SOME ISSUES OF INCREASING THE ENERGY EFFICIENCY OF SHIPS BY IMPROVING NAVIGATION METHODS

Collective monograph

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ABSTRACT

This monograph presents a comprehensive exploration of scientific and practical approaches to increasing the energy efficiency of maritime transport through the optimization of navigation methods. Against the backdrop of global efforts to reduce greenhouse gas emissions and rising fuel costs, the study offers a multidisciplinary framework that addresses key operational, technical, and digital strategies for minimizing fuel consumption across various ship operations.

The work is structured into thematic chapters that sequentially build an integrated understanding of energy-efficient navigation. Strategic models of ship control are proposed, focusing on minimizing route deviations through precise measurements and mathematical error decomposition. Route optimization under meteorological conditions is examined using advanced software systems, while the interplay between navigational risk and energy use is analyzed through multi-criteria decision-making approaches.

Particular emphasis is placed on vessel interaction scenarios, mooring operations, and port maneuvering, where energy-intensive auxiliary processes are analyzed through risk-based methodologies. Artificial intelligence is explored as a transformative tool for course-keeping and trajectory control, enabling significant gains in fuel efficiency and safety. The potential of underwater cargo transport and its energy advantages is introduced, alongside the integration of meteorological and hydrographic support systems using satellite and in-situ data. Inland waterway systems are considered as case studies for applying intelligent monitoring and real-time energy-navigational assessments.

This monograph represents the consolidated result of a three-year research project entitled "Theory and Practice of Energy Efficiency Management of a Marine Vessel", carried out by the Department of Navigation and Control of the Ship at Odesa National Maritime University (Registration No. 0122U201366). The research findings offer a unified model for improving maritime energy efficiency through smarter navigation and are intended for researchers, maritime practitioners, and policymakers working toward sustainable development in the shipping sector.

Keywords

Energy efficiency, ship navigation, route planning, fuel consumption, maneuvering, meteorological support, ECDIS, navigation safety, risk assessment, adaptive control, autonomous ships, propulsion systems, environmental impact, voyage optimization, underwater cargo vessels, digital strategies, artificial intelligence, condition monitoring.

CIRCLE OF READERS AND SCOPE OF APPLICATION

This monograph is intended for a wide audience working or studying in the fields of maritime transport, ship navigation, energy efficiency, environmental safety of shipping, marine engineering, and risk management.

The main target reader groups include:

1. Professional navigators – captains, officers, and other crew members directly responsible for ship handling, navigational decision-making, route planning, assessment of maritime and weather conditions, and efficient use of ship propulsion systems (Chapters 1, 4, 5).

2. Fleet managers and maritime company specialists, responsible for route development, fuel cost management, voyage performance assessment, fleet maintenance, CO_2 emission reduction, compliance with International Maritime Organization's regulations, implementation of energy-saving strategies, and adherence to international environmental requirements (Chapter 10).

3. Researchers and scientists in the fields of navigation, marine meteorology, and risk management engaged in the development of ship energy optimization methods, analysis of navigational factors affecting fuel consumption, maneuvering risk modeling, and the creation of digital models for maritime operations, including systemic assessments of navigational and energy safety (Chapters 3, 9).

4. Engineers and designers of ship control and navigation systems, who work on integrating automated routing systems, analyzing and implementing efficient propulsion systems, azimuth thrusters, rudder systems, and AI-based forecasting tools for navigation (Chapters 6, 10).

5. Software developers, analysts, and digital architects in the maritime industry, engaged in automated voyage planning, risk management AI, and digital safety modeling. These specialists build platforms for navigation support, energy consumption analysis, and dynamic voyage planning considering meteorological, hydrographic, and operational factors (Chapters 2, 3, 8).

6. Students, graduate students, and faculty of maritime education institutions, who study or teach disciplines related to ship navigation, energy efficiency, environmental protection, hydro-navigation, and digital technologies in maritime transport, as well as modern approaches to ship handling, technical maintenance, and energy-efficient ship design.

7. Maritime authorities and regulatory bodies, involved in developing standards, technical requirements, and regulations aimed at enhancing maritime safety and efficiency.

8. Port infrastructure and logistics professionals, who must address berthing risks, optimize terminal operations, and develop sustainable protocols for operations in restricted conditions (Chapter 5).

9. Developers of autonomous navigation systems and underwater vessel researchers, who may benefit from analyses of autonomous and submersible cargo ship development prospects (Chapter 7).

The scope of application of the approaches and results presented in the monograph includes:

– practical navigation in complex conditions (coastal waters, narrow passages, ice-covered areas) requiring flexible and adaptive decision-making with attention to energy consumption;

– planning optimal and alternative ship routes, including consideration of weather changes, currents, winds, waves, and emission control areas;

– evaluating the effectiveness of navigational decisions through the implementation of digital tools, route modeling, and real-time decision support systems;

– improving the technical training of specialists, developing navigator training methodologies, and fostering a culture of energy-efficient navigation in line with IMO 2050 strategy goals;

– providing scientific and practical justification for policies related to carbon footprint reduction, fleet modernization, and the integration of digital platforms in maritime transport;

– risk modeling and management related to maneuver selection, mooring, ship encounter avoidance, or sailing in adverse hydro-meteorological conditions.

Thus, the monograph serves not only as a theoretical contribution to the advancement of energy-efficient navigation but also performs a practical function, supporting decision-making in real-world maritime operations and facilitating the introduction of innovations in the maritime transport sector amidst the energy and climate challenges of the 21st century. It can also serve as a methodological foundation for further research in related fields.

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ABBREVIATIONS

AEO	Artificial Extended Objects
AIS	Automatic Identification Systems
ANFIS	Adaptive Network-based Fuzzy Inference System
ARPA	Automatic Radar Plotting Aids
AUV	Autonomous Underwater Vehicle
BVS	BON VOYAGE System
CGS	Closed-Loop Gain Shaping Method
CII	Carbon Intensity Indicator
CPA	Closest Point of Approach
DSS	Decision Support Systems
DVL	Doppler Velocity Log Navigation
ECDIS	Electronic Chart Display and Information System
EEDI	Energy Efficiency Design Index
EEOI	Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EKF	Extended Kalman Filter
ETA	Estimated Time of Arrival
FOPID	Fractional Order Proportion Integration Differentiation Controllers
FSA	Formal Safety Assessment
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
IMO	International Maritime Organization
IMUs	Inertial Measurement Units
LBL	Long baseline systems
LSTM	Long Short-Term Memory Networks
NOAA	National Oceanic and Atmospheric Administration
OSM	Open Sea Model
PSO	Particle Swarm Optimization Method
RBs	Responder Beacons
RIS	River Information Services
SBL	Short Baseline Systems
SPOS	Ship Performance Optimization System
TCPA	Time to CPA
USBL	Ultra-Short Baseline Systems
VTS	Vessel Traffic Services

INTRODUCTION

The modern shipping industry faces unprecedented challenges and opportunities in the pursuit of sustainability, operational efficiency, and regulatory compliance. A central tenet in this transformation is the enhancement of energy efficiency in maritime operations through improvements in navigation methods. This monograph systematically explores scientific, technical, and operational approaches to optimizing navigational decisions to reduce fuel consumption, emissions, and navigational risks. The chapters are structured to progressively develop and integrate concepts from strategic theory to applied system design, encompassing classical navigation, artificial intelligence, meteorological tools, and the emerging prospects of underwater and alternative fuel navigation.

Chapter 1. A strategic approach to energy-efficient methods of navigation, maneuvering and ship control. The foundation of the monograph is laid in Chapter 1, which outlines a strategic framework for improving energy efficiency through navigational methods rather than relying solely on hardware retrofits. It critically assesses current industry practices that prioritize technical upgrades and highlights the underutilized potential of operational strategies such as trajectory control, observation accuracy, and measurement refinement.

The chapter introduces a comprehensive model for evaluating vessel fuel consumption across various operational contexts. Through the application of mathematical modeling – particularly orthogonal decomposition of observation error distribution – it is demonstrated that energy consumption can be significantly reduced by optimizing the precision of navigational data. This method not only enables minimization of route deviation but also establishes a quantitative basis for real-time adjustments. The integration of strategic navigation, voyage planning, and situational control is shown to be a critical dimension in energy management, with benefits that span both economic and ecological outcomes.

Chapter 2. Energy-efficient ship route planning considering meteorological navigation conditions. Chapter 2 expands upon strategic navigation by introducing the role of meteorological conditions in energy-efficient route planning. It provides a detailed analysis of modern meteorological decision support systems such as SPOS, WNI, and BON VOYAGE, demonstrating their effectiveness in aligning navigational decisions with real-time and forecasted environmental data.

A case study on the Strait of Gibraltar illustrates how optimizing vessel trajectory according to hydrodynamic current profiles can yield fuel savings of up to 15%. The chapter emphasizes the necessity of integrating oceanographic

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models, current velocity datasets, and atmospheric reanalysis data into the route optimization process.

By coupling hydrometeorological variability with ship operational profiles, the chapter articulates a decision-making framework that allows captains and operators to select weather-optimized paths, reducing fuel use, time at sea, and greenhouse gas emissions. The result is a compelling argument for making meteorological data central to energy efficiency strategy.

Chapter 3. Consideration and assessment of navigational risks to improve energy-efficient ship management. In Chapter 3, the monograph addresses a crucial intersection between safety and efficiency by introducing navigational risk as a variable in energy management. It critiques conventional energy-saving approaches – particularly slow steaming – for their failure to consider navigational hazards posed by narrow channels, high-traffic zones, or adverse weather conditions.

The chapter presents a multi-criteria decision-making framework that incorporates fuel consumption, collision risk, and hydrometeorological conditions. A classification of navigational risks is developed, spanning technical, human, digital, and environmental categories. Risk assessment methods such as FMEA, HAZID, ETA, and risk matrices are presented as critical tools for integrating energy efficiency with safety management.

Digital navigation platforms, including NAPA, StormGeo, and Wärtsilä Voyage, are reviewed for their ability to enhance route planning through AI-powered risk modeling. The study also examines ISO 31000:2018 as a guiding structure for implementing adaptive maritime risk management. Ultimately, Chapter 3 argues that energy efficiency cannot be decoupled from navigational risk mitigation and calls for harmonized, data-driven systems that ensure both goals are met simultaneously.

Chapter 4. Choosing the best maneuver for vessel separation taking into account the energy efficiency of the trajectory. Chapter 4 transitions from voyage-level planning to tactical decision-making during ship encounters, particularly vessel separation and evasive maneuvering. Traditional maneuvering practices based solely on collision avoidance are contrasted with newer models that incorporate fuel consumption optimization into real-time decisions.

The chapter highlights the integration of radar overlay on ECDIS as a transformative approach that enhances situational awareness while enabling the calculation of energy-optimal maneuvers. It introduces a conceptual model based on the Open Sea Model, which predicts ship trajectories under different separation scenarios and quantifies fuel consumption implications for each alternative.

Special emphasis is placed on the trade-offs between safety and energy use in restricted areas or in low-visibility conditions. Through model-based analysis and system integration with AIS and ARPA, the study proposes a methodology that selects maneuver options minimizing route deviation, time loss, and fuel consumption. This chapter establishes that navigation technology, when coupled with performance modeling, can guide energy-smart tactical decisions even under intense navigational stress.

Chapter 5. Analysis of possible risks, which affect energy efficiency of the ship while maneuvering and mooring. Chapter 5 focuses on the energy-intensive nature of auxiliary operations, particularly maneuvering and mooring. It identifies a variety of risks that impact energy performance during these phases, including mechanical overloads, adverse current or wind conditions, and pilotage errors.

The chapter provides a risk matrix that categorizes energy efficiency hazards into ten thematic groups. It emphasizes the role of digital risk platforms – possibly operated by third-party entities such as insurance firms – to deliver real-time, round-circle assessments covering all stakeholders in a maneuvering operation.

Significant attention is given to new risk categories emerging from modern shipping practices, including AI malfunctions, cybersecurity threats, and autonomous tug behavior. The chapter advocates for real-time risk assessment systems capable of dynamically adjusting to evolving port conditions and external threats. The conclusion is clear: auxiliary navigation must no longer be treated as isolated from energy efficiency planning.

Chapter 6. Modern approaches to maritime navigation: integrating artificial intelligence into ship course-keeping systems. Chapter 6 presents a technological deep dive into how artificial intelligence can transform course-keeping systems to enhance both safety and energy performance. It traces the evolution of autopilot systems from classical PID controllers to neural networks, fuzzy logic systems, adaptive algorithms, and reinforcement learning.

AI-powered autopilots are shown to deliver superior accuracy in maintaining course under variable sea conditions, reducing fuel consumption by 10–15% and improving maneuverability. The study details the capabilities of backstepping control, LSTM prediction, and hybrid ANFIS systems in managing non-linear dynamics inherent in ship movement.

Furthermore, the integration of AI with azimuthal propulsion and energy-saving devices such as Becker Mewis Ducts demonstrates quantifiable improvements in efficiency. The chapter concludes that future energy-efficient maritime navigation systems will rely heavily on adaptive, intelligent automation capable of responding to disturbances in real-time without human intervention.

Chapter 7. Analysis of modern underwater navigation and design capabilities of underwater cargo vessels. Chapter 7 explores an innovative frontier: underwater cargo vessels as a paradigm shift in maritime logistics. In contexts marked by geopolitical instability, piracy, or restricted surface navigation, submerged transport offers an alternative with notable energy efficiency advantages.

The chapter surveys the current state of underwater navigation, including Doppler Velocity Logs, Long Baseline acoustic positioning systems, and Kalman filter-based data fusion. It introduces novel behavioral and hierarchical control system architectures that enable underwater vehicles to operate autonomously in dynamic environments with limited computational resources.

The potential for underwater freight corridors to reduce exposure to weather-related resistance, surface currents, and wave drag is examined, with projections suggesting increased route capacity and fuel savings. The chapter proposes that underwater vessels – once considered speculative – are increasingly viable and should be integrated into future discussions on sustainable and secure shipping solutions.

Chapter 8. Meteorological and hydrographic support of energy-saving maritime transport. Chapter 8 returns to the topic of environmental data support, focusing on the integration of meteorological and hydrographic tools for route optimization. It presents an interdisciplinary approach combining satellite altimetry, ARGO drifters, gravimetric monitoring (GRACE), and real-time buoy data.

A novel concept is introduced: using Earth's gravitational anomalies and geoid shape variations as predictive indicators of monsoon dynamics and sea-level shifts. This approach enhances long-term voyage planning in regions like the Indian Ocean, where monsoonal variability plays a critical role.

Technological and organizational models for data integration are proposed, including dynamic digital routing systems that synthesize hydrographic forecasts with ECDIS overlays and voyage management platforms. The chapter argues that deep integration of geophysical, meteorological, and navigational data streams forms the backbone of truly adaptive, energy-conscious shipping.

Chapter 9. Development of a system for assessing navigational and energy safety on inland waterways. Chapter 9 shifts focus to inland navigation, examining Ukraine's river systems as a testbed for integrated navigational and energy safety systems. It presents a system architecture combining sensor networks, River Information Services, and AI-based risk analysis tools.

The chapter highlights the infrastructural and ecological constraints specific to inland waterways – such as shallow waters, outdated fairway equipment, and fluctuating hydrological conditions – and proposes an energy-oriented safety assessment system that addresses these challenges. Key components include hydrometeorological sensors, AIS-based traffic visualization, and machine-learning-based forecasting modules.

The proposed system supports real-time decision-making, reduces fuel consumption, and minimizes environmental impact, aligning with broader goals of green transport and sustainable development. This chapter serves as a regional application of the monograph's wider theoretical and technological framework.

Chapter 10. Digital strategies for enhancing the efficiency of cargo ships maintenance. Modern merchant vessels play a crucial role in the global transportation system, enabling the movement of large volumes of cargo worldwide. This imposes high demands on the efficiency and reliability of shipboard equipment. Maintenance systems for cargo vessels are essential for ensuring their functional integrity and operational safety. However, several issues persist concerning the current state of ship maintenance systems. Specifically, the reliability and efficiency of technical maintenance are critical for optimizing operational costs and enhancing the overall performance of maritime transport. Well-defined maintenance system parameters can address these challenges and improve cargo vessel operations.

The operation of the cargo fleet under current conditions is characterized by a high degree of technological complexity, increasing energy costs, stricter environmental regulations, and the need to maintain competitiveness in the global shipping market. In this context, effective maintenance of ship systems is particularly relevant, as it helps reduce repair costs, ensures voyage safety, and lowers overall fuel consumption. Outdated maintenance approaches – focused on scheduled or breakdown-based repairs – do not reflect the actual technical condition of equipment and fail to meet required energy efficiency standards.

Within this framework, digital transformation serves as a key tool for modernizing cargo vessel maintenance systems. Digital technologies such as sensor networks, big data, predictive analytics, digital twin models, and artificial intelligence tools provide new opportunities for real-time technical condition monitoring, failure forecasting, and optimal maintenance planning. Especially important is the implementation of strategies that integrate digitalization with the principles of energy-efficient shipping.

The monograph establishes that the path to energy-efficient maritime transport is not confined to fuel substitution or hardware retrofits. Instead, it lies in a comprehensive transformation of navigational thinking – one that synthesizes strategic planning, AI-powered decision-making, environmental integration, risk management, and frontier technologies such as underwater freight.

By sequentially examining each aspect of ship operation – from open-sea voyage planning to inland waterway optimization – this work presents a unified scientific and practical framework. The result is a blueprint for next-generation maritime operations that meet the dual demands of economic competitiveness and environmental stewardship.

CHAPTER 1

A strategic approach to energy-efficient methods of navigation, maneuvering and ship control

Yevgeniy Kalinichenko

Abstract

This article will explore the various technologies and strategies available to improve energy efficiency on ships and provide a scientific analysis of their effectiveness. The research objectives include development of a comprehensive model for assessing vessel energy efficiency in the context of navigation operations, identification and analysis of key factors affecting fuel consumption during vessel's voyage, formulation of practical recommendations for implementing energy-efficient navigation methods. An innovative approach is presented to improving vessel energy efficiency through enhanced navigation methods, addressing the growing need for fuel consumption optimization in maritime transportation. Traditional approaches to vessel energy efficiency often focus on technical solutions, while the potential for optimization through improved navigation methods remains underexplored. The study introduces a comprehensive model for energy efficiency assessment that considers multiple operational factors affecting fuel consumption during vessel transit. It is provided a systematic approach to energy efficiency optimization, supported by mathematical models and practical recommendations for implementation. The results demonstrate the potential for significant reduction in fuel consumption through improved navigation methods, contributing to both economic efficiency and environmental sustainability in maritime operations. A method for increasing the energy efficiency of a vessel by minimizing the variance of the observation error with the introduction of an orthogonal decomposition of the distribution density of errors in navigation measurements is discussed. The results obtained can significantly increase the accuracy of the vessel's location and, as a consequence, improve its energy efficiency by reducing deviations from the optimal route. The proposed method for determining the ship's coordinates using the orthogonal decomposition of the error distribution density provides higher efficiency compared to the least square method.

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Improving the energy efficiency of ships is an important step in reducing the shipping industry's impact on the environment. There are various strategies and technologies that can be employed to achieve this goal, including hull coatings, waste heat recovery, energy management systems, hybrid propulsion systems, and wind propulsion. While each strategy has its advantages and limitations, their combined use can help improve the overall energy efficiency of ships and reduce their impact on the environment.

Keywords

Energy efficiency, vessels fuel consumption, wind propulsion technologies, ballast optimization, trajectory control, navigation methods, observation, orthogonal decomposition, measurement error.

1.1 Introduction

The shipping industry is a critical component of the global economy, with around 90% of the world's trade being transported by ships. However, the industry also has a significant environmental impact, contributing to around 2.5% of global greenhouse gas emissions. As such, there is a growing need to improve the energy efficiency of ships to reduce their environmental impact and comply with increasingly stringent regulations.

Improving energy efficiency on ships can also have significant economic benefits by reducing fuel consumption and operating costs. For example, a 2018 report by the International Maritime Organization (IMO) found that implementing energy efficiency measures could result in fuel savings of up to 75%, with corresponding reductions in emissions and operating costs.

1.2 Energy efficiency on ships. Strategic approach

Given the growing interest in improving energy efficiency on ships, there have been significant developments in technologies and strategies to achieve this goal. These range from advanced propulsion systems to hull coatings, waste heat recovery, and energy management systems. However, there is a need for further scientific analysis to assess the effectiveness of these technologies and strategies in different ship types and operating conditions, as well as to identify new solutions for improving energy efficiency in the shipping industry.

The shipping industry is a significant contributor to global greenhouse gas emissions, accounting for around 2% of global emissions (around 4% in EU) in 2019.

The primary source of emissions from ships is the burning of fossil fuels, which power the large diesel engines that propel the vessel through water (the shipping emission output varies on ship's types and their routes) (**Fig. 1.1, 1.2**).

The need to improve energy efficiency on ships is becoming increasingly urgent due to global efforts to address climate change. The IMO, a United Nations agency responsible for regulating shipping, has set targets to reduce greenhouse gas emissions from the shipping industry. These include a target to reduce the carbon intensity of international shipping by at least 40% by 2030, compared to 2008 levels, and to reduce total greenhouse gas emissions from international shipping by at least 50% by 2050, compared to 2008 levels.

Improving energy efficiency on ships can also have significant economic benefits. Fuel costs can account for up to 60% of a ship's operating costs, and reducing fuel consumption can result in substantial savings, plus as per post-pandemic and war/post-war circumstances fossil fuel price will continue to grow (despite fuel spread and availability) (**Fig. 1.3**).

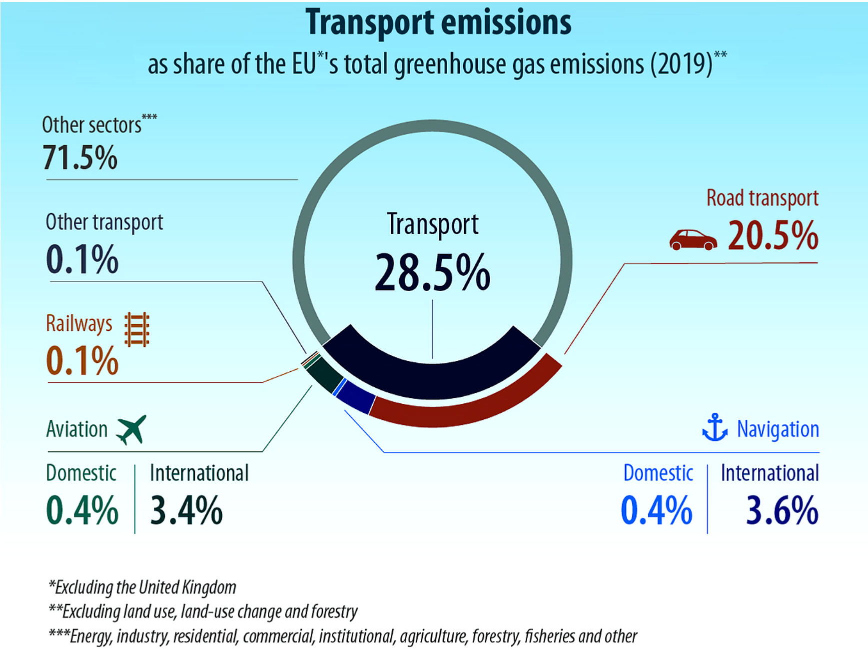

Fig. 1.1 Greenhouse gas emissions in EU, 2019
Source: [1]

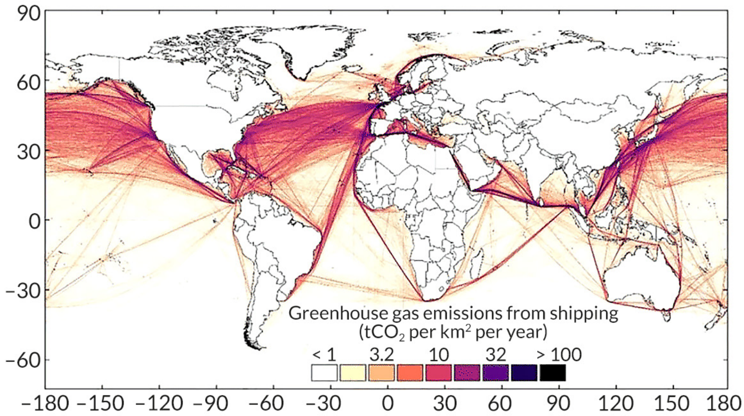

Fig. 1.2 Global distribution of gas emissions from shipping
(as per routes/traffic density, AIS)
Source: [2]

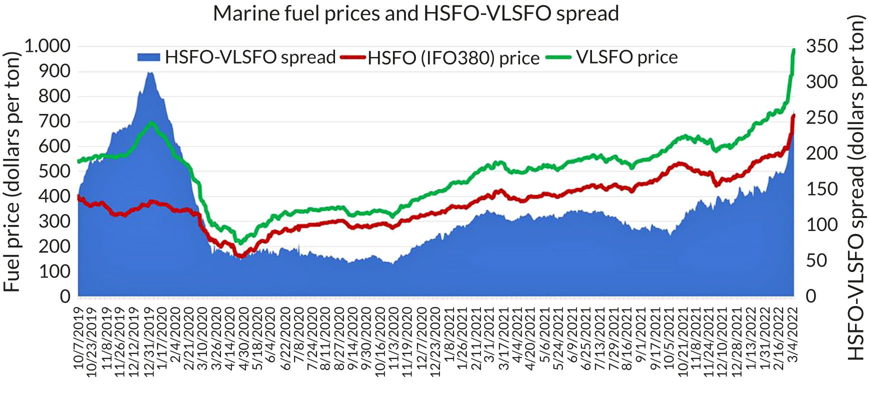

Fig. 1.3 HSFO/VLSFO prices worldwide, 2019–2022
(chart by "American Shipper" based on data from Ship & Bunker)
Source: [3]

Therefore, there is a growing need to identify and implement technologies and strategies to improve energy efficiency on ships. These can range from simple measures such as optimizing vessel speed and route planning to more advanced solutions such as hybrid or electric propulsion, hull coatings, waste heat recovery, and energy management systems.

There are several technologies and strategies that can be used to improve energy efficiency on ships, including but not limited to:

1. Hull coatings can be used to reduce drag and improve the flow of water around the ship's hull, thereby reducing fuel consumption. For example, a silicone-based coating can reduce frictional resistance by up to 20%, while a super-hydrophobic coating can reduce drag by up to 30% [4]. A study conducted by the IMO estimated that a silicone-based hull coating could result in fuel savings of up to 5%, depending on the ship's size and operating conditions. However, the effectiveness of hull coatings depends on the specific design and operating conditions of the ship, and some hull coatings may not be effective in all situations.

2. Waste heat recovery systems can capture and reuse heat generated by the ship's engine, reducing the amount of fuel needed to generate the same amount of power [5]. For example, a waste heat recovery system can recover up to 40% of the energy from the engine's exhaust gas. A study conducted by the European Commission estimated that a waste heat recovery system could result in fuel savings of up to 10%, depending on the ship's size and operating conditions. There are various waste heat recovery technologies available, including steam turbines, organic Rankine cycles, and thermoelectric generators.

