CHAPTER 8

Organizational and structural modeling of the integration of marine robotics into multilevel environmental and ecological monitoring systems

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Abstract

The section explores the basic theoretical and methodological principles of forming an organizational model for using marine robotics (MRO) as a tool for implementing systematic and scientifically sound environmental monitoring of the marine environment. Considering new challenges associated with large-scale environmental threats, military operations and increased anthropogenic load, special attention is paid to the development of conceptual approaches that allow for flexibility, sustainability and efficiency of the organizational structure. The focus of the analysis is a combination of a systems approach, engineering cybernetics, ecological systemology and the theory of management of complex socio-technical systems. A list of key principles for building an organizational model is proposed, which covers aspects of goal orientation, adaptability to dynamic external conditions, integration with national and international systems, technological compatibility, security, resource efficiency and transparency. Each of the investigated principles is formalized in the form of a mathematical organizational model, which forms the basis for the subsequent modeling of the functioning of the system in conditions of a dynamically changing environment, including, among other things, scenarios of post-conflict recovery and water resources remediation. Such an approach not only ensures the scientific validity of the construction of the organizational model but also provides tools for practical analysis of the effectiveness of its functioning, support for management decision-making, as well as optimization of interaction between all participants of the environmental monitoring system and risk management.

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The systematization of the obtained results becomes a key stage in the creation of an integrated management system of robotic platforms for the purposes of environmental and ecological monitoring and water resources remediation. Such a system is capable of scaling, adapting to various tasks and being integrated into the environmental policy of Ukraine, especially in conditions of post-conflict recovery and sustainable development.

Keywords

Marine robotics, autonomous systems, environmental and ecological monitoring, organizational model, adaptability, mathematical modeling, multilevel governance, resource efficiency, ecosystem sustainability, remediation.

8.1 Introduction

In the 21st century, the rapid growth of environmental challenges in the marine environment, in the context of military operations, man-made disasters and climate change, creates an urgent need to develop new approaches to environmental monitoring. Marine robotics (MRO) is considered by the scientific community as a promising tool in solving environmental control problems, due to its ability to operate autonomously, high maneuverability and adaptability in complex environments. However, the effective integration of MRO into the environmental monitoring system requires not only technical improvement, but also a scientifically sound organizational model that would ensure the coordinated functioning of socio-technical components within a multi-level management structure [1].

The scientific principles of forming such models are explored in the works of a few leading scientists. In particular, the methodological foundations of ecological robotics and complex adaptive systems are highlighted in the works of K. Rajan et al. and J. B. J. Harvey et al., which emphasize the importance of autonomous marine vehicles in sustainable development strategies [2, 3]. Hierarchical structures of robotic systems control under uncertainty with the issues of integrating MRO into national and transboundary monitoring systems are analyzed and considered in the studies of E. Fiorelli et al. [4]. In Ukraine, the issues of creating technological platforms for monitoring water areas using unmanned vehicles were raised in the works of V. Blintsov, G. Babkin [5], B. Gordeev, I. Sabutsky, A. Nadtochyi, V. Nadtochii, A. Burunin, O. Zbrutskyi, and others [6–9].

Despite the existing scientific developments, key issues related to the holistic organization of the functioning of marine robotics within the framework of environmental management systems remain unresolved. In particular, the problem of formalizing the structure of interaction between management levels (national, regional, operational), integrating marine robotics into legal, logistical and informational contexts, ensuring adaptability in crisis situations, as well as harmonizing national models with international standards and platforms, is relevant. The lack of a single structural and functional model that combines technical, institutional and strategic components hinders the widespread introduction of marine robotics into the practice of environmental monitoring.

The aim of this research is the development of the theoretical and methodological basis of the organizational and structural model of integration of marine robotics into multilevel systems of environmental and ecological monitoring and water resources remediation. Special attention is paid to ensuring efficiency, adaptability, resource justification, and resilience to external threats, considering the specifics of post-conflict recovery and the priorities of Ukraine's environmental policy in the context of European integration [10].

8.2 Systemic basis for forming an organizational model for using marine robotics for environmental and ecological monitoring

In the current conditions of increasing environmental threats in marine areas, caused by both natural and anthropogenic factors (in particular, the consequences of military actions, man-made accidents, and climate change), there is an objective need to create innovative organizational models that can ensure the effective, operational and safe functioning of marine environmental monitoring systems. MRO tools have significant potential in this area, but their implementation remains fragmented, technologically isolated and poorly integrated into the general structures of environmental management [11].

The main scientific problem is the need to develop a systemic basis for an organizational model that would consider the complexity and multicomponent nature of the socio-technical monitoring system, ensure its adaptability to crisis conditions, the ability to self-organize, as well as sustainable functioning in conditions of uncertainty, risks and limited resources. The lack of a formalized understanding of the interaction of structural levels, information flows, technical platforms and institutional participants limits the possibilities of practical implementation of MRO at the level of state or transboundary environmental policy.

Solving this problem requires the scientific substantiation of an open, hierarchically organized, cybernetically managed, and normatively integrated system that combines methodologies of systems analysis, management theory, ecological systemology, and crisis administration to create new generation organizational architecture in the field of marine monitoring [12].

The formation of an effective organizational model for the use of MRO is impossible without a clear definition of its systemic basis – a theoretical framework that allows for a comprehensive description of the structure, functioning, relationships and adaptability of the organizational system in a dynamic environment. In this context, the organizational model is considered as an open adaptive socio-technical system that integrates with:

– human components (operators, analysts, administrators) that provide task setting, decision making, and data interpretation;

– technical elements (unmanned aerial vehicles, sensors, service hubs) that implement the functions of collecting, transmitting and processing information;

– institutional mechanisms (legislation, protocols, standards) that formalize the interaction of participants;

– ecosystem factors (hydrology, climate, consequences of hostilities) that create the environment in which the system operates.

The system basis of the model is based on a combination of scientific approaches that ensure its integrity, adaptability, and functionality in the conditions of a complex marine environment (**Table 8.1**).

These approaches together form a scientifically sound, adaptive and effective organizational model that meets the challenges of modern marine environmental monitoring.

