June 2019, the MSC approved a draft of preliminary guidelines for MASS operations during its 101st session. Subsequently, in 2021, the IMO conducted a study to assess how existing instruments could be applied to MASS with different levels of automation. This analysis took place starting from the 103rd session of the MSC (May 2021) for safety treaties and the 108th session of the Legal Committee (- 2021). Later, in April 2022, during the 105th session of the MSC, a project was presented aimed at creating a regulatory code for the operation of MASS. Similarly, the FAL approved the results of the study on the treaties under its jurisdiction at FAL 46 in

May 2022. Meanwhile, the MSC approved the revised roadmap for the development of the MASS Code during its 108th session in May 2024 (International Maritime Organization - IMO, n.d.). This roadmap was approved through the joint MSC/LEG/FAL group, which was created to address the issues identified in the regulatory scope exercises carried out by these committees, through which actions are coordinated to address the legal, technical, and operational challenges of autonomous ships. Among the most notable advances of the group and the IMO in general, the initial definition of the Remote Operations Center (ROC) for controlling operational aspects of the MASS is included. Secondly, the definition of the Remote Operator, consisting of the assignment of a qualified person to operate a MASS from a Remote Operations Center. Thirdly, the assignment of responsibilities to a master, regardless of the degree of autonomy of the MASS. Finally, there is the definition and classification of the degrees of autonomy and control that a ship may have, in which four degrees can be identified: assisted operation on board, remote control with a crew on board, remote control without a crew on board, and fully autonomous operation *(International Maritime Organization - IMO, 2021)*.

The IMO roadmap for developing a MASS Code projects the completion and adoption of a non-mandatory code by May 2025. Subsequently, during the first half of 2026, a framework for an experience-building phase will be developed. In 2028, development of the mandatory MASS Code would commence, based on the non-mandatory code, considering amendments to the International Convention for the Safety of Life at Sea (SOLAS) for the adoption of the code. Finally, by - 1, 2030 at the latest, a mandatory code would be adopted, entering into force on January 1, 2032 (International Maritime Organization - IMO, n.d.).

Concurrently, provisional guidelines have been issued for trials of autonomous vessels under controlled conditions, seeking to offer a level of safety equivalent to that of traditional vessels. Despite technological advancements, autonomous vessel technologies have limitations, as trials are currently conducted on short routes. However, the expansion of longer voyages is being studied, and it has been noted that these trials could provide valuable information to adjust regulations *(International Maritime Organization - IMO, n.d., 2023)*.

Moreover, the importance of ensuring that personnel on board are qualified to operate these systems safely has been highlighted, and priority has been given to redefining key terminologies and the interaction of autonomous vessels with port systems. Additionally, the review and adaptation of the following instruments have been prioritized:

- SOLAS Convention, chapters II-1, II-2, III, IV, V, VI, VII, IX, XI-1, and XI-2.
- COLREG.
- Standards of Training, Certification and Watchkeeping Convention and Code.
- Standards of Training, Certification and Watchkeeping for Fishing Vessel Personnel Convention.
- International Convention on Load Lines, 1966, and its 1988 Protocol.
- International Convention on Maritime Search and Rescue, 1979.
- Codes: SSCI, IMSBC, IMDG, CIQ, CIG.
- International Ship and Port Facility Security Code (ISPS Code).
- International Convention on Tonnage Measurement of Ships, 1969.

These instruments have been examined in two stages. The first stage aimed to identify provisions that currently apply to MASS and to assess whether these allow, restrict, or require modifications. While the second stage evaluated the most suitable method for adapting or creating new provisions for MASS, considering existing instruments or the development of new regulatory instruments (International Maritime Organization - IMO, n.d., 2021).

During the exploratory studies conducted by the IMO, various member states were allowed to participate in examining mandatory instruments related to maritime safety and security. In a first instance, it was considered whether or not they applied to MASS. In a second stage, it was considered whether there were equivalences, or if amendments/ elaborations were necessary. This study resulted in the systematization of instruments reflected in the most appropriate approaches and the potential gaps to be filled *(International Maritime Organization - IMO, 2021)*.

Another important point that has been addressed is the jurisdiction and responsibilities of the flag state, as legal challenges related to the location of ROCs are being discussed, especially when they are located outside the territory of the vessel. Therefore, efforts will be made to establish relationships that allow the ROC to maintain control and supervision even when located outside the flag state of the vessel. Additionally, it is expected that future regulations will consider mechanisms for autonomy that allow MASS to operate safely at multiple levels of autonomy, with the possibility of a seamless transition between different control centers and operators, adapting to specific operational needs and scenarios.

Among the next steps in regulating autonomous ships, the need for studies and discussions in key areas such as certification and documentation of MASS, the guarantee of robust systems to ensure the cybersecurity and connectivity of MASS, and training on the technological and regulatory implications of MASS, especially for developing countries, has been identified.