3. Energy management systems can be used to optimize the operation of the ship's engines and equipment, reducing energy waste and improving efficiency [6]. These systems can monitor and control fuel consumption, adjust engine speed and power, and optimize equipment performance. A study conducted by the IMO estimated that an energy management system could result in fuel savings of up to 15%, depending on the ship's size and operating conditions. Energy management systems can also help reduce maintenance costs and extend the lifespan of the ship's equipment.

ISO 50001 is a voluntary international standard designed to be compatible and harmonized with other system standards, such as ISO 14001 for environmental management systems and ISO 9001 for quality management systems. It applies to organizations of any size, and provides requirements for establishing, managing and improving their energy consumption and efficiency. Certification to the standard can contribute to:

– improvement of energy performance, including energy efficiency, use and energy consumption;

– reducing environmental impact, including greenhouse gas emissions without affecting operations and simultaneously increasing profitability;

– continual improvement of the energy management systems;

– ensuring measurement, documentation, reporting and benchmarking of energy consumption;

– credible market communication about energy performance efforts.

Therefore, the abovementioned principles can be applied in developing various strategies for energy efficiency on ships directly, as these are something that navigators can control and maintain on the operational level.

4. Hybrid propulsion systems use a combination of conventional and electric power to reduce fuel consumption and emissions. For example, a ship equipped with a hybrid propulsion system can switch between diesel and electric power depending on the operating conditions, such as when entering and leaving ports. A study conducted by the European Commission estimated that a hybrid propulsion system could result in fuel savings of up to 30%, depending on the ship's size and operating conditions [6]. Hybrid propulsion systems can also help improve the overall performance and reliability of the ship's power system.

5. Wind propulsion systems can be used to harness the power of wind to reduce fuel consumption. These systems can range from simple sails to more advanced solutions such as rotor sails or kites [7]. A study conducted by the University of Delaware estimated that a rotor sail system could result in fuel savings of up to 10%, depending on the ship's size and operating conditions. While wind propulsion technologies are still relatively new, they have shown promising results in terms of reducing fuel consumption and emissions.

1.3 Increasing energy efficiency by improving navigation methods

The optimization of vessel energy efficiency represents a critical challenge in modern maritime transportation, driven by both economic pressures and environmental concerns. As global shipping continues to grow, the need for effective methods to reduce fuel consumption while maintaining operational safety and efficiency becomes increasingly important. Traditional approaches to energy efficiency improvement have primarily focused on technical solutions and vessel design modifications [8], while the potential for optimization through enhanced navigation methods remains insufficiently explored.

Recent studies have highlighted the significant impact of navigation practices on vessel fuel consumption. The relationship between vessel routing, weather conditions, and energy efficiency has been extensively documented, yet comprehensive approaches to optimizing these factors through navigation methods are limited. Current research indicates that proper navigation strategy can significantly affect fuel consumption, particularly in challenging weather conditions and confined waters [9].

The International Maritime Organization's regulations on vessel energy efficiency have created additional pressure for developing more sophisticated approaches to fuel consumption optimization. While existing studies have addressed various aspects of this challenge, a comprehensive methodology integrating multiple operational factors remains lacking. This gap is particularly evident in the context of real-time navigation decision-making and its impact on energy efficiency.

The core methodology centers on the energy efficiency criterion Q, which represents the total fuel consumption required for vessel transit. The general form of this criterion is expressed as

$$Q = q \times D \times S,$$

where q represents specific fuel consumption per ton-mile at average specified speed; D denotes vessel displacement; S indicates route length. The following requirements must be met

$$P < \left[P\right] \text{ and } S' > S,$$

where P – the accident probability; S' – the actual route length. In steady-state motion, the following expression is valid

$$V = \text{const or } Te = kV^2, \text{ i.e., } V = V\left(Te/k\right),$$

where V – the vessel's steady-state speed; Te – the propeller thrust force; k – the movement resistance coefficient.

The propeller thrust force Te, under otherwise equal conditions, depends on the current fuel consumption Gr, average draft T, and vessel trim ψ, i.e., $Te = f\left(Gr, T, \psi\right)$. In turn, coefficient k can be represented by two components: k_1 – hull resistance and k_2 – rudder blade resistance when deflected from the centerline. Component k_1 depends on vessel trim ψ, and k_2 depends on rudder blade steering frequency n, therefore $k = f(y, n)$.

Consequently

$$V = f\left(Gr, T, \psi, n\right).$$

The vessel's displacement D is by definition the sum of the light ship weight Po, ship stores weight Pz, cargo weight Pg, and ballast weight Pb, where

$$D = Po + Pz + Pg + Pb.$$

The actual route length S' is the sum of the planned route length S and additional distance losses $\Delta\delta$ caused by vessel drift relative to the programmed movement trajectory under external disturbances, i.e., $S' = \delta + \Delta\delta$.

Considering the above, it is possible to write

$$Q = \left(P_o + Pz + Pg + P'b\right)\left(S + \Delta S\right)q',$$

where q' – the weighted average fuel consumption that can take values $G'r$ different from Gr depending on the ratio of speeds V and Vz.

The values Po, Pz, Pg, and δ for a specific transit are constant parameters, while $P'b$, $\Delta\delta$, and q' are controlled variables.

Therefore, the general expression for the energy efficiency criterion Q can be written as

$$Q = f\left(P'b, \Delta\delta, q'\right).$$

Thus, based on the above, the task of improving energy efficiency can be formalized as an optimization problem, with Q chosen as the optimality criterion. The optimization problem itself takes the following form

$$Q \to \min;\ P < \left[P\right],$$

which takes into account the navigation safety constraint.

Analyzing the last expression, it is possible to conclude that minimization of the energy efficiency criterion Q is possible by solving three main tasks:

1. Minimization of required ballast $P'b$ for the transit.

2. Minimization of additional distance losses $\Delta\delta$.

3. Minimization of specific fuel consumption Gr through the relationship between propeller thrust force and vessel movement resistance.

These three directions define the conceptual basis for optimizing energy efficiency through improved navigation methods.

Development of the first approach may be relevant for container ships, where proper cargo placement during loading can minimize ballast intake to ensure vessel trim and stability.

The second approach involves minimizing trajectory error, which characterizes the difference between programmed and actual vessel movement trajectories, depending on the strategy for keeping the vessel on the programmed trajectory and the accuracy of position control.

The third approach allows changing the vessel's movement resistance, particularly through trim selection and rudder steering frequency, thereby achieving reduced specific fuel consumption.

The initial optimization problem can be represented as three independent component optimization problems for minimizing ballast quantity, distance losses, and specific fuel consumption.

The relationship between the average specified transit speed Vz and the vessel's steady-state speed V characterizes the current fuel consumption value. If $V > Vz$, then fuel consumption Gr can be reduced to value $G'r$, at which equality $V = Vz$ is achieved.

Thus, the research methodology incorporates three primary components:

1. Ballast optimization analysis. The study examines the relationship between ballast requirements and vessel efficiency, considering:

– static moments along longitudinal and vertical axes;
– cargo placement optimization;
– minimum ballast requirements for safe operation.

2. Trajectory control assessment. Analysis of factors affecting vessel trajectory, including:

– environmental impact on vessel movement;
– deviation from programmed route;
– optimal course correction strategies.

3. Fuel consumption optimization. Evaluation of specific fuel consumption based on:

– propeller thrust force relationships;
– movement resistance coefficients;
– impact of trim and rudder frequency.

Data collection involved analysis of operational records and theoretical modeling of vessel behavior under various conditions. The methodology employed both deterministic and probabilistic approaches to account for the dynamic nature of maritime operations [9].

It is possible to examine in more detail the possibilities for solving the three listed problems. The first component optimization problem of minimizing the required ballast for transit requires determining the necessary static moments Mx and My along the vessel's longitudinal and vertical axes, respectively, which ensure the required trim, longitudinal strength, and stability of the vessel. Cargo placement is performed in such a way that the resulting static moments are as close as possible to the required Mx and My. The static moments are brought to the necessary values by taking in minimal ballast.

As a first approximation, this problem can be formalized as follows. As previously indicated, let's choose the amount of ballast taken during container loading as the optimality criterion. Therefore, the optimality criterion is $I = Pb$, and the optimization problem itself is formalized as follows

$$Pb \to \min;\ Mx_1 < Mx < Mx_2;\ My_1 < My < My_2;\ Fi < [Fi],$$

where the second, third, and fourth lines are constraints on static moments according to seaworthiness requirements, and the last inequality limits the magnitude of the inertial force occurring during vessel rolling.

The following notations are used in the last expression:

– m and n – the number of ballast tanks and loaded holds respectively;

– Mx_1, Mx_2, My_1, My_2 – limiting boundary values of static moments satisfying seaworthiness requirements;

– Pg_i, xg_i, yg_i, zg_i – amount of cargo in the i-th cargo space and coordinates of its center of gravity;

– Pb_i, xb_i, yb_ii, zb_i – amount of ballast in the i-th ballast tank and coordinates of its center of gravity;

– Fi and $[Fi]$ – respectively, the largest inertial force acting on each loading container and the permissible value of inertial force.

To solve this optimization problem, it is first necessary to form a set Ω_1 of permissible loads satisfying seaworthiness constraints, and then from the obtained set, identify a subset Ω_2 satisfying the last constraint on arising inertial forces, where $\Omega_2 \subset \Omega_1$. Finally, from subset Ω_2, the optimal load is selected where the optimality criterion $I = Pb$ takes the minimum value.

Upon more detailed analysis of the optimization problem, it appears that there may be a subset of loads where the optimization problem constraints are achieved by container placement without taking ballast. Consequently, the adopted optimality criterion loses meaning, and as an optimality criterion, one can propose the maximum inertial force Fi acting on containers during vessel rolling, which should be minimized.

When determining inertial forces, one should consider the relationship between vessel loading and its rolling parameters, which determine the characteristics of arising angular accelerations and affect the magnitude of inertial forces.

The next task is minimizing distance losses, considering that these losses occur for two main reasons. First, the length of the actual trajectory is greater than the programmed one due to external disturbances, and second, during the voyage, dangerous approach situations arise and the vessel performs an avoidance maneuver, replacing a section of the programmed trajectory with an avoidance trajectory, leading to distance loss.

Consequently, the distance losses ΔS have two components ΔS_1 and ΔS_2. Component ΔS_1 determines distance losses due to the difference between programmed and actual trajectory lengths and is characterized by trajectory error, which is stochastic. Therefore, it is necessary to find the dependence of trajectory error on the parameters of the strategy for keeping the vessel on the programmed movement trajectory. The optimization problem involves selecting control strategy parameters that minimize the variance of trajectory error. If to denote D as the variance of trajectory error and u as the strategy for keeping the vessel on the programmed movement trajectory, then the task of minimizing component ΔS_1 takes the following form

$$D \to \min;\ u = u^* \in U,$$

where u^* and U – the optimal strategy and set of permissible strategies, respectively.

Let's consider component ΔS_2, where the vessel deviates from the programmed movement trajectory to perform an avoidance maneuver and then returns to it after completing the maneuver. Minimization of this component is achieved if the difference ΔS_i between the lengths of the programmed section S_i and the corresponding avoidance trajectory S_i' is minimal when performing each maneuver, i.e., $\Delta S_i = S_i' - S_i$. The avoidance trajectory has deviation and return sections to the programmed trajectory, and its length is always greater than the programmed trajectory section connecting the ends of the avoidance trajectory. The unchanging requirement for the avoidance trajectory is that the distance of closest approach between the vessel and the target must not exceed the maximum permissible value. The value ΔS_i depends on avoidance maneuver parameters, i.e., time and course of deviation, as well as time and course of turn to return to the programmed movement trajectory. If to denote K as the avoidance maneuver parameters, then obviously $\Delta S_i = f(K)$, and the task of minimizing component ΔS_2 of distance loss can be formalized as follows

$$\Delta S \to \min;\ D_{\min} > [D];\ K \in \Omega,$$

where Ω – the set of permissible maneuver parameters; $D_{\min}$ and $[D]$ – the distance of closest approach and its maximum permissible value, respectively.

The third task represents minimization of specific fuel consumption Gr through the relationship between propeller thrust force and vessel movement resistance, which depends on vessel trim and rudder blade steering frequency for keeping the vessel on the programmed trajectory. The vessel speed must not be less than the average speed Vz planned for the transit. In general, it is necessary to experimentally determine the dependence of specific fuel consumption $G'r$ on vessel trim, rudder blade steering frequency, and vessel speed, i.e., $G'r = f(y, n, V)$. Then, optimal values of trim ψ^* and n^* are selected, minimizing $G'r$ under the condition that the actual vessel speed V' is not less than Vz. This task can be presented as follows

$$G'r \to \min;\ V' > Vz;\ \psi^* \in [\psi];\ n^* \in [n].$$

Thus, improving energy efficiency through the development of more advanced navigation methods can be accomplished through four considered directions by solving the corresponding optimization problems presented in general form.

It should be noted that rudder blade steering frequency simultaneously affects both the accuracy of programmed trajectory implementation and movement resistance, which must be taken into account when solving optimization problems.

1.4 Improving energy efficiency by minimizing observation error variance

In modern maritime transport operations, the issue of improving the energy efficiency of vessels has become particularly relevant [10, 11]. One of the key factors influencing energy efficiency is the accuracy of the vessel's position determination [12]. Inaccuracies in observation lead to deviations from the optimal route and, consequently, to increased fuel consumption [13]. Therefore, the development of methods to enhance observation accuracy is an important scientific and practical challenge.

A significant number of scientific studies have been devoted to improving the accuracy of vessel positioning. In [14], methods for assessing the reliability of navigation and the application of orthogonal decomposition of the error distribution density in navigation measurements are considered. Study [15] focuses on measurement processing methods and the statistical interpretation of their effectiveness. Paper [16] examines the identification of navigation error distribution laws using mixed distributions of two types. However, the issue of improving overall energy efficiency by minimizing the dispersion of observation errors still requires further research [17–19].

As shown in [14], the system of likelihood equations takes the form

$$\begin{cases} \sum\limits_{i=1}^{n} \sin\alpha_i \dfrac{\partial}{\partial \xi_i} \ln\left[f_i(\xi_i)\right] = 0, \\ \sum\limits_{i=1}^{n} \cos\alpha_i \dfrac{\partial}{\partial \xi_i} \ln\left[f_i(\xi_i)\right] = 0, \end{cases} \tag{1.1}$$

$$\xi_i = X\sin\alpha_i + Y\cos\alpha_i - r_i,$$

where n – number of position lines; α_i and r_i – the direction of the gradient and the transfer of the i-th position line; f_i – density of error distribution of navigation measurements.

Considering that in the general case the correct ratio is

$$\frac{\partial}{\partial \xi_i}\ln\left[f_i(\xi_i)\right]=\frac{\frac{\partial}{\partial \xi_i}f_i(\xi_i)}{f_i(\xi_i)},$$

therefore, taking into account the above equality, the system of likelihood equations (1.1) takes the following form

$$\begin{cases}\sum_{i=1}^{n}\sin\alpha_i\frac{\frac{\partial}{\partial \xi_i}f_i(\xi_i)}{f_i(\xi_i)}=0,\\ \sum_{i=1}^{n}\cos\alpha_i\frac{\frac{\partial}{\partial \xi_i}f_i(\xi_i)}{f_i(\xi_i)}=0,\end{cases} \qquad (1.2)$$

$$\xi_i=X\sin\alpha_i+Y\cos\alpha_i-r_i.$$

The study [10] proposes using an orthogonal decomposition as the probability density function of navigation measurement errors. It is shown that the best agreement with the histograms of measurement errors is achieved by using only the first term of the orthogonal decomposition, which has the following analytical expression

$$f_i(\xi_i)=(2\pi)^{-1/2}\sigma_i^{-1}\exp\left(-\xi_i^2/2\sigma_i^{-1}\right)\left\{1+\frac{\left(\mu_{4i}/\sigma_i^4-3\right)}{24!}\left[\left(\xi_i/\sigma_i^2\right)^4-6\left(\xi_i/\sigma_i^2\right)^2+3\right]\right\},$$

where μ_{4i}/σ_i^4-3 (kurtosis of the distribution); μ_{4i} – the fourth central point of error; σ_i^2 – error variance.

Let's find the expression of the first derivative $\partial/\partial\xi_i \ln f_i(\xi_i)$ for the given orthogonal decomposition:

$$\frac{\partial}{\partial \xi_i}\ln f_i(\xi_i)=\frac{\partial}{\partial \xi_i}\ln\left\{\begin{array}{l}(2\pi)^{-1/2}\sigma_i^{-1}\exp\left(-\xi_i^2/2\sigma_i^2\right)\times\\ \times\left[1+\frac{\left(\mu_{4i}/\sigma_i^4-3\right)}{24!}\left[\left(\xi_i/\sigma_i^2\right)^4-6\left(\xi_i/\sigma_i^2\right)^2+3\right]\right]\end{array}\right\},$$

or

$$\frac{\partial}{\partial \xi_i}\ln f_i(\xi_i)=-\xi_i/\sigma_i^2+\left\{\frac{\left(\mu_4/\sigma^4-3\right)}{4!}\left[4\xi_i^3/\sigma_i^8-12\xi_i/\sigma_i^4\right]\right\}\Big/Q,$$

where

$$Q=\left[1+\frac{\left(\mu_4/\sigma^4-3\right)}{4!}\left[\left(\xi_i/\sigma_i^2\right)^4-6\left(\xi_i/\sigma_i^2\right)^2+3\right]\right].$$

Substituting this expression into the original system of equations, it is possible to obtain

$$\begin{cases}\sum\limits_{i=1}\sin\alpha_i\left\{-\dfrac{\xi_i}{\sigma_i^2}+\dfrac{\dfrac{\left(\mu_{4i}/\sigma_i^4-3\right)}{(4)!}\left[4\xi_i^3/\sigma_i^8-12\xi_i/\sigma_i^4\right]}{\left[1+\dfrac{\left(\mu_{4i}/\sigma_i^4-3\right)}{(4)!}\left[\left(\xi_i/\sigma_i^2\right)^4-6\left(\xi_i/\sigma_i^2\right)^2+3\right]\right]}\right\}=0;\\ \sum\limits_{i=1}\cos\alpha_i\left\{-\dfrac{\xi_i}{\sigma_i^2}+\dfrac{\dfrac{\left(\mu_{4i}/\sigma_i^4-3\right)}{(4)!}\left[4\xi_i^3/\sigma_i^8-12\xi_i/\sigma_i^4\right]}{\left[1+\dfrac{\left(\mu_{4i}/\sigma_i^4-3\right)}{(4)!}\left[\left(\xi_i/\sigma_i^2\right)^4-6\left(\xi_i/\sigma_i^2\right)^2+3\right]\right]}\right\}=0;\\ \xi_i=x\sin\alpha_i+y\cos\alpha_i-r_i.\end{cases}$$

In the case of equidistant position lines $\sigma_i^2=\sigma^2$ and $\mu_{4i}=\mu_4$ the previous system of equations takes the following form

$$\begin{cases}\sum\limits_{i=1}\sin\alpha_i\left\{-\dfrac{\xi_i}{\sigma^2}+\dfrac{\dfrac{\left(\mu_4/\sigma^4-3\right)}{(4)!}\left[4\xi_i^3/\sigma^8-12\xi_i/\sigma^4\right]}{\left[1+\dfrac{\left(\mu_4/\sigma^4-3\right)}{(4)!}\left[\left(\xi_i/\sigma^2\right)^4-6\left(\xi_i/\sigma^2\right)^2+3\right]\right]}\right\}=0;\\ \sum\limits_{i=1}\cos\alpha_i\left\{-\dfrac{\xi_i}{\sigma^2}+\dfrac{\dfrac{\left(\mu_4/\sigma^4-3\right)}{(4)!}\left[4\xi_i^3/\sigma^8-12\xi_i/\sigma^4\right]}{\left[1+\dfrac{\left(\mu_4/\sigma^4-3\right)}{(4)!}\left[\left(\xi_i/\sigma^2\right)^4-6\left(\xi_i/\sigma^2\right)^2+3\right]\right]}\right\}=0;\\ \xi_i=x\sin\alpha_i+y\cos\alpha_i-r_i.\end{cases}\qquad(1.3)$$

Solving this system of equations and having the value of the variance σ^2 and the fourth central moment μ_4 of the output error distribution, the observed coordinates of the vessel are determined without using the expression for the probability density function of the position line errors.

To estimate the efficiency, it is necessary to compute the improper integrals *q*, *p*, and *s* using the expressions provided in [15]

$$q=\int_{R1} f(x)\left\{\frac{\left[\frac{\partial^2}{\partial x^2}\varphi(x)\right]\varphi(x)-\left[\frac{\partial^2}{\partial x^2}\varphi(x)\right]^2}{\varphi^2(x)}\right\}dx;\ p=\int_{R1} f(x)\left\{\left[\frac{\frac{\partial}{\partial x}\varphi(x)}{\varphi(x)}\right]^2\right\}dx;$$

$$s=\int_{R1}\frac{\left[\frac{\partial}{\partial x}f(x)\right]^2}{f(x)}dx.$$

Let's assume there are *n* position lines which errors follow a distribution that differs from the Gaussian law – for example, a mixed distribution of the first type [16] with density function $f_1(x)$. Let's estimate the accuracy of the vessel's coordinates when they are computed using the method that applies the orthogonal expansion of the density function.

To eliminate scale parameters in the density function $f_1(x)$ and its expansion $\varphi(x)$ and ensure their compatibility, let's consider their corresponding normalized density functions $g_1(x)$ and $\psi(x)$, where *x* – a standardized and centered random measurement error. In this case

$$g_1(x)=\frac{B_1}{\left(x^2/(2n-1)+1\right)^{n+1}}. \tag{1.4}$$

Here $B_1=\dfrac{2^{2n}\left[(n)!\right]^2}{(2n-1)^{1/2}\pi(2n)!}$ – normalizing factor, *n* – significant integer parameter.
The variance of *x* is 1, and the fourth central moment is

$$\mu_4=\frac{(2n-1)^2 n!\left[2(n-2)\right]!24}{2(2n)!(n-2)!}.$$

Orthogonal density decomposition $\psi(x)$ of a normalized random variable with unit variance has the following form

$$\psi(x)=\frac{1}{\sqrt{2\pi}}\exp\left(-x^2/2\right)\left[1+\frac{(\mu_4-3)}{24}\left(x^4-6x^2+3\right)\right].$$

For convenience, let's denote $f_N(x)=\frac{1}{\sqrt{2\pi}}\exp\left(-x^2/2\right)$, therefore

$$\psi(x)=f_N(x)\left[1+\frac{(\mu_4-3)}{24}\left(x^4-6x^2+3\right)\right]. \tag{1.5}$$

Efficiency e_R of the ship coordinates in this case is determined by the expression

$$e_R=\frac{q^2}{ps}, \tag{1.6}$$

where p, q and s – improper integrals that depend on densities $g_1(x)$ and $\psi(x)$.

Let's write the expressions of the nonproprietary integrals p, q and s depending on the densities $g_1(x)$ and $\psi(x)$

$$q=\int\limits_{R1} g_1(x)\left\{\frac{\left[\frac{\partial^2}{\partial x^2}\psi(x)\right]}{\psi(x)}\right\}dx-p;\ p=\int\limits_{R1} g_1(x)\left\{\left[\frac{\frac{\partial}{\partial x}\psi(x)}{\psi(x)}\right]^2\right\}dx;\ s=\int\limits_{R1}\frac{\left[\frac{\partial}{\partial x}g_1(x)\right]^2}{g_1(x)}dx.$$

Calculating the value of the integral p requires an expression for the derivative $\frac{\partial}{\partial x}\psi(x)$

$$\frac{\partial}{\partial x}\psi(x)=f_N(x)\left\{-x+\frac{(\mu_4-3)}{24}\left[-x^5-10x^2-15x\right]\right\}.$$

Therefore, the improper integral p is calculated using the expression

$$p=\int\limits_{R1}\frac{B_1}{\left(x^2/(2n-1)+1\right)^{n+1}}\left\{\frac{-x+\frac{(\mu_4-3)}{24}\left[-x^5-10x^2-15x\right]}{1+\frac{(\mu_4-3)}{24}\left(x^4-6x^2+3\right)}\right\}^2 dx. \tag{1.7}$$

To calculate the value of the integral q, an expression $\frac{\partial^2}{\partial x^2}\psi(x)$ for the second derivative should be found

$$\frac{\partial^2}{\partial x^2}\psi(x)=f_N(x)\left[Q(x)+\frac{(\mu_4-3)}{6}\left(-2x^4+9x^2-3\right)\right],$$

where

$$Q(x)=\left(x^2-1\right)\left[1+\frac{\left(\mu_4-3\right)}{24}\left(x^4-6x^2+3\right)\right].$$

Therefore

$$q=\int_{R1}\frac{B_1}{\left(x^2/(2n-1)+1\right)^{n+1}}\left\{\frac{Q(x)+\frac{\left(\mu_4-3\right)}{6}\left(-2x^4+9x^2-3\right)}{1+\frac{\left(\mu_4+3\right)}{24}\left(x^4-6x^2+3\right)}\right\}dx-p. \tag{1.8}$$

Let's find an expression for the nonproprietary integral *s*, for which it is possible to use the expression of the standard density of the unnormalized error, which has the form

$$f_1(\xi)=\frac{A_m}{\left(\xi^2/2+\lambda\right)^{m+1}},$$

where

$$A_m=\frac{2^{2m}\left(m!\right)^2}{\sqrt{2\pi}\left(2m\right)!}\lambda^{m+1/2}. \tag{1.9}$$

In [14] it is shown that for a given density the improper integral s takes the following form

$$s=\frac{(n+1)(2n+1)}{(2n-1)(n+2)}. \tag{1.10}$$

An evaluation of the effectiveness e_R was carried out for density $g_1(x)$ with values of the essential parameter equal to 2, 3, 4, 5, 6, 8, 10. **Table 1.1** shows the values of the normalizing factor B_1 and the fourth central moment μ_4 for the specified values of the parameter *n*. The calculation of the improper integrals *p* and *q* was carried out according to expressions (1.7) and (1.8) by Simpson's method with integration limits from –6 to 6, which includes all normalized and centered random variables. The integral *s* was calculated according to formula (1.10). Evaluation of efficiency e_R was carried out using expression (1.6) and its value is given in the second line of **Table 1.1**.

The paper [14] presents the results of calculating the efficiency e_G of the vessel coordinates in the case of the distribution of position line errors according to the mixed law of the first type with the density $g_1(x)$, and the calculation of coordinates was performed by the least squares method. Efficiency value e_G are also given in **Table 1.2**.

Table 1.1 Value of the normalizing factor B_1 and the moment μ_4

n	2	3	4	5	6	8	10
B_1	0.4903	0.4558	0.4402	0.4314	0.4257	0.4187	0.4147
μ_4	9	5	4.2	3.857	3.667	3.462	3.353

Table 1.2 Efficiency e_G and e_R distribution density $g_1(x)$

n	3	4	5	6	8	10
e_G	0.893	0.934	0.955	0.968	0.980	0.987
e_R	0.994	1	1	1	1	1

Analysis of **Table 1.2** shows high efficiency e_R of the ship's coordinates obtained by the proposed method of applying orthogonal decomposition, which exceeds the efficiency e_G coordinates calculated by the method of least squares.

