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Technological Transformation and Future Perspectives in Autonomous Maritime Systems

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Abstract

This article examines the growing role of autonomous systems in the defense and maritime sectors within the context of the historical and societal transformations driven by technology. It highlights how technological innovations, particularly since the Industrial Revolution, have shaped systemic transformations, while information and communication technologies have redefined societal life and global dynamics. In the military domain, the use of unmanned systems and artificial intelligence (AI)-supported platforms is emphasized as replacing traditional warfare tools with more effective and flexible technologies. The study focuses on the development of autonomous maritime vehicles, emphasizing their operational advantages and strategic importance for national security. Unmanned maritime vehicles undertake critical missions, ranging from combating asymmetric threats to environmental monitoring, while offering significant benefits such as cost efficiency and risk reduction. However, the limitations of autonomous systems include deficiencies in communication infrastructure, susceptibility to electronic jamming, and legal and ethical challenges. It is anticipated that future warfare technologies will derive strategic advantages from swarm intelligence, machine learning, and AI-based systems. These systems have the potential to perform complex tasks in a coordinated manner without human intervention. However, challenges such as cybersecurity threats, legal and ethical regulations, and societal acceptance must be addressed carefully for the widespread adoption of these technologies. In this context, the integrated development of autonomous systems, supported by innovation and collaboration processes, is expected to lead to significant transformations in military and civilian domains in the future. These systems, leveraging advancements in information technologies, AI, and sensor systems, will achieve more efficient and sustainable operational capabilities, offering both economic and strategic advantages. In conclusion, as the importance of autonomous systems continues to grow in the coming years, innovative strategies and disciplined management approaches will be required for their effective use. In the future, the adaptability of autonomous systems and capabilities such as swarm intelligence will play a game-changing role in both military and commercial operations.

Keywords: Autonomous maritime systems, artificial intelligence, robotics, sensor technologies

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1. Introduction

Technology has always played a central role in historical and societal transformations and continues to be one of the most critical drivers of global change processes today. The formation and institutionalization of industrial societies shaped by economic developments largely resulted from technological innovations. Additionally, the integration of knowledge accumulated during the information revolution into this process has laid the groundwork for the development of modern production facilities.

Technological advancements are progressively reducing the demand for human labor across various sectors, with automation and artificial intelligence (AI)-powered robots replacing manual work. This transformation creates favorable conditions for the transition to knowledge-based economic systems while also revealing a direct relationship between economic growth facilitated by technology and military power. Today, civil and military sectors exhibit an interdependent structure through shared knowledge and technology networks.

When examining historical processes, it is evident that early wars were predominantly aimed at territorial expansion. However, during the 19^{th} and 20^{th} centuries, the focus of warfare shifted to expanding economic resources and increasing production capacity. In the present era, the core of conflicts revolves around the control and management of information [1]. Historically, technological leadership in the policies of major powers has often focused on military technology [2]. Therefore, technological advancement has progressed in parallel with the transformation of military power throughout history [3].

The maritime industry has been one of the sectors most significantly impacted by the Industrial Revolution. The development of armored warships facilitated technological advancements in weapons and devices, while the growth of the shipbuilding industry played a crucial role in strengthening nations' maritime dominance. For instance, European states' development of gunpowder-based weaponry and long-range ocean-going ships enhanced their superiority over other nations, allowing them to expand their spheres of hegemony both on land and at sea. These advancements provided a significant foundation for the establishment of Western colonial dominance in the early 19^{th} century [4].

Throughout human history, the development of military technology has been shaped by numerous significant milestones, including the use of gunpowder in firearms, the advent of steam-powered ships, the introduction of armored vehicles on the battlefield, and the invention of submarines, radar, and military jets. Today, information and communication technologies, AI, and robotic systems are permeating every aspect of social life, especially in economic, political, and sociological domains, driving rapid and comprehensive transformations.

In this context, militarily powerful states are increasingly relying on the capabilities provided by unmanned systems while reducing the number and costs of manned systems. Unmanned aerial vehicles have emerged as one of the most effective tools of warfare in this regard. In the near future, the concept of military security is expected to be reshaped based on the capabilities of autonomous or remotely controlled combat platforms equipped with AI.

In addition to the challenges of operating large manned platforms, shrinking military budgets and smaller force structures are key factors driving nations toward unmanned systems. Consequently, security agencies must effectively leverage the technological transformation brought about by unmanned vehicles and systems to provide strategic, swift, flexible, and agile responses to current and future crises.

Future wars are anticipated to be shaped by semi-autonomous and fully autonomous systems powered by AI technologies. These systems are expected to be significantly more effective than traditional manned warfare platforms. As the use of unmanned systems in combat and conflict surpasses the use of manned weapons and systems, a fundamental shift in the nature of wars and conflicts will occur, leading to an era dominated by autonomous devices and weapons.

Unmanned systems not only have the potential to reduce human-related risks and perform tasks beyond the capabilities of manned vehicles, but they also act as force multipliers, creating synergy among operational elements by enhancing the execution of assigned tasks.

2. General Requirements and Methods for Autonomous Systems

With the enhancement of weapon systems' capabilities through information technologies, the design of systems equipped with AI and various algorithms, capable of autonomously selecting the most effective methods in warfare and operating automatically, emerges as a transformative phenomenon for the culture of conflict. Parties achieving technological superiority have the opportunity to leverage this advantage to establish a form of technological dominance. Today, the most effective technological dominance is achieved through autonomous systems managed by computer programs and equipped with automated functions (Table 1) [5].

