TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 19 Number 4 December 2025
DOI: 10.12716/1001.19.04.23

The Transition of the Maritime and Port Industry Toward Automation: A Focus on Maritime Autonomous Surface Ships (MASS)

A. Bąk
Maritime University of Szczecin, Szczecin, Poland

ABSTRACT: The maritime and port industry is undergoing a profound technological transformation, driven by the need to improve operational efficiency, safety and the protection of both the maritime and land environment. At the heart of this transformation is the development and deployment of Maritime Autonomous Surface Ships (MASS). This article examines the technological foundations, benefits, challenges and future prospects of MASS, as well as their interaction with port automation systems. It provides an overview of the International Maritime Organization's (IMO) framework for autonomous shipping, key real-world case studies and critical regulatory, cyber-security and operational integration challenges. The findings indicate that while significant barriers remain, the momentum towards a more automated and intelligent maritime ecosystem is irreversible.

1 INTRODUCTION

The maritime industry plays a key role in facilitating global trade, transporting around 90% of goods by volume through international waters (Towards a green and just transition, 2023). However, increasing cargo volumes, environmental concerns, labor shortages and safety requirements have driven the sector towards technological innovation and automation. The fourth industrial revolution has introduced digital technologies such as artificial intelligence (AI), the internet of things (IoT) and big data analytics into maritime operations. Central to this transformation is the emergence of Maritime Autonomous Surface Ships (MASS) - vessels capable of navigating and operating with varying degrees of autonomy. This has been linked equally to rising fuel prices, tight delivery schedules and increased competition. Automation enables real-time decision-making, route optimization and predictive maintenance, which contributes to lower operating costs and better resource utilization (QinetiQ Ltd et al., 2013). The human factor is not insignificant, where it is estimated that human error remains the leading cause of maritime accidents, accounting for approximately 75-96% of incidents, including collisions, run-ins, onboard fires and machinery failures (Bureau of Transportation Statistics and MacroSys, LLC, 2024). These errors are often due to factors such as cognitive overload, fatigue, miscommunication and limited situational awareness among crew members. As maritime operations become more complex and technologically intensive, the likelihood and consequences of such errors become more pronounced, highlighting the urgent need for technological interventions that enhance navigational safety and operational reliability. In response, the integration of automated navigation systems, sensor fusion technology and artificial intelligence (AI)-based diagnostics has emerged as a transformative approach to mitigating human-related hazards. Automated navigation systems aid real-time decision-making by continuously processing environmental data, maritime traffic information and vessel dynamics to support optimal routing and the concept of collision avoidance.

These systems are reliance on the sometimes-flawed judgement of the officer navigation, thus minimizing the risk of omission or misjudgment during critical navigational tasks.

Navigation sensor data fusion plays a complementary role by aggregating data from a wide range of onboard instruments - including radar, GPS (Global Positioning System), sonar, LIDAR (Light Detection and Ranging) and meteorological sensors - to create a coherent and dynamic situational awareness model. This comprehensive data integration enables more accurate threat detection and better response to rapidly changing conditions at sea. In addition, AI-based diagnostic systems contribute to improved safety and operational continuity by enabling predictive maintenance and real-time anomaly detection. By continuously monitoring the performance of critical shipboard systems, these tools can identify early signs of mechanical degradation or failure, enabling rapid intervention before dangerous events occur. This paper presents technical roadmap analysis.

2 MARITIME AUTONOMOUS SURFACE SHIPS (MASS)

As the maritime industry moves towards increased automation and digitalization, the International Maritime Organization (IMO) has established a structured framework for classifying marine autonomous surface ships (MASS). This framework, outlined in the IMO's regulatory scoping exercise on the use of MASS (IMO, 2021), defines four different degrees of autonomy. Each degree reflects an advanced level of automation, remote control and decision-making capability, serving as a standardized benchmark for both development and technological integration across the global shipping industry.