Standardization Activities

Standardization is a key factor in the adoption of new technologies by a country's industrial fabric. Standards provide an overview of the international requirements applicable to marine autonomous vehicles, from communication infrastructure to cybersecurity and safe operation. This work has identified some standardization spaces that are maintained by some countries for marine autonomous vehicles, conducting the search at the following levels:

- International level: led by organizations such as ISO and IEC, which define standards applicable globally.
- Regional level: led by entities such as CEN-CENELEC in Europe.
- National level: includes standards developed by national organizations such as AENOR (Spain) and DIN (Germany).

Among the findings regarding standards developed by ISO and IEC technical committees, applicable to the navigation and operation of autonomous vehicles, are those detailed in Table 1.

The study also identified documents published by classification societies such as Bureau Veritas, DNV GL, ABS, and Lloyd's Register, which establish standards and guidelines to ensure the safety and efficiency of autonomous ship operations. These guidelines and recommendations provide direction on aspects such as autonomy, remote control, interoperability, and cybersecurity, establishing a normative basis that supports the standardization of autonomous maritime technologies in different regions and sectors. The scope of the documents developed by the classification societies is presented in Table 2.

In addition to technical standards and documents from classification societies, some countries have introduced regulatory initiatives, such as the United Kingdom and Norway, which have implemented voluntary codes of practice and administrative circulars for autonomous vehicles. These regulations propose safety and operational standards aimed at equating the safety level of autonomous ships with that of conventional ships.

Table 1. Technical standards developed by ISO and IEC applicable to the navigation and operation of autonomous vehicles.

Standard	Scope
ISO/TS 23860:2022	Provides specific terminology on autonomous ship systems, enabling unified technical communication.
ISO 16425:2024	Establishes specifications for the installation of onboard communication networks, optimizing interoperability between equipment.
ISO 19847 ISO 19848:2024	They address data management on ships, defining requirements for onboard servers and structuring sensor data from machinery and equipment, supporting efficiency in operational data collection and analysis.
ISO 28005-1 ISO 28005-2	Standards on electronic port dispatch, specifying message structures and key data elements for transit and port entry/exit control.
Serie IEC 61162	This series covers digital interfaces for data communication between navigation and radio communication systems, enabling the secure and reliable exchange of information between multiple systems on board and between ship and shore.
IEC 63154:2021 IEC 63173-2:2022	Standards that establish general requirements for cybersecurity and secure ship-to-shore communication, essential for the operation of autonomous systems under the risk of cyber-attacks.

Table 2. Documents prepared by classification societies.

Classification societies	Year	Code or Title	Reach
Bureau Veritas	2019 2022	NI641 R01 NR 681	Provide guidelines on design and operation of autonomous surface vessels, with recommendations on degrees of automation and remote control.
DNV GL	2018	Class Guideline DNVGL-CG-0264	Suggests a framework for the implementation of autonomous technologies, including processes for obtaining approvals for non-conventional concepts.
ABS	2019	Advisory on Autonomous Functionality	Publishes a guide to standalone functionality, detailing everything from automation to the development of secure remote operations.
Lloyd's Register	2024 2017	Maritime Autonomous Surface Ships LR Code for Unmanned Marine Systems	Present guidelines to ensure that autonomous operation systems meet safety standards at each stage of development, integrating specific maintenance and operation requirements.
ClassNK	2020	. Guidelines for Automated/ autonomous Operation on Ships	

In Colombia, the adoption and development of technical standards for autonomous vehicles present challenges due to the structure of the industry and the existing regulatory framework. To date, the industry has only undertaken specific research projects for the development of some of these vehicles, and no regulatory practices have yet been evidenced from regulatory bodies. The national standardization body is working on international participation to bring national experts to international standardization forums in order to exchange experiences on autonomous vehicles and support the development of international standards on this topic.

Discussion

This study examines the development and implementation of the regulatory framework for the operation of autonomous ships (MASS and USV), highlighting the advances and challenges that arise when adapting maritime regulations to emerging technologies. This study offers a comprehensive perspective by analyzing regulatory challenges and providing an overview of the topic through a mapping of developments at the academic level, the IMO, and some standardization bodies. The findings suggest that, although the development of subsystems and algorithms for autonomy has advanced significantly, the global regulatory framework faces significant challenges in updating to safely and efficiently integrate these vessels into traditional maritime environments.