Autonomous maritime vehicles have significant potential as force multipliers in the realm of unmanned systems. These vehicles reduce risks to manned vessels and personnel, providing a cost-effective and human-resource-efficient solution for a wide range of applications, from traditional

Table 1. Algorithm distribution analysis for autonomous maritime systems

Method	Typical application areas	Common use	Example studies/Projects
PID	Heading control, station keeping, path following	High	YARA Birkeland (NTNU), low-level control loops in most commercial systems
LQR	Optimal stabilization, linear model-based control	Medium	Research vessels with model-based state feedback (e.g., maritime testbeds)
MPC	Collision avoidance, constrained path planning	High	Rolls-Royce autonomous vessels, ASV-Global path tracking
RL	Learning-based maneuvering, dynamic environments	Emerging	Sea Hunter DARPA (U.S. Navy), RL-based harbor navigation studies
DL	Environmental perception, sensor fusion	Experimental	Object recognition in autonomous harbor monitoring (LiDAR/Camera fusion)
Fuzzy Logic	Obstacle avoidance, uncertain environments	Low	Fuzzy ship heading control under changing sea state
Heuristic (e.g., GA, PSO, ACO)	Route planning, multi-agent coordination	Medium	NATO MUSCLE Project-multi-agent formation control with GA

PID: Proportional-Integral-Derivative, LQR: Linear Quadratic Regulator, MPC: Model Predictive Control, RL: Reinforcement Learning, DL: Deep Learning, ASV: Autonomous Surface Vehicles, LiDAR: Laser Detection and Ranging

warfare to small-scale regional conflicts. Additionally, they address defense needs such as combating asymmetric threats and terrorism, contributing to nations' ability to achieve their strategic goals.

Rapidly advancing technology, along with commercial and military requirements, has expanded the autonomous maritime vehicle market, creating substantial opportunities for both established manufacturers and new entrants aiming to join the sector. However, among the three primary categories of unmanned vehicles (air, land, and maritime), maritime vehicles have received the least attention and funding in recent years. Nevertheless, considering the cost efficiency and risk-reducing advantages of unmanned maritime vehicles, this trend is expected to shift significantly in favor of maritime systems in the near future. Today, the global unmanned maritime vehicle market has evolved into a dynamic ecosystem driven by new research, development, and procurement initiatives.

From a military perspective, unmanned maritime vehicles are primarily used for missions such as reconnaissance, surveillance, mine countermeasures, anti-submarine warfare, and combating terrorism and smuggling. Additionally, nations rely on these systems to address challenges such as irregular migration and illegal activities, safeguard commercial maritime logistics, protect offshore energy infrastructure, and monitor the marine environment. These vehicles play a critical role in observing relevant activities and enabling effective and timely responses in these areas.

Unmanned Maritime Systems (UMS) can operate on or beneath the surface of the sea. Surface-based unmanned vehicles are referred to as Autonomous Surface Vehicles (ASVs), while those operating underwater are known as Unmanned Underwater Vehicles [6].

Unmanned ships are defined as vessels capable of operating autonomously or via remote control without requiring a crew. In this context, unmanned systems are positioned as an overarching concept that also encompasses autonomous ships.

In European maritime circles and by the International Maritime Organization (IMO), unmanned ships are defined as vessels "capable of operating with varying degrees of independence from human interaction". For such vessels, the terms "Unmanned Surface Vehicles" (USVs) and "Maritime Autonomous Surface Ships" are commonly used (Figure 1) [7,8].

The primary vulnerabilities of unmanned systems include the limited range of operations due to their short range, the need for protection, the requirement for interoperability with other systems, the demand for wide bandwidth for communication, sensitivity to electronic jamming, and limited capability in handling uncertainties compared to manned systems [9]. Another significant vulnerability of autonomous weapons and systems is that their software is often open-source, making it susceptible to being purchased or copied.

Unmanned systems used autonomously offer various advantages, such as immunity to communication interruptions since they are not controlled from a remote command center, resistance to electronic jamming, and the difficulty of determining their location (Table 2) [5].

Advancements in engineering, sensor technology, and particularly computer systems and information technology,

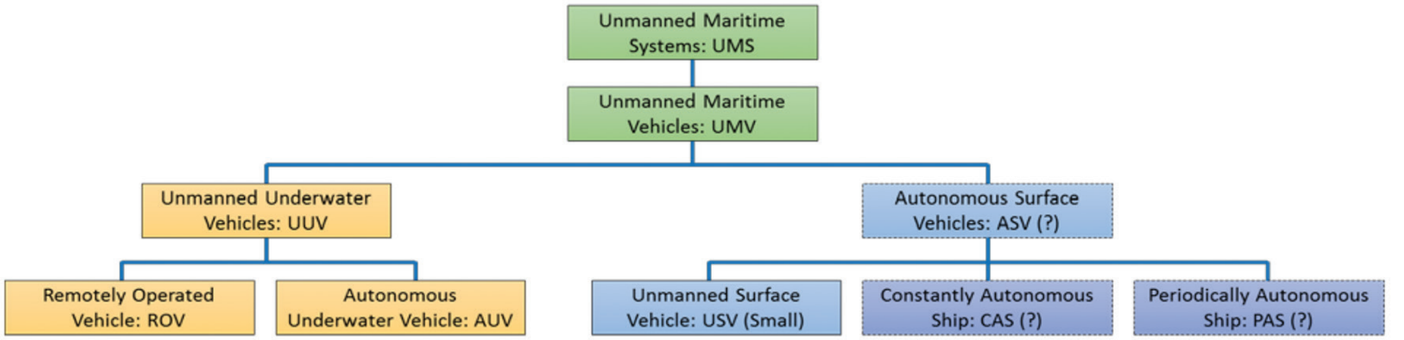

Figure 1. General classification of unmanned maritime systems [8]