Let's consider the situation when position line errors are distributed according to a mixed law of the second type [16] with density $f_2(\xi)$. Let's find an expression for the purpose of evaluating the efficiency of the ship's coordinates based on its calculation using equations (1.3) with the use of orthogonal density decomposition.

As in the previous case, let's use normalized densities $g_2(x)$ and $\psi(x)$, where x – normalized and centered random measurement error. Moreover

$$g_2(x)=\frac{B_2}{\left(x^2/2n+1\right)^{n+3/2}}.$$

In this expression $B_2=\dfrac{(2n+1)!}{(2n)^{1/2}2^{2n+1}(n!)^2}$ – normalizing factor, and the central fourth moment $\mu_4=\dfrac{n^2 24(n-2)!}{8n!}$.

Expressions of the improper integrals p, q and s depending on the densities $g_2(x)$ and $\psi(x)$ have the form

$$q=\int_{R1} g_2(x)\left\{\frac{\left[\frac{\partial^2}{\partial x^2}\psi(x)\right]}{\psi(x)}\right\}dx-p;\ p=\int_{R1} g_2(x)\left\{\left[\frac{\frac{\partial}{\partial x}\psi(x)}{\psi(x)}\right]^2\right\}dx;\ s=\int_{R1}\frac{\left[\frac{\partial}{\partial x}g_2(x)\right]^2}{g_2(x)}dx.$$

Taking into account the previously obtained expressions for the derivatives $\frac{\partial}{\partial x}\psi(x)$ and $\frac{\partial^2}{\partial x^2}\psi(x)$ improper integrals *p* and *q* are calculated using expressions:

$$p=\int_{R1}\frac{B_2}{x^2/(2n+1)^{n+3/2}}\left\{\frac{-x+\frac{(\mu_4-3)}{24}\left[-x^5-10x^2-15x\right]}{1+\frac{(\mu_4-3)}{24}(x^4-6x^2+3)}\right\}^2 dx, \tag{1.11}$$

$$q=\int_{R1}\frac{B_2}{x^2/(2n+1)^{n+3/2}}\left\{\frac{Q(x)+\frac{(\mu_4-3)}{6}(-2x^4+9x^2+3)}{1+\frac{(\mu_4-3)}{24}(x^4-6x^2+3)}\right\}^2 dx-p. \tag{1.12}$$

Similarly to the previous case, in [14], a solution of the improper integral *s* was obtained, which has the following form

$$s=\frac{(2n+3)(n+1)}{2n(n+5)}. \tag{1.13}$$

For density $g_2(x)$ efficiency e_R was calculated, and the value of the significant parameter is 2, 4, 6, 8, 10. **Table 1.3** shows the value of the normalizing factor B_2 and the fourth central moment μ_4 for the listed values of the parameter *n*.

Table 1.3 Value of the normalizing factor B_2 and the moment μ_4

n	2	4	6	8	10
B_2	0.4688	0.4350	0.4233	0.4173	0.4137
μ_4	6	4	3.6	3.43	3.33

According to expressions (1.11) and (1.12), the improper integrals p and q were calculated by Simpson's method within the limits of integration from −6 to 6. The integral s was calculated by formula (1.13). Using expression (1.6), the efficiency estimate was calculated, and its obtained values are given in the second row of **Table 1.4**.

Results of the calculation of the efficiency e_G of the vessel coordinates in the case of the distribution of position line errors according to the mixed law of the second type with density $g_2(x)$, and the calculation of the coordinates was performed by the least squares method given in [14]. The efficiency e_G values are also given in **Table 1.4**.

Table 1.4 Efficiency e_G and e_R distribution density $g_1(x)$

n	**3**	**4**	**5**	**6**	**8**	**10**
e_G	0.917	0.945	0.962	0.971	0.982	0.988
e_R	0.996	1	1	1	1	1

Analyzing **Table 1.4**, let's note the high efficiency e_R of the ship's coordinates calculated by the proposed method of applying orthogonal decomposition, which exceeds the efficiency e_G coordinates obtained by the least squares method.

Thus, by applying the orthogonal expansion of the density of errors of the position lines and calculating the coordinates of the vessel's location using the system of equations (1.3), the dispersion of the observation error is reduced, which leads to increased energy efficiency.

1.5 Conclusion

In conclusion, improving the energy efficiency of ships is an important step in reducing the shipping industry's impact on the environment. There are various strategies and technologies that can be employed to achieve this goal, including hull coatings, waste heat recovery, energy management systems, hybrid propulsion systems, and wind propulsion. While each strategy has its advantages and limitations, their combined use can help improve the overall energy efficiency of ships and reduce their impact on the environment.

Study demonstrates that significant improvements in vessel energy efficiency can be achieved through enhanced navigation methods. Key conclusions include:

1. The potential for fuel consumption reduction through combined optimization approaches.

2. The feasibility of implementing proposed methods without major technical modifications.

3. The importance of integrating multiple optimization strategies for maximum effectiveness.

The findings support the development of more sophisticated navigation protocols that prioritize energy efficiency while maintaining operational safety and effectiveness. The study contributes to the broader field of maritime energy efficiency by providing practical, implementable solutions based on navigation optimization.

The proposed method of determining the coordinates of the vessel using orthogonal expansion of the density of the error distribution provides higher efficiency compared to the least square method. At the same time, for both types of mixed error distribution laws, almost full efficiency (close to 1) is achieved already at $n \geq 4$. Reducing the dispersion of the observation error allows to increase the accuracy of determining the location of the vessel and, as a result, improve its energy efficiency.

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CHAPTER 2

Energy-efficient ship route planning considering meteorological navigation conditions

Nadiia Vasalatii

Abstract

The aim of this study was to examine and address all aspects related to various ship optimization systems, as well as to analyze the impact of currents in the Strait of Gibraltar on the fuel efficiency of maritime vessels and to substantiate navigational decisions that allow for the optimization of energy consumption.

The necessity for the modernization of meteorological support has been considered, and the convenience, speed, and reliability of using software for navigational route adjustments have been demonstrated. Their impact on the management of maritime operations and the enhancement of safety has been analyzed. The influence of hydrodynamic currents in the Mediterranean Sea on the energy efficiency of maritime transport has been studied. Taking into account the spatial and temporal variability of current characteristics, an analysis was conducted on their effect on vessel maneuverability and fuel efficiency. Satellite observations, ERA5 atmospheric reanalysis data, and in-situ NOAA studies were used to construct a current velocity map of the Strait of Gibraltar.

Approaches for optimizing maritime routes considering currents were proposed with the aim of reducing fuel consumption and CO_2 emissions. It was shown that adjusting a vessel's course in accordance with the direction of currents can reduce fuel consumption by up to 15%.

Keywords

Energy efficiency, navigational route optimization, fuel consumption, ocean currents, meteorological conditions, energy model, Mediterranean Sea, Strait of Gibraltar, current velocities, water masses.

2.1 Introduction

Climate change is causing more frequent and severe weather events, such as tropical cyclones, storms, and abnormal waves. This increases the risks to maritime

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navigation, especially in sea areas with high traffic density. The use of meteorological software helps ships to quickly adapt their routes to changing conditions and avoid hazardous zones.

Economic fluctuations and rising fuel prices are prompting shipowners to seek ways to minimize operational costs. Route optimization using programs such as SPOS, WNI, and BON VOYAGE allows for a reduction in fuel consumption by selecting the most economical routes, taking into account current weather conditions.

Environmental standards are being tightened globally, requiring a reduction in harmful emissions such as CO_2 from maritime transport. Route optimization can reduce voyage time and fuel consumption, which in turn lowers the environmental impact of shipping activities.

Modern meteorological computer programs help to mitigate the risk of accidents or damage to vessels caused by adverse weather conditions. This is particularly relevant for large cargo ships, tankers, or passenger liners, where accidents can have catastrophic consequences for human lives and the environment.

2.2 Optimization of maritime routes through meteorological decision support systems: SPOS, WNI, and BON VOYAGE

In modern maritime navigation, reducing fuel consumption and minimizing harmful atmospheric emissions are pressing issues. One of the most effective approaches in this regard is the implementation of energy-efficient routing, which relies on real-time adjustment of ship routes based on current meteorological conditions. This method not only optimizes fuel usage but also ensures safer and more reliable voyages.

With the advancement of computer technologies and artificial intelligence, meteorological software tools have become increasingly accurate and reliable, thereby enhancing their operational efficiency. Improved algorithms enable precise weather forecasting and automatic suggestions for optimal routing, reducing the influence of human error in decision-making processes.

The growth of global trade continues to drive the expansion of maritime transportation, thereby increasing the demand for safe and cost-efficient routes. Computer-based navigation systems have become critical tools for shipowners and operators, assisting them in achieving optimal performance.

Effective vessel management depends on accurate meteorological forecasting and route optimization. Rapid changes in weather conditions can significantly impact both the safety and efficiency of maritime operations. Meteorological computer systems provide real-time solutions for route adjustment by accounting for atmospheric factors.

Thus, the use of meteorological software in navigation has become increasingly relevant for the maritime industry, as it addresses current challenges related to weather variability, resource efficiency, and operational safety.

To implement this concept in practice, specialized software packages such as SPOS, WNI, and BON VOYAGE are actively employed. These systems were developed to support decision-making processes for route planning based on meteorological data [1].

These systems allow for the consideration of wind conditions, wave states, currents, and other meteorological factors to formulate the most energy-efficient ship route (**Fig. 2.1**).

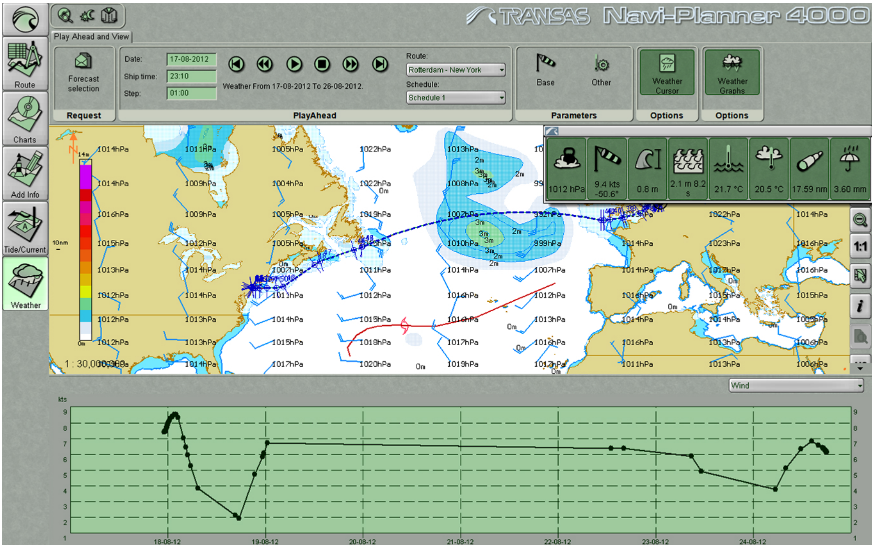

Fig. 2.1 Ship voyage optimized based on weather forecasting using DTN SPOS

Meteorological computer systems share common functional features that enable them to:

– receive forecast weather maps updated in real-time (in GRIB, NetCDF formats);

– analyze the impact of weather factors (wind, current, wave height) on possible ship trajectories;

– construct alternative routes and select the best one based on criteria such as minimizing fuel consumption, reducing transit time, decreasing mechanical stress on the vessel, and ensuring safe navigation.

Integrate weather-optimized routes into ECDIS or other electronic navigation systems for automated course plotting.

Each system has its own distinctive features.

SPOS (Ship Performance Optimization System) focuses on adaptive routing and calculating energy consumption considering the specific characteristics of the vessel. It provides weather forecasts and assists the ship captain in selecting the optimal route by accounting for the effects of wind, waves, and currents on the ship.

SPOS capabilities include:

− providing up to 9-day forecasts with global coverage;

− importing routes from Transas ECS into SPOS;

− subscription, receipt, and display of weather forecasts twice daily;

− calculating multiple routes considering weather conditions;

− comparing route results;

− creating optimal routes and exporting them back to Transas ECS;

− saving the best route as a voyage plan with daily updates.

A notable feature of this program is its ability to analyze historical data and predict the influence of weather conditions on fuel consumption and transit time. Additionally, SPOS allows integration of these data with other onboard systems, making the decision-making process more comprehensive [3].

WNI (Weathernews Inc.) enables shipowners to monitor their fleets online while accounting for weather risks across all transit zones. The program also provides real-time meteorological data and route recommendations, considering possible changes in weather conditions. WNI uses machine learning algorithms to improve forecast accuracy and can be integrated with automatic ship control systems, ensuring maximum adaptability to changes in the navigational environment [4].

The **BON VOYAGE System (BVS)** offers tools for meteorological data analysis and route optimization, helping to avoid hazardous weather conditions and improve voyage efficiency. BVS allows modeling of various weather development scenarios and analyzing their impact on the route, which is particularly useful when navigating challenging regions such as the North Atlantic Ocean or southern latitudes [5]. The software suite is deeply integrated with AIS, enabling ETA forecasting and calculation of expected CO_2 emissions.

In practice, these programs have already demonstrated their effectiveness in real maritime operations. For example, in 2018, a Maersk container vessel using SPOS managed to avoid severe storm conditions in the Pacific Ocean, resulting in a savings of several days in transit time and a significant amount of fuel. Similarly, WNI is used by many cruise lines for route planning, providing maximum passenger comfort and minimizing the impact of stormy weather.

Following the implementation of weather-dependent route adjustments by shipping companies, the following outcomes have been recorded:

– reduction of fuel consumption by 5–10%, corresponding to savings of tens of tons on transatlantic voyages;

– decrease in CO_2 emissions by 3–8%, directly contributing to IMO decarbonization targets;

– improved ETA accuracy, helping to avoid penalties and disruptions in logistics chains;

– enhanced navigation safety, especially in storm-prone areas such as the North Atlantic, Indian Ocean, and South China Sea.

It is also important to note that even a minor route alteration – for instance, a deviation of 50–80 nautical miles – can significantly change the effects of wind and waves on the vessel, resulting in substantial energy savings.

One of the primary advantages of using meteorological software is the reduction of fuel costs. According to various studies, route optimization with the help of these programs can save up to 10% of fuel over long distances, which significantly impacts the overall expenses of shipping companies. Moreover, fuel savings also lead to a reduction in greenhouse gas emissions, an important factor in the context of international environmental protection commitments. At a fuel price of 600–700 USD per ton, saving even 10 tons per voyage translates into 6,000–7,000 USD, which is economically justified even for small-tonnage vessels. For large bulk carriers or container ships, the potential savings increase substantially.

Additionally, considering the implementation of carbon taxes and CII/EEXI regulations, the use of weather-driven routing directly affects the company's environmental indicators and its competitiveness in the freight market.

The development of meteorological software for maritime navigation continues. One promising direction is the integration of these programs with artificial intelligence systems, which will automate decision-making and make navigation even safer and more efficient. Another prospect is the use of real-time satellite data, which will provide even more accurate weather forecasts [6, 7].

2.3 Ensuring meteorological safety of shipping using the SPOS program

The existing information support systems on maritime shipping routes exert a controlling influence on vessel navigation safety, as well as on maneuvering and vessel traffic flow under constrained navigation conditions. Depending on the state of the navigational information environment, the causes of hazards and emergency situations arise. Until recently, when a vessel was not regarded as an object of waterway information security, the consideration of marine exposure risk factors – which are constantly expanding due to the unpredictability of the volume of data received about natural, technological, economic, and socio-political changes in globalized shipping – was neglected.

At the same time, the relativity of the actual navigational situation on waterways is often explained by deficiencies in the existing scientific and instrumental tools responsible for adequately reflecting the navigational environment. These shortcomings cause distortions of the information space and erroneous situational assessments, thereby creating conditions conducive to accidents. Accordingly, instrumental tools in the form of methods and models of shipping information security have become a top priority in the development of vessel traffic management systems. Their operation is regarded as a key guarantee for ensuring the reliability, sufficiency, and timeliness of managed maritime content.

Amid the global push towards shipping decarbonization, fuel consumption optimization has acquired strategic importance. One of the most effective tools in this context is vessel routing that takes meteorological conditions into account, allowing the reduction of main engine load by utilizing favorable wind and current conditions.

Modern marine vessels are capable of navigating in challenging weather conditions; however, wind, waves, strong opposing currents, and a range of other hydrometeorological factors affect the speed and course of ships and, consequently, the efficiency of shipping operations. These influences lead to increased voyage duration, greater risk of deck damage and cargo shifting, deteriorated working and resting conditions for the crew, and reduced comfort for passengers. Therefore, contemporary consideration of hydrometeorological conditions enhances not only the safety of navigation but also the economic performance by optimizing fleet operations. Utilizing favorable weather conditions represents a significant reserve for reducing maritime transportation costs.

Currently, the description of atmospheric and oceanic phenomena and processes is based on the concept of their complex interactions. Numerical models and advanced physical-statistical forecasting methods are employed to theoretically justify atmospheric phenomena such as frontal tropical cyclones and winds. To explain wave excitation processes, techniques like level oscillation tracking, spectral, and harmonic analysis are used. Additionally, many new theoretical frameworks and practical recommendations are being developed for the analysis and characterization of sea ice as a hazardous phenomenon in navigation.

The application of fundamental principles of marine meteorology and oceanography for shipping needs has led to the emergence of a specialized science –

hydrometeorological support for the navigation of the maritime fleet. This includes a set of measures implemented by the State Hydrometeorological Committee, the Ministry of the Maritime Fleet, other agencies, and ship crews.

An integral part of hydrometeorological support in shipping is the organization of hydrometeorological observations onboard vessels. These observations are used for the operational assessment of hydrometeorological impacts on navigation and for transmitting data to primary organizations where they are processed and analyzed to produce weather forecasts at sea.

The largest provider of meteorological forecasts in Europe, Singapore, and the USA is MeteoGroup. The group employs approximately 100 meteorologists who offer services in nine European languages. Meteorological experts provide forecasts, support, monitoring, and consulting services 24 hours a day, 365 days a year. Moreover, MeteoGroup's specialized research team continuously develops proprietary forecasting systems and methods.

One of their key products, and among the most functional solutions already applied in practice, is the Ship Performance Optimization System (SPOS) – specialized software designed to enable captains and navigation officers to adjust route calculations based on the provided weather information and specific vessel characteristics. This allows the captain to plot the optimal route – both in terms of safety and efficiency – under prevailing weather conditions.

MeteoGroup, together with major ECDIS providers, has combined two key products to deliver an ideal integrated solution for ship route optimization – SPOS integrated with navigational routing in ECDIS.

With the introduction of SPOS, a new method of ship routing that accounts for weather conditions was created. This software is a tool that helps the captain and watch officers onboard make informed decisions regarding voyage planning based on weather conditions.

Using the Ship Performance Optimization System enables safe and efficient global navigation by reducing fuel consumption and promoting a cleaner environment. Installed onboard, SPOS is a leading weather-aware ship routing system. With SPOS, a vessel's route can be optimized considering weather factors such as currents, wave height, wind speed and direction, and other meteorological elements.

The meteorological bureau MeteoGroup prepares a comprehensive set of accurate weather information for oceanic regions and coastal waters. This information includes forecasts of wind speed and direction, wave height and period, as well as data on tropical storm forecasts and ice edge boundaries. Weather information is sent by email to many vessels, and the crew can display the forecasts in a presentation format of their choice.

To evaluate the results of different routes within SPOS, the following analysis tools are available:

− comparative tables;

− charts;

− diagrams.

Once a user selects the preferred route to follow, it can be saved as a voyage plan. With new weather forecasts automatically received daily, the voyage plan can be updated, and the impact on ETA is easily monitored as weather conditions change (**Fig. 2.2**). At the end of the voyage, SPOS provides a full route log.

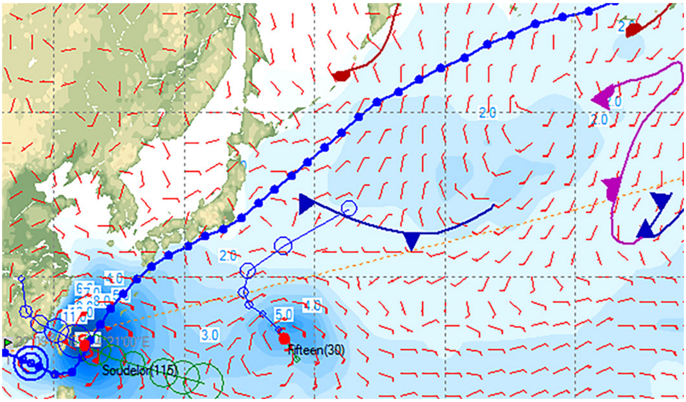

Fig. 2.2 Weather-aware map in the SPOS software

The SPOS system is implemented in several modules designed for use both onboard vessels and onshore.

SPOS On-board is a local module installed on the vessel that allows route planning taking into account current weather data. The captain or navigator can quickly review the impact of meteorological factors on fuel consumption for each segment of the route.

SPOS Fleet Management is a tool for operators and dispatchers ashore that provides centralized analysis of the fleet, routes, and forecasted weather changes.

RouteGuard is a routing and ship performance analysis service. Based on weather information combined with the expertise of qualified meteorologists and navigators, RouteGuard offers vessels optimal routes for any voyage.

Choosing the optimal route and achieving maximum ship performance requires accurate and detailed weather information. RouteGuard helps save time and fuel, reduce CO_2 emissions, and optimize planning based on precise ETAs, while keeping the crew, vessel, and cargo safe.

Ship performance analysis reports contain information necessary to identify underperformance and corresponding corrective actions.

All modules integrate with the Electronic Chart Display and Information System (ECDIS), ensuring full automation of route construction and data exchange with navigation systems.

SPOS does not have its own communication system; instead, it uses the ship's existing email system or internet connection. This simplifies operation for the crew, as they are already familiar with this system, and regular email is supported by the office.

Secondly, this approach saves money and time because the forecast is automatically sent to the mailbox along with other messages. In most cases, SPOS can automatically place messages into the mailbox using a so-called MAPI connection. However, this can also be done manually by saving files on the local hard drive. If an internet connection is available, HTTP can be used.

Several types of communication exist with SPOS:

− subscription to weather forecasts;

− receiving daily weather forecasts and optionally sending reports to the office.

Subscription to forecasts and receiving weather updates are critical for SPOS.

The SPOS system has two sources of weather information needed for route planning:

− a forecast database updated by email from MeteoGroup;

− climatological databases.

For route calculations, forecast data are used as long as the simulated voyage falls within the forecast range. Otherwise, climatological data are used at the end of the forecast period. The dedicated climatological database contains monthly average values for surface pressure, wind, wind waves, and ocean currents. The area covered by the climatological database spans from 75°N to 60°S latitude and 180°W to 180°E longitude, with a resolution of 2.5°.

Forecast data are available four times a day and cover the entire globe from 90°N to 90°S. Preliminary tidal data are divided into ocean regions such as the North Atlantic and the southern part of the Pacific Ocean (at a resolution of 2.5°), as well as smaller areas like the South China Sea and the Mediterranean for coastal waters (at a higher resolution of 1.0°).

Ocean forecasts are available for 5 and 9 days ahead, while coastal areas are forecasted up to 5 days in advance. Users can choose between a standard forecast, which includes wind, waves, and ocean currents, or an extended forecast that also covers precipitation, air temperature, visibility, and icing risk. Additionally, high-resolution parameters can be selected.

Routes planned with SPOS take into account wind direction and strength, wave height and direction, the hydrodynamic resistance of the vessel caused by wave motion, temperature changes affecting water viscosity, and ocean currents, including the Gulf Stream and trade winds in the oceans.

Forecast information is sourced from global meteorological systems (NOAA, ECMWF) and is updated daily or hourly. For each route option, SPOS provides alternatives ranked by parameters such as fuel savings, transit time, and safety conditions. The navigation team can select the optimal balance of these parameters according to transportation priorities.

The SPOS system demonstrates high efficiency in achieving fuel cost reduction and optimizing vessel routing by incorporating up-to-date meteorological data. Practical use of the system on commercial and passenger vessels confirms its significant impact on improving fuel efficiency, enhancing navigation safety, and ensuring environmental compliance with modern international shipping standards.

One of the key performance indicators of SPOS is fuel savings ranging from 5% to 15%, depending on the vessel type, route length, weather conditions, and correct interpretation of forecast data by the crew. For example, on transatlantic routes (Rotterdam – New York), fuel savings reach 20–25 tons per voyage, equivalent to a cost reduction of 10,000–15,000 USD. In the cruise sector, SPOS application helps avoid storm activity zones while maintaining passenger comfort and reducing the load on the propulsion system.

SPOS not only optimizes fuel consumption but also improves the accuracy of vessel Estimated Time of Arrival (ETA) forecasting. Thanks to daily updates of weather forecasts and the ability to promptly adjust the course, the vessel can:

− avoid delays related to weather conditions;

− reduce the need for "schedule chasing", which typically leads to excessive fuel consumption;

− coordinate port arrival more accurately, optimizing logistical operations at the berth.

Successful implementation of this functionality was demonstrated in the Maersk fleet, where ETA accuracy improved on average by 8–12%, alongside a reduction in energy consumption.

Since fuel savings directly contribute to reducing CO_2 emissions, implementing SPOS aligns with the IMO 2020 regulations and the CII/EEXI goals aimed at decarbonizing shipping. For every ton of fuel saved, CO_2 emissions are reduced by an average of 3.1 tons. Therefore, saving 20 tons of fuel per voyage corresponds to a reduction of over 60 tons of CO_2 emissions.

Route optimization also allows avoiding areas of heavy seas, which reduces hull vibration loads, the risk of damage to propeller and steering systems, and main engine wear by minimizing unnecessary speed fluctuations.

In the long term, this leads to lower maintenance costs and extends the service life of major components.

Table 2.1 presents a comparison of voyages conducted with and without SPOS, based on aggregated operator reports.

Table 2.1 Comparison of voyages conducted with and without SPOS

Indicator	Without SPOS	With SPOS
Fuel consumption (tons/voyage)	240	210
Transit time (hours)	180	174
CO_2 emissions (tons/voyage)	744	651
Average engine load	85%	78%
ETA deviation	± 6 hours	± 2 hours

The SPOS system demonstrates high efficiency in real-world shipping conditions by ensuring energy-saving, stable, and safe navigation. Further integration of SPOS with automated course control systems, digital twins of vessels, and satellite weather forecasting enables this tool to be considered a standard for energy efficiency management in the global fleet of the 21st century.

In practice, the use of SPOS allows achieving:

− a reduction in fuel consumption by 5–15%, depending on the type of vessel, route, and weather conditions;

− a corresponding reduction in CO_2 emissions due to lower fuel consumption;

− improved estimated time of arrival by avoiding adverse weather zones and reducing waiting times;

− decreased mechanical stress on the vessel's systems, reducing wear and tear.