The system framework provides the ability to model the organizational model of the MRO as a complex, living, capable of development structure, which combines technological solutions, institutional mechanisms, ethical constraints, and a strategic vision of sustainable development.

Within this system paradigm, MROs are considered as autonomous sensor-control units capable of interacting both with each other and with other elements of ecosystem management (monitoring centers, analytical hubs, international platforms, etc.). The organizational system must provide feedback, adaptation to changing conditions (weather, man-made, political), as well as resistance to risks (military, logistical, information).

The model is based on the idea of a digital complex multi-level hierarchical structure, covering strategic (national), regional and operational levels of management. Such a structure allows for both centralized decision-making and local flexibility in responding to specific challenges. Each level of the system has a specific functional specialization: strategic planning, coordination of operations, data processing, operation of weapons and ammunition, maintenance and logistics [12, 13]. The system framework assumes a multi-level hierarchy, where each level performs specific functions and has defined boundaries of responsibility (**Table 8.2**, **Fig. 8.1**).

Table 8.1 Scientific approaches to the system basis of the marine robotics model for environmental and ecological monitoring

Approach	Description
Systemic approach	Allows to consider the model as a holistic integrated system in which technical, informational and organizational elements interact. Ensures consistency between subsystems: MRO, environmental data, logistics, management and feedback
Cyber-physical approach	Provides a combination of physical processes (actions of the MRO in the environment) with digital components (sensors, computing, communication). Allows for real-time operation due to constant exchange between environmental objects and analytical platforms
Hierarchical approach	Defines a three-level management structure: central, regional, and operational levels. Provides for the distribution of powers, responsibilities, areas of action and forms of interaction between levels
Process approach	Focused on describing and optimizing the sequence of actions within environmental missions. Allows modeling of tasks, resources, information, and operational management flows to ensure continuous operation
Situational approach	Provides for flexible adaptation of system actions depending on environmental conditions, threat level, or new goals. Used to generate response options in the mode of unpredictability or instability
Synergistic approach	Helps achieve a mutual reinforcement effect between system elements – when the interaction of robotic tools, operators, analytical units and management structures increases the overall efficiency of the system compared to the isolated functioning of its parts

Table 8.2 Multi-level hierarchical management structure of the model for the use of marine robotics for environmental and ecological monitoring

Level	Function
Central (national)	Strategic planning, financing, and integration with international structures
Regional	Coordination of field missions, logistics, data processing, and personnel training
Operative	Direct operation of the MRO, data collection and transmission, maintenance

The central (national) level of management plays a key role in shaping the strategy of functioning and development of the organizational model of using marine robotics for environmental and ecological monitoring. It is at this level that the national policy in the field of environmental monitoring of the marine environment is determined, priorities, goals and directions for integrating MRO into the national ecological security system are formulated, considering current and projected threats, including the consequences of military actions, climate change and man-made factors.

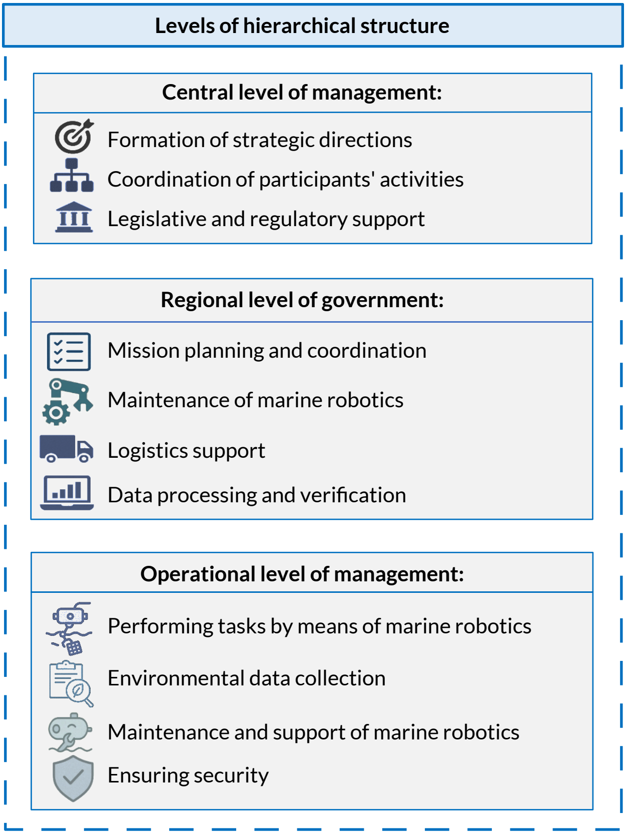

Fig. 8.1 Levels of the hierarchical structure of the management model for the use of marine robotics for environmental and ecological monitoring

One of the fundamental functions of the central level is the development of the regulatory framework, technical regulations, procedures for interagency cooperation and standards for the collection, processing and use of environmental information. It is also here that strategic planning of the institutional environment takes place: the creation and regulation of the activities of state marine and environmental management centers, technical hubs, analytical laboratories, training centers, as well as the coordination of participation in international marine and environmental programs.

Financial planning and system support are carried out at the central level: determining the volume of budget funding, developing state target programs, distributing financial resources between regional levels, and seeking international donor support. An important component is ensuring digital infrastructure and cybersecurity: from establishing data protection protocols to implementing cloud platforms and satellite monitoring, considering interoperability requirements with international information systems. The central level is also responsible for international coordination, representing Ukraine in global and regional initiatives on maritime safety and environmental protection, ensuring the harmonization of Ukrainian environmental protocols with the norms of international maritime and environmental law, and coordinating cross-border actions within the framework of technical assistance or operational response projects. In addition, the national level provides system analytics, forecasting changes in the marine environment, assessing the effectiveness of the MRO operation, forming quality indicators, and recommendations for updating software and technical components of the system, as well as developing scenarios for scaling the system in accordance with future challenges [14, 15]. This level is a consolidating core and performs the function of strategic management of the entire hierarchy of the organizational model.