Table 2. Comparative analysis of algorithms in autonomous systems under real-world maritime conditions

Algorithm	Accuracy	Robustness	Computational efficiency	Adaptability
PID	Good	Moderate	Excellent	Low
LQR	Excellent	Moderate	Good	Moderate
MPC	Excellent	Good	Moderate	Moderate
RL	Excellent	Excellent	Low	Excellent
DL	Excellent	Good	Low	Excellent
Fuzzy logic	Moderate	Excellent	Moderate	Moderate
Heuristic (GA, PSO, etc.)	Moderate	Moderate	Moderate	Moderate

PID: Proportional-Integral-Derivative, LQR: Linear Quadratic Regulator, MPC: Model Predictive Control, RL: Reinforcement Learning, DL: Deep Learning

have enabled greater utilization of the potential of unmanned systems. However, today's unmanned systems are far from being fully autonomous in making and executing decisions as often perceived. Due to the sensitive nature of tasks such as weapon usage, these systems currently operate primarily through methods that involve human oversight.

The Unmanned Systems Integrated Roadmap published by the U.S. Department of Defense defines unmanned systems as either "self-administered" or "self-decision-making" systems based on their capabilities and designs. In this context, unmanned systems are categorized into three main types: semi-autonomous (human in the loop), supervised autonomous (human on the loop), and fully autonomous (human out of the loop) [10]. The fundamental assumption of this classification is that future unmanned systems will require more advanced capabilities than the current systems, which possess limited autonomy. Furthermore, these capabilities are expected to include the simultaneous sharing of critical data, such as situational awareness and targeting information, with other unmanned systems and manned platforms. This will necessitate an enhancement in the interoperability capacity of unmanned systems [6].

The United Nations Convention on the Law of the Sea states that ensuring adequate crew onboard ships, in accordance with international standards, is the responsibility of the flag state. Additionally, the International Convention for the Safety of Life at Sea, which establishes minimum safety standards for the construction, equipment, and operation of commercial ships, mandates that flag states ensure an adequate number of personnel to guarantee the safe navigation of ships.

In this context, Lloyd's Register, IMO and Society of Automotive Engineers has classified the levels of autonomy and control methods for maritime vessels as outlined below (Table 2) [11].

Table 3. Comparison of autonomy level definitions by Lloyd's register [12], International Maritime Organization, and Society of Automotive Engineers International

Level	Lloyd's Register-Maritime	IMO-Maritime Autonomous Surface Ships	SAE-Automotive
0	No automation; all decisions and actions by human crew	Not formally defined	No automation-Full human control of all operations
1	Decision-support only; onboard crew makes all final decisions	Ship with automated processes and decision support	Driver assistance-System assists with steering or acceleration (e.g., cruise control)
2	Automated control with human-in-the-loop onboard	Remotely controlled ship with crew onboard	Partial automation-System controls both steering and acceleration; driver monitors
3	Automated decision-making and control; remote control capability	Remotely controlled ship without crew onboard	Conditional automation-Vehicle handles all tasks, but human must intervene when requested
4	Remotely controlled or supervised from shore, with high automation	Fully autonomous ship: capable of operating independently without human intervention	High automation-Vehicle performs all tasks under defined conditions; no driver attention needed
5	Fully autonomous ship, no human involvement at any time	(Covered under level 4 implicitly)	Full automation-Vehicle can handle all conditions, no human driver required

IMO: International Maritime Organization, SAE: Society of Automotive Engineers

Autonomous systems, while operating as programmed, require robust protection against external interference. Exploiting gaps in engagement rules poses a potential risk of disrupting these systems. Additionally, unlike humans, autonomous systems lack empathy - at least at present - which prevents them from exercising judgment in avoiding escalation or disproportionate actions during conflicts.

Despite the advantages offered by unmanned systems, any vulnerabilities within the system could be exploited, potentially escalating tensions and leading to conflict. Therefore, a highly cautious approach must be adopted when deploying such systems, particularly in sensitive operations [13].

Recent advancements in artificial intelligence, sensor technology, and communication systems have enabled the development of more advanced unmanned maritime vehicles with autonomous operation and real-time data collection capabilities. These systems utilize sophisticated sensors, sonars, and imaging technologies to gather valuable data for scientific research, defense, and commercial applications in marine and underwater environments (Figure 2).

Today's electronic technologies have the capability to distinguish between a warship and a commercial vessel. Additionally, maritime and civil aviation regulations, along with navigational and flight safety measures, ensure that neutral and friendly entities do not enter the operational area, thereby minimizing the risk of collateral damage. Due to the nature of naval warfare, autonomous weapon systems can be programmed to target only military objectives for ethical and legal reasons, ensuring full compliance with the principles of military necessity, target discrimination, and proportionality.