The further development of energy-efficient routing is associated with the use of artificial intelligence to forecast weather scenarios and make real-time automatic decisions, as well as the creation of digital twins of vessels, which will allow even more accurate modeling of the environmental impact on energy consumption. Integration with autopilot and autonomous navigation systems will enable dynamic routing without human intervention.

2.4 Energy efficiency of shipping under the influence of hydrodynamic currents in the Mediterranean Sea

The global maritime industry is currently under pressure from requirements for decarbonization and improved fuel efficiency. Considering that maritime transport accounts for about 90% of global trade and over 3% of worldwide greenhouse gas emissions [8], the issue of energy-efficient shipping becomes extremely relevant.

One of the less studied but significant factors influencing fuel consumption and vessel navigation is hydrodynamic currents. In particular, the Mediterranean Sea and the Strait of Gibraltar have a complex water circulation structure, featuring a pronounced two-layer current system that creates both challenges and opportunities for energy-saving route optimization.

The Mediterranean Sea is characterized by its enclosed nature, significant evaporation, and limited freshwater inflow, which form a unique hydrodynamic system. These conditions establish a two-layer circulation: surface waters flow in from the Atlantic Ocean, while deeper waters return, transporting warm, highly saline Mediterranean water. This circulation pattern determines both micro- and macro-scale current dynamics.

The main node of water mass exchange is the Strait of Gibraltar, approximately 58 km long and up to 13 km wide. It facilitates the water exchange between the Atlantic Ocean and the Mediterranean Sea. According to calculations, the average inflow of surface waters from the Atlantic is about 70,000 m^3/s, while the deep outflow ranges between 40,000 and 50,000 m^3/s depending on seasonal conditions [9].

The water balance of the Mediterranean Sea is a key factor determining not only the overall hydrodynamic conditions in the region but also the spatiotemporal distribution of currents that significantly affect maritime transport conditions. The water balance is primarily shaped by four main components: inflow through the Strait of Gibraltar, river runoff, precipitation, and evaporation.

Current estimates indicate that annual evaporation from the surface of the Mediterranean Sea is approximately 1300 mm/year, corresponding to over 1800 km^3 of water. In comparison, total precipitation over the sea is only about 700 mm/year (around 1000 km^3), while river runoff is about 300 km^3/year. Thus, the overall water deficit exceeds 500 km^3 annually, which forces the Strait of Gibraltar to compensate with its two-layer circulation.

The surface inflow of less dense, cooler, and less saline Atlantic waters occurs at an average speed of 1–2 knots at depths up to 100–150 m. The deep outflow of warmer, highly saline Mediterranean waters forms at depths of 300–800 m, where current speeds reach 0.5–1 knot.

This circulation pattern significantly influences maritime routes – especially along the coasts of the Iberian Peninsula, North Africa, and in the Alboran Sea area. Vessels moving against the surface Atlantic inflow face additional resistance, while those traveling in the opposite direction can use the currents to improve fuel efficiency.

The hydrodynamic influence of currents on a vessel is a decisive factor in route planning, fuel consumption calculation, and ensuring energy-efficient navigation. In both open sea and coastal areas, currents can have either a favorable or adverse effect on vessel movement, altering its speed relative to the seabed, course direction, and energy expenditure required to overcome hydrodynamic resistance.

The hydrodynamic load can be described by the following formula:

$$C = f \cdot L \cdot d \cdot V_T,$$

where C – transverse load due to the current; f – empirical coefficient (dependent on hull shape and conditions); L – length at waterline; d – draft (ft); V_T – current velocity.

This model allows estimating the additional load that the ship's main power plant must compensate for during maneuvering or straight-line movement, taking into account the drift caused by currents.

In the study of energy-efficient ship routing, a comprehensive approach is used to analyze data combining multi-component processing of marine, meteorological, and hydrodynamic information. To ensure result accuracy and high resolution of calculations, both satellite and in-situ data sources are applied, alongside numerical modeling that enables assessment of the impact of weather and hydrological factors on the energy efficiency of maritime transport, as well as machine learning methods.

As input materials for calculating current speeds in the Strait of Gibraltar and specific areas of the Mediterranean Sea, data from the National Oceanic and Atmospheric Administration (NOAA) [10] were used. NOAA WaveWatch III is employed to evaluate the state of the sea surface, particularly wave fields. The input data also include results of in-situ expedition studies of temperature and salinity distributions of seawater at different sections in selected Mediterranean areas (**Fig. 2.3**).

As an alternative information source for assessing water mass exchange between the Mediterranean Sea and the Atlantic Ocean, high-precision climate reanalysis data providing hourly data with a spatial resolution up to 0.25° (~25 km) from ERA5 [11] were utilized, covering precipitation and evaporation for the period 2002–2020.

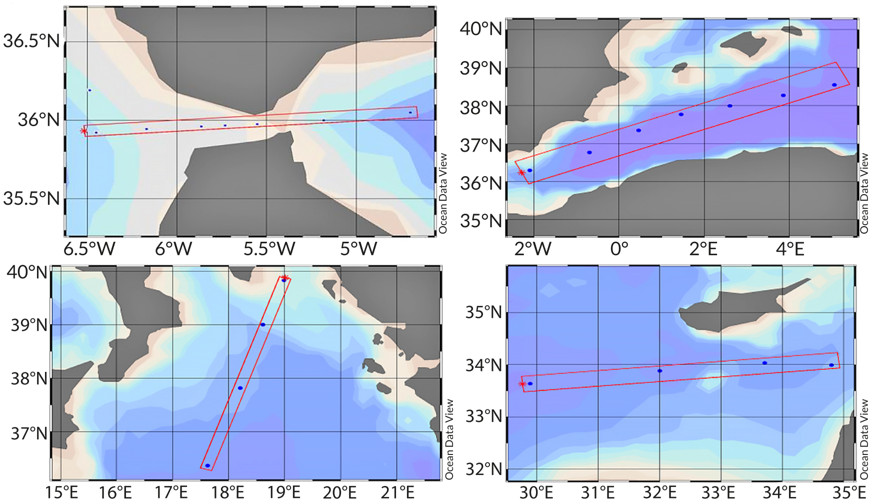

Fig. 2.3 Location of cross-sections in the Mediterranean Sea area

Research methodology is based on an interdisciplinary approach combining maritime navigation, hydrodynamics, meteorology, computational fluid dynamics, ship energy models, and numerical optimization. The primary goal is to develop and test algorithms for determining the most energy-efficient ship routes, minimizing energy consumption under complex marine conditions.

At the first stage, the research objective is formulated as minimizing energy (fuel) consumption along a route of a given length between the start and end points, subject to the following constraints:

– safety (avoiding hazardous areas such as storms, ice, shallow waters);
– time delivery constraints;
– navigational requirements (routes, depths, TSS lanes);
– spatiotemporal variability of hydrometeorological conditions.

Based on spatiotemporal fields (wind, waves, currents), data arrays are created for each maritime region in NetCDF/GRIB2 format. AIS data is used for reconstructing actual routes and conducting comparative analysis. Additionally, a digital map of marine obstacles is generated in vector format.

Building an energy model is a key step for quantitative assessment of a ship's energy consumption along a route under real hydrometeorological conditions. For the Mediterranean Sea area, characterized by complex circulation, the presence of permanent and seasonal currents, as well as spatial heterogeneity of wave regimes, this model must consider the interactive effects of the following factors, included in general formula for calculating instantaneous energy consumption

$$E(t)=\frac{\left[R_0+R_{wave}(t)\pm R_{current}(t)\right]\cdot V(t)}{\eta(t)},$$

where R_0 – ship resistance in calm water (determined by hull type, draft, speed, and vessel mass); R_{wave} – wave resistance (additional resistance caused by head or side waves); $R_{current}$ – hydrodynamic effect of currents (a decrease or increase in total resistance depending on the direction and speed of the current relative to the vessel's movement); η – efficiency of the propulsion system, which depends on engine load, RPM, propeller type, and varies under conditions of fluctuating speed.

The circulation system of the Mediterranean Sea is shaped by several key factors:

– the main countercurrent along the southern coast (Libya, Egypt);

– the Ligurian, Ionian, and Aegean cyclonic currents;

– the strong reverse flow of the Alghero-Provencal current (from west to east) and its branches;

– seasonal reversibility in the Aegean Sea due to wind action (Etesian winds).

In modeling energy consumption, the following are considered:

– the vector component of the current relative to the vessel's direction;

– vertical variation in current velocity, especially relevant for vessels with deep draught;

– turbulence and drift, which affect energy consumption during maneuvering or course changes;

– integration of current fields (from CMEMS or HYCOM data) at every waypoint with temporal resolution.

Corrected resistance accounting for currents is calculated using the formula

$$R_{current}=f\left(\rho,V_{rel},A_{wet},C_D\right),$$

where $V_{rel}=V_{ship}-V_{current}$ – speed of the vessel relative to the current; A_{wet} – wetted surface area of the hull; C_D – resistance coefficient dependent on the Reynolds number; ρ – density of seawater.

Total energy consumption along the route is calculated as the numerical integration over the trajectory

$$E_{total}=\int_{t_0}^{t_1}\frac{\left[R_0+R_{wave}(t)\pm R_{current}(t)\right]\cdot V(t)}{\eta(t)}dt.$$

This integration is performed discretely for each route segment (for example, every 10–15 nautical miles or every 30 minutes of simulation), taking into account the corresponding hydrometeorological conditions at the location.

The presented model is applied to construct energy maps of maritime areas where fuel consumption increases due to opposing currents or wave systems; to optimize routes by avoiding zones with high wave resistance or strong head currents; and to analyze the sensitivity of energy consumption to changes in current direction (e.g., in the Ionian Sea during summer/winter seasons).

The developed ship energy model, which considers the influence of currents, wave conditions, and wind loading in the Mediterranean Sea, enables a thorough analysis of the mechanisms of energy consumption at various stages of the maritime route. Based on the results obtained, a number of critical factors determining the ship's energy efficiency level have been identified.

The presence and direction of currents have a direct impact on energy consumption: modeling data show that favorable currents can reduce fuel consumption by 8–12%, while opposing currents, especially in narrow regions (the Strait of Gibraltar, the Strait of Sicily), can lead to overconsumption of 15% or more.

Wave conditions play a complex role in energy usage – when wave heights exceed 2.5 m, resistance to movement increases by 20–25%, which particularly affects vessels with large tonnage. Moreover, the dependence of energy consumption on wave direction is asymmetric – side waves cause course instability, while head waves directly increase hydrodynamic resistance.

The interaction between different environmental factors (currents + waves + wind) is nonlinear.

For example, a combination of headwind with waves and a lateral current shift can lead to a "hydrodynamic reversal" effect, requiring constant course corrections and increasing energy consumption by up to 18%.

Seasonal analysis of energy consumption shows that during the winter period, when wind activity and wave energy are at their peak, fuel consumption on average rises by 10–15% compared to the summer period. This necessitates seasonal adjustments to routing and navigation strategies.

High efficiency of using numerical current forecasts (in particular, from the Copernicus Marine Environment Monitoring Service) in real-time adaptive routing has been demonstrated. Optimized scenarios achieved fuel savings of up to 9.5% by changing the route according to current direction shifts.

Future research should focus on integrating machine learning into energy models, allowing automatic adaptation of route parameters to rapidly changing marine conditions. This approach opens the prospect for developing next-generation intelligent navigation systems aimed at sustainable development and maximum energy efficiency in maritime transport.

2.5 Conclusion

The use of meteorological software systems such as SPOS, WNI, and BON VOYAGE significantly enhances the safety and economic efficiency of maritime transportation. Their integration with other navigational systems enables more informed decision-making in route selection, thereby reducing weather-related risks, cutting fuel consumption, and lowering harmful emissions. This is especially critical amid current global environmental challenges. Further development of these technologies, particularly their integration with artificial intelligence systems, opens new opportunities for improving maritime operations management.

Route adjustments considering meteorological conditions via SPOS, WNI, and BON VOYAGE have proven to be effective tools for energy-efficient ship navigation. This approach achieves fuel savings, improves safety, and promotes environmentally responsible shipping.

In the future, the integration of such systems with AI modules, autonomous control, and satellite platforms will make weather-dependent routing an integral part of digital navigation.

The continuous implementation and updating of cutting-edge technologies and software onboard maritime fleets have made route planning more convenient, faster, and reliable by accounting for weather factors, economic aspects, and navigation safety.

An analysis and review of the SPOS system demonstrate that this software allows the easy construction of optimal routes based on weather forecasts for sailing areas, estimation of probable fuel consumption, safe port anchoring, and automatic notification of shipowners regarding weather conditions during voyages.

Energy-efficient ship route planning considering meteorological conditions is one of the key directions for sustainable development in shipping. Tools like SPOS provide practical realization of this concept and show significant potential in reducing costs, emissions, and risks. Further digitalization and the advancement of analytical platforms will make these solutions standard practice in the maritime industry.

A detailed analysis of the energy model confirms that integrating hydrodynamic environmental factors into navigational planning is a critical condition for achieving energy-efficient shipping in the Mediterranean Sea. Implementing such models in practice helps reduce fuel and operational costs, minimize greenhouse gas emissions – which aligns with the International Maritime Organization's decarbonization goals for maritime transport – and enhance the reliability and safety of voyages through more accurate navigation condition forecasting.

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CHAPTER 3

Consideration and assessment of navigational risks to improve energy-efficient ship management

Olena Rossomakha

Abstract

The section reveals the relationship between energy efficiency of shipping and navigational safety, which is of particular relevance in the context of the implementation of strict international environmental regulations (EEDI, EEXI, CII) and the growing requirements for optimizing fuel consumption. It is determined that classical methods of energy saving, in particular, reducing the speed, cannot be considered in isolation from the risks associated with the operation of a ship in difficult navigational conditions – narrow straits, areas of high traffic or unstable hydrometeorology.

The aim of the study is to develop an integrated approach to ship management that simultaneously takes into account energy efficiency and navigation risks. For the first time, the expediency of using multi-criteria routing models based on fuel consumption, accident risk, and current hydrometeorological conditions is substantiated. The article presents decision-making algorithms taking into account navigation safety constraints, which allow to adapt management actions in real time.

IMO requirements for fleet energy efficiency are outlined, as well as ways to implement them both technically and operationally. The role of digital solutions, including ECDIS, DSS, NAPA, StormGeo, Wärtsilä Voyage platforms, which support the crew in making informed decisions during the voyage, is emphasized. Particular attention is paid to the use of artificial intelligence methods for risk forecasting based on large amounts of data.

The article systemizes the classification of navigation risks (technical, human, digital, environmental), as well as methods of their assessment: qualitative (FMEA, SWOT, HAZID) and quantitative (ETA, FTA, risk matrices). The article considers the formation of an integrated hazard map, which includes trajectory points of the ship's route, maneuvering characteristics, weather forecasts, the state of equipment and crew training. It is shown that the combination of digital platforms, mathematical modelling and engineering analysis ensures informed decision-making.

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An approach to building a decision support system is proposed, taking into account changes in the external environment, technical characteristics of the vessel and the level of navigation threat. The effectiveness of digital routing based on multicriteria analysis for simultaneously achieving safety and fuel efficiency is proved. The importance of the ISO 31000:2018 standard for the formation of adaptive risk management systems in maritime transport is emphasized.

The results obtained have significant scientific and applied potential. They can be used in the practice of ship-owning companies, dispatch centers, maritime administrations, as well as in the process of crew training. Priority areas for further research include improving risk forecasting models, harmonizing international standards with the specifics of the Ukrainian fleet, and implementing unified information and analytical decision support systems.

Keywords

Navigational risks, energy-saving, shipping, multi-criteria planning, digital navigation systems, safety management, IMO indices (EEDI, EEXI, CII), artificial intelligence in shipping, risk assessment, adaptive ship management.

3.1 Introduction

Modern shipping is developing rapidly in the face of growing environmental challenges and stringent international regulatory requirements. Reducing greenhouse gas emissions has become a key issue for the shipping industry, leading to the emergence of new approaches to energy-efficient ship management. At the same time, ensuring navigation safety remains a priority, requiring consideration of complex and interrelated risks that arise during navigation in an environment of heightened uncertainty. As a result, there is a need to develop integrated approaches that simultaneously achieve energy efficiency goals and ensure navigation safety.

Global shipping demonstrates a steady increase in the volume of maritime traffic, which accounts for more than 80% of international trade [1].

The expansion of vessel sizes, the complexity of operational processes, and growing efficiency requirements pose new challenges to maritime safety.

Despite the development of shipbuilding and navigation systems, the number of serious accidents remains stable, indicating that existing risk management approaches are not sufficiently effective [2].

Particularly noteworthy is the impact of the human factor, which, according to numerous studies, is responsible for 75% to 96% of maritime accidents.

The review [2] systematizes data on the impact of psychological, organizational and ergonomic factors on shipping safety.

Paper [3] emphasizes the importance of applying human reliability analysis methods to help predict behavioral deviations of personnel in critical situations.

Paper [4] develops a fundamental "Swiss cheese" model that demonstrates how multiple levels of protection can be ineffective under a certain combination of human and organizational errors.

In today's digitalized maritime industry, world scientists propose using artificial intelligence methods to analyze large amounts of data, which allows for earlier detection of threats [5].

Research [6] shows that a safe climate in companies and the size of the fleet play a key role in preventing incidents. The relevance of the study is due to the fact that existing energy efficiency management strategies mostly consider economic and technical factors, while not sufficiently taking into account navigation risks. This can lead to decisions that reduce the efficiency of ship operation in a particular navigation situation. Risk assessment is becoming a key element in optimizing decisions related to route, speed, ship systems and fuel consumption.

The aim of the study is to develop methodological approaches to taking into account navigational risks in the system of energy-efficient ship management to improve the efficiency and safety of maritime transport. The subject of the study is navigation risks and their impact on the parameters of energy efficiency of ship operations. The object is the process of managing the operational characteristics of a vessel in the face of external and internal risks.

The objectives of the study include: analyzing existing risks in shipping, studying methods for their assessment, investigating the relationship between navigation risks and energy efficiency parameters, and developing a decision-making algorithm that takes into account both factors.

The scientific novelty of the work lies in the systematic approach to the integration of navigation risk models with energy management systems, which allows for synergy between safety and efficiency of ship management. The practical significance of the obtained results lies in the possibility of implementing the proposed models in automated decision support systems for shipmasters and dispatch services.

3.2 Theoretical foundations of energy efficient ship management

The current state of maritime transport is determined not only by increasingly stringent environmental requirements, but also by the need to improve the economic efficiency of fleet operations. Shipping companies are focusing on the rational use of energy resources, reducing fuel costs and complying with international sustainability standards. In particular, according to the policy of the International Maritime Organization (IMO), all ships must comply with a number of regulations, such as the Energy Efficiency Design Index (EEDI) for newly built ships, the Energy Efficiency Existing Ship Index (EEXI) for existing ships, and the Carbon Intensity Indicator (CII), which determines the intensity of carbon emissions during fleet operation [7].

Meeting IMO requirements means that shipowners must implement both technical solutions (hull shape optimization, modernization of propeller and rudder systems, transition to alternative energy sources) and operational measures. Among the latter, smart voyage planning is particularly important, including weather forecasting, speed optimization (e.g. slow steaming), route analysis with regard to navigational complexity, and the implementation of decision support systems (DSS) [8].

However, despite the undoubted benefits of energy-saving practices such as reducing speed or changing trajectory, they cannot be applied without risk analysis. For example, reducing speed in narrow or confined waters reduces the vessel's maneuverability, which can lead to accidents such as collisions, piles, and groundings.

In 2013, the IMO introduced EEDI for new ships, which measures energy efficiency in g CO_2/tons-mile, stimulating technical innovation (lower combustion quality, optimized propulsion systems, improved hulls). Stiffness requirements are expected to be tightened every five years, with a minimum 30% efficiency improvement required by 2025.

In June 2021, the IMO adopted amendments to the EEXI (technical assessment of the changed energy efficiency of ships over 400 GT) and CII (annual monitoring of the CO_2 emissions indicator) - both came into force on 1 November 2022, and their mandatory implementation began on 1 January 2023 [9]. The CII includes a rating of ships from A (best) to E (worst); ships with a D rating for three consecutive years or E for one year must submit corrective measures.

The IMO has set a target of reducing the carbon intensity of shipping by ≥ 40% by 2030 compared to 2008, with a further goal of zero emissions by 2050 [7].

Scientific research emphasizes the need to combine energy management with navigation risk analysis. For example, risk assessment at the stage of voyage planning (Risk-based Voyage Planning) helps to avoid a conflict between economic feasibility and safety [10].

Digital navigation systems play an important role in this process. In particular, the use of ECDIS electronic charts with hydrographic information quality assessment (CATZOC) allows calculating the permissible dynamic water reserve under the keel, taking into account chart errors, hydrometeorology, ship draft and pitch.

This is especially relevant in complex areas such as canals, port approaches, and river mouths [11].

An additional means of improving safety and energy efficiency is the Trajectory Points methodology. It allows not only to plan a course but also to identify high-risk areas, such as fairway bends, areas of limited depth, and pile-up zones.

An analysis of accidents on the above-mentioned canals in 2015–2021 showed that the vast majority of incidents occurred due to insufficient adaptation of speed regimes to hydrological conditions and the navigation situation. In particular, frequent groundings occurred due to neglect of recommendations on permissible draft based on water level forecasts.

This data confirms that the use of dynamic decision support systems based on multifactorial analysis (weather, depths, vessel restrictions, traffic) can significantly improve both safety and energy efficiency [12].

Digital platforms such as Maersk ECOvoyage, NAPA Voyage Optimization and StormGeo are being actively implemented around the world, providing automatic route adjustment depending on changes in the environment [13]. This allows to reduce fuel consumption by 3–7% depending on the vessel class [8].

According to the updates to the Ship Energy Efficiency Management Plan (SEEMP Part III), each operator must create an operational plan for CII improvement that takes into account both route performance and planned upgrades [7]. The document should also specify risk management mechanisms in accordance with ISO 31000:2018, which emphasizes the importance of assessing the impact of each management decision on safety [14].

Modern software allows to generate dynamic risk maps, taking into account real-time data variables: AIS, VTS data, weather forecasts, water levels, and the movement of other vessels. For example, the use of Big Data and machine learning algorithms in platforms such as Fleet Operations Solutions allows not only to optimize the course but also to predict danger long before it occurs [15].

3.3 Theoretical foundations of navigation risk management

Navigational risk is the probability of an undesirable event occurring during a sea voyage, which may have negative consequences for the crew, vessel, environment or cargo. According to research, navigation risk arises from a number of factors: technical, technological, environmental and human. IMO recommends defining risk as the product of the probability of an event and the severity of its consequences. This allows not only to classify risks but also to assess their priority. The main types of risks are technical, technological, environmental, human, and the latest ones related to the introduction of artificial intelligence. Each of them has its own nature and specifics, but in the practice of maritime transport, they often operate simultaneously, reinforcing each other. The human factor remains the most common cause of accidents. Crew mistakes, fatigue, and non-compliance with procedures remain relevant even in the face of automation. The introduction of digital solutions is accompanied by new threats, such as AI algorithm failures, cyber attacks, and imperfect interfaces. This is compounded by natural phenomena such as climate change, storms, icing, and shifts in seasonality. Modern shipping is gradually forming an understanding of the systemic nature of risks, which requires not only the identification of hazards but also the development of adaptive models for their analysis. Thus, effective risk management requires a combination of technical expertise, digital monitoring technologies, and the active participation of the crew in creating a safe environment on board [16].

Navigation risks are a set of potential threats that may arise during a sea voyage and affect the safety of the vessel, crew, cargo and the environment. Managing these risks is a prerequisite for ensuring the smooth, efficient and safe operation of ships in modern shipping. The concept of 'navigation risk' covers a complex system of interrelated technical, natural, organizational and human factors that form the potential for an accident to occur.

Scientific research shows that navigation risks should be classified according to various criteria: sources of occurrence, probability of occurrence, severity of consequences and scale of impact. In particular, the systematic approach considers the division into technical, human, environmental, organizational and emerging risks (e.g., those related to digital systems and AI. An important factor is also the consideration of synergistic effects and systemic interaction of elements, which complicates the forecasting of identified risks.

One of the fundamental principles of risk management is the need not only to identify risks, but also to analyze, monitor and respond to them as part of voyage planning. Domestic researchers have shown that traditional methods of transition planning, as set out in the Bridge Procedures Guide, are insufficient in terms of forecasting and taking risks into account. In particular, the current IMO recommendations do not include a separate stage of navigational risk assessment when planning a route. This requires modernizing approaches to risk management through the introduction of engineering analysis, the construction of hazard matrices, and improved waypoint planning that takes into account the ship's maneuvering properties in real time.

The results of the statistical data analysis show that the most common risks are grounding, collisions, piles and equipment failure. In each case, there are certain accident-prone sections of the route for which the probability of an incident can be calculated based on historical data and the physical and geographical characteristics of the navigation area. Expert estimation methods, such as those used by insurance companies, allow modelling the sequence of events, their consequences and economic losses. Engineering methods, on the other hand, rely on quantitative analysis of the frequency of events and are appropriate for operational analysis immediately before a voyage.

The systematization of risks in the form of classifications, which allow choosing appropriate control and response methods, is of particular relevance. The universal classification proposed by DSTU ISO 31000:2018 Risk Management. Principles and guidelines (ISO 31000:2018, IDT), allows for consideration of internal and external risks, as well as their distribution by the level of consequences - from acceptable to catastrophic. According to this standard, risk management should not only prevent losses, but also contribute to the achievement of shipping objectives by ensuring the sustainability of ship operations (**Fig. 3.1**).

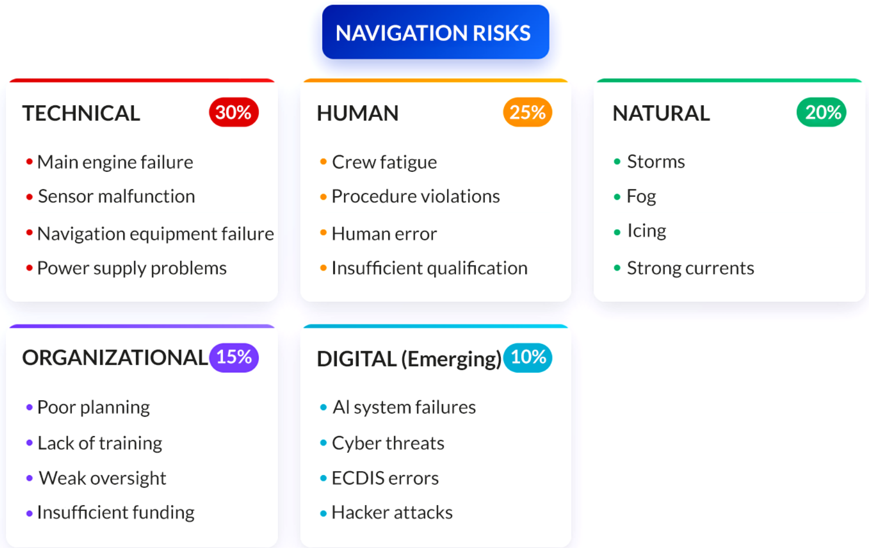

Fig. 3.1 Classification of navigation risks in accordance with ISO 31000:2018
Source: author's own developments based on [17]

Thus, effective navigation risk management requires a systematic approach that combines elements of classification, forecasting, planning, control and correction. The application of such approaches is a key condition for ensuring the safety of maritime transport and forming a reliable basis for the implementation of energy-efficient ship management in difficult navigational conditions.