The regional level is a critically important component of the management hierarchy, since it is at this level that the strategy formulated by the central authorities is practically implemented, considering the specific geographical, ecological, technogenic and social context of each marine region. Its main task is to ensure operational coordination, technical management, logistical support and initial analytical processing of data obtained from marine robotics within a defined water area or coastal zone. The functions of the regional level include the organization and control of the implementation of environmental monitoring missions in accordance with the plans approved by the national centers. Within the framework of this task, regional units form schedules for the deployment of environmental monitoring missions, determine observation areas, and adjust mission routes considering local weather conditions, hydrological conditions or identified threats. They also coordinate with related agencies: the Sea Ports Administration, the State Emergency Service of Ukraine, the Environmental Inspectorate and municipal services involved in the implementation of local environmental protection measures.

At the regional level, MRO maintenance is carried out, including preparation, charging, calibration of sensors, software updates, scheduled and emergency repairs.

For this purpose, technical hubs are created – service centers with appropriate equipment, spare parts, test pools and qualified personnel. A separate role is played by the logistics function: ensuring the smooth operation of missions requires the availability of vehicles, support vessels, ground infrastructure for communications, communication channels, points of maintenance and storage of weapons. Regional centers are responsible for monitoring resources, managing personnel and coordinating responses in case of unforeseen situations. In addition, it is at the regional level that the primary processing and verification of data received from robotic platforms is concentrated. The data undergoes primary quality control, pre-processing, georeferencing, and visualization and is transmitted to the central level or scientific and analytical centers for deeper analysis. Part of the data can be used at the local level for operational decision-making regarding local environmental incidents, identification of pollution sources, and formation of emergency response protocols.

Regional structures also play an important role in training and certifying personnel, including MRO operators, data analysis specialists, and technical personnel. In cooperation with higher education institutions and scientific institutions, regions can act as basis for conducting study missions, training, internships, and testing innovative solutions. The regional level acts as the operational and technical core of the system, ensuring the transformation of strategic decisions into practical actions, connecting national policy with specific environmental objectives in coastal and marine zones. It creates the prerequisites for the continuity of the system's functioning, its flexibility, territorial differentiation and the ability to respond quickly.

The operational level is the basic and at the same time critically important link in the hierarchical structure of the organizational model for the use of marine robotics for environmental and ecological monitoring. It is at this level that the direct implementation of field tasks takes place: deployment, operation, maintenance and feedback of robotics with the physical environment. The operational level provides daily, routine, but technically complex activities that are the basis of the entire environmental monitoring system.

Operational level functions are focused on the execution of missions by means of MRO, which involves preparing the vehicles for launch, performing navigation, following the specified routes, activating the relevant sensor systems and ensuring the stable collection of environmental data. Operators perform these tasks according to instructions and technical scenarios received from regional or central control centers, adapting them in real time to specific conditions on the ground: hydrological, weather, technical or security. At the operational level, a primary ecosystem picture of the monitoring area is formed: indicators of water quality, depth, presence of pollution, remains of military equipment, explosive objects, biological markers, noise signatures, etc., are recorded. The collected data is transmitted via ground stations or satellite channels to the regional center. In case of detection of critical situations (oil spills, mass death of marine organisms, detection of explosive objects), the operational level initiates a direct emergency information channel.

Another important function of this level is the maintenance and daily maintenance of the technical condition of the missile defense system. This includes charging batteries, calibrating sensors, checking hydraulic and navigation systems, identifying and eliminating faults, updating on-board software, and checking the tightness of the hulls [15]. Such maintenance is carried out either in the field (on vessels or in mobile stations) or within the framework of stationary technical support points.

The operational level is also responsible for the safety of operations, both in a technical, environmental and legal sense. MRO must operate within authorized zones, comply with international maritime law, and not pose a threat to maritime transport, fisheries or natural habitats. In war or post-conflict situations, this level also faces the risks of mine hazards, radiation or chemical contamination.

In addition to the technical component, the operational level also includes the human factor: a team of operators, technicians, and junior specialists who operate in the field. Their interaction is based on strict adherence to protocols, equipment skills, and the ability to respond quickly to non-standard situations.

The operational level is the "final link" of the system, which translates strategic decisions and plans into concrete actions in the real environment. The accuracy of environmental assessments, the speed of response to threats, and the overall effectiveness of the organizational model in the field of marine monitoring depend on its coordinated work.

The transformation from a hierarchical structure to an organizational model in the field of marine robotics for environmental purposes reflects the evolution of the management system, from a rigidly defined division of functions to a holistic, flexible mechanism for coordinating the interaction of all involved elements.

The hierarchical structure sets a framework in which each level (central, regional, operational) performs specific functions: from strategic planning to direct task execution. However, in the complex, dynamic maritime environment, this is not enough.

The organizational model details the ways of interaction between levels, considers information flows, physical actions and management decisions, combined into contours. It provides not only vertical commands, but also horizontal connections, allows for quick response to changes, and integrates technical, information and analytical elements into a single functional space. Such a model provides a balance between centralized control and local autonomy, between algorithmic solutions and adaptive behavior of technical means. It is the basis for the implementation of intelligent technologies for controlling marine robotic systems, capable of effectively operating in the field of environmental monitoring and protection of the aquatic environment.

The organizational model is a dynamic, adaptive and managed system that interacts with the external environment through three main circuits: physical (impact and effects on the ecosystem), information (data collection, processing, transmission) and management (goal formation, decision-making, response to changing situations). These circuits ensure the continuity of the system's functioning even under conditions of instability – in the event of failures, emergencies or changes in the political or environmental context (**Fig. 8.2**).

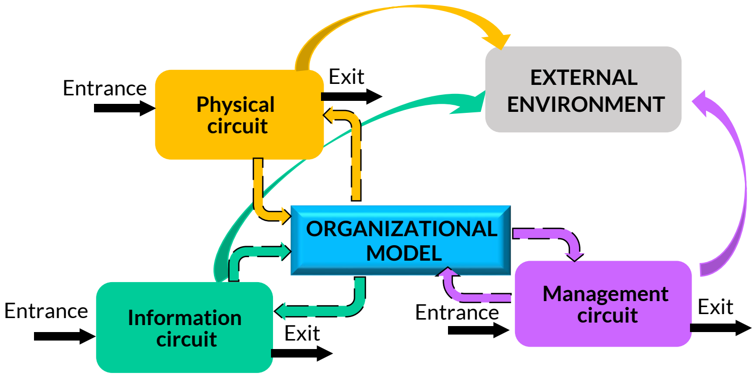

Fig. 8.2 Organizational model of using marine robotics for environmental and ecological monitoring

An analytical representation of the input and output elements of each of the three contours of the organizational model, formed based on **Fig. 8.2**, is presented in **Table 8.3**.