Automation and robotics are among the most critical elements in the development of unmanned systems, enabling these vehicles to operate autonomously or semi-autonomously without human control. These technologies play a pivotal role in enhancing the capabilities, efficiency, and effectiveness of unmanned systems across various domains.

Automation facilitates autonomous navigation and the execution of predefined tasks in unmanned systems. This allows the vehicles to plan their routes and missions, avoid obstacles, and adapt to changing environments without human intervention. Operators can program tasks, set routes, and define targets through software interfaces. Moreover, automation optimizes the operation of payloads, sensors, and onboard devices, managing processes such as automatic control systems, fault detection and response mechanisms, sensor calibration, data collection, and image processing. These processes enable unmanned vehicles to collect and analyze information in real time (Figure 3).

The rapid advancements in AI and maritime technologies allow UMS to operate in a coordinated manner at predefined levels of autonomy. The success of joint maritime operations involving unmanned systems relies on reliable and robust information networks to support propulsion, machinery operation, and mission execution. Manned warships, in turn, must enhance their capabilities in monitoring the maintenance and repair processes of the unmanned vessels they host, as well as in effectively utilizing weaponry and information systems [16].

Integrating a hybrid fleet composed of manned and unmanned platforms poses several challenges under existing

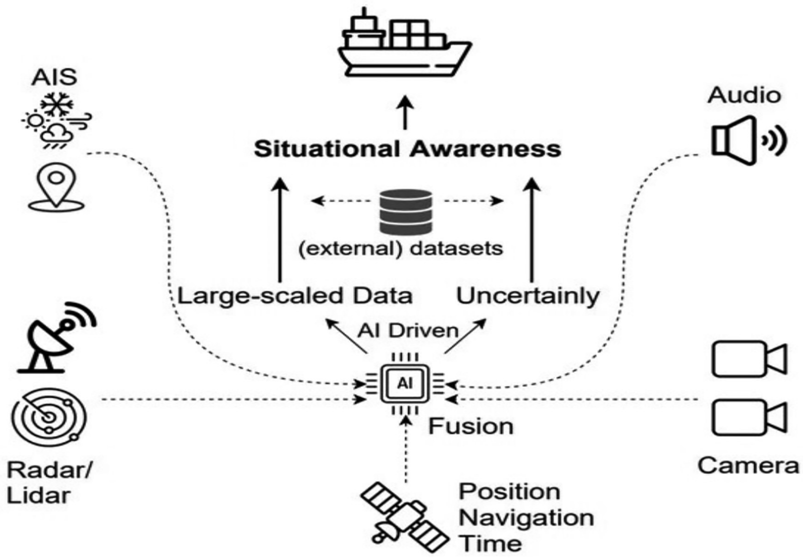

Figure 2. General overview of an AI-focused maritime situational awareness system [14]

AI: Artificial intelligence

international laws. These challenges include conducting operations in compliance with the rules of armed conflict, determining the legal status of unmanned platforms as ships, and implementing regulations to ensure safe navigation at sea.

3. Advances in Autonomous Maritime Systems: AI, Decision-Making, and Simulation Platforms

Significant progress has been made in machine learning applications for autonomous systems, particularly in decision-making, prediction, optimization, and threat detection processes. These advancements are driving developments in areas such as more powerful computational capabilities and intelligent algorithmic functionality. Optimizing the capabilities of autonomous systems increasingly requires specialized computational technologies, including software models for simulation purposes, software development processes for autonomy and mission planning, large data repositories integrating analytics and machine learning, and the integration of open-source commercial software into systems [Figure 4) [17].

AI-based navigation systems enable unmanned maritime vehicles to operate autonomously in complex environments such as open seas, ports, and coastal areas. These systems utilize route planning algorithms to optimize navigation paths based on factors such as weather and sea conditions, maritime traffic, and mission-specific objectives, ensuring efficient and safe operation of unmanned vehicles.

Machine learning algorithms play a crucial role in tasks such as real-time map creation, obstacle detection, underwater object identification and classification, and safe route planning for autonomous platforms. During these processes, data collected from sensors like satellite positioning systems, radar, and sonar are analyzed. With the assistance of AI and machine learning techniques, UMS can effectively perform tasks such as environmental sensing, monitoring, search and rescue operations, maritime security and surveillance, control and decision-making, preventive maintenance, and system fault monitoring (Table 4).

The integration of AI and machine learning algorithms into UMS has revolutionized these systems, significantly enhancing autonomy, systemic intelligence, and operational effectiveness across a wide range of applications. Dr. Jacquelyn Schneider, an assistant professor at the U.S. Naval War College, asserts that the winners of future wars will be nations that can most effectively leverage autonomy and human-machine integration [19].

Research continues to integrate robotic technologies with autonomous systems in areas such as big data processing, motion sensor technology, voice and image recognition, human-machine interaction, and decision-making processes. The design of unmanned ships must focus on developing obstacle detection and avoidance capabilities that account for real-world conditions to ensure navigational safety. Additionally, supporting remote control requires a range of sensor components, including visual and thermal camera systems, long- and short-range precision radars, laser detection and ranging devices, GPS, Automatic Identification System (AIS), and Electronic Chart Display and Information System (Figure 5) [20].