This study underscores significant gaps and ongoing advancements in the regulatory landscape for MASS and USVs. The existing body of literature, while rich in technical developments, reveals a noticeable lag in legal and regulatory frameworks, which have not kept pace with the rapid technological innovations within the maritime industry. However, various authors approach the topic from different perspectives, focusing on aspects such as cybersecurity, liability, the role and training of the human element, and operational safety, and examining how current regulations align with the operational needs of autonomous vessels. Key studies, such as those by Horne *et al*. (2023), highlight substantial challenges, suggesting that existing maritime laws may need substantial adaptations to accommodate different levels of vessel autonomy. The review also identifies the pressing need for comprehensive and flexible regulatory frameworks to address the various levels of autonomy and operational environments. For instance, while remotely controlled vessels may fit within current maritime conventions, fully autonomous vessels demand new legal standards to address issues like human oversight, decision-making responsibilities, and the role of remote operators. The literature suggests that achieving regulatory cohesion will require a blend of global guidance and regionally adaptive measures, reflecting the varying maritime governance contexts.

This analysis includes a review of the fundamental role played by the IMO in establishing preliminary guidelines and creating a roadmap towards a specific regulatory code for MASS. This effort encompasses a series of modifications to existing international conventions with the aim of ensuring that MASS operate with safety standards equivalent to those of conventional vessels. However, the diversity of levels of autonomy and the complexity of operational environments have made evident the need for a flexible and collaborative approach that allows for continuous adjustments to the regulatory framework in response to technological advances.

Furthermore, the study reviews of standardization activities, given the relevance of establishing global standards for autonomous navigation. International organizations such as ISO and IEC play a fundamental role in providing a solid technical framework for the development of safe and reliable autonomous systems. However, it is important to note that the rapid evolution of this technology poses challenges for keeping standards up-to-date and ensuring their effective application in various maritime contexts. The study highlights the development of norms by various standardization bodies that can potentially be applied to MASS and USVs. While several norms address aspects of navigation, communication networks, cybersecurity, and operational safety, only one of these standards has been explicitly designed for MASS. Additionally, classification societies have contributed to this regulatory landscape by developing specific guidelines and documentation that address the unique requirements of MASS.

Technical standards provide a solid foundation for the development of specific regulations, ensuring the safety and interoperability of autonomous systems. However, it is essential that regulators maintain a balance between the flexibility needed to adapt to innovation and the need to protect maritime safety. Collaboration between standardization bodies and regulators will be key to achieving a successful transition to autonomous navigation. At the national level, the adaptation and adoption of these international standards represent a challenge, especially in developing countries like Colombia, where infrastructure and the regulatory framework are still limited. The creation of specific technical standards and the strengthening of local capacities and operator training will be necessary to allow for the effective integration of MASS into the fluvial and maritime regional context.

Conclusions

This study examines the regulatory and normative framework for the operation of autonomous vessels in real-world environments, highlighting the limitations and advancements of current standards in relation to rapid technological progress. The study focuses on the relationship between developments in maritime vehicle autonomy and the need to establish robust regulatory frameworks that address both technological demands and the social and legal implications of these innovations.

The analysis begins with a review of the literature on the regulation and norms applicable to autonomous vessels, including studies covering topics ranging from safety and certification to human-technology interaction in the context of autonomous operation. Secondly, the paper analyzes the role of the IMO in establishing a global regulatory framework, advancing towards the creation of a Code for Maritime Autonomous Surface Ships (MASS). The IMO has developed interim guidelines and is revising existing treaties to adapt them to MASS, considering key elements such as safety, cybersecurity, and operator training. The regulatory process includes defining roles and responsibilities for remote operators and control personnel, as well as classifying the levels of autonomy of these vessels. Finally, the standardization work of international organizations such as ISO and IEC is highlighted, which have developed standards related to cybersecurity, communication, and data management that can be applied to autonomous vessels. These technical standards cover everything from cybersecurity requirements to interoperability between systems, providing a basis for global and regional standardization. Standards are key to the development of national regulatory frameworks, supporting the adaptation of the maritime industry towards autonomous navigation technologies.

The entry into operation of vessels in real-world contexts will be a reality in the near future and there must necessarily be convergence points between the technological aspect and the social component. To date, the latter has not restricted the progress of the former. Considering the potential impacts and advantages arising from the coexistence of new technologies with conventional ones, it is expected that the social debate will develop in such a way that the regulations are timely and appropriate.

Contributions

- Luis Castano-Londono: Contribution: Conceptualization, data collection, formal analysis, research, methodology, software, resources, supervision, validation, visualization, writing of the original manuscript, writing - revision and editing.
- Edwin Paipa-Sanabria: Contribution: Conceptualization, formal analysis, funding acquisition, research, project administration, resources, supervision, validation, writing-revision, and editing.
- María Belén Orozco-Lopez: Contribution: data collection, formal analysis, research, methodology, software, resources, visualization, writing of the original

manuscript, writing - revision and editing
- Mateo Torres-Gonzalez: Contribution: data collection, formal analysis, research, methodology, visualization, writing of the original manuscript, writing - review and editing.
- Gersson Torres-Baquero: Contribution: Conceptualization, data collection, research, resources, supervision, validation, writing of the original manuscript.

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