Information interaction in the system has a vertical and horizontal nature: data is transmitted from the MRO to regional and central hubs, and from there – back in the form of control signals, missions or action scenarios. In parallel, horizontal exchange between elements at the same level operates – for coordination of decisions, clarification of data, operational duplication or backup.

The central element of the system framework is the functional goals, which describe the desired results of the system's activities in quantitative and qualitative form: coverage of water areas by monitoring, accurate and speed of threat detection, resource efficiency, and compliance with international standards. This function is a key parameter for optimizing the model architecture, action algorithms, and strategic management.

Table 8.3 Analytical representation of input and output elements of the contours of the organizational model of the use of marine robotics for environmental and ecological monitoring

Contour	Essence	Input elements	Output elements
Physical circuit	The influence and interaction of the organizational model with the natural environment	Hydrometeorological conditions (temperature, waves, currents)	MRO impact on the marine environment (e.g. cleanup, contamination containment)
		Level of water pollution (chemical, biological indicators)	Change in ecosystem parameters due to system actions
		Presence of explosive objects or man-made remains	Environmental modification (interventions, demining, biomonitoring)
		Morphological characteristics of the water area (depth, bottom relief)	Digital signals from technical means, spatio-temporal coordinates of actions
Information circuit	Processing and transmission of environmental, technical and situational information	Telemetry, sensor data from robotic platforms	Analytical reports, maps, risk assessments
		Satellite and sonar images	Data transmitted to control centers
		Signals about malfunctions, risks, and incidents	Interpreted signals for decision making
		External information flows (forecasts, regulatory restrictions	Information support for strategic planning
Management circuit	Goal formation, decision making and regulation of system behavior	Results of information analysis	Planned MRO missions (routes, modes, tasks)
		Political, legal and environmental requirements	Emergency protocols
		Real-time situation assessment	Management decisions: reallocation of resources, adjustment of strategy
		Strategic goals or objectives from the government, international structures	Updated adaptation goals and scenarios

The system also has the properties of learning and self-improvement through data accumulation, analysis of previous missions, implementation of machine learning, and predictive models of changes in the ecological state. It is capable not only of reacting, but also of proactively forming scenarios of the development of events.

8.3 Principles of organizational model formation

The formation of an organizational model for the use of MRO for the purposes of environmental and ecological monitoring is based on a combination of the principles of organizational management theory, ecological systemology, engineering cybernetics, and the theory of complex socio-technical systems. In modern conditions considering the consequences of the war in Ukraine, there is a growing need to build adaptive and sustainable organizational models capable of ensuring sustainable monitoring of the marine environment based on the latest technologies [16].

The basis of the model is a structural-functional approach, which allows reflecting the logic of the relationship between entities (scientific institutions, operators, environmental services, international partners) and technical components (unmanned marine vehicles, control stations, service hubs, analytical platforms, etc.).

Within this approach, the organizational model should provide:

– institutionalization of powers and a clear division of functions between interested structures;

– integration of research and applied activities on the development and improvement of marine robotic platforms;

– ensuring sustainable information exchange between field operators, scientific centers and management bodies;

– adaptation to the ecological dynamics of marine areas, considering the consequences of military operations, pollution, changes in the hydrological regime, etc.;

– optimization of resource provision, including human, material, financial and information resources.

The formation of an effective organizational model for the use of MRO should be based on several key principles that ensure its scientific validity, systemic integrity, adaptability to crisis conditions, and orientation towards the sustainable development of marine ecosystems.

Table 8.4 presents the main principles, considering wartime conditions and reconstruction needs.

Table 8.4 Principles of the methodological basis of the model for the use of marine robotics

Principle	Description
Goal-oriented	The organizational structure should be aimed at achieving specific goals: preventing environmental disasters, detecting pollution, monitoring the state of the marine environment, and assessing the consequences of hostilities for marine ecosystems. In focus: monitoring water areas, in particular in ports, river mouths, areas with the probable presence of explosive objects
Adaptability and crisis resilience	The model should consider unforeseen risks, including military threats, cyber incidents, and logistical disruptions. It should be flexible to allow for rapid reorientation of resources in the event of emergencies or changes in the political context
Integrations	Marine robotics equipment should be organically integrated into the national environmental monitoring system, interact with other environmental, defense and research structures, as well as with international partners. Integration includes data exchange, protocol coordination, joint missions
Hierarchies	The structure should ensure a clear division of functions between central, regional and executive elements. The hierarchy should identify key coordinators (state agencies, command centers) and executors (operational teams, operators, service departments)
Scientific validity	The construction should be based on system analysis, the use of modern methods of environmental forecasting, digital modeling, GIS-technologies and machine learning for automated processing of MRO data
Technological compatibility and standardization	The use of robotic systems should involve the unification of interfaces, data transfer protocols, and interaction algorithms, which allows for easy integration of new platforms, sensors, and equipment from different manufacturers
Security and ethical responsibility	The MRO operation must comply with the requirements of environmental safety, international maritime law and humanitarian law in terms of preventing negative impacts on the environment or interference with the sovereignty of territories. In wartime, it is especially important to consider the dual (civilian-military) use of technologies
Openness and cooperation	The organizational model should facilitate transparent data exchange with the scientific community, public organizations, and environmental initiatives. Cooperation with foreign partners allows not only strengthen potential, but also to accelerate the implementation of new developments
Resource efficiency	Rational use of financial, human and technical resources should be based on assessing the effectiveness of operations, optimizing MRO routes, and forecasting maintenance and logistics needs
Continuity	The system for organizing the MRO operation must function on a permanent basis, regardless of changes in the political or military situation. Continuity is ensured by resource redundancy, system autonomy, and highly qualified personnel

The principle of goal orientation implies that the entire structural and functional model of the use of marine robotics should be aimed at achieving clearly defined environmental, safety and socially significant results. This means that the functioning of each element of the system, from the central management body to the direct executor at the operational level, should be subordinated to the implementation of a specific goal. This approach avoids the dispersion of resources and ensures consistency of actions at all levels. Goals set the functional logic of the system, determine which technologies, types of devices and sensors should be involved, how missions and response algorithms are formed, how resources are distributed, and what information is a priority for collection and analysis. In crisis conditions, the ability of the model to switch between long-term strategic guidelines, medium-term tasks and operational goals is of particular importance. It is goal orientation that provides the model with direction, development logic and clear measurability of effectiveness. It allows ensuring that the work of the MRO meets the real needs of environmental security, humanitarian response, and international cooperation.