3.4 Methods for assessing navigation risks

Navigation risk management is based on a systematic assessment that includes methods for identifying, analyzing, forecasting and controlling hazards during sea crossings. The basis for this approach is the recognition of the limited human and technical resources in a dynamic maritime environment and the need to make decisions under uncertainty. In this context, the role of risk assessment methods as a tool for reducing the likelihood of emergencies and mitigating their consequences is growing.

The most common methods include both qualitative and quantitative approaches. Qualitative methods, such as HAZID, FMEA, SWOT analysis and expert interviews, are focused on identifying potential threats and assessing their impact on safety. They provide a general idea of the level of risk, but their subjectivity limits their accuracy. In contrast, quantitative methods (FTA, ETA, statistical modelling, probabilistic scenarios) are based on the use of accident statistics, technical parameters of ships and sea conditions, which allows for the construction of formalized models with the calculation of the probability and scale of consequences (**Table 3.1**).

Table 3.1 Comparison of navigation risk assessment methods by type, advantages and limitations

Method	Type	Advantages	Limitations
FMEA	Qualitative	Simple to use, systematic approach	High level of subjectivity
HAZID	Qualitative	Early hazard identification	Does not provide numerical risk values
FTA/ETA	Quantitative	Scenario building, process formalization	Requires large amounts of data and time
FSA	Mixed	Comprehensive analytical approach	High implementation complexity
Risk Matrix	Mixed	Visual control, operational efficiency	Does not account for factor interactions

Qualitative – descriptive analysis wihtout numerical values
Quantitative – mathematical analysis with numerical results
Mixed – combination of qualitative and quantitative approaches

Source: author's own development

To make effective management decisions in shipping, it is necessary to implement risk assessment systems that include both quantitative and qualitative approaches. Qualitative methods, such as Formal Safety Assessment (FSA), SWOT analysis, are used to preliminarily identify threats that may arise in an uncertain environment. Quantitative methods, such as Fault Tree Analysis and Event Tree Analysis, allow modelling the probability of events and predicting the consequences. One of the most effective is the FSA method recommended by the International Maritime Organization. It includes five stages: hazard identification, risk assessment, analysis of measures to control them, cost-effectiveness assessment, and conclusion. Additional methods used in maritime practice include HAZID, FMEA and the ALARP principle, which focuses on reducing risk to a level that is reasonably acceptable. The development of digital technologies has helped to adapt these approaches to the real maritime environment. Modern ships use AIS, ARPA, and weather information to build real-time risk assessment models. In particular, risk matrices are effective in the navigation environment, where the level of danger is determined by a combination of the probability of an event and the scale of its consequences. The use of machine learning systems that analyze a large array of historical and current data can improve the accuracy of the assessment and warn the crew of critical deviations in time. All of this contributes to improving the safety of maritime transport and allows for adaptation to environmental changes.

An important role in the risk assessment process is played by building an integrated hazard map that takes into account navigational conditions, vessel characteristics, crew readiness and other factors. Such a map allows to identify the most critical areas of the route at the planning stage of the passage, as well as to adjust the trajectory in accordance with changes in the external environment. Of particular value is the use of trajectory points tied to specific maneuvering parameters of the vessel, which allows for an assessment of the safety margin when navigating in restricted areas.

Engineering assessment methods that use scenario modelling allow to simulate the development of an emergency situation over time, identify key events that may affect its course, and propose preventive measures. Such models are the basis for building digital decision support systems, which are increasingly being implemented in the shipping industry. These systems integrate information from navigational instruments, automatically generate risk levels and suggest the best course of action for the crew.

An important tool remains the method of building risk matrices that combine the probability of an event occurring with the level of its consequences. Such matrices are widely used in maritime practice for rapid situation assessment and decision-making. Combined with geoinformation technologies, these matrices allow for the construction of dynamic risk maps for the entire ship's route. In addition, modern safety indices (e.g., Navigational Risk Index, Collision Risk Index) provide a quantitative integration of various risk factors into a single model that supports informed decision-making on board.

To summarize, an effective assessment of navigational risks is only possible with the integrated use of both qualitative and quantitative analysis tools, involving digital technologies, mathematical modelling and a systematic approach to managing shipping safety. Further development in this area is aimed at creating adaptive platforms capable of real-time assessment of the situation and offering the safest and most effective scenarios for crew actions.

3.5 The relationship between navigational risks and energy efficient ship management

In maritime transport, energy efficient management is closely linked to navigation safety. Reducing a vessel's speed to save fuel can significantly increase risks in the event of unpredictable weather conditions, narrow straits or increased traffic. That is why management decisions must be made with a balance between risk and efficiency in mind (**Fig. 3.2**). Optimizing a vessel's route involves taking into account a range of parameters, from weather forecasts and traffic to geopolitical factors and environmental restrictions. In practice, this is implemented through the use of multi-criteria analysis, such as AHP or TOPSIS methods, which allow for a reasonable choice between alternatives based on risk, fuel consumption and carbon emissions. Modern digital systems, such as Wärtsilä Voyage or Syro AI, automate route decision-making based on a predictive model that takes into account both economic and safety performance. The use of machine learning algorithms ensures rapid updating of route parameters in response to changes in the situation. This achieves a dynamic balance between energy efficiency and navigational safety. In the future, an important area of research will remain the integration of risk analysis models into the structure of energy management systems and their synchronization with international standards in the field of environmental protection and navigation safety.

Integrating energy efficiency principles into navigation practices requires consideration of navigational risks, as any management decision aimed at reducing fuel consumption may also affect safety levels. This is especially important in difficult hydrometeorological conditions, high traffic intensity, and limited maneuverability in port areas or channels. It is well known that reducing ship speed, as a classic measure to improve energy efficiency, can negatively affect ship maneuverability, potentially increasing the likelihood of accidents in narrow or shallow areas.

In recent years, research has been actively developing models that combine risk and energy consumption indicators. In particular, an approach is used to construct an optimal route with minimization of the aggregate risk indicator and fuel consumption. This is achieved using multi-criteria models that take into account not only weather conditions and vessel characteristics, but also the probability of critical events along the route. It is advisable to use machine learning elements to predict changes in the navigational environment, which allows the route to be adapted in real time to avoid risky areas.

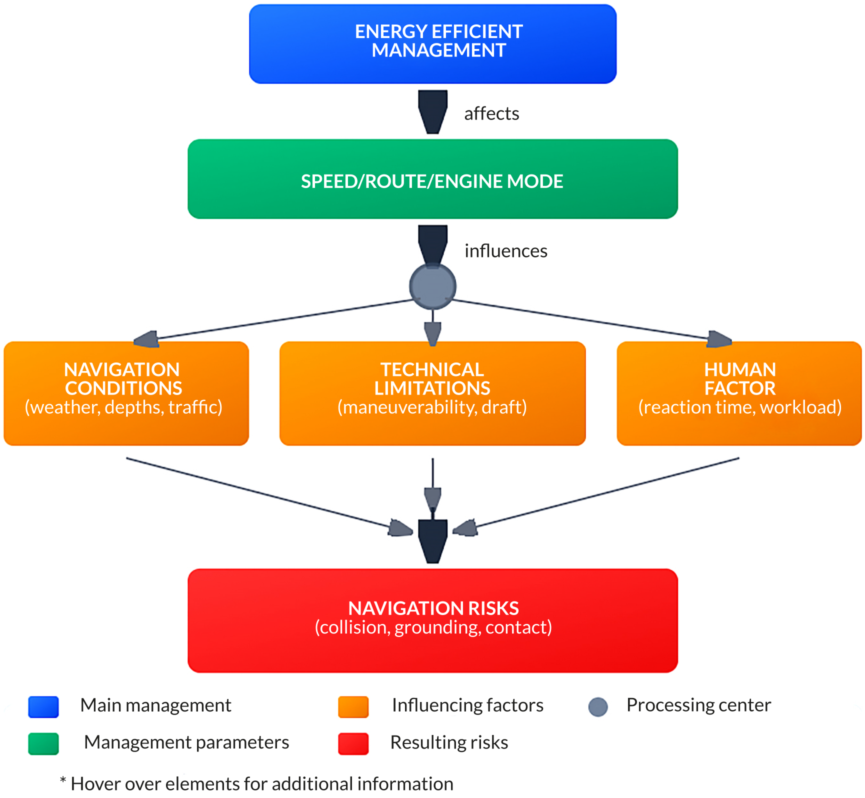

Fig. 3.2 The relationship between energy efficiency and navigation risks
Source: author's own development

The use of digital vessel traffic services (VTS) and automated navigation systems with real-time risk assessment opens up new horizons for harmonizing safety and energy efficiency. In particular, integrated platforms such as Navi-Planner or Wärtsilä FOS enable dynamic routing that minimizes both fuel consumption and navigational risk (**Fig. 3.3**). Such solutions are important not only in terms of efficiency, but also for compliance with MARPOL environmental standards and the CII index.

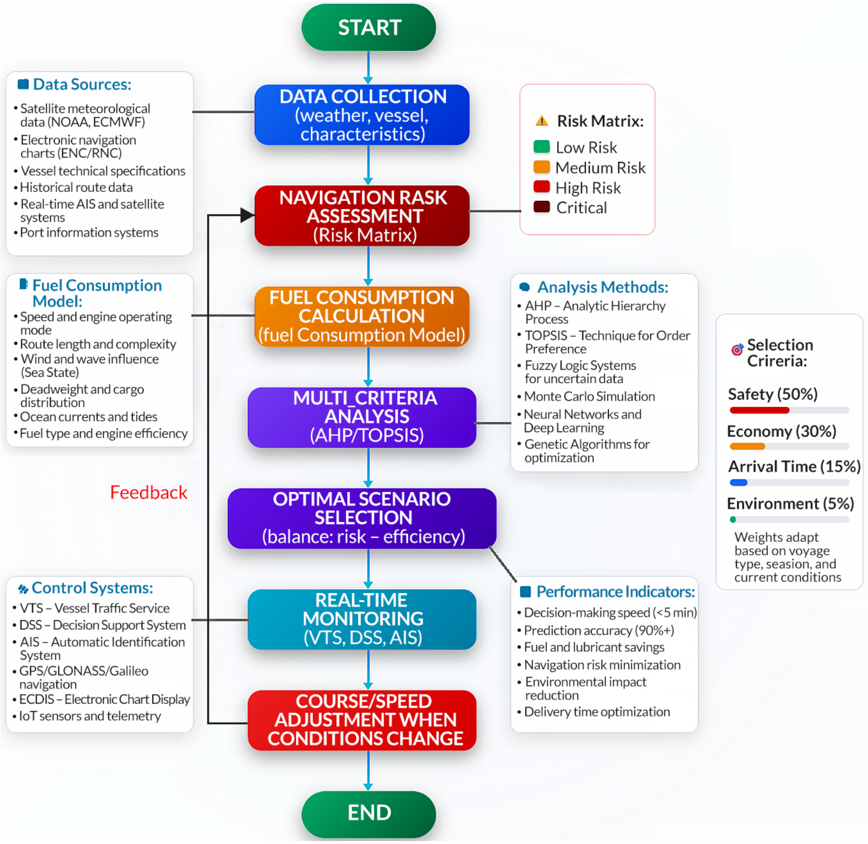

Fig. 3.3 Decision-making algorithm taking into account navigation risk and energy efficiency
Source: author's own development

The key to this is the formation of a unified concept in which navigation risks act as a constraint or criterion in the task of minimizing energy consumption. For example, a route that bypasses a dangerous area with complex bottom topography may be more energy-efficient than a direct but risky route. Therefore, it is important to implement algorithms that give preference to comprehensive assessment rather than isolated optimization of a single indicator.

In conclusion, it should be emphasized that energy-efficient ship management without systematic consideration of navigational risks is a limited and potentially dangerous approach. Only a combination of digital analysis tools, multi-criteria modelling and adaptive management strategies can achieve a sustainable balance between the cost-effectiveness and safety of maritime transport.

3.6 Conclusions

The research showed that effective management of a ship's energy consumption can't be done separately from navigational safety. There's a close link between operational decisions on route, speed, and energy saving, and the level of risks that come up in the marine environment. Global practice shows that neglecting this relationship can lead to an increase in accidents or a decrease in fleet efficiency.

The theoretical foundations of energy-efficient ship management were considered, the main types of navigational risks were classified, and methods for their quantitative and qualitative assessment were analyzed. Particular attention was paid to formalized methods (FSA, ALARP, FMEA), which allow decisions to be justified in conditions of uncertainty. The use of models that combine safety and energy efficiency criteria as a basis for building a multi-criteria decision-making algorithm was proposed. The feasibility of using digital platforms and artificial intelligence to model real-time situations, taking into account risks and fuel consumption, was demonstrated.

The first part demonstrated that the implementation of international requirements for energy efficiency indices (EEDI, EEXI, CII) is accompanied by the introduction of modern digital technologies, route analysis and adaptive management of ship performance parameters. At the same time, traditional speed reduction as a method of energy conservation creates additional risks in complex navigation areas, which necessitates flexible and dynamic control systems.

The second part systematizes approaches to classifying navigation risks by source, nature of origin and scale of impact. Navigation risks cover not only technical and natural factors, but also human factors and digital threats. Effective management of such risks involves not only their identification, but also continuous monitoring and forecasting, as confirmed by examples of accidents in the internal waters of Ukraine and international practice.

The third part is devoted to methods for assessing navigational risks. Both qualitative methods (FMEA, HAZID, SWOT) and quantitative methods (ETA, FTA, statistical modelling) are considered. Particular attention is paid to the construction of integrated hazard maps, risk matrices and digital decision support systems (DSS). It has been established that only the comprehensive use of tools involving data on the vessel, the environment and the human factor allows for a rapid response to changes in the navigational situation.

The fourth part analyses the relationship between navigational risks and energy efficiency. It proves that the isolated application of energy-saving measures without taking safety into account is ineffective. The optimal solution is to use multi-criteria routing models that allow a balance to be struck between safety and economy. The promising nature of digital platforms (Wärtsilä FOS, Navi-Planner) and real-time risk assessment systems for dynamic vessel traffic management has been confirmed.

Thus, the feasibility of implementing a systematic approach to energy-efficient ship management based on an integrated assessment of navigational risks has been substantiated, opening up new opportunities for improving both the safety and cost-effectiveness of maritime transport. Prospects for further research lie in improving mathematical models for risk prediction, developing digital adaptive control systems, harmonizing international standards taking into account the specifics of the Ukrainian fleet, and creating unified information and analytical platforms to support decisions in shipping.

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CHAPTER 4

Choosing the best maneuver for vessel separation taking into account the energy efficiency of the trajectory

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Abstract

Traditional ship passing methods are mostly focused on minimizing the risk of collision without considering fuel consumption, which complicates achieving sustainable development goals in maritime transport. At the same time, rising fuel costs, tightening international environmental regulations, and the need to reduce greenhouse gas emissions highlight the importance of integrating energy efficiency principles into the navigation decision-making process.

This work examines the functional capabilities of overlaying radar imagery on the ECDIS display as one of the key tools supporting energy-efficient maneuvering during ship passing. The advantages and limitations of integrating radar information with electronic navigational charts are analyzed, as well as the impact of such integration on improving navigation accuracy, reducing collision risks, and supporting sustainable fuel use. The relevance of integrating radar information with ECDIS to enhance real-time situational awareness is substantiated. It is shown that combining radar data with ECDIS significantly reduces the risks of erroneous decisions in conditions of limited visibility and high traffic density, and also provides better situational interpretation for making energy-efficient maneuvering decisions. It is determined that such integration is a key component of modern navigation decision support systems, as it allows consideration of the real situation and characteristics of target objects while accounting for safe and economically feasible courses.

The implementation process of collision avoidance systems using models aimed at ensuring navigational safety is analyzed, along with revealing their potential for optimizing energy consumption in maritime transport. A conceptual model for selecting the optimal ship passing maneuver is proposed, based on the combination of safety criteria and fuel consumption minimization. Special attention is given to the use of the Open Sea Model (OSM) as a tool for forecasting and evaluating movement trajectories considering various ship interaction scenarios. Particular

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focus is placed on the challenges of integrating this system with modern navigation complexes, including ECDIS, Automatic Identification Systems (AIS), and radars, to ensure real-time operation.

Keywords

Energy efficiency, ship passing, collision avoidance, movement trajectory, ECDIS, radar, data integration, Open Sea Model, modeling, maritime navigation, navigational safety, AIS, route optimization, maneuvering.

4.1 Introduction

In the current conditions of intensive development of global maritime trade and increasing traffic on major shipping routes, the issue of safe ship passing becomes particularly relevant. Every year, millions of interactions occur in the World Ocean between vessels that require prompt decisions regarding course or speed changes to avoid collisions. Traditionally, the primary objective of maneuvering has been to comply with the rules of passing according to the International Regulations for Preventing Collisions at Sea (COLREGs-72). However, in the context of modern requirements for energy efficiency in shipping and greenhouse gas emission reduction, a new dimension emerges – the search for maneuver options that not only ensure safety but also minimize the ship's energy consumption.

The introduction of new environmental regulations by the IMO, such as EEDI, EEXI, and CII, poses a challenge for shipping companies to optimize the operational parameters of vessels [1]. In this context, it is important not only to choose optimal navigation routes but also to minimize the impact of non-standard maneuvers, particularly evasive maneuvers, on overall fuel consumption. Since passing maneuvers typically require changes in speed, course, or both simultaneously, they can cause significant deviations from energy-efficient trajectories, leading to fuel overconsumption, increased voyage time, and, consequently, higher operational costs.

Recent scientific research shows growing interest in developing adaptive decision support systems capable of considering not only geometric and navigational parameters of the situation but also energy consumption characteristics, hydrometeorological conditions, engine type, and the behavior of other vessels. In this regard, the development of models that provide multi-criteria evaluation of possible evasive maneuvers, taking into account both safety and energy efficiency, is a topical task in modern maritime navigation.

The problem of selecting the optimal maneuver becomes especially complex in narrow or restricted navigation areas, where the evasion zone is limited, and spatial and temporal parameters of interaction with other vessels become critical. Under such conditions, precise assessment of mutual vessel dynamics, real-time situation forecasting, and integration of obtained data into navigation systems, including the Electronic Chart Display and Information System (ECDIS), automatic radar plotting aids (ARPA), and machine vision systems, are necessary [2].

This chapter of the monograph considers an integrated approach to selecting the best ship passing maneuver, combining the analysis of the navigational situation, application of formalized safety rules (COLREGs), and energy consumption models of vessel movement. Special attention is paid to methods for evaluating maneuver options based on fuel consumption, time loss, safety, and route deviation criteria. Examples of calculations, objective function models, and decision-making algorithms adapted for real use in ship navigation systems are presented.

Thus, this chapter represents a logical combination of theoretical principles of maritime navigation, modern energy efficiency concepts, and practical tools of digital ship control. The presented material can form the basis for developing intelligent navigation assistants capable not only of responding to passing situations but also proactively forecasting energy-saving movement strategies in conditions of intensive maritime traffic.

4.2 Radar image overlay on ECDIS: significance for energy-efficient maneuvering in ship passing situations

With the increasing density of maritime traffic and growing demands for reducing greenhouse gas emissions, the need arises not only for safe but also for energy-efficient ship maneuvering. One of the crucial factors influencing collision avoidance decisions is the quality and accuracy of navigational information that ensures situational awareness for the navigator. In this context, the radar image overlay function on the ECDIS display gains special importance, as it combines the advantages of both systems: the tactical detail of radar and the strategic information from the electronic chart. This, in turn, creates conditions for optimal selection of the passing trajectory with minimal energy consumption.

The radar system is a key navigational tool for both collision avoidance and energy-efficient maneuver planning. Thanks to its ability to detect targets and assess the dynamics of surrounding traffic, radar provides the basis for timely decision-making. However, radar displays are generalized and schematic, requiring trade-offs in operation such as:

− choosing between wider coverage and better target resolution;
− balancing noise suppression with the risk of losing weak targets;

− displaying absolute movement versus assessing relative risk;
− selecting display orientation (HEAD UP or NORTH UP);
− stabilization relative to the seabed or the sea;
− integrating data versus avoiding information overload;
− interface convenience versus functional flexibility.

Considering modern requirements for energy-efficient navigation – which entails minimizing maneuvers, fuel consumption, and time loss – high-quality integration of radar information with ECDIS plays a particularly important role. The Radar Overlay mode enables overlaying radar images, ARPA data, and AIS information directly onto the electronic chart, creating a unified information environment for making energy-optimized maneuvering decisions.

A critical aspect is that all relevant navigational data (own ship, targets, coastline, obstacles) are presented in a single scale, orientation, and coordinate system. This allows the navigator to:

− quickly assess the dynamic situation;
− correlate actual target echoes with their positions on the chart;
− choose the most energy-efficient passing option considering safe zones, acceleration, turning angles, and possible hydrometeorological constraints.

Radar and ECDIS integration technologies include "digital NMEA integration" and radar processors [3]. The former allows entering tracked target data into the ECDIS if the radar has ARPA capability; the latter provides analog-to-digital conversion of the radar video signal and input of this signal into the ECDIS, as illustrated n **Fig. 4.1**.

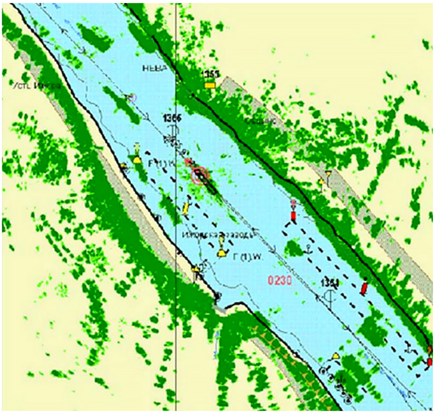

Fig. 4.1 Radar image overlay on ECDIS display

It is important that not only ARPA data but also raw radar data are integrated with chart data. Integration of the electronic chart with radar, or at least providing the user with the ability to overlay selected SENC information, ensures a system that can be used to prevent groundings and avoid collisions. The operator receives the following up-to-date information on a single display: own ship's position, all other vessels in the maritime area, and all charted objects and hazards.

Radar overlay and target correlation have particular value:

− for position fixing, since the overlay provides continuous radar position fixing without requiring manual intervention from the navigator;

− for real-time position monitoring by cross-checking the electronic position fixing system (EPFS), e.g., GPS.

When ECDIS and radar are overlaid on a single display, they create a system that can be used both for navigation and collision avoidance. As specified in IMO performance standards, radar information may be added to the ECDIS display provided it does not degrade the display quality and is clearly distinguishable from the electronic navigation chart. The IMO performance standard also requires that both ECDIS and radar use a common reference system (e.g., WGS 84) and that the chart and radar image correspond in scale and orientation.

Modern navigation suites are based on the integration of systems such as ECDIS, ARPA, AIS, GNSS (GPS/GLONASS/Galileo), gyro and inertial navigation systems, autopilots, power management systems, as well as meteorological modules. Leading manufacturers of marine navigation equipment, such as Transas (Wärtsilä Voyage), Kongsberg, Furuno, Raymarine, and JRC, offer high-tech solutions that support both safe navigation and energy-efficient vessel management.

Modern ECDIS platforms, such as Navi-Sailor 4000 or K-Bridge ECDIS, incorporate the following functionalities:

− automatic calculation of CPA/TCPA considering AIS and ARPA data;

− recommendations for course or speed changes taking into account traffic-restricted zones;

− display of radar image layers with position error compensation;

− assessment of traffic trends and likelihood of critical situations.

Let's consider the aforementioned radar integration in Navi-Sailor and the advantages of such integration. Navi-Sailor 3000 ECDIS can be equipped with a special Radar Integrator Board (RIB) from Transas. The RIB converts the radar video signal into digital form, enabling radar image overlay on the electronic chart [4].

The advantages of the radar integrator include:

− unique combination of electronic chart and radar image overlay on a single display;

− ARPA functions with tracking capability of up to 500 targets simultaneously;

− advanced voyage data recording;
− control over brightness, gain, sea and rain clutter on the screen;
− full compatibility with all Navi-Sailor products;
− OEM toolset.

With radar data displayed over the chart background, potentially confusing effects become visible that might otherwise go unnoticed on the radar screen. Three main effects should be taken into account:

1. The first relates to radars with antenna beamwidth – the larger the physical size of the antenna, the narrower the beamwidth, typically around one-degree azimuth. As a result, any object, even a point target such as a buoy, appears enlarged by the same angular extent on the display. For example, a buoy one nautical mile from the radar with a one-degree beamwidth antenna appears about 30 meters wide on the chart, and the farther from the radar, the larger it appears. Moreover, angular enlargement is not the only type of distortion; distance is also increased due to the finite length of radar pulses. For short pulses around 50 nanoseconds, distortion can reach 10 meters; for medium and long pulses, the effect is even stronger (**Fig. 4.2**).

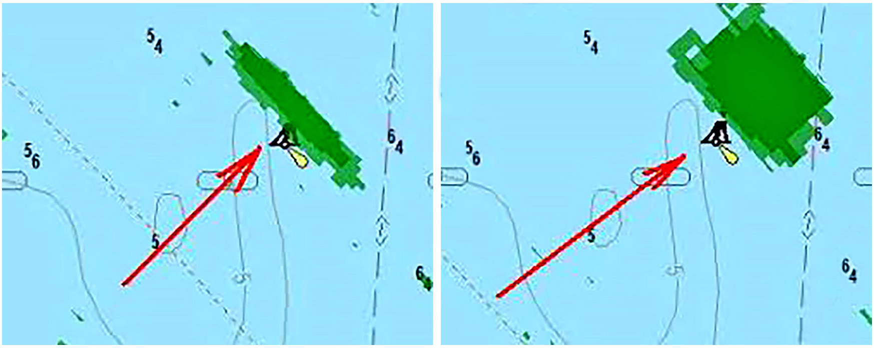

Fig. 4.2 Short-pulse image of the buoy (left) and long-pulse image (right)

2. The same factors lead to another confusing visual effect – the radar returns from the coastline generated at sharp angles appear farther from the shore than they actually are (red sectors in **Fig. 4.3**). Radar returns created at nearly right angles (blue sector in **Fig. 4.3**) do not exhibit such distortion. It is precisely the chart background beneath the radar overlay that helps to reveal this effect.

3. The third effect is that the radar reflection of the coastline does not necessarily coincide with its actual position on the chart. This is because most radar signals are reflected from steep slopes or large coastal structures, while gentle slopes produce

weak reflections and may be practically invisible on the radar image. **Fig. 4.4** shows the actual position of the coastline (red dashed line), which does not correspond to the visible radar echoes.