We distinguish between the following degrees of autonomy:

1. Ship with automated processes and decision support (human-centered automation). At this initial level of autonomy, ships are equipped with systems that automate specific functions or support decision-making, such as collision avoidance, route optimization or machinery and equipment diagnostics. However, the crew remains on board and retains full responsibility for ship operations and decision-making. These systems increase safety, efficiency and operational awareness, reducing crew workload and minimizing human error, but do not eliminate the need for human intervention. The degree closely follows current industry practices including bridge automation, ECDIS systems, dynamic positioning systems and integrated bridge systems (IBS).
2. Remotely operated vessel with crew on board. At this level, the vessel can be operated remotely - usually from a shore-based control center - while reducing the presence of crew on board. In this configuration, remote operators can take direct control of navigational or propulsion functions under certain conditions, while shipboard personnel are available to intervene as needed. This stage serves as an interim stage that allows real-time testing of remote control technology under safe and supervised conditions. It provides operational flexibility and redundancy, enabling human oversight in critical situations, while exploiting the advantages of shore-based monitoring and control.
3. A remotely piloted vessel with no crew on board. This level represents a significant change in operational philosophy. Vessels at this level are fully controlled and monitored remotely, without the physical presence of a crew on board. All navigational, mechanical and safety functions are operated from the control center. At this level, the control system must be fault-tolerant and protected against hacking attacks. Vessels with a third level of autonomy present complex regulatory and technical challenges, particularly in collision prevention (COLREG) regulations, liability, search and rescue and incident response protocols.
4. A fully autonomous vessel capable of independent operation and decision-making. This is the highest level of autonomy and includes vessels that are capable of managing operations autonomously without human intervention, both on board and ashore. These ships use advanced artificial intelligence, machine learning and sensor fusion technologies to interpret environmental conditions, assess risk, make decisions and independently perform navigational and operational tasks. Such vessels require highly advanced onboard systems capable of real-time situational awareness, fault tolerance and adaptive learning to operate safely in a complex and dynamic maritime environment.

This multi-level classification system is crucial in guiding the development of international regulatory frameworks, technical standards and safety protocols related to autonomous shipping. By defining the operational scope and capabilities of each level, IMO's MASS autonomy degrees provide a common language for stakeholders - regulators, technology developers, shipowners, insurers and classification societies - to assess risk, develop compliance strategies and implement automation technologies in a structured and progressive manner. In addition, the framework supports the alignment of MASS development with existing maritime conventions such as SOLAS (Safety of Life at Sea), COLREG (International Regulations for Preventing Collisions at Sea) and MARPOL (International Convention for the Prevention of Pollution from Ships), ensuring that the evolution of autonomous ships takes place in a safe, sustainable and legally consistent context. Numerous studies have demonstrated the effectiveness and cost savings resulting from the use of autonomous ships. This is undoubtedly a forward-looking solution that shipping companies are gradually implementing (L. Kretschmann et al., 2017).

The integration of Maritime Autonomous Surface Ships (MASS) into port environments represents a fundamental shift in how ships and ports communicate and operate. Unlike traditional manned vessels, MASS rely heavily on digital communication, automation, and real-time data exchange with port systems to safely and efficiently enter, dock, unload, load, and depart. Before an autonomous ship arrives at the port, a series of digital interactions occur. The ship engages in automated voyage planning and notification by transmitting its Estimated Time of Arrival (ETA), intended route, cargo information, and any special requirements, such as berth type or draft limitations, to the port's Vessel Traffic Service (VTS) and Port Management Information System (PMIS). Additionally, a process of digital pre-clearance takes place, where customs, immigration, and quarantine declarations are submitted electronically in advance, often through blockchain-secured platforms, thereby minimizing the need for human inspections. Simultaneously, berth allocation is managed by the port's AI-driven berth management system, which uses real-time data on traffic and berth availability to assign a berth for the arriving MASS, aiming to optimize fuel efficiency and minimize turnaround time.