The next principle of the methodological basis of the model for using marine robotics is the principle of adaptability and crisis resistance.

The principle of adaptability and crisis resilience is key to building a structural and functional model for the use of MRO in conditions of high dynamism and uncertainty of the external environment. It determines the ability of the system not only to perform functions in standard conditions, but also to ensure its viability, efficiency and recovery during crisis events, in particular – military operations, man-made disasters, sudden changes in climatic and hydrological characteristics.

This principle implies that the organizational model should be able to change the configuration of its structure, mission routes, interaction algorithms, resource allocation priorities, and chains of command in accordance with changing external circumstances. Adaptability is manifested in the ability to scale up or down individual system components, reconfigure the MRO software in real time, reassign functions between management levels, and change decision-making logic based on new data.

In practical terms, this principle is implemented through flexible system architecture, the availability of adaptive software modules, mobile technical hubs, an extensive data reception/transmission network, and a system of operational duplication of critical functions. Its implementation is a prerequisite for the long-term stability, reliability, and efficiency of marine robotics as an environmental response tool in the 21st century.

The principle of integration is no less important than other principles in the methodological basis of the model for the use of marine robotics.

The principle of integration in the model of using MRO for environmental and ecological monitoring means building a system in which all elements: technical, informational, organizational and functional – are interconnected, interact based on a single logic and complement each other to achieve a common goal. Integration ensures the integrity of the system, its ability to comprehensively act, interagency cooperation, technology compatibility and continuous data exchange.

The principle of integration is the foundation for building an effective, controllable and adaptive system in which marine robotics plays the role not of an isolated tool, but of an active element in an interacting network of decisions, actions and responsibilities. It ensures consistency, coherence and efficiency in the implementation of environmental protection and crisis missions in the complex conditions of the marine environment [17, 18].

The principle of hierarchy in the model of using MRO for environmental and ecological monitoring means building a multi-level management system in which functions, powers, responsibilities, and information flows are clearly distributed between levels – from strategic (central/national) to operational (MRO missions in the field).

This principle allows for the effective functioning of the system due to:

– consistency of goals between levels;

– effective delegation of tasks;

– stable management in difficult situations;

– adaptation and localization of solutions according to the specifics of the region or task.

The principle of hierarchy is based on the idea of centralized strategic planning with the simultaneous ability to decentralize response. This allows maintaining a balance between formativeness, predictability of actions and flexibility in the field. The central level is responsible for policy, standards, strategic financing, goal setting and coordination of national and international efforts. The regional level adapts the policy to the specifics of specific water areas, organizes inter-institutional interaction and coordinates local resources. The operational level carries out the missions of the MRO, exercises direct control over technical means, conducts environmental monitoring and ensures the implementation of instructions received from above [19, 20].

The principle of scientific validity in the model of using MRO for environmental and ecological monitoring implies that all management, engineering, technological and organizational decisions should be based on the results of scientific research, proven theoretical concepts and empirical data. This principle ensures that the MRO system is not a random or situational entity, but is based on systemic analysis, interdisciplinary knowledge and scientific logic, which increases its effectiveness, accuracy and long-term viability.

Scientific validity requires the integration of knowledge from the following key areas: hydro ecology, oceanography, information technology, artificial intelligence, mechatronics, system management, environmental safety, and the regulatory framework for maritime activities. This means that the planning of MRO missions, decision-making algorithms, sensor locations, survey routes, and data processing methods must be designed based on models that consider environmental patterns, risks, process dynamics, and predictive scenarios.

The principle of scientific validity is the key not only to the effective functioning of MROs, but also to their sustainable integration into the environmental safety management system. It ensures the transition from reactive to proactive management, where decisions are made not after the fact, but based on the analysis of trends, models and scenarios confirmed by scientific data.

The principle of technological compatibility and standardization is key to the effective integration of MRO tools into complex systems for environmental monitoring, humanitarian demining of water areas, and emergency response. This principle ensures the coordinated operation of heterogeneous technical tools, information systems, control protocols, and communications within one or more organizational and technical structures.

Technological interoperability implies the ability of MROs, both autonomous and manned, to operate in an interconnected environment, where devices of different types (surface, underwater, airborne), from different manufacturers, with different software platforms, can exchange data, coordinate actions and ensure continuity of operation in real time. This is achieved through the unification of interfaces, the use of open data exchange protocols, and compliance with international or national standards (e.g., IEEE, ISO, NATO STANAG, ITU) [19, 20].

Ultimately, the principle of technological interoperability and standardization is not just an engineering convention, but a strategic prerequisite for creating a sustainable, scalable, safe, and efficient marine robotics system capable of meeting the challenges of environmental security in the 21st century. Its implementation guarantees the integrity of the infrastructure, flexibility of development, responsiveness, and quality of data for decision-making.

The principle of safety and ethical responsibility in the use of marine robotics for environmental and nature protection monitoring is a system-forming element that defines the permissible limits of design, implementation and operation of such technologies. Its content is to ensure technical, informational, environmental and social safety while minimizing risks to people, the environment, infrastructure, as well as adhering to the principles of humanism, transparency, inclusiveness and legal responsibility [19, 20].

The operation of marine resources in open seas or coastal ecosystems is always associated with potential threats, both man-made and biological, legal or geopolitical in nature. Ensuring security means having mechanisms for preventive risk analysis, designing reliable management systems with multi-level redundancy, compliance with international maritime and environmental law, and protecting data from interference by third parties or organizations. The issue of cybersecurity requires special attention, since most marine resources are part of network structures operating in real time.