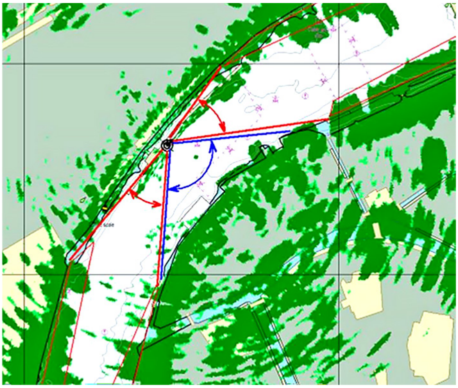

Fig. 4.3 Radar echoes of the coastline at sharp observation angles

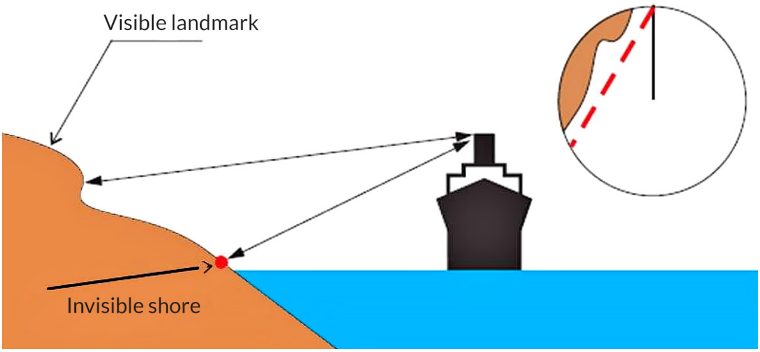

Fig. 4.4 Radar-visible and radar-invisible sections of the coastline

However, such discrepancies between the coastline depicted on radar images and that shown on charts are quite common and well-known (**Fig. 4.5**).

Considering the integration of radar and ECDIS, let's examine how navigation system failures can affect the operation of ECDIS.

The most critical failures are related to cartographic errors. It can only be assumed that such errors do occur, and therefore, nautical charts can never be considered completely reliable (there have been documented cases of islands missing from navigation charts). The key question is whether the navigator is capable of detecting errors of this kind [5].

Among all ECDIS functions, radar overlay is the most effective in such situations, as acknowledged in IMO Circular No. 255. A discrepancy between the coastline on the chart and the radar image may indicate a cartographic error, although other possible causes of visual distortions of the coastline, as described above, should also be taken into account. Sometimes, cartographic errors on charts arise from inaccuracies in the transformation between local datum and the WGS-84 geodetic coordinate system. Errors of this kind introduce a systematic offset of the actual position of the line or area – the red arrows of approximately equal length and direction in **Fig. 4.6** illustrate this effect.

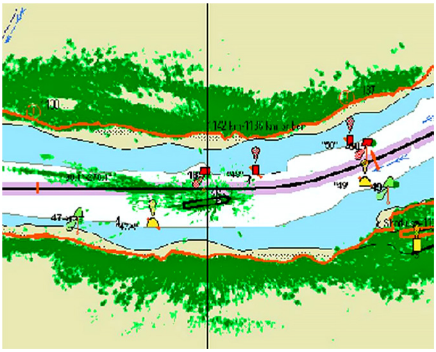

Fig. 4.5 Non-systematic (random) discrepancy between radar imagery and the charted coastline

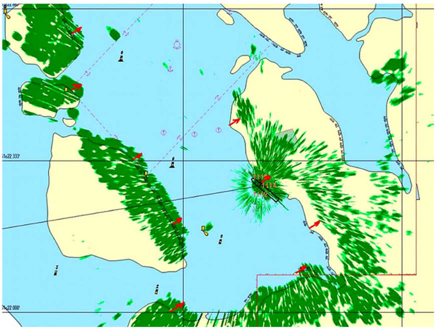

Fig. 4.6 Displacement of radar imagery caused by datum transformation errors

Advantages of Modern Radar Overlay Integration. Monitoring an ECDIS route can be significantly enhanced by adding a radar video layer as an underlying "background". This allows the navigator to compare, at any moment, the actual exposed part of shallow water or isolated hazards revealed at low tide with their positions as shown on the Electronic Navigational Chart (ENC) [6].

On the ECDIS, the ENC layer always has priority over the radar overlay, ensuring that full ECDIS route monitoring capability is not compromised. The radar layer also does not obscure critical ENC elements such as shorelines, submerged rocks, or drying areas during low water conditions.

By combining and integrating radar and ECDIS functions, an Integrated Navigation System (INS) assists the navigator not only in route monitoring and collision avoidance but also in maintaining the integrity of navigation sensors [7].

To avoid excessive clutter on the radar display, careful consideration should be given to the amount of ENC information included in the background layer. However, the navigator is not restricted to the minimal ENC display required for route monitoring, which typically demands at least the standard ENC presentation.

Integrity monitoring of other sensors is a key functionality of the INS. For example, using ENC data as a background for radar displays can help detect any displacement or failure of position and heading sensors.

Considering all these points, it can be concluded that operating modern radar systems is vastly easier than it was only a few years ago. Thanks to intelligent software on multifunction displays and multi-core processing power (e.g., four processors in the Raymarine series), the user rarely needs to adjust settings to obtain a high-quality radar image. Apart from selecting the appropriate range, tuning the TUNE and GAIN settings on each radar has the greatest influence on the image quality. In most modern radar systems, these settings are automated, and manual adjustments are only beneficial under special circumstances [8].

By enabling radar overlay, the navigator can effectively verify the operation of the ECDIS in real time. It can be argued that the radar overlay feature is not only a safety tool but also an essential element in ensuring energy-efficient maneuvering, meeting the demands of modern digital navigation. Thanks to automated adjustment algorithms (GAIN, TUNE) and multi-processor data handling, contemporary radar systems allow the navigator to focus on decision-making rather than system tuning, thus increasing operational efficiency during real-time ship handling.

Consequently, ECDIS with radar overlay evolves from a simple monitoring instrument into a decision support tool for rational, safe, and energy-efficient maneuvering. This is particularly critical in congested waters where the choice of evasion angle, speed, or timing of a maneuver has a decisive impact on fuel consumption reduction.

4.3 Ensuring navigational safety through the development of collision avoidance strategies based on the Open Sea Model

Maritime safety remains a paramount concern; however, contemporary trends increasingly emphasize improving the energy efficiency of vessel movements. Optimizing collision avoidance maneuvers with minimal fuel consumption reduces operational costs and mitigates environmental impact [9]. Risks threatening maritime safety pose significant dangers to human life, the environment, and property. Ship collisions constitute one of the most critical threats that, despite classical mitigation methods, require modern systems and technologies for effective resolution.

One promising approach is the development of collision avoidance systems based on modeling, particularly the OSM collision avoidance system [10]. This system not only supports navigators in making safe decisions for vessel passing but also promotes trajectory optimization considering energy efficiency, thereby reducing fuel consumption and ecological burden.

Modeling vessel passing processes and developing corresponding systems serve as vital tools that integrate diverse data and algorithms to assess collision risks and calculate optimal movement trajectories, addressing both safety and energy expenditure minimization. Collision avoidance models are complex analysis and forecasting systems that, using current and predicted data on vessel positions, courses, speeds, weather conditions, and other factors, generate recommendations for avoiding hazardous situations and selecting energy-saving routes.

Collision avoidance models compute parameters such as Closest Point of Approach (CPA), Time to CPA (TCPA), potential collision courses, and other vessel movement characteristics [11]. The use of algorithms and mathematical models enables risk assessment and the development of recommendations for navigators and vessel traffic operators to prevent collisions.

These models typically handle large datasets and employ various algorithms, including route optimization, classification, and prediction methods, to analyze and forecast scenarios that may lead to collisions. However, it is important to remember that collision avoidance models provide recommendations and decision support, while the final responsibility for maritime safety decisions lies with shipowners, vessel operators, and coastal state authorities [12].

These models differ from existing ship collision avoidance systems by their high accuracy in considering geographic voyage conditions, seabed topography, and other factors affecting vessel movement.

They provide a more precise and realistic forecast of vessel movements in the open sea, offer a broader scope of analysis and prediction of possible scenarios, and enable real-time implementation with data visualization. Such models account for a wide range of potential collision situations, including different vessel types, varying speeds, routes, and other parameters. As a result, by following the recommended actions, these models help enhance maritime safety and efficiency, reduce collision risks, and facilitate decision-making for navigators and vessel traffic system operators [13].

Various methods and technologies are employed to implement ship collision avoidance systems. One approach is the use of the Open Sea Model, which represents a dynamic maritime environment that includes information about vessel locations, courses, and speeds. A general description of building a collision avoidance system based on the OSM includes:

– data collection and acquisition: gathering essential data for the model, including information about target positions, courses, speeds, and other relevant parameters from multiple sources such as AIS (automatic identification system), radar, satellite imagery, or even simulated data;

– data preprocessing: segregation and processing of acquired data, including filtering out noisy or unreliable data, converting data formats if necessary, and ensuring consistency and accuracy;

– development of the OSM model: creating a visual representation of the maritime environment and surroundings. This model must include vessel locations, courses, and speeds as obtained from the data. It should also support real-time updates as new data arrive and are processed;

– collision risk assessment: using the OSM to evaluate collision risk between vessels by calculating parameters such as CPA, TCPA, and potential collision courses based on vessel positions, courses, and speeds. Various algorithms and methods, such as nearest neighbor search or collision risk assessment models, may be applied to identify potential collision scenarios;

– decision making: based on risk assessment, the system makes decisions to avoid possible collisions. This may involve generating collision alerts or warnings for vessel operators, suggesting course or speed adjustments, or even issuing autonomous commands to the ship's navigation control system;

– visualization and operator interface: providing a user-friendly interface that visualizes the model and offers real-time updates on vessel locations, collision risks, and recommended actions. The interface should be intuitive and easy to use, enabling quick and well-informed decisions by vessel operators;

– integration: seamless integration of the collision avoidance system with the ship's navigation system and other bridge equipment to ensure reliable communication and execution of recommended collision avoidance maneuvers (**Fig. 4.7**).

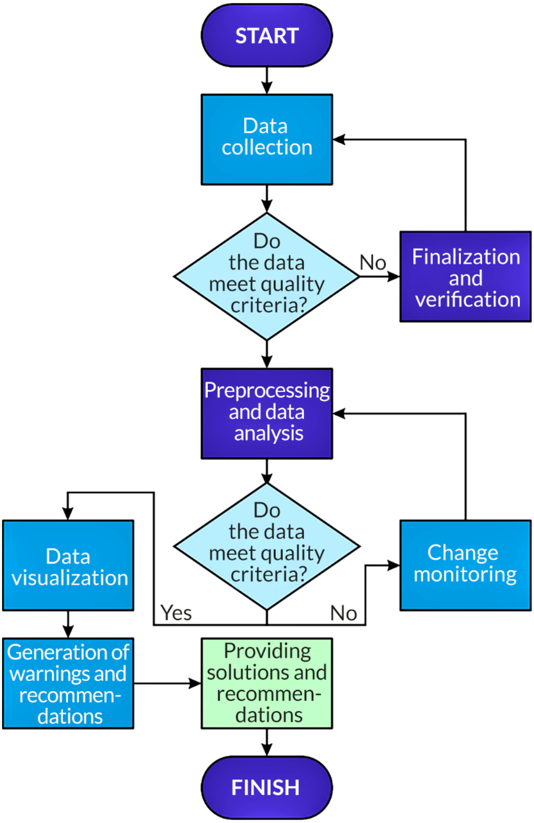

Fig. 4.7 Block diagram of the OSM functionality

It is important to note that the implementation of anticollision systems requires adherence to complex regulations, safety considerations, and integration with existing navigation systems. Continuous collaboration with experts and compliance with industry standards are critical to ensuring system effectiveness. The ability to update the OSM in real time is a key aspect of the proper functioning of collision avoidance systems.

Real-time updates and the adaptability of the OSM to changing open sea conditions enable the collision avoidance system to remain relevant and effective in the continuously evolving maritime environment. This is essential for enhancing maritime safety and preventing accidents.

The risk assessment methodology in the OSM-based collision avoidance system includes calculating important parameters such as CPA and potential collision courses. The following section discusses this methodology and the decision-making process based on collision risk evaluation:

1. Calculation of Closest Point of Approach (CPA). The Closest Point of Approach is the point on the trajectories of two vessels where the distance between them reaches its minimum value. The CPA calculation is based on data about the positions and movements of vessels received by the OSM. The system analyzes the vessels' trajectories and determines the moment when the distance between them is minimal. This allows assessing the closest possible point of approach and the potential risk of collision.

2. Calculation of potential collision courses. Potential collision courses are different directions of vessel movement that may lead to a collision if maintained. The collision avoidance system uses information about the current courses and speeds of the vessels to compute potential collision courses. This enables evaluating the likelihood of collision if vessels continue along their current trajectories.

3. Decision-making process. The results of collision risk assessment, including CPA and potential collision courses, are used to generate warnings and recommendations for the navigators. The system provides information about potential collision threats and suggests corrective actions regarding the vessel's course or speed to reduce collision risk. These alerts and recommendations can be delivered via the ship's navigation system interface or other communication means. It should be noted that the ship's crew can use these collision risk assessment results to make informed decisions and avoid collisions. Additionally, navigators may take actions such as changing course or speed to evade potentially dangerous situations. Automated warning and control systems may also be activated, which can signal collision risks and autonomously take measures to mitigate those risks.

Overall, the collision risk assessment methodology and decision-making process in the collision avoidance system using OSM provide navigators with information and recommendations to manage collision risks and enhance safety in the maritime environment.

The use of an interface that visualizes the OSM plays an important role in the collision avoidance system. This interface delivers real-time information to navigators about vessel positions, collision risks, and recommended actions, increasing situational awareness and facilitating timely decisions. Key features of the OSM visualization interface include:

1. Vessel visualization: the interface displays the positions of vessels on the maritime chart in real time. Vessels are marked on the map with symbols indicating their

type and status. This allows navigators to clearly see the current positions of vessels and their interactions.

2. Collision risk indication: the interface may use different colors or markers to indicate potential collision risks between vessels. For example, vessels near the CPA can be highlighted with bright colors or markers. This enables navigators to quickly identify potentially hazardous situations.

3. Warnings and recommendations: the interface provides warnings and recommendations based on the collision risk assessment results. This may include alert messages, audible signals, or visual indicators. Additionally, the interface can suggest course or speed adjustments to reduce the risk of collision.

4. Additional information: the interface can provide supplementary information about each vessel, such as its identification data, characteristics, and planned route. This helps navigators to better assess the situation and make informed decisions.

Using an interface that visualizes OSM data enables navigators to have a clear understanding of the current situation, detect potential collision risks, and apply recommended actions. This increases their situational awareness and supports timely decision-making to ensure navigation safety.

Since OSM is one of the most widely used collision avoidance models, its core idea is that each vessel moves in its own direction and at its own speed and can change course or speed to avoid collisions with other vessels. Therefore, the model uses a method to calculate the expected position of each vessel based on its current position, speed, and course, as well as the movement parameters of other vessels.

The model calculates the distance between every pair of vessels and determines whether a collision threat exists. If a threat is detected, the model provides recommendations to adjust the speed and course of each vessel to avoid the collision.

There are many variations and improvements of collision avoidance models, and numerous companies and organizations develop their own models and software for collision avoidance at sea. However, all of them are based on mathematical formulas and algorithms to determine optimal decisions.

One of the most common and accurate methods is the Vincenty formula, which allows precise calculation of the distance between two points on the Earth's surface by using the length and azimuth of the geodesic line between them. It is more accurate than simpler formulas that assume the Earth is a perfect sphere and can be expressed in various forms [14].

Let:

– a – major axis of the Earth;

– b – minor axis of the earth;

– $f - 1 - b/a$ – approximate amount of Earth's compression;

– $L=\lambda_2-\lambda_1$ – longitude difference;
– $U_1=\arctan\left((1-f)\times\tan(\varphi_1)\right)$ – given latitude for the point 1;
– $U_2=\arctan\left((1-f)\times\tan(\varphi_2)\right)$ – given latitude for the point 2;
– $\lambda=L$ – initial approximation for longitude;
– $\lambda_{i+1}=\lambda+\Delta\lambda$ – new longitude, calculated iteratively.
Then

$$\sin\sigma=\sqrt{\left(\left(\cos U_2\times\sin\lambda_{i+1}\right)^2+\left(\cos U_1\times\sin U_2-\sin U_1\times\cos U_2\times\cos\lambda_{i+1}\right)^2\right)}; \quad (4.1)$$

$$\cos\sigma=\sin U_1\times\sin U_2+\cos U_1\times\cos U_2\times\cos\lambda_{i+1}; \quad (4.2)$$

$$\sin\alpha=\cos U_1\times\cos U_2\times\sin\lambda_{i+1}/\sin\sigma; \quad (4.3)$$

$$\cos^2\alpha=1-\sin^2\alpha; \quad (4.4)$$

$$\cos 2\sigma_m=\cos\sigma-2\times\sin U_1\times\sin U_2/\cos^2\alpha; \quad (4.5)$$

$$C=f/16\times\cos^2\alpha\times\left(4+f\times\left(4-3\times\cos^2\alpha\right)\right); \quad (4.6)$$

$$\Delta\lambda=L+(1-C)\times f\times\sin\alpha^{*}\times\left(\sigma+C\times\sin\sigma\times\left(\begin{matrix}\cos 2\sigma_m+C\times\cos\sigma\times\\ \times\left(-1+2\times\cos^2 2\sigma_m\right)\end{matrix}\right)\right), \quad (4.7)$$

where φ_1 and λ_1 – latitude and longitude of the first point; φ_2 and λ_2 – latitude and longitude of the second point; $\Delta\lambda$ – change in longitude; $s=b\times(1-f)\times A$ – distance between points; A – azimuth (direction of travel) from the first point to the second point; σ – central angle between two points on the Earth's surface; α – initial azimuth (direction).

For example, in order to calculate the distance between two points on the Earth's surface using Vincent's formulas, it is necessary to sequentially solve the system of equations using the iteration method:

1) calculate the given latitude U_1 and U_2 for each point;
2) using an initial approximation for longitude λ, calculate the new longitude λ_{i+1};
3) calculate the central angle σ, and also the initial azimuth α;
4) using σ and α, calculate the distance s between the points.

If the resulting value of s is close enough to the distance given for the search, it is considered the final result. If not, s is used to calculate a new approximation for the longitude λ and the steps are repeated 2–4, until the desired accuracy is achieved.

The Vincenty formula is an accurate method for calculating the distance between two points on the Earth's surface, taking into account the planet's ellipsoidal shape, unlike simplified spherical models. This is crucial for developing modern models and algorithms used in ship collision avoidance systems, especially in conditions of heavy traffic, narrow channels, straits, and approaches to ports.

The application of the Vincenty formula ensures a more precise determination of distances between vessels, which in turn allows for more accurate trajectory prediction and the development of optimal routes for avoiding conflict situations from the perspectives of both safety and energy efficiency. This is critically important for navigation in complex conditions where even minor positioning errors can lead to increased fuel consumption or heightened collision risk.

The advantages of using the Vincenty formula in navigational support and collision avoidance systems include:

1. Increased calculation accuracy and improved energy-efficient route planning. Precise distance calculations enable decision-making systems to build more rational vessel routes that minimize unnecessary deviations, maneuvers, and course changes. This directly reduces fuel consumption and lowers greenhouse gas emissions.

2. Consideration of real geographic and navigational conditions. By accounting for geodetic features of the Earth, such as its ellipsoidal shape, actual seabed topography, and marine currents, the system can model optimal routes that avoid zones of increased resistance or unnecessary delays. This improves fuel management and enables selection of the most energy-saving trajectories.

3. Enhanced safety combined with reduced costs. Accurate information on potential conflict situations allows for minimizing the need for emergency maneuvers, which are usually accompanied by inefficient energy use (sudden speed changes, course alterations, braking). Predictable collision avoidance with minimal energy expenditure becomes possible only under conditions of high accuracy in navigational models.

4. Optimization of logistics and operational efficiency. Rational route management and avoidance of inefficient vessel divergences contribute to reducing time spent at sea, which lowers operational costs, improves adherence to delivery schedules, and ensures stability in logistics chains.

Collision avoidance systems integrated with high-precision distance calculation algorithms, such as the Vincenty formula, are an important tool not only for ensuring maritime safety but also for optimizing energy consumption. They enable timely and accurate assessment of potential threats, formulation of predictable and energy-efficient avoidance scenarios, and support decision-making aimed at the rational use of resources.

At the same time, the implementation of such systems requires a careful approach:
– compliance with standards;
– consultation with experts;
– adaptation to existing infrastructure;
– technical integration with navigation equipment.

Only under these conditions can their full potential be realized to reduce fuel consumption, lower environmental impact, and ensure sustainable and safe maritime logistics.

By combining high-precision geodesy, real-time data, and intelligent forecasting, collision avoidance systems using the Vincenty formula become a powerful tool for enhancing the energy efficiency of shipping and the sustainable development of the maritime industry as a whole.

4.4 Conclusion

The function of overlaying radar imagery onto ECDIS is a key tool not only for ensuring navigational safety but also for energy-efficient management of vessel maneuvering during passing or crossing situations. The integration of radar, ARPA, AIS data, and electronic charts provides an objective and timely assessment of the surrounding environment, enabling decisions that minimize fuel consumption, risks, and delays.

Further development of automatic maneuver optimization algorithms based on integrated ECDIS and radar data is advisable, allowing adaptive real-time support for the navigator.

Collision avoidance systems are important tools for enhancing maritime safety, as they help reduce collision risks and create conditions for making effective decisions to prevent accidents.

However, it is important to note that the implementation of model-based collision avoidance systems requires complex measures, adherence to regulations and standards, expert consultations, and integration with existing navigation equipment to ensure their effectiveness and compliance with industry requirements.

By utilizing advanced technologies and real-time data, model-based collision avoidance systems represent a promising solution for improving maritime safety, ensuring high accuracy in predicting vessel routes, and assessing collision risks. This enables operators and system developers to take appropriate actions to maintain safety, respond promptly to potential conflict situations, and improve the efficiency of decision support systems, thereby contributing to safer navigation and the protection of the marine environment.

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CHAPTER 5

Analysis of possible risks, which affect energy efficiency of the ship while maneuvering and mooring

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Abstract

The aim of this study is analyzing possible risks connected to the energy efficiency of the ship, specifically at the time of ship's maneuvering in the restricted waters on the way to the port and during mooring operations. The situation in the world's merchant fleet significantly changed during recent years – speed of the ships and their sizes significantly increased, many new technologies appeared. So, another aim of the research is to learn new risks, imposed in the modern shipping. Also, the aim was to search connection of energy efficiency risks to the other aspects of the ship's safety. Nowadays, there are some new safety aspects appeared: cybersecurity, safety of new fuels (which were not used before on-board ships), problems of the crew competency in new technologies and new operations, use of autonomous tugs, possibility of war risks, use of artificial intelligence. These new aspects should be taken into account, as well as the probability of sudden changes in the situation, like weather change, current effect, breakdown of the equipment or traditional human error. It is analyzed also several methods of the risk's calculation, including adding of the environmental condition and human element to the traditional formula of the risk calculation. All risk parameters were grouped into ten groups, possible methods of the risk assessment for each parameter were learned. Also use of the new digital technologies is reflected, the best way of avoiding human error seems to be computer-based risk assessment, which would be more effective if independent server or special platform is used. Such platform to be belonged to insurance company, per example. The best effectiveness of such electronic system expected to be achieved by using round-circle risk assessment, which includes calculation of risks of all participants of operation and general risk assessment of the whole process. The particular attention is given to the new risk parameters, recently imposed into the maritime industry and to the new opportunities of the risk management, given to us by the modern technologies, in particular IT technologies and artificial intelligence.

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Keywords
Energy efficiency, risk analysis, risk assessment, maneuvering, mooring, ship operations.

5.1 Introduction

The speed of the ships and their sizes significantly increased in the recent years. At the same time the speed loading and discharging operations also increased. Those operations, which took weeks a decade ago, now could be done withing days or even hours. In view of this, ship managers and charterers are taking all possible efforts to speed up auxiliary operations, like maneuvering, mooring, bunkering, receiving supply, etc.

On the other hand, there is a requirement to keep energy efficiency of the ship at some certain acceptable level during the whole trip of the ship. Moreover, such very important operations as docking, undocking, maneuvering in the port waters and during approaching the port must be fulfilled safely with all necessary safety precautions.

This task becomes more difficult because port traffic is constantly increasing all over the world, thus it is necessary to provide ship managers and the ship's staff with the effective and reliable tools for the risk assessment of such operations.

Traditionally, some risk evaluation models are used [1], based on complex analysis of various stages of the operation [2], however it is not fully corresponded to the modern requirements, dictated by high-speed changes of the situation. In such circumstances the big room of errors and delays appears, which can lead to damage, financial losses and even bigger negative consequences [3].

It is also necessary to mention, that usually risk management on board of the ship is fulfilled by simple filling up the checklists and tickling proper boxes prior beginning the operation [4]. Such approach has many disadvantages: possible formal approach (without checking real situation before tickling box), filling up the checklist post factum (after operation is completed, because very often ship's officers have very limited time to do this before the operation commenced), possibility of human error due to rush, caused by necessity to do a lot of actions in the very limited time and by the shortened crew (which is more and more often nowadays).

So, it is essential to have the tool, which will give an opportunity to fulfil risk assessment in the real time mode. This was recognized by the International Maritime Organization, which highlighted the need for simplified assessment methods suitable for real-time applications. Energy efficiency is one of the key topics of IMO agendas [5, 6], which is also important to take into account while planning and fulfilling auxiliary port operations, such as maneuvering and mooring of the ship.

5.2 Energy efficiency during maneuvering operations

Maneuvering and mooring mode is significantly different from the sea mode of the ship. It is characterized by higher energy consumption by its nature – many auxiliary mechanisms to be started (additional generators, thrusters, mooring winches, windlass, capstan, pumps, etc.), main engine consuming more fuel in maneuvering mode. Additional energy consumers and risks associated are shown in the **Table 5.1**.

Table 5.1 Additional energy consumers during maneuvering and mooring operations and risks to energy efficiency associated

Energy consumers	Risks
– main engine in maneuvering mode; – additional auxiliary engine(s); – windlass and capstan; – mooring winches; – thruster(s); – additional pumps; – additional bridge equipment; – additional lights	– failure of the mechanism due to technical problems; – failure due to poor maintenance; – failure due to poor quality of fuel; – failure due to overload; – failure due to human error

However, there are some risks, which can increase energy consumption even more, such as necessity to reverse main engine in emergency, presence of strong current or simply worsening of the weather conditions. Besides that, there are some new risks appeared last decades because of technology progress [7] (**Table 5.2**).

Table 5.2 Risks associated with emergency and new risks

Emergency risks	Possible preventive measures
1	2
Emergency revers failure	Check the reverse before maneuvering
Overload due to the current	Learn the situation with the current before entering the area
Overload due to the wind squall	Learn weather forecast, engage spare generator in advance
Wrong actions of pilot	Monitor actions of pilot in order to avoid human error
Wrong actions of tug	Monitor the whole process of operation, have anchors ready to drop
New risks	Possible preventive measures
Failure due to unknown properties of new fuel	Have ready traditional fuel, not to overload engines
Cyber attack	Cyber protection

Continuation of Table 5.2

1	2
Militant attack	Avoiding enter ports under possible military attack
Failure of the new technology mechanism due to lack of crew training	Provide a crew training in time
Collision due to mistake of remotely operated autonomous tug	Always be alert and ready to use anchors and other measures
Artificial intelligence mistake	Double check devices using AI, have readily available conventional equipment

Energy efficiency during maneuvering operations and mooring is worse than in normal sea mode. It is highly depending on some accidental risks, which should be taken into account. In addition, in the recent time, new risks arisen, which are also quite important to take them into consideration.