When the MASS enters the port's controlled waters, real-time coordination becomes crucial. The ship engages in vessel-to-infrastructure (V2I) communication by continuously exchanging information with systems such as the Vessel Traffic Management Systems (VTMS), smart buoys and navigational aids, Remote Traffic Control Centers (RTCC), and dynamic signs and signals. At the same time, there is continuous situational awareness sharing, where both the MASS and the port exchange real-time data on position, speed, heading, weather and water conditions such as current, depth, and wind, as well as information on traffic density and potential collision risks. In addition, human operators at the port's control center maintain remote supervision and override capability, enabling them to monitor the MASS's movements in real time and intervene manually if anomalies or emergencies are detected.

Autonomous berthing is one of the most complex maneuvers, requiring close cooperation between the MASS and port systems. The assigned berth is equipped with smart berth and mooring systems, including autonomous mooring devices such as vacuum pads and smart bollards, as well as automated fender and bumper systems that assist in ensuring safe docking. During the approach, the MASS relies on precision maneuvering technologies, using onboard sensors such as LiDAR, radar, and GPS-RTK to achieve centimeter-level positioning, supplemented by real-time corrections provided by the port's local differential GPS or other positioning aids. Once the vessel is docked, terminal equipment coordination takes place, with dockside cranes, Automated Guided Vehicles (AGVs), and other cargo handling systems synchronizing operations with the MASS for efficient loading and unloading activities.

When the vessel is ready to leave, a series of automated processes guide its departure and post-departure activities. Departure notices and documents are automatically filed and cleared with port authorities through an automated clearance system. If necessary, smart tugboat coordination is activated, with autonomous tugs assisting the MASS in undocking and navigating out of the port. Throughout the departure, the port's Vessel Traffic Management System (VTMS) manages traffic by coordinating the ship's exit route, taking into account the movements of other vessels and prevailing environmental conditions. Even after the ship leaves the berth, continuous monitoring ensures that the MASS remains in communication with the port until it safely clears the harbor area.

The interaction between MASS and port systems represents a highly orchestrated digital handshake, relying on continuous data sharing, predictive analytics, and advanced automation technologies. Ports like Rotterdam, Singapore, and Hamburg are already pioneering these systems, laying the groundwork for a future where autonomous ships and smart ports operate symbiotically to create safer, faster, and greener global shipping.

3 TECHNOLOGICAL FACTORS SUPPORTING MASS

Artificial intelligence (AI) and machine learning (ML) are playing a key role in the development and deployment of maritime autonomous surface ships (MASS), enabling real-time decision-making, predictive analysis and adaptive control across multiple operational domains. These technologies enhance both the safety and efficiency of ship operations by processing vast amounts of data from onboard sensors and external information systems, so to speak, mapping the complex marine environment into useful information.

One of the options implemented by AI algorithms is route optimization that analyses a number of dynamic variables, such as vessel maneuvering characteristics, fuel consumption, sea state, steady as well as tidal currents, wind conditions and traffic density. Unlike traditional static routing systems, AI models can adjust routes in real time to minimize travel time, fuel consumption and exposure to hazardous conditions. Machine learning algorithms enhance situational awareness by classifying and tracking static and dynamic obstacles. Computer vision systems, powered by convolutional neural networks (CNNs), process optical and infrared camera data to detect nearby vessels and navigational objects. Combined with radar, LIDAR, AIS (Automatic Identification System) and sonar data, these systems provide a multimodal perception model capable of understanding and predicting the behavior of surrounding vessels (Figure 1). Deep learning models provide predictive collision avoidance by assessing not only an object's current position, but also its speed, trajectory and probability of violating safe passing distances (P. Shunmuga Perumal et al., 2020) . These models can autonomously initiate course corrections or alert remote operators to intervene if necessary. In addition, AI models take into account weather conditions by integrating meteorological data, wave forecasts and satellite imagery to predict adverse conditions such as storms, ice fields or storms. Predictive analytics allow the vessel to proactively re-route, reduce speed or adjust ballast and trim configurations to maintain stability and appropriate levels of safety. Natural language processing (NLP) techniques are also used to interpret weather bulletins and safety advice, further enhancing autonomous decision-making. The ability to dynamically adapt to environmental changes is particularly important in polar operations, where environmental variability is high and real-time human decision-making may be limited by limited communications at higher latitudes.