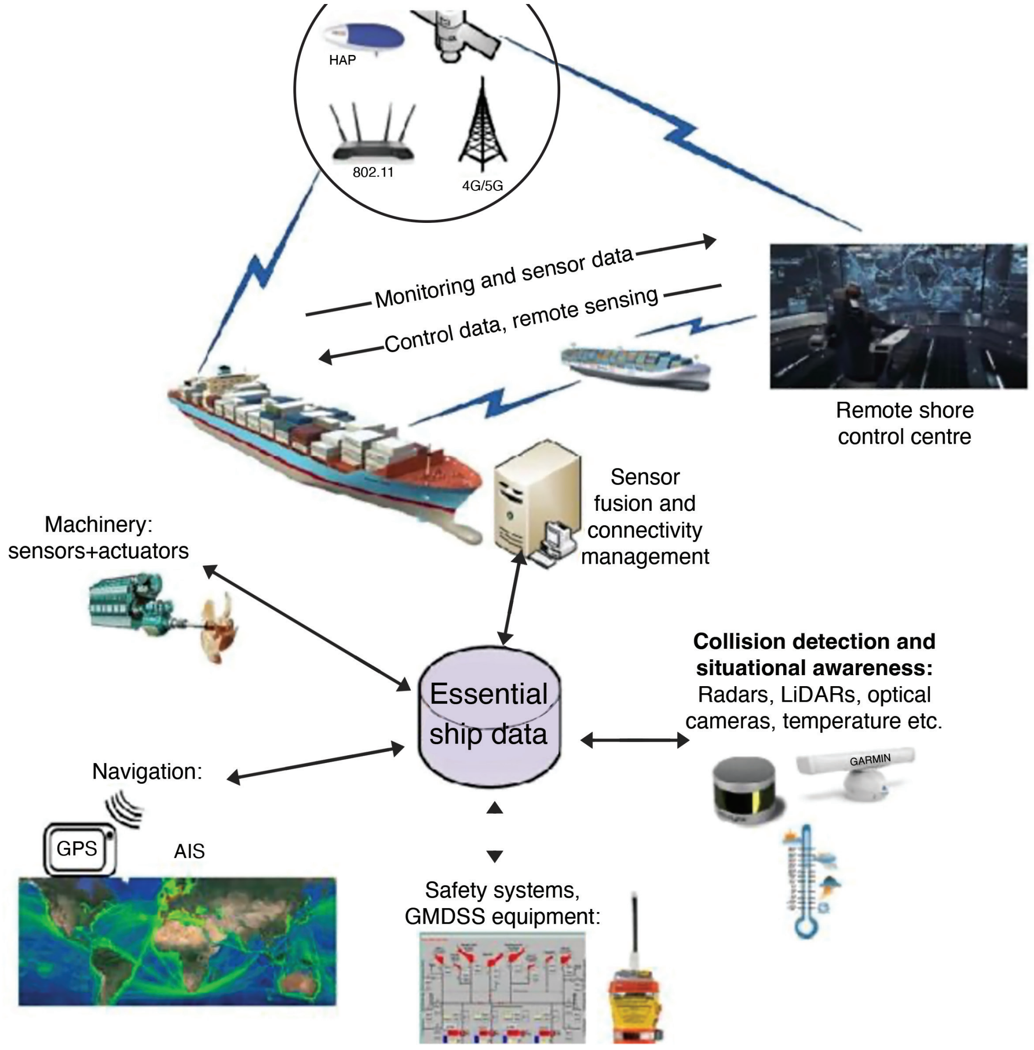

Figure 3. Communication architecture of an autonomous ship [15]

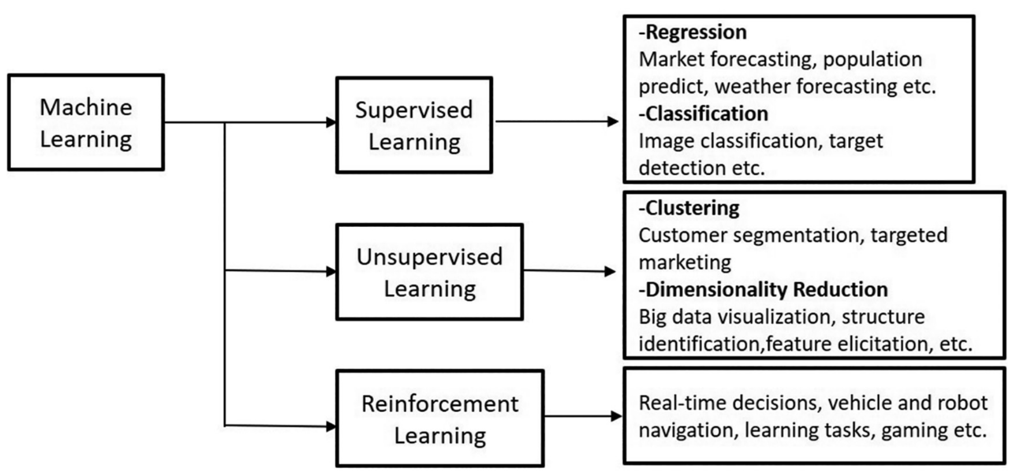

Figure 4. Different types of machine learning in autonomous systems [18]