Safety and ethical responsibility are not only a requirement for the functioning of the MRO but a holistic philosophy that ensures the legitimacy, trust, and sustainable development of marine robotics technologies in the context of environmental protection, social consent, and responsible risk management.

The principle of openness and cooperation in the model of using MRO means provides for an institutional, technological and communication orientation towards transparency of actions, intersectoral interaction and multi-level partnership as the basis for the sustainable functioning and development of environmental monitoring and environmental protection activities in the marine environment.

This principle is based on the recognition that contemporary challenges, such as the degradation of marine ecosystems, the effects of military operations, climate change or anthropogenic pressure on coastal zones, cannot be solved solely by the efforts of individual institutions or government bodies. The MRO application in such conditions requires the involvement of a wide range of stakeholders: scientific institutions, government agencies, international organizations, local governments, voluntary and community structures, commercial operators and equipment manufacturers.

Openness and collaboration not only reduce social and environmental risks but also create added value for MRO technologies, transforming them from highly specialized technical solutions into a platform for broader ecosystem management in the areas of security, science, and environmental protection.

The principle of resource efficiency in the use of MRO for environmental and ecological monitoring is a key tool for achieving a balance between technological efficiency, economic feasibility, environmental efficiency and operational sustainability. In the context of integrated marine environmental management, it defines the way in which all types of resources – material, energy, information, financial and human – are allocated, used and re-engaged to achieve maximum effect with minimal cost.

In general, the principle of resource efficiency sets not only the technical logic for building a marine robotics model, but also the strategic framework for managing all resource flows, which guarantees sustainability, economic feasibility, rapid payback, and environmental safety of the implementation of marine robotic systems in crisis and peacetime conditions.

The principle of continuity in the model of using MRO for environmental and ecological monitoring determines the ability of the system to function stably, systematically and with a guarantee of prompt recovery after external disturbances or crisis events. This principle becomes especially relevant in unstable environments, were natural, man-made or military factors can lead to the shutdown of observation systems or the loss of critical environmental information.

Continuity in the context of MRO is not only the regularity of monitoring missions, but also the ability to ensure technological, informational, personnel and institutional sustainability of the system. It is implemented through a combination of infrastructure readiness, operational reserve, backup, multi-agent management architectures and rapid response procedures.

Overall, the principle of continuity in a marine robotics system ensures that environmental monitoring is not dependent on human error, random events, or infrastructure limitations. It forms the basis for creating a reliable, self-healing, decentralized system capable of operating in the face of turbulence, climate change, environmental threats, or emergencies.

8.4 Mathematical formalized representation of principles

To create a holistic analytical basis for describing, analyzing and optimizing the functioning of the model of using marine robotics in conditions of complex and dynamic interaction of natural, technical and organizational factors, it is possible to form a mathematical representation of ten principles of forming an organizational model for environmental and ecological monitoring. This model allows to generalize the content of each principle in the form of mathematical relationships that reflect the dependencies between the key parameters of the system's functioning. This approach provides the ability to model the behavior of the system in various situations, including under conditions of uncertainty, risks and limited resources [21, 22]. Through mathematical abstraction, a basis is created for developing tools for assessing the effectiveness, adaptability and sustainability of the organizational structure, as well as for building scenarios for making management decisions based on parametric data and objective criteria. This allows to integrate marine robotics into environmental monitoring systems, considering both strategic and operational aspects of management [23–25]:

1. Mathematical representation of the principle of goal orientation. For each MRO r_i, the correspondence of the goal t_j must be determined

$$\forall r_i \in R, \exists t_j \in T: \mu\left(r_i, t_j\right) \to \max, \tag{8.1}$$

where $\mu(r_i, t_j) \in [0, 1]$ – the measure of the task's suitability; $T = \{t_1, t_2, ..., t_m\}$ – set of goals (monitoring, detection, support, etc.); $R = \{r_1, r_2, ..., r_n\}$ – the set of MRO tools.

2. Mathematical representation of the principle of adaptation. The system must remain stable under changing external conditions θ

$$\lim_{\Delta\theta \to 0} \left| \frac{\partial F}{\partial \theta} \right| < \varepsilon, \tag{8.2}$$

where ε – the permissible limit of sensitivity of the functional to changes; F – functional quality or efficiency of the entire system; θ – a set of external conditions (for example, military situation, weather conditions, regulatory restrictions).

3. Mathematical representation of the integration principle. There is a function for integrating data from various sources

$$I = \sum_{i=1}^{n} D(r_i) \cup D_{\text{other systems}} \Rightarrow \text{compatible model} \Rightarrow \text{analytics}, \tag{8.3}$$

where $D(r_i)$ – a set of data collected by robot r_i.

4. Mathematical representation of the principle of hierarchy. A hierarchical control structure S is formed as a directed graph

$$G = (S, E), \tag{8.4}$$

where E – directions of subordination, $depth(G) = d$; d – hierarchy level (usually 3: central – regional – local); $S = \{s_1, s_2, ..., s_k\}$ – a set of structural divisions (regional centers, operator stations, etc.).

5. Mathematical representation of the principle of scientific validity. For each element of the system, a model is used

$$F(r_i) = f(D(r_i), \theta, M), \tag{8.5}$$

where M – a mathematical or empirical model for assessing efficiency; $D(r_i)$ – a set of data collected by robot r_i; θ – a set of external conditions (for example, military situation, weather conditions, regulatory restrictions).

6. Mathematical representation of the principle of technological compatibility. A set of MRO R must have a common standard σ and fulfil

$$\forall r_i, r_j \in R, \text{compatibility}(r_i, r_j) \geq \alpha, \tag{8.6}$$

where $\alpha \in [0,1]$ – minimum allowable compatibility level; $R = \{r_1, r_2, ..., r_n\}$ – a set of marine robotics (MRO) tools.

7. Mathematical representation of the principle of safety and ethical responsibility. The functioning of the system must not exceed the regulatory permissible risk

$$P_{risk}\left(r_i\right) \leq P_{marginal} \forall r_i \in R, \tag{8.7}$$

$R = \{r_1, r_2, ..., r_n\}$ – a set of MRO tools.