The core of artificial intelligence applications is real-time data fusion, in which heterogeneous data sources

- from GNSS (Global Navigation Satellite System) to engine diagnostics - are aggregated and interpreted to create a coherent operational model of the vessel and its environment. Bayesian inference, Kalman filtering and deep learning with reinforcement are among the techniques used to filter noise, manage uncertainty and support probabilistic inference in a dynamically changing marine environment (Alamoush and Ölçer, 2025). AI and ML models are tightly integrated with autonomous control systems, including adaptive autopilots, energy management systems and error detection modules. For example, AI-assisted autopilot systems not only maintain course and heading, but also take into account real-time traffic separation systems (TSS), exclusion zones and dynamically changing maritime traffic regulations. Similarly, predictive maintenance algorithms analyze vibration data, temperature profiles and usage patterns to detect anomalies and predict component failures, reducing downtime and improving safety by scheduling maintenance appointments in advance.

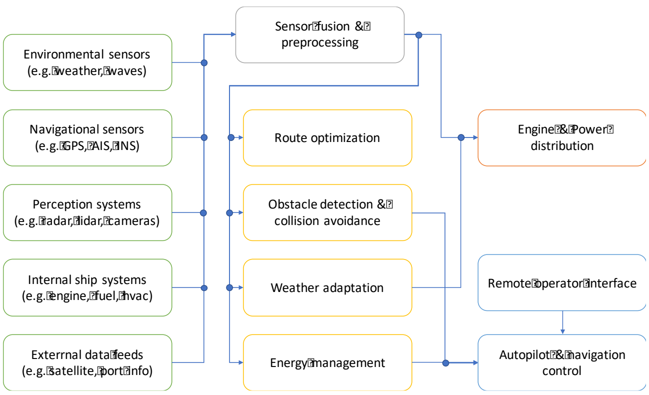

Figure 1. Data flow in autonomous ship control systems. Source: own development.

Sensor integration is a fundamental pillar of maritime autonomous surface ships (MASS), enabling them to perceive, interpret and respond to complex marine environments without direct human intervention. Unlike conventional vessels, which rely primarily on human observation and isolated sensor systems, autonomous vessels use a wide range of sensing technologies to develop a comprehensive and multidimensional understanding of their operational context.

4 USE OF THE NEW S-100 ENC ELECTRONIC CHART STANDARD IN ECDIS

As a core carrier for sensor fusion and data integration, the S-100 standard serves as a critical technical foundation for MASS environmental perception. The newly developed International Hydrographic Organization (IHO) S-100 Universal Hydrographic Data Model provides a standardized framework for the integration of different data sets, while the Electronic Chart Display and Information System (ECDIS) software serves as the primary platform for visualizing and managing navigational information.

The maritime industry is undergoing a significant technological transformation with the introduction of the S-100 Universal Hydrographic Data Model, developed by the International Hydrographic Organization (IHO). This new standard represents a key evolution from the existing S-57 standard, which has governed the creation of electronic navigational charts (ENCs) for decades. The S-100 architecture is designed to meet the growing requirements for data integration, interoperability and increased functionality in modern navigation systems. The S-100 standard is not limited to navigation charts; it is a versatile and flexible data model capable of handling a wide range of geospatial data types. These include bathymetric data, marine spatial planning, tides, currents and meteorological information. This versatility allows S-100-based ENCs to offer richer, multi-dimensional visualization of the marine environment, enabling mariners to make more informed decisions.

The S-57 standard, which came into force in 1992, is the primary ENC standard, focusing on encoding nautical information into a digital format that is used by ECDIS (Electronic Chart Display and Information Systems). It is primarily geared towards navigational requirements, handling standard chart data using a relatively rigid, file-based data model focused on vector data. It is largely based on ISO/IEC 8211, a file format standard that works well for static data sets, but lacks the adaptability to incorporate non-standard data types or real-time data.