Table 4. Software tools and simulation platforms for autonomous maritime systems

Tool/Platform	Purpose	Description/Use case
MATLAB marine toolbox	Modeling & control design	Toolbox for marine vehicle dynamics, control design (PID, LQR, MPC), wave modeling
Simulink	Block-diagram simulation	Used for simulating marine autopilots, mission control, sensor integration
MOOS-IvP	Autonomy engine for marine vehicles	Open-source tool for mission planning, behavior-based control, especially for USVs/UUVs
ROS2	Middleware for robotic control	Widely used in autonomous robotics; marine extensions available; works with sensors & navigation
Gazebo + ROS2 (UUV Simulator)	3D physics-based marine simulation	Used for simulating autonomous underwater vehicles (AUVs/UUVs), sensor feedback, physics
ArduPilot/Mission planner	Real-time USV firmware and GCS	Open-source autopilot with USV mode; good for building and testing small-scale autonomous boats
Unity/Unreal engine	Visualization & HMI simulation	Ideal for simulating human-machine interaction and visual autonomy environments
OpenSeaLab	Real-time ocean data visualization	For training, testing algorithms with real-world oceanographic and vessel data
QGIS + AIS data	Geospatial traffic data analysis	Useful for analyzing vessel movement patterns and creating data-driven navigation models
BlueROV2/BlueSim	Commercial AUV with associated simulation	Often used in research labs; ROS-compatible underwater platform for algorithm testing

ROV: Robot Operating System, PID: Proportional-Integral-Derivative, LQR: Linear Quadratic Regulator, MPC: Model Predictive Control, AUV: Autonomous Underwater Vehicles, UUV: Unmanned Underwater Vehicle, AIS: Automatic Identification System

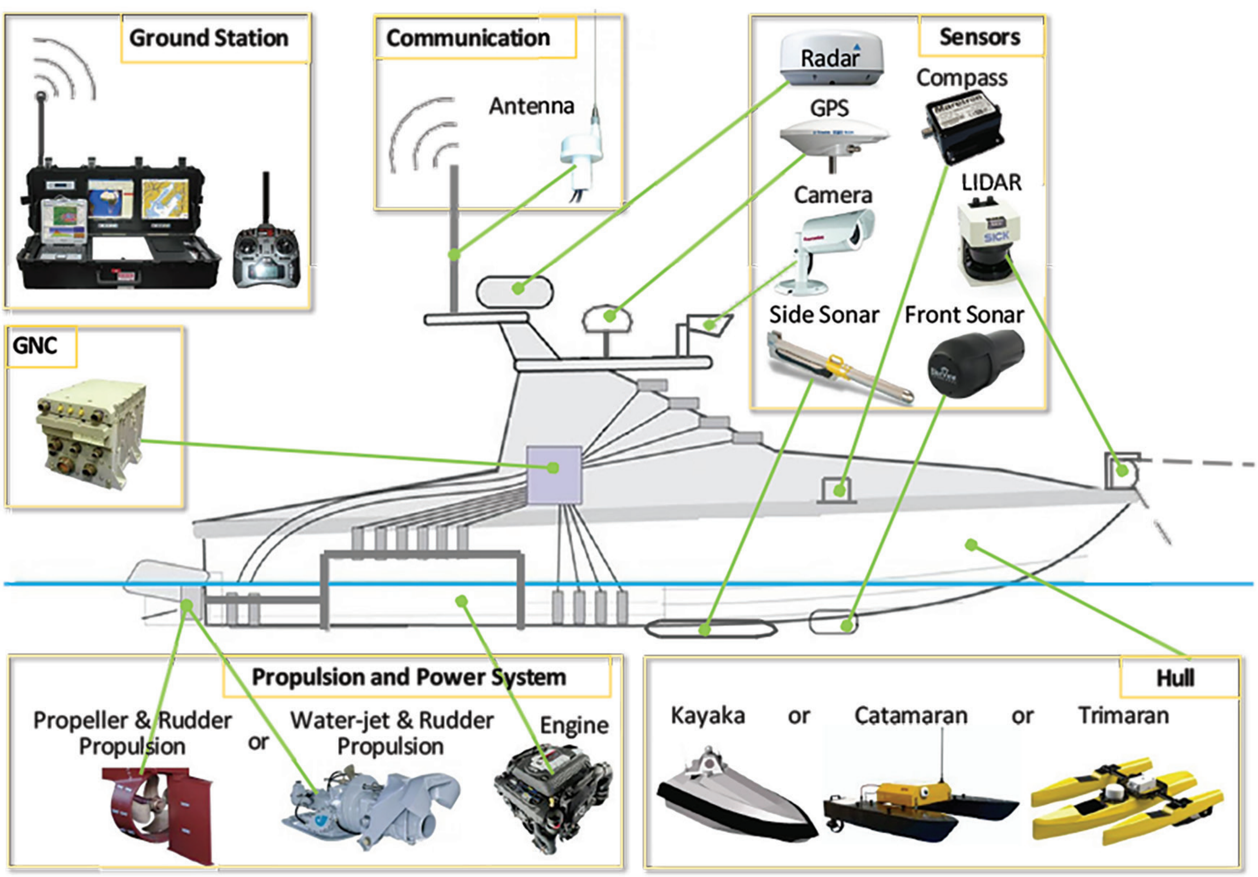

Figure 5. System requirements for autonomous maritime vehicles [21]

UMS are equipped with various technologies designed to address the following tasks and requirements:

• **Environmental Sensing and Monitoring:** Sonar and radar systems, along with hydrophones, are used for underwater activity surveillance. Environmental sensors measure parameters such as water temperature, salinity, and pH levels.