5.3 Risks calculation

Usually, risk evaluation could be assessed by multiplying the probability of the risk and the severity of the possible consequences of the event

$$R = P \times C, \tag{5.1}$$

where P represents the probability of occurrence and C indicates the severity of the consequence.

It is particularly valued for its simplicity and effectiveness in quickly gauging risk levels [8].

However, this is not the only approach to the calculation of the risk. For example, International Maritime Organization, recognizing necessity of simplifying approach to the risk management on board the ships, anyway, added one more element to (5.1)

$$R = P \times C \times V, \tag{5.2}$$

where V means vulnerability of the system [9].

To our opinion vulnerability is more applicable to the cyber security, or other systems, where it is possible to assess this vulnerability more or less precisely before getting down to the calculations. In the situation of the assessment of risks imposed to the maneuvering/mooring operations and energy efficiency, associated with them, another approach looks to be more feasible.

It is possible to delete vulnerability from (5.2), but to take into account some other factors, like effects of external environment (environmental conditions – wind squall, strong current, waves, decreasing of visibility, etc.) and, of course, influence of human element, which will be definitely present in any operation anyway.

Thus, let's use following formula

$$RF = P \times C \times E \times H, \tag{5.3}$$

where P – probability (to be evaluated based on historical data and operational records, considering incident frequency within similar conditions, type of the ship, and others); C – severity of the possible consequences (preferably to be classified on a five-point scale, ranging from minor impacts (e.g., minor property damage) to severe consequences (e.g., loss of the ship or major environmental damage); each consequence score is assigned based on previous incident reports and the potential impact of similar events on port operations; E – environmental conditions, means a variable accounting for external factors that affect the operation, including wind speed, current strength, wave height, and visibility (each environmental factor is rated on a scale from 1 (optimal conditions) to 5 (extremely adverse conditions)); H – human factors, means a component that reflects the influence of crew experience, training, and fatigue levels on risk (the human factor score is similarly scaled from 1 (highly competent and alert) to 5 (low competence or high fatigue)).

Data for each variable (P, C, E, and H) were gathered through a combination of historical analysis and port records [10]. Statistical methods were used to identify typical values for each variable under various port conditions. The extended R model might be applied to various scenarios within the port environment to evaluate its effectiveness in risk identification. Each scenario to be analyzed by computing an R score, which was then used to categorize risks as low, moderate, or high. This categorization helps prioritize response strategies and preemptively address high-risk situations based on the calculated R. Of course, in the absence of the statistics, the other methods of the assessment of probability and severity to be used – like expert assessment for example [11].

Let's apply the model, described in [11] to the calculations of risks, connected to the energy efficiency during the maneuvering and mooring operations. **Table 5.3** shows calculation of risks in various possible scenarios.

Table 5.3 Risk calculation in different scenarios

Sample scenarios	Probability (*P*)	Consequence (*C*)	Environmental (*E*)	Human element (*H*)	Risk (*R*)
Scenario 1: optimal weather, experienced crew	2	3	1	1	6
Scenario 2: moderate weather, inexperienced crew	3	4	2	4	96
Scenario 3: poor weather, experienced crew	3	5	4	2	120
Scenario 4: high risk, adverse weather, fatigued crew	4	5	5	5	500

Assumptions for sample scenarios:

– *P* (Probability): assumed based on frequency of incidents in similar operational contexts; scaled from 1 (low probability) to 5 (high probability);

– *C* (Consequence): defined based on the potential impact of incidents, ranging from minor property damage (1) to severe environmental or human harm (5);

– *E* (Environmental conditions): rated on a scale from 1 (optimal conditions, clear weather, low currents) to 5 (highly adverse conditions, poor visibility, high currents);

– *H* (Human factors): rated from 1 (high crew expertise, alertness) to 5 (low crew expertise, high fatigue).

The results indicate that the *R* value varies significantly depending on the values assigned to *E* and *H*, highlighting the importance of environmental and human factors in real-time risk assessment. For instance:

– Scenario 1 represents a relatively low-risk situation due to optimal weather and an experienced, alert crew, resulting in an *R* of 6;

– Scenario 2 shows increased risk ($R = 96$) due to a moderately adverse environment combined with an inexperienced crew, suggesting that additional precautions or adjustments in operation may be necessary;

– Scenario 3 depicts an even higher risk ($R = 120$) due to poor weather conditions, even with a skilled crew. This score indicates the potential need to delay the operation until conditions improve;

– Scenario 4 represents a high-risk scenario ($R = 500$) with both adverse weather and a fatigued crew, strongly advising against proceeding with tug operations under these conditions.

Such method of the risk calculation improves situational awareness: the extended *R* model enables ship operators and crews to assess risk dynamically, adjusting operations based on real-time information.

It gives also possibility for efficient resource allocation: high *RF* values in specific scenarios suggest when additional resources or preventive measures are necessary, allowing the ship to take a decision on more generators engagement to avoid overload or even blackout in the emergency situation (in most cases it gives an opportunity to avoid emergency situation at all).

Using this method, it is possible to be sure in our decision-making, thus it is possible to take informed decisions on whether to proceed, delay, or adjust operations, balancing safety and operational efficiency.

The results support the use of the extended R model as a practical tool for maritime risk assessment while maneuvering, particularly within the confined, high-traffic conditions of port areas, where it is possible to take care about ship's energy efficiency anyway.

5.4 Risk management using IT technologies

As is mentioned above, it is necessary to process the data constantly, in the real-time mode – it is necessary a continuous monitoring of the risks during the whole process of the operation. Such opportunity gives using of modern IT technologies, which will allow to process much more data, then human can do, also electronic server can process all data (even changeable) in the real time mode.

All data, which are necessary for risk assessment process, could be divided into three types: constant data (which are unchangeable and could be upload from ship's computer – type of the ship, year of build, name, IMO number, type of engine, type of fuel, etc.); data, which need operator's assistance (checkup of readiness of the mechanisms as example); live data from ship's mechanisms and devises (engine mode, start/stop of the mechanisms, loading conditions of the motors, etc.). The process of the data transfer goes on separately for these various types of data (**Fig. 5.1**).

Thus, there is an opportunity to have live risk assessment during the whole time of the operation. Server, to be used for such data processing, should be allocated with the company, however ideally, such server to be independent (belonging, for example, to insurance company) for the purpose of processing other important data at the same time (data of the other participants of the operation in particular).

As was said above, the data are divided by type, at the same time they are divided in time as well: some are processed before the operation, but some data to be processed continuously during operation in the real-time mode. In the next figure (**Fig. 5.2**) is shown the possible algorithm of various data processing.

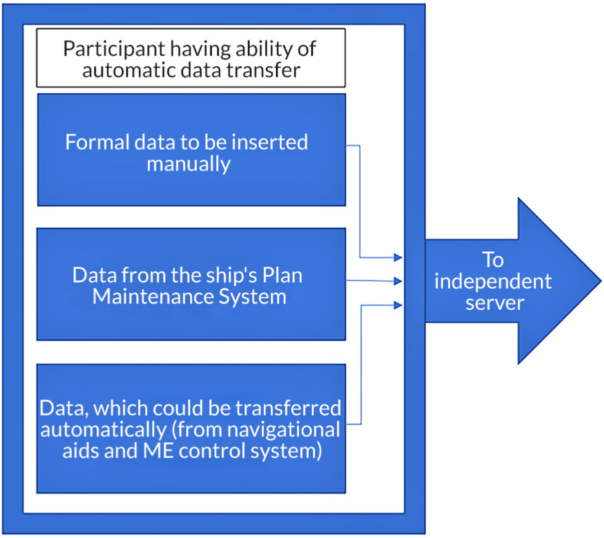

Fig. 5.1 Three types of data, generated by the ship to be processed by the special independent server
Source: [12]

In order to have real results and manage the risks in the most efficient way, it is necessary to indicate risk parameters, which are important for the particular purpose (energy efficiency in our case) and decide which methods of the risk assessment are possible to use. Better to group risk parameters for better understanding, as it is done in the **Table 5.4**.

It is necessary to add some comments to the **Table 5.4**: in the first group there are parameters, which might be dependent from other: for example, actual condition of the ship depends not on its age only, but on its type, so it should be taken into consideration. Also it might be not enough certain data for statistical analysis of the age of the ship, because ship's condition also highly depends on proper maintenance (rating of the shipping company could be very useful). Such problems could be mitigated by application of expert assessment method; however, such method require quite big number of experts for obtaining correct data.

Each flag and each classification society have their own requirements to safety; thus, it is possible to use for assessment their ratings (PSC and/or P&I and/or MoU – all of them are rating flags and classification societies). All of these data to be collected from various sources: PSC, MoUs, GISIS, Equasis, etc. for Statistical analysis.

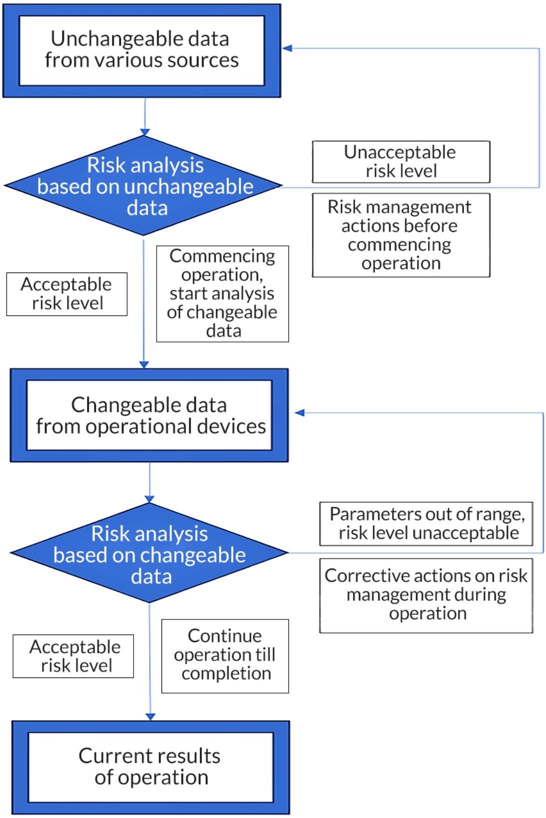

Fig. 5.2 Algorithm of data processing at the independent server

Table 5.4 Risk parameters and possible methods of their assessment

Group of parameters	Risk parameter	Method of assessment
1	2	3
I group (unchangeable parameters)	Year of built of the ship	Expert assessment
	Type of the ship	Expert assessment
	Name of the shipping company (ship's manager)	Expert assessment
	Flag of the ship	Ratings
	Classification society	Ratings

Continuation of Table 5.4

1	2	3
II group (depends on ship/company names)	Number of non-conformities by PSC	Statistical analysis
	Number of detentions by PSC	Statistical analysis
	Number, type and level of accidents, the ship was involved	Statistical analysis
	If the ship participates in the Green award programme or similar	Statistical analysis
III group (Ship's docs)	If all ship's documents are available	Statistical analysis
	If ship's documents are valid	Statistical analysis
	If some of the documents is not valid – analysis of the type of document and reason of invalidity	Statistical analysis
IV group (crew documents)	If crew complement is in order according to the Minimum safe manning certificate	Statistical analysis
	If crew STCW documents all are valid	Statistical analysis
	If all crew STCW documents are verified, verification based on access to national verification system of the particular seafarer	Statistical analysis
	Experience of the seafarers – total seaservice of each seafarer and its seaservice on the particular type of the ship	Statistical analysis
	Age of the seafarers	Statistical analysis
V group (Ship's SMS)	How many nonconformities issued	Statistical analysis
	How many of them connected to the mooring operations/equipment	Statistical analysis
	How many accidents connected to mooring operations/equipment happened	Statistical analysis
	If there were repeated accidents	Statistical analysis
	How many near miss cases, connected to mooring operations/equipment found	Statistical analysis
VI group (Ship's equipment)	Number of navigational aids on board – is there sufficient number or redundant number of navigational aids	Statistical analysis
	Manufacturers of navigational aids (their rating in the industry)	Ratings
	Is there sufficient number or redundant number of auxiliary engines and how many are in operation	Statistical analysis
	Number of mooring aids	Statistical analysis
	Number of thrusters	Statistical analysis

Continuation of Table 5.4

1	2	3
VII group (Ship's PMS)	Was maintenance and check of the mooring equipment done as per plan	Events tree analysis
	Were spare parts requested for mooring equipment delivered and installed	Events tree analysis
	Were mooring ropes changed/checked according to schedule	Events tree analysis
VIII group (variable parameters)	Working parameters of ship's main engine – if there any malfunction, tendency to change to dangerous level	Bayesian networks or Markov chains
	Working parameters of steering gear – if there any malfunction, tendency to change to dangerous level	Bayesian networks or Markov chains
	Working parameters of auxiliary engines – if there any malfunction, tendency to change to dangerous level	Bayesian networks or Markov chains
	Navigational parameters – if any tendencies to run aground, if any risk to run against navigational obstacle, if any risk of collision	Bayesian networks or Markov chains
	Parameters of inertial navigation system	Bayesian networks or Markov chains
IX group (weather conditions)	Weather shore station and ship's meteorological station – if any tendency to worsen	Bayesian networks or Markov chains
	Light conditions – from light sensors	Bayesian networks or Markov chains
X group (cybersecurity data)	Data exchange with the ship in order to find potential risk of interference into the system	Bayesian networks
	Continuous ship's system checks on the matter of optimal performance	Bayesian networks

Sources of data for the first and second groups could be easily found with the help of Artificial Intelligence. Several AI tools could be used for such purpose (**Table 5.5**), but the best result seems to be obtained with the help of Perplexity. It is necessary to stress, AI could be used just for searching the sources of data, but not for collecting data themselves at present.

Basing on the characteristics of the platforms, it is possible to say that several platforms might be used for placing of the risk-assessment system. It might be more feasible, than ordinary server. However, it is necessary to realize that for full-scale tasks of the system, AI tool should be properly trained, otherwise many errors can happen. The only purpose, which could be fulfilled by AI for the moment – searching the sources of information. The best results were achieved with Proplexity.

It is necessary to stress: searching of particular data is not guaranteed (for example: statistics of accidents with particular ship – results not be found or found erroneous data), but searching for the sources gives quite good result. Basing on such results, system can obtain proper data using the ordinary search machine.

Table 5.5 Suitability of various AI tools for the purposes of risk assessment

AI name	Applicability for the risk assessment
Microsoft Azure	Platform, which could be used for placing the system
TensorFlow	Limited application for our purposes
OpenAI (includes ChatGPT)	Very limited abilities, high probability of errors
Google AI Platform	High opportunities, however, prospects of use for our purposes are not so clear
Amazon Web Services	Platform, which could be used for placing the system
NVIDIA Deep Learning AI Software	Not suitable
Dataiku	Could be used for our purposes
H2O.ai	Could be used for calculation and analysis of data, might be used for our purposes
Rainbird	Not suitable
Caffe	Not suitable
Perplexity	Suitable as a search engine

Source: [12]

While applying statistical analysis to the parameters in the fifth group (**Table 5.4**), it seems absolutely necessary to take into account Heinrich law (in a workplace, for every accident that causes a major loss, there are 29 accidents that cause minor losses and 300 accidents that cause no losses).

A very important part of this concept is adding to the list of parameters to be assessed some variable data – means data which are changing during operation. Modern state of IT technologies gives the opportunity to analyze such data in the real time mode, which allow to predict possible malfunctions of mechanisms or dangerous change of the situation.

Every of these ten groups, even every risk parameter needs specific approach to calculate probability of the negative event. There are various methods to be used for that. The task for designers of the risk management system is to choose the most suitable method for every parameter. In reality it could be adjusted after practical implementation of first version of the risk monitoring internet platform.

5.5 Practical importance

Actually, the importance of the correct energy efficiency risk assessment is not about energy efficiency only. Almost all factors, which are important for the safety of the ship, affect also its energy efficiency. On the other hand, mistake in energy efficiency calculation may lead to overload of the electrical equipment, and, in worst case, to breakdown of the all system.

As an example, breakdown itself may cause half a million losses, besides that, fine for the possible pollution could be around hundred thousand dollars and the idling of the ship due to accident can cause another one-two hundred thousand dollars [13].

Such consequences might be caused by the same risk factors, which can cause incompliance with energy efficiency. Among them are: poor maintenance of the mechanisms and equipment, unknown parameters of new fuels, lack of crew training, crew incompetence, human errors, sudden weather change, etc.

Thus, correct approach to the energy efficiency risk analysis will lead to correct analysis of the risks, associated with the other safety aspects.

Using of the modern digital technologies can make the process of the risk assessment easier and more effective. Practically, "paper" risk assessment is not effective any more: on the most ships at least shipboard computer is used for this purpose. It might be also computer of the management company, but the most reliable solution seems to be use of the independent server of the insurance company. Such computer (or any independent platform with the special software) might be also used for the complex round-circle risk assessment for the all participants of the operation. Such approach will give the opportunity to make independent assessment not of every participant only, but of all operation in complex, highlighting "weak links" and making risk management much more effective [14–16].

Also there is a wide room for improvement of this concept and the whole algorithm of the risk assessment in general [17].

5.6 Conclusions

Energy efficiency of the ship is a significant part of seafarers' job now. It is not a simple task, which is much more difficult to achieve, when the ship is on the way to the port – maneuvering and in the process of mooring alongside. Assessment of the risks, associated to the energy efficiency, is helpful to the other aspects of the ship's safety risk assessment – it is not about the environment protection only, but about general safety issues of the ship in the maneuvering mode.

Same, like with the other aspects of mooring operations, energy efficiency risk assessment is better to fulfil with the help of modern technologies – special internet platform for round-circle risk assessment, artificial intelligence and other tools.

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CHAPTER 6

Modern approaches to maritime navigation: integrating artificial intelligence into ship course-keeping systems

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Abstract

This paper presents a comprehensive analysis of contemporary trends in automatic ship control systems with particular emphasis on artificial intelligence technology integration in autopilots, propulsion systems, and energy efficiency enhancement in maritime transport. The study covers the evolution from classical PID controllers to intelligent control systems, including neural networks of various architectures, fuzzy logic, adaptive algorithms, and modern machine learning systems.

Special attention is given to systematic analysis of AI technology applications for ship course keeping tasks, automatic trajectory control in complex navigation conditions, propulsion system optimization, and comprehensive optimization of ship system energy consumption. The advantages and fundamental limitations of various approaches to intelligent ship control are thoroughly examined, along with their impact on maritime safety, economic efficiency of maritime transport, and environmental aspects of shipping. A deep analysis of autonomous navigation development prospects and the critical role of AI in creating intelligent maritime transport systems of the future is conducted. The research includes comparative analysis of traditional propeller installations and azimuthal propulsion complexes, modern developments in energy-saving devices such as Becker Mewis Ducts, and integration of adaptive control systems with propulsion technologies.

Results demonstrate that integration of advanced AI technologies in autopilot systems enables achieving significant improvements in course control accuracy by 25–35%, substantial fuel consumption reduction by 10–15%, qualitative enhancement of overall maritime safety. Azimuthal thrusters provide 32% reduction in incident rates and 33–67% improvement in maneuvering characteristics compared to traditional systems. Energy-saving devices achieve fuel savings up to 8% for slow full-form vessels.

The work systematizes and critically analyzes results of modern research on fuzzy controllers, neural network autopilots of various architectures, hybrid ANFIS systems,

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backstepping control methods, LSTM networks for trajectory prediction, reinforcement learning, event-triggered approaches, and predictive control technologies.

Keywords

Autopilot, artificial intelligence, navigation, energy efficiency, neural networks, autonomous ships, course stability, trajectory control, marine automation, navigation safety, adaptive control, propulsion systems, intelligent transport systems.

6.1 Introduction

Modern maritime navigation is experiencing fundamental changes driven by rapid development of digital technologies and artificial intelligence methods. Traditional automatic ship control systems based on classical control theory principles are gradually being supplemented and replaced by intelligent systems capable of adapting to changing environmental conditions and optimizing navigation processes in real-time.

Ensuring precise maintenance of a ship on a given course is one of the fundamental tasks of navigation, directly affecting safety and economic efficiency of maritime transport. In conditions of intensifying maritime cargo transportation, automation of ship course-keeping processes becomes particularly relevant. The relevance of research in adaptive neural network ship course control systems is determined by several factors.

Growing intensity of maritime transport and increasing number of vessels in confined waters raise risks of emergency situations. Statistics show that most maritime accidents (51.5%) occur in inland waters, with human factors accounting for 59.1% of total accident causes [1]. The International Maritime Organization has set ambitious goals to reduce greenhouse gas emissions in the maritime industry by 40% by 2030 and 70% by 2050 compared to 2008 levels [2].

Traditional automatic ship course control systems based on PID controllers have limitations related to insufficient adaptability to changing navigation conditions [3]. A significant problem of traditional course stabilization systems is inadequate consideration of wave disturbances, leading to significant deviations from the given course during storm conditions. Research shows that under conditions of significant sea disturbance, traditional systems demonstrate average course deviation of 4–5°, which is unacceptable for safe navigation.

Growing requirements for maritime safety, environmental constraints, and the need to improve economic efficiency of maritime transport stimulate development of new approaches to navigation automation. Development of autonomous shipping concepts requires creation of reliable and efficient control systems capable of functioning in various navigation conditions without human intervention.

Classical ship autopilots based on PID controllers have fundamental limitations related to their linear nature and the need for precise parameter tuning for each specific vessel and sailing conditions [4]. Traditional controllers, while providing acceptable control quality under stationary conditions, significantly yield to adaptive neural network systems in presence of uncertainties and external disturbances. The nonlinear nature of ship dynamics, especially at large rudder angles or in heavy seas, requires application of more sophisticated control methods [3].

With development of artificial intelligence and neural network technologies, new possibilities have emerged for creating more flexible and efficient course stabilization systems. Neural network algorithms allow accounting for the nonlinear nature of ship dynamics, adapting to changes in external conditions and operating modes, and learning based on accumulated experience [5]. This makes them a promising tool for solving the task of maintaining a ship on course under influence of various disturbing factors.

Modern ocean shipbuilding is at the stage of significant technological transformations driven by growing requirements for energy efficiency and environmental friendliness of maritime transport [2]. Traditional propeller installations, which have long been the standard in shipbuilding, are gradually giving way to more modern systems, particularly azimuthal propulsion complexes [1, 6]. This trend is driven not only by the pursuit of increased energy efficiency, but also by the need to ensure better ship maneuverability in conditions of increasing intensity of maritime transport and development of new sea routes, including Arctic waters.

The purpose of this research is to provide comprehensive analysis of modern approaches to AI technology integration in marine autopilot systems, assess their impact on energy efficiency, analyze modern propulsion technologies, and determine prospects for autonomous navigation development. The work aims to systematize accumulated experience in applying intelligent technologies for ship course keeping tasks and identify the most promising directions for further research.

6.2 Evolution of autopilot systems and artificial intelligence integration

The development of automatic ship control systems has passed through several stages, each characterized by implementation of new technological solutions and control methods. Early autopilots were simple mechanical devices capable of maintaining a ship's set course using gyrocompass and steering gear.

Significant progress in ship autopilots occurred with electronic systems introduction and automatic control theory development. Several main approaches to ship course control have been identified: course control method, deviation control, disturbance control, and control based on long-term prediction principles [4].

Historically, various modifications of PID controllers were used for automatic ship course keeping. Despite relative simplicity of implementation, they have disadvantages when operating under changing external influences [3]. In course control method, the ship is controlled by compass without considering external disturbances and sailing circumstances. Waypoint steering mode "from WP to WP" is sequentially applied after each turn to a new route segment. In deviation control, ship course changes each time when position is determined and unacceptable displacement from planned trajectory is established. Different course control methods have their specific features and application areas, as illustrated in **Fig. 6.1**.

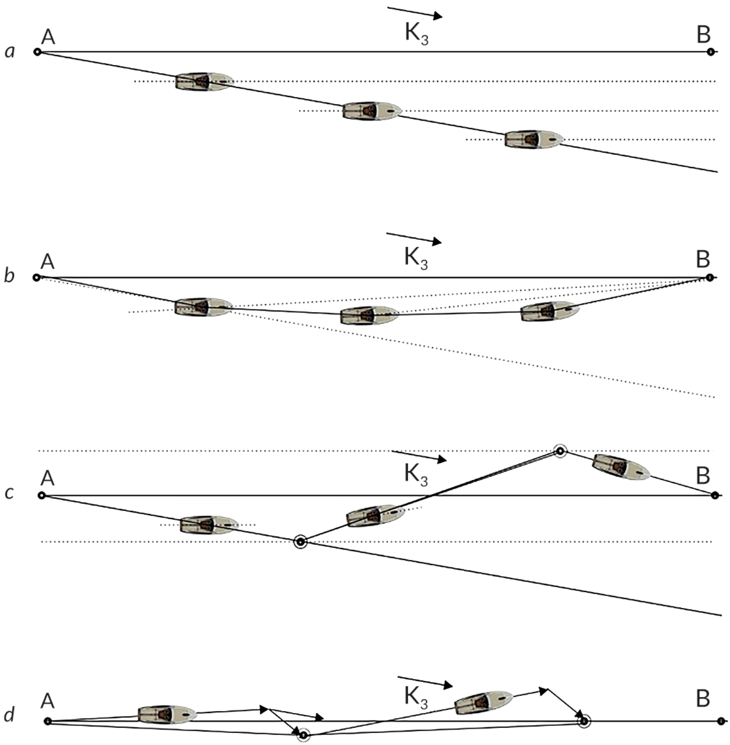

Fig. 6.1 Main approaches to ship course control: *a* – course control method; *b* – from "WP to WP"; *c* – deviation control; *d* – disturbance control
Source: [4]

Classical PID controllers have substantial limitations. With proportional control law (P-controller), course stabilization system with course-unstable ship is inoperable. For course-stable ships, P-controller is ineffective. PID controller in steady state provides astatic course stabilization system but requires precise coefficient tuning.

6.2.1 Mathematical models for ship dynamics

Effective ship course control requires adequate mathematical description of its dynamics. Most research utilizes the second-order Nomoto linear model, which is relatively simple and suitable for course control system synthesis

$$G(s)=\frac{K_R}{s(T_R s+1)}, \tag{6.1}$$

where K_R and T_R – ship maneuverability indices.

For more complete description of ship motion, a nonlinear model is considered

$$\ddot{\psi}=\alpha\dot{\psi}+\beta\dot{\psi}^3-\gamma\delta-K_d, \tag{6.2}$$

where $\alpha=-1/T_R;\beta=-\alpha/T_R;\gamma=K_R/T_R$, and K_d – represents external disturbances.

In real marine environment conditions, ship model parameters are not constant and are subject to influence of various factors, necessitating application of adaptive control methods. Particular complexity is presented by modeling ship dynamics in confined waters where additional hydrodynamic effects of interaction with shores and shallows arise.