The S-100 standard was developed as an extension and enhancement of the S-57 and was adopted as a draft in 2010. It provides a more flexible and versatile architecture that can support a wider range of data types and applications beyond traditional navigation. The S-100 is designed to be 'future-proofed' to better support new technologies such as 3D visualization, high-resolution bathymetry and real-time data integration. It uses a more modern, flexible data model based on the ISO 19100 series for geographic information standards (OBP, 2025) . It can handle vector, raster, grid and point cloud data, along with other complex data types such as images and even dynamic, time-sensitive data. It allows support for additional applications such as high-resolution weather overlays, real-time tidal information and current maritime traffic. It offers greater interoperability with non-hydrographic systems as it is built on a platform that supports Open Geospatial Consortium (OGC) standards and XML-based data (OGC, 2019) . It includes several S-100 'product specifications' that define how different types of data (such as tides, currents, weather) can interact within the same platform, increasing its potential for integration with GIS and real-time systems. At the same time, it enables more advanced visualisation, supporting both 2D and 3D imaging. It also facilitates higher resolution displays and can include more detailed data for complex map elements, enabling richly detailed representations of underwater topography, weather models and dynamic marine information. It supports real-time data integration dynamically updating data such as water levels, tidal and steady currents or weather patterns. This makes it especially dedicated in dynamic applications such as vessel traffic services (VTS) management or real-time hazard warnings.

The key features of the S-100 ENC are:

- Increased data precision, ENC S-100s provide higher resolution data and more detailed visualization compared to their S-57 counterparts;
- improved interoperability, the S-100 standard enables seamless integration with other datasets, supporting compatibility between different marine applications and systems;
- real-time updates, incorporating dynamic data such as tides, currents and weather, ensures navigators have access to the most up-to-date information;
- scalable for future technologies, the S-100 is designed with future advances in mind, supporting new technologies such as autonomous navigation and e-navigation.

Among the most relevant elements of the S-100 standard are:

- S-101 ENC (Electronic Navigational Charts) - basic navigation charts with improved symbology;
- S-102 Bathymetric Surface Data - high-resolution depth models for precise calculations of water reserves under the keel;
- S-104 Water level information - real-time tidal and water level updates;
- S-111 Surface currents - dynamic oceanographic data for route optimization;
- S-129 Underkeel Clearance Management - a dynamic underkeel clearance management system operating on real-time dynamic data.

5 REMOTE MONITORING AND CONTROL

In the context of Maritime Autonomous Surface Ships (MASS), remote monitoring and control systems serve as an important bridge between vessel autonomy and human supervision. Particularly relevant for second and third degrees of autonomy, as defined by the International Maritime Organization (IMO, 2021), these systems enable shore operators to supervise, intervene and control vessels from shore control centers (SCCs) when necessary. The effectiveness and safety of remotely managed operations depends on advanced communication infrastructure, real-time data exchange and robust control architectures. Reliable communication systems with high bandwidth and low latency are the foundation of remote operations. These typically include:

- satellite communications (SATCOM). Satellite networks in geostationary orbit, medium earth orbit (MEO) and low earth orbit (LEO) provide global connectivity, and LEO constellations (e.g. Starlink (Starlink, 2025) , OneWeb (Eutelsat, 2025)) offer the high-speed, low-latency bandwidth needed for telemetry and real-time video transmission. SATCOM is essential for operations in remote ocean regions beyond terrestrial signal coverage.
- 5G mobile networks. In coastal areas, 5G and maritime LTE networks offer ultra-low latency communications for data exchange between ships and land. These technologies are ideal for ports, inland waterways and coastal routes where real-time response times are critical.
- Hybrid networks and failover systems. To ensure continuity, ships often use hybrid networks that dynamically switch between satellite, 5G and Wi-Fi based on availability and performance. There are also redundant channels to maintain control during disruptions.

Shore Control Centers (SCCs).