• **Accurate Positioning and Route Planning:** For precise navigation in open seas and coastal areas, global navigation satellite systems (GNSS) are utilized. In cases of GNSS signal interruptions, inertial measurement units, Doppler velocity units for seabed-referenced speed measurement, and dynamic positioning systems are essential.

• **Surveillance and Reconnaissance:** Optical and infrared cameras, radar systems, and AIS are employed to monitor maritime traffic and detect threats.

• **Sensor Data Integration:** Sensor data fusion techniques integrate information from multiple sensors. Machine learning algorithms analyze this data to enhance maritime security and surveillance capabilities. Predictive analytics techniques are used to anticipate potential risks in dynamic marine environments, plan proactive responses, and optimize mission outcomes.

• **Route Optimization and Decision Support:** Decision support systems are utilized to optimize navigation routes, minimize travel time, fuel consumption, and environmental impact, and provide real-time insights, recommendations, and situational awareness.

These technologies enable UMS to perform their tasks efficiently, safely, and effectively.

Autonomous systems, which enhance operational efficiency, reduce costs, and provide strategic advantages in the defense and maritime sectors, are recognized as innovative technologies. In this context, Multi-Criteria Decision-Making (MCDM) methods offer a comprehensive and scientific framework to evaluate the strategic importance and operational impacts of autonomous systems.

One such method, the Analytic Hierarchy Process (AHP), quantitatively contributes to decision-making by analyzing the relative importance of criteria within a hierarchical structure, systematically prioritizing the identified criteria. Another method, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), ranks alternatives based on their proximity to the ideal solution, enabling the objective selection of the most suitable option.

These methods provide decision-makers with the opportunity to develop scientific and objective strategies by addressing autonomous maritime systems in the context of technology, operational requirements, safety, and ethical-legal standards. Consequently, the analyses offered by MCDM methods serve as valuable tools for strategic planning and play a significant role in shaping technology and defense policies.

4. Future Outlook of Autonomous Systems: Findings

The future of autonomous unmanned systems presents significant potential for innovation and societal impact. Advances in artificial intelligence, robotics, and sensor technologies are expected to further enhance the capabilities of autonomous systems, enabling them to perform increasingly complex tasks in diverse environments. However, challenges such as cybersecurity threats, ethical and legal issues, and societal acceptance of autonomous technologies highlight the need for interdisciplinary collaboration and the development of appropriate policies. Nevertheless, it is evident that AI and robotics hold the potential to revolutionize industries and enhance efficiency.

In the future, unmanned systems are expected to be equipped with more advanced autonomous capabilities. These platforms will need enhanced capabilities to communicate directly with each other without human intervention to perform tasks in a coordinated manner. Furthermore, their interoperability is anticipated to surpass current levels [6].

Below are some of the challenges and development opportunities for autonomous systems in the future:

• **Energy Storage:** Advances in energy storage technologies, such as fuel cells and advanced batteries, will enable unmanned and autonomous maritime systems to operate for extended durations and achieve greater operational ranges. Continuous operations will facilitate long-term research activities and consistent monitoring of marine environments.

• **Underwater Communication:** Improving underwater communication capabilities remains a critical challenge for autonomous underwater systems. Developing reliable, high-bandwidth communication systems for data transmission, command-and-control, and remote operation will enhance the effectiveness and autonomy of these systems.

• **Regulatory Frameworks:** Clear regulatory frameworks and guidelines are essential to ensure the safe and compliant operation of autonomous maritime systems in marine environments. Addressing navigation and collision avoidance rules, data privacy, and environmental protection regulations will facilitate the broader integration of these systems into maritime operations and ensure their compatibility with other systems.

• **Sensor Technology and Data Analytics:** The effective use of sensor technologies and data analytics will remain a critical component of UMS. These advancements will allow autonomous systems to operate efficiently in challenging marine environments and navigate with situational awareness.

• **Cybersecurity Threats:** Operations involving the transmission of large volumes of information or the use of classified weapon systems through cyber technologies could overwhelm critical platforms, such as aircraft carriers and air defense systems, within the operational theater. To successfully execute operations aimed at denying access to physical and informational domains, planning cybersecurity measures and countermeasures is essential [22].

To minimize risks and prevent accidents associated with the use of autonomous systems, prioritizing security, reliability, and resilience is critical. Cybersecurity measures, fault-prevention mechanisms, and backup procedures must be incorporated into the design, testing, and operation of these systems. Additionally, developing legal, ethical, and sustainable solutions will reduce risks for both personnel and civilians. Supporting innovation in unmanned system technologies should be a key part of research and development efforts.

Designing autonomous systems with a modular structure to adapt to various task types is of great importance. Defining weapon, system, and device configurations suitable for mission profiles will increase the flexibility of these systems. Furthermore, software infrastructure should be designed to allow easy integration of new versions and updates in parallel with technological advancements.

In the coming years, autonomous systems equipped with swarm intelligence are expected to work in coordination, enhancing operational efficiency. These systems can minimize risks and maximize mission success in complex tasks. Supported by AI, swarm intelligence, and machine learning techniques, these systems must be integrated into national defense ecosystems with a comprehensive strategy to ensure the sustainability of unmanned vehicles.