8. Mathematical representation of the principle of openness. The level of data openness is described through the accessibility metric

$$A\left(D\right) = \frac{\left|D_{open}\right|}{\left|D_{all}\right|} \geq \delta, \tag{8.8}$$

where δ – the regulatory level of transparency; $D(r_i)$ – a set of data collected by robot r_i.

9. Mathematical representation of the principle of efficiency. Optimization model of resource minimization when achieving goals

$$\min_{x \in X} C\left(x\right) \text{provided that } F\left(x\right) \geq F, \tag{8.9}$$

where x – the system deployment parameters; $C(x)$ – costs; F – the functional quality or efficiency of the entire system.

10. Mathematical representation of the principle of continuity. The model should have the lowest coefficient of loss of functionality during failures

$$\phi = \frac{F_{after\ malfunction}}{F_{normative}} \geq \gamma, \tag{8.10}$$

where $\gamma \in [0.7, 1.0]$ – the target level of continuity; F – the functional quality or efficiency of the entire system.

The mathematical formulation of an organizational model for the use of marine robotics for environmental and ecological monitoring is based on the combination of ten key principles in the formalized equation. The efficiency of the system at time t, denoted as $E(t)$, is determined by the weighted sum of the values of each of the principles

$$E\left(t\right) = P_1 \cdot w_1 + P_2 \cdot w_2 + \cdots + P_{10} \cdot w_{10}, \tag{8.11}$$

where $P_1, \ldots, P_{10}$ – values reflecting the degree of implementation of each of the 10 principles of the organizational model; $w_1, \ldots, w_{10}$ – weight coefficients reflecting the significance of each principle in the overall structure; $E(t)$ – the integral function of the efficiency of the organizational model over time.

This equation allows for modeling and optimizing the functioning of marine robotics systems depending on changing priorities, weighting factors, and environmental conditions. If necessary, nonlinear growth dynamics functions can be added to the model, such as logistic dependencies or exponential decay of the influence of individual factors over time.

The constructed mathematical representation of the ten principles of functioning of the organizational model of using MRO allows moving from conceptual organizational to the applied stage of modeling and simulation of the dynamic behavior of the system. In the proposed structure, the principles act not only as normative or conceptual guidelines, but also as quantitatively determined parameters that directly affect the functioning of the system in the decision space [24–26].

The mathematical description of each principle through the corresponding functions of efficiency, compatibility, risk or adaptability provides the possibility of integrating them into the target control function, which models the dynamic behavior of the system over time. This approach allows for analyzing the sensitivity of the system to changes in individual principles, assessing their mutual influence, and predicting the effectiveness of management decisions in different scenarios of the MRS operation.

At this stage, it becomes appropriate to use computer modeling tools to conduct simulations that simulate the functioning of the system under conditions of changing one or more principles. This allows not only to test hypotheses about their impact, but also to form optimal management strategies that provide a balance between adaptability, efficiency, security and other critically important characteristics of the organizational model.

A simulation of the implementation of ten key principles of the organizational model for the use of marine robotics for environmental and ecological monitoring demonstrates the dynamics of the implementation of each principle over a 12-month period. The modeling results are based on formalized mathematical dependencies that describe the weight of the influence of each principle on the overall effectiveness of the functioning of the organizational structure of the system. The simulation uses nonlinear growing functions of the logistic curve type, which consider both the initial inertia of implementation and the saturation of the effect under resource constraints and organizational interaction.

The dynamics of each principle in the graph reflect the level of its integration into the organizational model at a specific point in time. The most rapid growth is observed for the principles of flexibility, integration and risk orientation, which indicates the high priority of these factors in the current conditions of environmental uncertainty and military threats. On the contrary, the principles of stability and hierarchy have a slower implementation dynamic, which is explained by the need to adapt to changing external conditions.

Mathematical simulation also allowed to analyze the interdependencies between the principles of how increasing the efficiency of coordination contributes to the faster implementation of the principle of adaptability, or how the balance between centralization and decentralization affects the stability of the functional interaction of departments. According to the simulation results, the overall efficiency of the system reaches a peak value after 10 months of implementation, which correlates with the inertial phase of the deployment of technical resources and personnel training.

The simulation demonstrates that applying science-based principles to the design of an organizational model for marine robotic systems predictably achieves environmental monitoring goals in complex environments. This provides a theoretical and applied foundation for further scaling up the concept in a national and international context.

To analyses the functional dynamics of the organizational model of using marine robotics for environmental and ecological monitoring, a simulation was conducted based on mathematically formalized management principles.

The model considers six of the ten key principles: goal orientation (P_1), adaptability (P_2), crisis resistance (P_3), integration (P_4), hierarchy (P_5), and resource efficiency (P_{10}).

Each of the principles is presented as a dynamic function that models the change in the corresponding parameter over time (**Fig. 8.3**).

The simulation structure provided for 10 conditional time units was divided into 100 intervals. The goal orientation principle (P_1) was modeled as a function with a maximum at the central time point, simulating optimal mission performance. Adaptability (P_2) had a sinusoidal character, reflecting its sensitivity to environmental changes. Crisis resistance (P_3) demonstrated monotonic growth, integration (P_4) – logistic growth, hierarchy (P_5) remained stable, and resource efficiency (P_{10}) gradually decreased over time.

The overall efficiency of the system was determined as an aggregate function of six principles with corresponding weighting factors

$$E_{total}(t)=\sum_{i=1}^{6} w_i \cdot P_i(t), \tag{8.12}$$

where w_i – the weights according to the importance of each principle.