Remote operations are conducted from SCCs - shore-based facilities manned by trained operators who monitor the condition of the vessel and can take partial or full control if necessary. SCCs typically have:

1. Real-time dashboards - provides live telemetry from navigation systems, engine performance information, fuel consumption, environmental sensors and internal diagnostics.
2. Video and audio feeds - High-resolution cameras and microphones installed on board transmit visual and audio data to the SCC, offering situational awareness similar to that from the ship's bridge.
3. Decision support systems - analytics based on artificial intelligence help remote operators to make optimal decisions.
4. Manual and redundant control - in degrees 2 and 3 of autonomy, operators retain the ability to take control of autonomous systems to manually control, change speed or shut down the vessel's systems in an emergency or in the event of a system failure.

Remote control systems offer full manual override functionality, allowing operators to immediately take command in the event of an onboard AI system malfunction or safety hazard. This is essential for COLREG compliance and building confidence in autonomous operations. To ensure reliability, remote control systems are designed to operate with secure and redundant communication protocols, minimising the risk of total loss of communications. In the event of a disconnection, autonomous failure modes are activated, such as automatically releasing the vessel, stopping or returning to a predefined safe waypoint. Furthermore, cyber security is a fundamental requirement given the vulnerability of wireless systems. Encrypted communications, multi-component authentication, intrusion detection systems and continuous threat monitoring are integrated into both the ship's infrastructure and the SCC to prevent malicious access or tampering.

Remote monitoring and control systems are not just surveillance tools - they are integral to the architecture of autonomous vessels. Enabling real-time surveillance, diagnostic support and emergency intervention, they serve as a safety net that supports autonomous decision-making while ensuring regulatory compliance and operational reliability. With the development of communication networks and artificial intelligence systems, it is expected that the role of remote operations will increase, paving the way for higher levels of autonomy while maintaining the necessary human supervision where necessary.

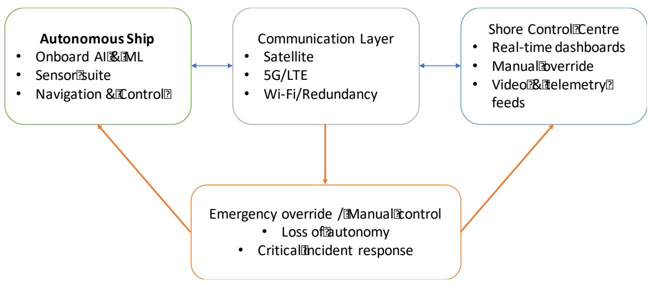

Figure 2. Remote monitoring and control flow in Maritime Autonomous Surface Ships (MAAS).

The block diagram shown at Figure 2 illustrates the architecture for remote monitoring and control in Maritime Autonomous Surface Ships (MASS). It highlights the connection between the autonomous vessel, the communication infrastructure (e.g. satellite, 5G) and the Shore Control Centre (SCC), along with a dedicated emergency path for critical interventions. MASS rely heavily on digital infrastructure, making them vulnerable to cyber threats. Ensuring secure communication channels, system redundancy and on-board defense mechanisms are key to secure deployment (DNV, 2023).

6 CASE STUDIES AND REAL-WORLD EXAMPLES

Among the many attempts to build an autonomous ship, it is worth mentioning the projects that have been successfully completed and implemented. These include:

– Yara Birkeland (Norway):
  Is widely recognized as the world's first fully electric and autonomous container ship, representing a major innovation in maritime transport. Developed through a collaboration between Yara International, a leading Norwegian chemical and fertilizer company, and Kongsberg Maritime, a specialist in autonomous and maritime technologies, the project aims to demonstrate how zero-emission vessels can support both sustainability goals and operational efficiency in short-sea shipping. The ship not only marks a technological breakthrough but also sets an important precedent for the decarbonization and automation of global shipping.