Collaboration between academia and industry should be prioritized strategically to strengthen the knowledge and technological infrastructure of the autonomous maritime systems sector. Developing creative solutions for training qualified human resources, effectively utilizing this infrastructure, and enhancing competitiveness is essential. In the near future, the concept of military security is expected to be reshaped by the capabilities of AI-supported autonomous platforms. These platforms can increase situational awareness, enable faster and more accurate decision-making, and effectively handle tasks that pose risks to human life (Table 5).

The sustainability and effectiveness of autonomous maritime systems depend on successfully managing the risks and limitations these technologies may encounter. In particular, making these systems resilient against cybersecurity threats and compliant with ethical and legal standards will significantly enhance their success and societal acceptance. Addressing legal gaps, ethical concerns, and aligning with international regulations will support the broader adoption of autonomous maritime systems.

Moreover, combining MCDM methods such as AHP and TOPSIS with innovative approaches supported by machine learning, swarm intelligence, and AI-based technologies will enhance the sustainability and effectiveness of these systems in both military and civilian applications.

Advances in autonomous surface and underwater systems offer new opportunities for maritime surveillance, environmental monitoring, commercial operations, and scientific research. Progress in technology, integration, and collaboration will enhance the capabilities and effectiveness of these systems, paving the way for safer, more efficient, and sustainable maritime operations. Unmanned systems provide unique capabilities for reconnaissance, surveillance, and naval operations, granting strategic advantages to navies. As technology evolves, these systems will offer innovative solutions to address challenges and threats, shaping the future of maritime operations.

5. Conclusion and Evaluation

The proliferation of autonomous systems plays a significant role in transforming 21st-century military power. Robotics, autonomous systems, and AI-based capabilities have become the cornerstones of modern warfare strategies. These technologies reduce the reliance on human involvement while enabling the successful execution of more complex and risky missions.

Rapid technological advancements compel a reevaluation of traditional practices and the development of innovative strategies. Enhancing capabilities in areas such as data analytics, cybersecurity, and autonomous systems necessitates a flexible and proactive approach. To establish a more effective defense structure against modern threats, traditional strategies must be reinterpreted within the framework of emerging technologies, with existing strategies modified as needed.

Continuous advancements in sensor technology, AI, and unmanned systems are increasingly shaping the future of naval operations. These systems also assist navies in operating more cost-effectively in challenging maritime environments. In this context, it is crucial to clearly define strategic objectives and establish appropriate task groups. Smaller, highly capable unmanned assets, which are likely to constitute the future combat fleet, can also serve as part of task groups, contributing to the achievement of these strategic goals [23].

Table 5. Selected case studies of control methods in real-world autonomous maritime systems

Project/Vessel	Application domain	Method used	Performance highlights	Type
Sea hunter-DARPA (USA)	Long-range autonomous patrol and ASW	RL + Classical control (PID/LQR)	Robust navigation in dynamic environments; adaptive obstacle avoidance	Military
Rolls-Royce AAWA project	Commercial cargo ship autonomy	MPC + Deep RL	Accurate route planning, real-time collision avoidance	Commercial
NTNU-YARA Birkeland	Autonomous zero-emission cargo ship	PID/Classical control	Energy-efficient station keeping and harbor maneuvers	Commercial
NATO MUSCLE	Multi-agent underwater & surface surveillance	GA + Distributed RL	Optimized multi-vehicle coordination under communication constraints	Military
Kongsberg maritime-ASV	Autonomous harbor and offshore operations	Fuzzy Logic + PID	Reliable control in uncertain marine conditions (e.g., weather, currents)	Commercial
MIT-USV experimental platform	Experimental adaptive path planning	RL + MPC hybrid	Dynamic decision making in simulated real-time maritime environments	Research

ASW: Anti-submarine Warfare, PID: Proportional-Integral-Derivative, RL: Reinforcement Learning, MPC: Model Predictive Control, GA: Genetic Algorithms, ASV: Autonomous Surface Vehicles

To strengthen the strategic advantages of autonomous maritime systems and optimize their performance, the broader application of MCDM methods, such as AHP and TOPSIS, is considered essential. These methods not only enhance the current performance of systems but also contribute to the development of more resilient configurations capable of addressing future risks. This approach, supported by MCDM methods, ensures the sustainability of autonomous maritime systems while establishing a solid foundation for achieving strategic objectives. As a result, innovative technologies in the defense and maritime sectors can be utilized more effectively and reliably.

Once countries develop unmanned vehicles, they must equip them with the necessary sensors, information technology, and AI capabilities to ensure seamless functionality without personnel shortages. Additionally, a guiding and proactive management approach should be adopted when defining strategic objectives related to the use of these vehicles. Parallel to advancements in information technology, the integration of innovations into systems, the creation of purpose-built modular designs, and the operation of a disciplined process to align new investments with existing resources and strategic needs are imperative [24].

In conclusion, capabilities such as swarm intelligence and machine learning, which enable autonomous systems to perceive their environment, adapt to threats, and perform complex tasks, will play a game-changing role in the future of warfare technologies.

Footnotes

Authorship Contributions

Concept: U. B. Çelebi, Design: U. B. Çelebi, Data Collection or Processing: S. Kula, Analysis or Interpretation: U. B. Çelebi, Literature Review: S. Kula, Writing: S. Kula.

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