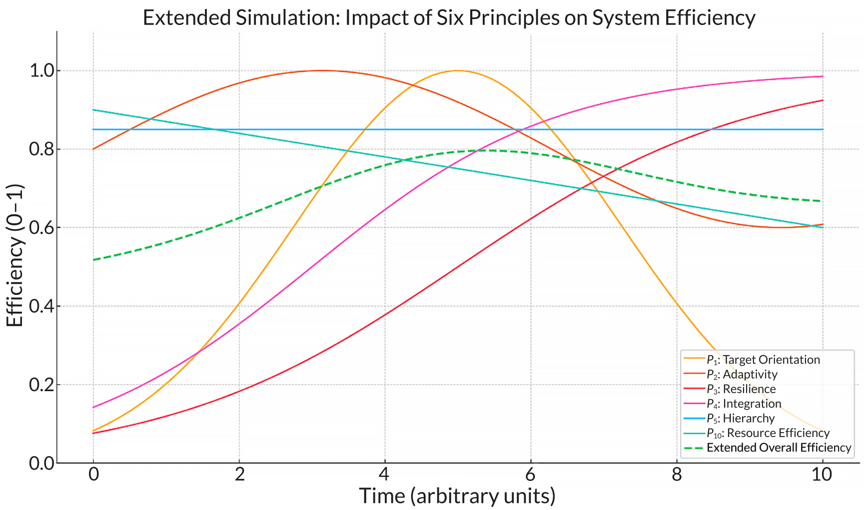

Fig. 8.3 Simulation of the impact of model principles on the efficiency of using marine robotics over time

The efficiency of the system shows a change over time, depending on the interaction of the principles. The maximum generalized efficiency is achieved when there is a balance between high crisis resistance, integration and peak goal orientation. The decrease in efficiency at the end of the simulation is due to the degradation of resource efficiency, despite the stable indicators of other principles.

The simulation showed that the effectiveness of the organizational model of the MRO is a nonlinear function of the cumulative influence of the principles. The balanced development of adaptability, crisis resistance and resource management are critical for maintaining stable operation in a dynamic environment. The results obtained can be used to develop management scenarios, optimize decisions and increase the sustainability of real-time environmental monitoring.

The simulation conducted based on mathematically formalized principles allowed for the revelation of the nature of the dynamic behavior of the organizational model of the use of marine robotics in time. The change in the indicators of adaptability, crisis resistance, resource efficiency and other characteristics was modeled in accordance with the defined functional dependencies. The aggregated efficiency of the system at each point in time was determined as the weighted value of all principles, which allowed tracing how their fluctuations affect the overall result.

To specify and expand the obtained simulation results, typical scenarios of the system functioning were formed, each of which reflects a specific combination of the values of key principles at a fixed point in time or within a certain situational model. The scenario table (**Table 8.5**) systematizes these options, allowing for the comparison of the impact of different management strategies on the overall effectiveness of the MRO functioning. Each scenario describes a unique configuration of the levels of principles, as well as the corresponding value of integrated effectiveness, which allows for assessing the advantages and disadvantages of each strategy in the context of environmental monitoring and crisis conditions.

Table 8.5 Scenarios for simulating the effectiveness of the functioning of the organizational model for the use of marine robotics

Scenario	P_1: Target orientation	P_2: Adaptability	P_3: Crisis resistance	P_4: Integration	P_5: Hierarchy	P_{10}: Resource efficiency	Overall efficiency
Baseline	0.85	0.8	0.6	0.75	0.85	0.9	0.802
Crisis growth	0.7	0.6	0.95	0.6	0.8	0.7	0.722
Resource decline	0.85	0.75	0.7	0.8	0.85	0.5	0.718
Adaptive recovery	0.9	0.95	0.85	0.9	0.8	0.75	0.848
Hierarchical optimization	0.75	0.7	0.65	0.7	0.95	0.8	0.762

The table of simulation scenarios demonstrates the variability of the functioning of the organizational model of the use of marine robotics (MRO) in different conditions, considering six key principles: goal orientation, adaptability, crisis resistance, integration, hierarchy and resource efficiency. Each scenario models a certain configuration of parameters that reflects the management or environmental situation. The base scenario is characterized by balanced values of all principles and serves as a benchmark for comparing other options. The "crisis growth" scenario models crisis conditions when the crisis resistance indicator increases, but due to a decrease in adaptability, integration and resource efficiency, the overall system efficiency does not reach high values. In the "resource decline" scenario, a significant decrease in resource efficiency is observed, which significantly affects the overall efficiency, despite the relatively high indicators of other principles. The "adaptive recovery" scenario demonstrates the highest level of overall system efficiency due to high values of adaptability, integration and goal orientation, which ensures recovery after critical situations. In the hierarchical optimization scenario, an increased level of hierarchy contributes to management stability, but an insufficient level of adaptability and crisis resistance limits the potential of the system. Comparison of the scenarios confirms that achieving high efficiency requires not only a balance between the principles, but also a priority strengthening of adaptability, integration and rational use of resources. In combination with digital technologies such as geographic information systems (GIS), virtual and augmented reality (AR/VR), machine learning (ML), the Internet of Things (IoT), blockchain, and 3D modeling, it is possible to obtain a digital model for using MRO as a tool for systematic and scientifically sound monitoring and restoration of the marine environment after disasters and post-war affected territories [27]. This ensures the comprehensive stability and flexibility of the system in a dynamic environment.

8.5 Conclusion

This section presents a holistic vision of the organizational model of the use of MRO in environmental and ecological monitoring, formed based on a structural-functional approach, considering the complex dynamics of the external environment, especially in conditions of military activity, remediation, and post-crisis recovery. Additionally, various methods aimed at mitigating these environmental impacts in the near future are considered. The constructed model encompasses three interconnected circuits – physical, informational, and managerial – which ensure its stability, adaptability, and ability for autonomous functioning. An important element is the mathematically formalized representation of ten key principles, such as goal orientation, adaptability, crisis resistance, hierarchy, integration, technological compatibility, resource efficiency, security, openness, and continuity. Such formalization allows modeling the functioning of the system in conditions of uncertainty and change, as well as creating tools for making effective management decisions based on objective criteria.

The results of the simulation modeling carried out based on the proposed model show the interdependence of the system's efficiency on the balanced implementation of the mentioned principles. A special role is played by adaptability, crisis resistance, and resource efficiency, which ensure the system's ability to respond to extreme situations. The developed system behavior scenarios make it possible to assess risks, form flexible management strategies, and contribute to increasing the sustainability of environmental and ecological monitoring and the effectiveness of measures for the restoration of aquatic ecosystems.

Thus, this research forms a scientifically substantiated basis for further improvement of management models using MRO, integrating achievements in the fields of organizational management, ecological systemology, engineering cybernetics, and simulation modeling, considering the tasks of ensuring the environmental safety of water resources.

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