Table 1.Technical specifications of Yara Birkeland. Source: https://www.yara.com/news-and-media/media-library/press-kits/yara-birkeland-press-kit/

Feature	Details
Type	Container shiip
Length	80 m
Beam	15 m
Depth	12 m
DWT	3200
Cargo capacity	120 TEU
Battery capacity	6.8 MWh
Propulsion	Two azimuth & two tunnel thrusterrs
Speed (Max)	13 kn
Speed (Economic)	6-7 kn

– MOL and NYK (Japan):
  MOL has launched several projects aimed at advancing "Smart Ship" technology, integrating automation, remote control, and AI-based decision-making. A key part of their strategy is developing autonomous navigation systems for various types of vessels, including ferries, containerships, and tankers.
  NYK Line is advancing its own "Autonomous Ship Project" as part of the wider consortium under the DFFAS (Designing the Future of Full Autonomous Ship) Project, involving more than 30 Japanese companies. NYK's efforts focus not only on onboard automation but also on land-based operational support systems.
– Rolls-Royce and Kongsberg:
  Two major players, Rolls-Royce Marine (now largely acquired by Kongsberg Maritime) and Kongsberg Gruppen, have been instrumental in pushing the boundaries of maritime automation. Their collaborative and independent efforts have laid the technical and operational foundation for the development of Maritime Autonomous Surface Ships (MASS). The companies have developed not only onboard autonomous technologies but also the crucial shore-based remote operation centers that will monitor and, when necessary, control fleets of unmanned vessels. Their work is reshaping the shipping industry by combining advanced engineering, artificial intelligence, robotics, and real-time communications. They have proposed and tested following platforms:
  1. MV Falco (Finland, 2018) – demonstrated a remotely operated and fully autonomous ferry crossing in the busy Turku archipelago.
  2. ASKO Autonomous Barges (Norway) – Kongsberg developed fully autonomous electric barges for Norwegian retailer ASKO, replacing truck deliveries across Oslo Fjord.
  3. Sea Trials of Yara Birkeland (2020–2023) – full-scale autonomous trials without onboard crew in coastal waters.
– Port of Rotterdam (Netherlands):
  The Port of Rotterdam, Europe's largest seaport and one of the busiest in the world, is internationally recognized as a leader in "smart port" innovations. As maritime transport moves towards greater automation with Maritime Autonomous Surface Ships (MASS), Rotterdam is actively transforming its infrastructure, management systems, and operational strategies to become fully compatible with autonomous vessels. Using cutting-edge technologies like Artificial Intelligence (AI), the Internet of Things (IoT), digital twins, and predictive analytics, Rotterdam is not just optimizing current logistics but also future-proofing itself for an era dominated by autonomous and sustainable shipping.

Table 2. Major Smart Port projects related to MASS. Source: https://www.portofrotterdam.com/en/building-port

Project name	Description
PortXchange Synchronizer	A digital platform that enables port call optimization by sharing real-time data among shipping lines, terminals, and nautical service providers, improving berth planning for both manned and autonomous ships.
Pronto	An application that offers real-time updates for ship agents and captains, coordinating all activities during a port call, aiming for the synchronization needed in MASS interactions.
Digital Twin "HydroMeteo"	Focused on detailed real-time water and weather data to optimize ship maneuvers, crucial for the safe arrival of autonomous vessels.
Smart infrastructure program	Deployment of smart quays and autonomous mooring systems, preparing physical facilities for self-docking MASS.
Autonomous drones and vehicles	Trialing aerial and ground drones for inspection, monitoring, and delivery tasks, supporting autonomous ship operations.

The Port of Rotterdam exemplifies the future of maritime logistics, where AI, IoT, digital twins, and autonomous vessels work in seamless harmony. Its pioneering efforts are setting a global benchmark, ensuring that as MASS becomes more common, ports will be ready—not just to accommodate them, but to thrive in a new age of smart, green, and autonomous shipping.

7 CONCLUSIONS

Current maritime conventions, such as SOLAS and UNCLOS, presume the presence of a crew on board. Adaptation of these regulations is required to define responsibilities, certification and operational rights for MASS ((IMO, 2021)). Another problem of remote control and vessel autonomy is cyber intrusion. Consequently, securing shipboard networks and control centres remains a top priority. The high capital cost of autonomous systems, coupled with the uncertainty of the return on investment, currently discourages their widespread use by investors, especially among small and medium-sized enterprises.

However, technological development is difficult to stop and what now seems costly or reasonably impossible will be readily available in the near future through AI systems. One only has to look at the hybrid and semi-autonomous ships already in operation in various parts of the world or in the testing phase. Future research focuses on:
– interoperability between MASS and port systems;
– models of human-autonomy teamwork;
– The ethics of machines in decision-making by artificial intelligence;
– scalable cyber security solutions.

The evolution of maritime autonomous surface vessels represents a paradigm shift in the maritime and port industry. With improved safety, cost efficiency and environmental performance, MASS have the potential to redefine global shipping. However, the road ahead requires overcoming regulatory, technical and economic challenges. Through continued innovation and international collaboration, MASS and wider maritime infrastructure automation can become the cornerstones of a smarter, safer and more sustainable global trade network.

REFERENCES

[1] Towards a green and just transition. in Review of maritime transport / United Nations Conference on Trade and Development, Geneva, no. 2023. Geneva: United Nations, 2023.
[2] QinetiQ Ltd, LR Group, and University of Strathclyde, Eds., Global marine trends 2030. London: Lloyd's Register Group, 2013.
[3] Bureau of Transportation Statistics and MacroSys, LLC, 'Transportation Statistical Annual Report 2024', United States Department of Transportation, Dec. 2024. doi: 10.21949/E0KQ-GF72.
[4] IMO, 'MSC.1/Circ.1638 "OUTCOME OF THE REGULATORY SCOPING EXERCISE FOR THE USE OF MARITIME AUTONOMOUS SURFACE SHIPS (MASS) "'. IMO, 2021. Accessed: Mar. 28, 2025. [Online]. Available: https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/MSC.1-Circ.1638%20-%20Outcome%20Of%20The%20Regulatory%20Scoping%20ExerciseFor%20The%20Use%20Of%20Maritime%20Autonomous%20Surface%20Ships...%20(Secretariat).pdf
[5] P. Shunmuga Perumal et al., 'Lidar Based Intelligent Obstacle Avoidance System for Autonomous Ground Vehicles', Int. J. Recent Technol. Eng. IJRTE, vol. 8, no. 6, pp. 2466–2474, Mar. 2020, doi: 10.35940/ijrte.F8029.038620.
[6] A. S. Alamoush and A. I. Ölçer, 'Maritime Autonomous Surface Ships: Architecture for Autonomous Navigation Systems', J. Mar. Sci. Eng., vol. 13, no. 1, p. 122, Jan. 2025, doi: 10.3390/jmse13010122.
[7] OBP, 'ISO/TR 19120:2001(en) Geographic information — Functional standards'. 2025. Accessed: Mar. 31, 2025. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:tr:19120:ed-1:v1:en
[8] OGC, 'OGC Hierarchical Data Format Version 5 (HDF5®) Core Standard'. OGC, 2019. Accessed: Mar. 31, 2025. [Online]. Available: https://docs.ogc.org/is/18-043r3/18-043r3.html?swpmtx=d3087dd852f3d68a0aba3e3de57ff11f&swpmtxnonce=6e01a73972
[9] Starlink, 'Starlink'. 2025. Accessed: Mar. 31, 2025. [Online]. Available: https://www.starlink.com
[10] Eutelsat, 'OneWeb'. 2025. Accessed: Mar. 31, 2025. [Online]. Available: https://oneweb.net
[11] DNV, 'Maritime Cyber Priority 2023', 2023. [Online]. Available: https://brandcentral.dnv.com/original/gallery/10651/files/original/5edc9dcb-4dfb-448c-a766-cb065f28a47b.pdf
[12] L. Kretschmann, H.Ch. Burmeister, C. Jahn, "Analyzing the economic benefit of unmanned autonomous ships: An exploratory cost-comparison between an autonomous and a conventional bulk carrier", Research in Transportation Business & Management, Volume 25, 2017, Pages 76-86, ISSN 2210-5395, https://doi.org/10.1016/j.rtbm.2017.06.002.