6.2.2 Parameter identification methods

An important element of building effective course control systems is accurate identification of ship model parameters. Existing identification methods can be divided into two main groups: offline identification methods requiring preliminary data collection and processing, and online identification methods allowing parameter estimation during ship motion. For ship course control tasks, online identification methods are of greatest interest, among which the Extended Kalman Filter (EKF) method is particularly effective. This method allows real-time estimation of parameters α, β, and γ based on measurements of heading angle, angular velocity, and rudder angle.

The EKF identification algorithm consists of the following steps:

1) system state prediction based on previous parameter estimates;

2) error covariance matrix updating;

3) Kalman gain coefficient calculation;

4) parameter estimate correction based on current measurements;

5) covariance matrix updating.

Experimental research shows that EKF identification provides fast convergence of ship model parameter estimates and high motion prediction accuracy, making it an effective tool for adaptive control systems [7].

6.2.3 Neural network identification and architecture types

An alternative approach is using neural networks for ship model parameter identification. Backpropagation (BP) neural networks demonstrate high efficiency in solving nonlinear dependency approximation and system dynamics prediction tasks. For ship model parameter identification, a two-layer BP neural network is used with heading angle, angular velocity, and rudder angle values at previous steps as inputs, and predicted model parameter values as outputs.

Hidden layer neurons use nonlinear activation functions like Sigmoid, providing capability to approximate complex nonlinear dependencies. Network training is performed using backpropagation method with gradient descent algorithm. Analysis of experimental research results shows that BP neural networks provide high accuracy of ship model parameter identification with average prediction error of only 0.28% and training time of about 3.51 seconds, making this approach suitable for real-time systems [8]. Recent years have seen development of approaches to ship control based on artificial neural networks. Using neural network models as predictive components of ship trajectory stabilization systems has been proposed. This approach allows predicting changes in ship position and making corrections to control inputs in advance.

Neural network models for ship course control are divided into several types:

1. Multilayer perceptrons with backpropagation training demonstrate effectiveness in approximating nonlinear dependencies [5]. These networks provide good accuracy for static nonlinear mapping but have limitations in handling temporal dependencies.

2. Recurrent neural networks allow accounting for temporal dependencies in ship dynamics [5]. These architectures are particularly effective for sequence prediction and can model the dynamic behavior of maritime systems over time.

3. LSTM networks (long short-term memory) effectively account for temporal dependencies in ship dynamics, providing 30–40% higher accuracy in predicting ship behavior compared to traditional models [5]. LSTM architecture ensures effective handling of long-term dependencies and gradient vanishing problems.

4. Neuro-fuzzy systems combine advantages of neural networks and fuzzy logic, providing interpretable decision-making capabilities while maintaining learning abilities [2].

5. Deep reinforcement learning networks capable of learning optimal control strategies through interaction with the environment [9]. These systems can adapt to changing conditions and optimize control policies based on accumulated experience.

Research in deep learning demonstrates that this approach allows significantly improving ship control quality under complex navigation conditions [10]. However, application of such methods requires significant computational resources and large datasets for training.

6.2.4 Fuzzy logic implementation

The revolutionary transition to intelligent autopilot systems began with fuzzy logic implementation in maritime automation. Fuzzy autopilots have been developed for ships experiencing shallow water effect in maneuvering, demonstrating that fuzzy controllers can effectively work with inaccurate and incomplete information, which is especially important in maritime conditions [11].

The fuzzy autopilot uses heading signal and yaw rate signal to produce rudder angle command without using lateral offset from nominal track. Input variables undergo fuzzification, fuzzy associative memory rules are applied, and output set defuzzification is performed. Simple methods for generating fuzzy course controllers for marine ships have been developed that build controllers without using training data, utilizing conventional triangular sets without complex overlaps or expert judgments. Simulation results demonstrate that course stabilization systems synthesized with fuzzy controllers possess robust properties and effectively stabilize given ship course under various operating conditions [12].

6.2.5 Neural network systems and hybrid ANFIS systems

Further development of intelligent autopilots relates to neural networks and machine learning technologies implementation. Neural network systems for ship heading and position control have shown that artificial neural networks are widely applicable for both course keeping and course changing maneuvers [13]. Thruster-based control systems are more effective in dynamic positioning of ships, as they can automatically maintain predetermined position and heading using thrust force. This approach is particularly beneficial for vessels requiring precise positioning capabilities [13].

Hybrid neuro-fuzzy systems (ANFIS – Adaptive Network-based Fuzzy Inference System) combine advantages of fuzzy logic and neural networks. Ship steering autopilots based on ANFIS framework and conditional tuning schemes utilize five-layer structure for membership function parameter optimization, as shown in **Fig. 6.2** [14].

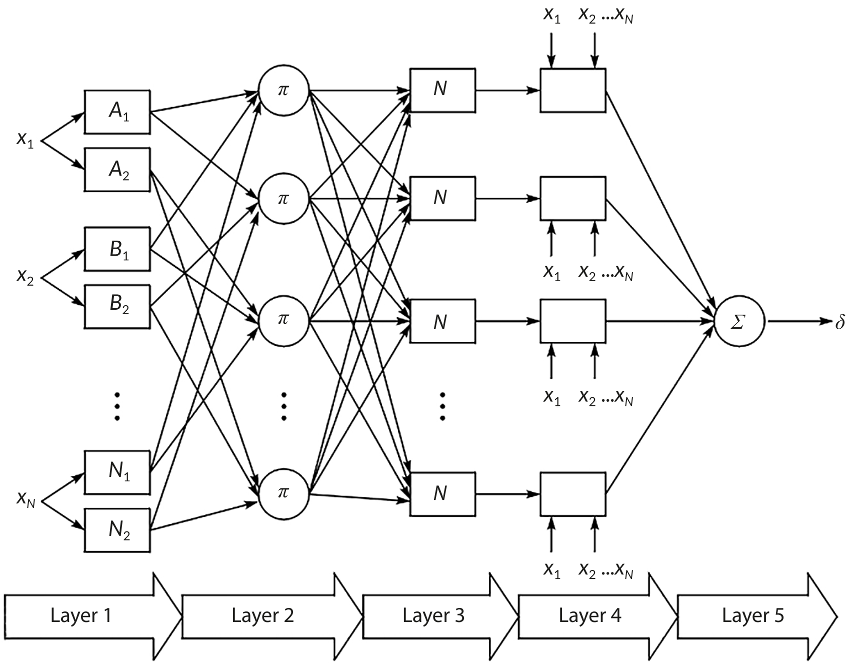

Fig. 6.2 ANFIS layer structure for ship steering autopilot
Source: [14]

ANFIS uses hybrid learning algorithm to identify membership function parameters of two inputs with single output. Simulation results show that proposed autopilots provide more adaptive and robust control performance compared to traditional PD fuzzy controllers under typical sea conditions [14].

6.2.6 Advanced control methods

Fuzzy track-keeping autopilots for ship steering have been developed with automatic tuning methods for parameter optimization. Standard Sugeno-type fuzzy autopilots demonstrate robustness and good performance in cases without sea current influence. However, in presence of sea current disturbances, additional fuzzy gain controllers (FGC) are implemented to adjust input and output variables of fuzzy autopilots [15].

Backstepping methods combined with neural networks show promising results for ship course control. Adaptive neural network robust course-keeping controllers have been developed to address uncertainties and unknown time-varying environmental disturbances in nonlinear ship course control systems [16]. Neural networks compensate nonlinear terms while adaptive laws estimate neural network weights and bounds of unknown environmental disturbances. First-order commanders are introduced to solve the "explosion of complexity" problem in traditional backstepping design methods [16].

Adaptive fuzzy H_∞ control methods for ship steering problems have been compared with nonlinear backstepping control approaches. The overall control signal consists of equivalent control for plant linearization through state vector feedback and supervisory control with H_∞ terms that compensate parametric uncertainties and external disturbances [17]. Unknown parts of plant models are approximated by neuro-fuzzy approximators, providing advantages over backstepping control which assumes knowledge of plant dynamic models [17].

6.3 Advanced neural network control architectures

Based on analysis of existing research [2, 10], optimal neural network system architecture for ship course keeping tasks can be determined. Such a system should include the following functional blocks:

– **Identification Block** – implemented as a multilayer perceptron designed to determine current dynamic characteristics of the ship based on motion data. Optimal architecture with two hidden layers provides sufficient accuracy with acceptable computational complexity;

– **Predictive Model** – based on LSTM recurrent neural network that effectively accounts for temporal dependencies in ship dynamics. LSTM architecture provides 30–40% higher accuracy in predicting ship behavior compared to traditional models [5]. Using recurrent neural networks allows effective prediction of ship position changes 5–10 seconds ahead, enabling advance correction of control inputs. Accuracy of such prediction reaches 85–90% under normal navigation conditions;

– **Controller** – implemented as neural network regulator generating control input to steering device. Effectiveness of deep reinforcement learning algorithms for controller implementation is emphasized [9];

– **Adaptation Block** – designed for correcting neural network parameters during operation based on control efficiency assessment.

6.3.1 Transfer learning and adaptation

Using transfer learning techniques allows significantly reducing time and data volume required for neural network training for new ship types [5]. This is particularly important for practical application of neural network systems in real conditions. Neural network systems demonstrate capability to adapt to changing navigation conditions. Traditional systems require manual reconfiguration when ship loading or weather conditions change, while neural network systems can automatically adapt to new conditions within 15–20 minutes of operation [10]. Particularly important is the ability of neural network systems to adapt to changing navigation conditions.

Analysis of scientific research [1, 2, 10] allows drawing conclusions about effectiveness of applying neural network algorithms for ship course keeping. Comparative analysis of traditional control systems based on PID controllers and systems using deep learning shows significant advantages. Results demonstrate that under moderate sea conditions (2–3 points), neural network systems provide 25–30% reduction in average course deviation compared to PID controllers. Under strong sea conditions (4–5 points), advantages of neural network approach become even more pronounced - deviation reduction up to 40%.

Neural network systems demonstrate smoother rudder angle changes, reducing steering device wear by 15–20% and providing fuel savings up to 3–5% during long voyages [1]. This economic benefit makes neural network systems attractive for commercial maritime operations.

6.3.2 Fractional order PID controllers

One direction for improving adaptive course control systems is using fractional order proportion integration differentiation (FOPID) controllers. These controllers are generalizations of classical PID controllers and provide higher flexibility in parameter tuning

$$G_c(s)=k_p+\frac{k_i}{s^{\lambda}}+k_d s^{\mu}\ (0<\lambda<2.0<\mu<2), \tag{6.3}$$

where λ and μ – orders of integral and differential terms respectively.

FOPID controllers have additional degrees of freedom (integration and differentiation orders), allowing more precise shaping of control system frequency characteristics and ensuring better quality indicators. However, parameter tuning of such controllers is a complex task requiring special optimization methods.

For FOPID controller parameter optimization, the particle swarm optimization (PSO) method is effectively applied. This method belongs to the class of metaheuristic optimization algorithms and is based on modeling social behavior of organism groups such as bird flocks or fish schools.

The PSO optimization algorithm for FOPID controller parameter tuning includes the following steps:

1) population initialization with random controller parameter values;
2) objective function evaluation for each particle;
3) updating best positions for each particle and entire population;
4) updating particle velocities and positions;
5) convergence condition checking and repeating steps 2–4 until desired result is achieved.

An integral control quality criterion considering regulation error and control energy expenditure is used as objective function for optimization. Integration of BP neural network methods for ship model parameter identification with PSO-optimized FOPID controllers allows creation of highly effective adaptive course control systems providing optimal balance between speed, accuracy, and robustness.

6.3.3 Trajectory modeling with Bézier curves

An important element of ship course control system development is trajectory modeling. The traditional approach using linear segments to connect route points does not correspond to real ship dynamics and leads to significant errors in automatic control. More effective is using rational Bézier curves for trajectory modeling.

A second-order rational Bézier curve can be effectively parameterized considering ship dimensions, draft, and angular trajectory

$$W_2=\frac{L_{\varphi}}{\nabla(1-c)S_{drift}}, \tag{6.4}$$

where L – ship length; φ – angular path; ∇ – displacement; S_{drift} – drift path; c – dimensionless coefficient.

Using Bézier curves for ship trajectory modeling allows accounting for ship maneuverability constraints, ensuring smooth course changes, and minimizing deviations from given route. Additionally, this approach combines well with adaptive neural network control systems as it allows generating realistic reference signals for control systems [18].

6.3.4 Control system integration and performance optimization

Based on identified ship model parameters, adaptive controller synthesis for course control is performed using multiple integrated approaches. One of the most effective methodologies is the closed-loop gain shaping (CGS) method, which allows forming desired transfer function of closed control system and ensures high stability of neural network course keeping systems to model inaccuracies and external disturbances [7]. The CGS approach provides systematic framework for designing robust controllers that maintain performance under varying operational conditions. The method formulates control law based on desired closed-loop characteristics, enabling precise shaping of system response while maintaining stability margins. Integration with EKF identification creates adaptive framework that continuously updates controller parameters based on real-time system identification [7].

Comparative analysis of different ship course control methods based on mathematical modeling confirms advantages of adaptive neural network systems. Modeling results demonstrate that adaptive CGS controller based on EKF identification provides significantly faster rise time (18.511 s) compared to traditional PD controller (70.648 s) and classical CGS controller (110.181 s) [7]. This performance improvement represents 74% reduction in settling time compared to conventional approaches.

Further advancement in control system performance is achieved through integration of PSO and FOPID methods with neural network prediction of ship model parameters [8]. The particle swarm optimization algorithm enables optimal tuning of fractional-order controller parameters, while neural networks provide accurate real-time model identification. This hybrid approach combines the robustness of fractional-order control with adaptive capabilities of neural networks. Experimental research demonstrates that integrated PSO-FOPID-neural network systems provide fast stabilization on given course (2.75 s) with minimal regulation error (0.065), significantly exceeding traditional control system performance [8].

The system achieves optimal balance between transient response speed and steady-state accuracy while maintaining robustness to parameter variations and external disturbances.

The integration of multiple AI technologies creates synergistic effects that enhance overall system performance. Neural networks provide nonlinear mapping capabilities and learning functions, while fuzzy logic contributes linguistic rule-based reasoning and uncertainty handling. ANFIS systems combine these advantages, providing interpretable control decisions with adaptive learning capabilities [14]. For large marine vessels operating in confined waters, ensuring high accuracy of trajectory following during maneuvering becomes particularly critical. Using adaptive neural network control systems combined with Bézier curve-based trajectory modeling allows significantly improving navigation safety and control efficiency [18]. The approach enables precise path planning that accounts for shallow water effects, traffic density, and environmental constraints.

Event-triggered control mechanisms provide additional performance benefits by optimizing computational resource utilization while maintaining control quality [19]. The event-triggered approach activates control updates only when system state deviates beyond predefined thresholds, reducing unnecessary computations and energy consumption. This methodology proves particularly valuable for autonomous vessels with limited onboard computational resources.

Modern integrated control systems incorporate multiple sensor fusion techniques to enhance state estimation accuracy. Data from inertial navigation systems, GPS, gyrocompasses, anemometers, and other sensors are processed using advanced filtering algorithms to provide robust state estimates under varying environmental conditions [3]. Machine learning algorithms enable real-time sensor fault detection and compensation, ensuring continued operation even with sensor degradation.

The performance validation of integrated control systems requires comprehensive testing under diverse operational scenarios. Simulation studies demonstrate superior performance metrics including reduced overshoot, faster settling times, improved disturbance rejection, and enhanced robustness to model uncertainties. Field testing confirms these simulation results, showing practical benefits in real maritime operations. System integration challenges include computational complexity management, real-time implementation constraints, and ensuring fail-safe operation modes. Modern marine control systems address these challenges through hierarchical control architectures, distributed processing, and redundant safety systems. The integration of AI technologies must maintain maritime safety standards while providing enhanced performance capabilities.

6.4 Propulsion systems and energy efficiency optimization

Energy efficiency issues in maritime transport are gaining increasing relevance in context of global climate change mitigation efforts and improving economic efficiency of shipping. The International Maritime Organization (IMO) has set ambitious goals to reduce greenhouse gas emissions in the maritime industry by 40% by 2030 and 70% by 2050 compared to 2008 levels [2]. This drives the search for and implementation of innovative technical solutions in ship propulsion systems.

Traditional propeller installations, which have long been the standard in shipbuilding, are gradually giving way to more modern systems, particularly azimuthal propulsion complexes. This trend is driven not only by the pursuit of increased energy efficiency, but also by the need to ensure better maneuverability of ships in conditions of increasing intensity of maritime transport.

Azimuthal propulsion complexes (azipods) represent gondola installations with electric drive that can rotate 360°. Main advantages of azipods include: absence of mechanical energy transmission, improved maneuverability, reduced noise and vibration, greater efficiency in ice conditions, and smaller engine room dimensions.

According to ABB research, azipods enable 5–15% fuel consumption reduction depending on vessel type and operating conditions, 30–50% reduction in mooring operation time, and 15–20% improvement in ice-breaking capability.

Analysis of statistical data from leading classification societies (DNV GL, Lloyd's Register, Bureau Veritas) for 2015–2023 shows that vessels with azipods demonstrate 1.9 incidents per 1000 vessel-days compared to 2.8 incidents for traditional propulsion systems. Maneuvering characteristics improvements include 33% reduction in turning circle diameter, 34% reduction in stopping distance, and 67% improvement in position-keeping accuracy [2].

Becker marine systems developments represent significant innovations in propulsion efficiency. The Becker Mewis duct, an energy-saving device for slow full-form vessels, provides up to 8% fuel savings, SO_x and CO_2 emission reductions, and 2–3-year payback period. For high-speed vessels, the Becker Mewis duct twisted achieves approximately 3% fuel savings while reducing vibration and improving course stability. The Becker flap rudder provides optimized profile, reduced weight, improved maneuverability, and maximum lift force with flap deflection up to 100°. The innovative Becker twist rudder with twisted leading edge reduces cavitation, minimizes rotational losses, increases propulsive efficiency, and reduces fuel consumption and equipment wear.

6.4.1 AI-enhanced trajectory control and energy optimization

Advanced trajectory tracking and control methodologies demonstrate significant potential for energy savings. Trajectory tracking performance using GPR-MPC (Gaussian process regression model predictive control) shows significant improvements in ship trajectory control [20] (**Fig. 6.3**). The GPR-MPC approach represents advancement over traditional model predictive control by incorporating uncertainty quantification and adaptive learning capabilities.

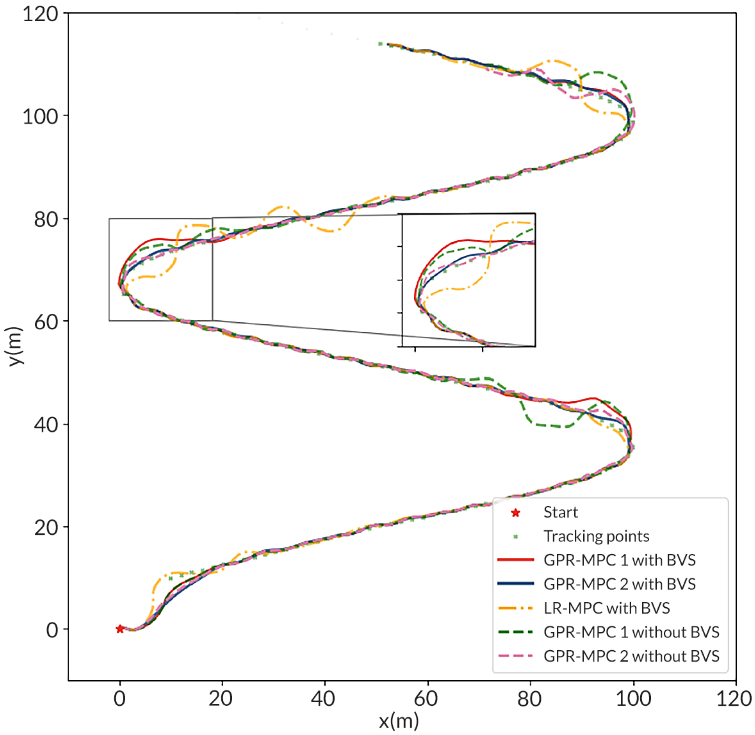

Fig. 6.3 Trajectory tracking performance of GPR-MPC 1, GPR-MPC 2, and LR-MPC with reference trajectory
Source: [20]

Results demonstrate that BVS strategy significantly improves trajectory tracking performance with approximately 50% improvements in heading control and

30% improvements in surge speed control [20]. Event-triggered adaptive control maintains system performance while significantly reducing control updates and energy consumption [19].

6.4.2 Adaptive steering control for azimuth thrusters

For vessels with azimuthal thrusters, specialized adaptive steering control systems have been developed. These systems employ modified PD controllers with adaptive derivative components that preserve performance while reducing overshoot effects. The control law adapts the derivative gain based on course error, providing smooth and efficient steering responses.

Azimuth thruster control systems integrate multiple sensors and use neural networks for optimal thrust allocation and direction control. The adaptive laws are designed to estimate thruster dynamics and compensate for unknown environmental disturbances while maintaining stability and minimizing energy consumption.

6.4.3 Intelligent energy management integration

Modern AI-based autopilot systems integrate multiple information sources including data from inertial navigation systems, GPS, gyrocompasses, anemometers, logs, echo sounders, radars, and automatic identification systems (AIS). Machine learning enables efficient processing and interpretation of this heterogeneous information for optimal control decisions.

Eniram systems demonstrate that intelligent speed optimization allows 3–5% reduction in propulsion fuel consumption by considering over 1.5 billion daily measurements from various sensors. The system accounts for current effects, weather conditions, shallow water effects, engine efficiency at different loads, and regional speed restrictions.

6.5 Limitations and challenges

Despite obvious advantages, neural network approaches have several limitations:

– **Computational Complexity** – implementation of neural network algorithms requires significant computational resources, which can be problematic for existing ship control systems. Real-time processing of complex neural network models may strain onboard computing capabilities;

– **Training Requirements** – effective neural network operation requires significant data volumes and training time. Quality of training data directly affects system performance, and collecting sufficient maritime operational data can be challenging;

– **Interpretability** – neural network models often represent "black boxes", complicating analysis of their operation and certification by relevant supervisory authorities. This lack of transparency can be problematic for safety-critical maritime applications where decision-making processes must be understood and verified;

– **Robustness Concerns** – neural networks may be sensitive to input data variations outside their training domain, potentially leading to unpredictable behavior in novel situations not encountered during training;

– **Regulatory Challenges** – maritime regulations and certification processes have not yet fully adapted to accommodate AI-based control systems, creating barriers to widespread adoption.

6.6 Conclusions

Conducted analysis of modern approaches to maritime navigation automation demonstrates fundamental changes in maritime transport technologies driven by rapid artificial intelligence development. AI technology integration in marine autopilot systems and propulsion complexes opens unprecedented opportunities for improving maritime safety, enhancing course control accuracy, and significantly reducing energy consumption. Evolution from classical PID controllers to intelligent control systems based on neural networks, fuzzy logic, and machine learning represents a qualitative leap in maritime automation development. Modern autopilot systems equipped with AI technologies can adapt to changing sailing conditions, account for nonlinear ship dynamics characteristics, and effectively compensate external disturbance effects [5, 10].

Analysis of research results demonstrates high effectiveness of applying adaptive neural network methods for ship course control. The most effective is hybrid architecture including identification block based on multilayer perceptron, predictive model based on recurrent neural network, neural network controller, and adaptation block [5]. Research results show that neural network approaches provide higher course keeping accuracy compared to traditional methods, especially under complex navigation conditions, with average course deviation reduction reaching 40% under strong sea conditions.

Fuzzy controllers provide robust control under uncertainty conditions and can effectively operate without precise mathematical ship models [11, 12]. Fuzzy autopilots for ships experiencing shallow water effect demonstrate effectiveness in challenging conditions [11]. Simple fuzzy controllers ensure robust properties of course stabilization systems [12].

Hybrid systems combining various AI technologies show best results in practical applications. ANFIS systems provide high control quality while maintaining decision interpretability [14]. Simulation results demonstrate that proposed autopilots provide more adaptive and robust control performance compared to traditional controllers.

Key advantages of neural network approaches include adaptability to changing navigation conditions, ability to account for nonlinear ship dynamics, capability for predicting ship behavior and self-learning during operation. LSTM networks provide 30–40% higher prediction accuracy compared to traditional models [5]. Deep reinforcement learning methods enable optimal control strategy development through environmental interaction [9].

Fractional Order PID controllers optimized using particle swarm optimization methods allow achieving optimal balance between system speed and transient process quality [8]. Application of rational Bézier curves for ship trajectory modeling combined with neural network control methods ensures high accuracy of given course following and effective maneuvering [18].

Backstepping methods combined with neural networks demonstrate effectiveness for compensating nonlinearities and uncertainties in ship course control systems [16]. Introduction of first-order commanders solves "explosion of complexity" problems in traditional backstepping methods.

Particularly significant are achievements in ship system energy efficiency and propulsion technologies. Azimuthal propulsion complexes provide 5–15% fuel consumption reduction depending on vessel type and operating conditions, 30–50% maneuverability improvement, and 15–20% ice-breaking capability enhancement [1, 6]. Statistical analysis shows 32% accident rate reduction for vessels with azipods compared to traditional propulsion systems [2]. Modern energy-saving devices such as Becker Mewis ducts achieve fuel savings up to 8% for slow full-form vessels and up to 3% for high-speed vessels. Advanced trajectory tracking methods demonstrate significant improvements in ship trajectory control with trajectory tracking performance enhancement of 50% in heading control and 30% in speed control [20]. Event-triggered approaches enable additional reduction of computational load and energy consumption while maintaining control quality [19].

Comparative analysis of various control methods shows that adaptive CGS controller based on EKF identification provides faster rise time (18.511 s) compared to traditional PD controller (70.648 s) and classical CGS controller (110.181 s) [7]. Further system improvement through PSO and FOPID method integration with neural network model parameter prediction allows achieving even higher control quality indicators [8]. Neural network systems demonstrate smoother rudder angle changes, reducing steering device wear by 15–20% and providing fuel savings up to 3–5% during long voyages. These economic benefits make neural network systems attractive for commercial maritime operations.

Autonomous shipping development creates new requirements for AI systems, including decision-making capability in critical situations, cybersecurity assurance, and reliable operation under limited communication conditions [10]. Adaptive fuzzy systems show capability for self-tuning and performance improvement in presence of environmental disturbances [15].

However, AI technology implementation in maritime industry faces several challenges, including ensuring system reliability and safety, interface and protocol standardization, qualified personnel training, and regulatory framework development. Computational complexity, training data requirements, and interpretability concerns remain significant barriers to widespread adoption.

Future development prospects relate to machine learning algorithm improvement, increasing computational power of ship systems, expanding sensor technology capabilities, and developing hybrid architectures combining neural network methods with traditional control approaches. Integration of neural network control systems with e-navigation technologies and autonomous vessels represents a promising direction for future research [10]. Obtained results have important practical significance for improving automatic control systems of marine vessels and can be used in developing new generations of autopilots with improved course stabilization characteristics. Full realization of AI potential in navigation will require comprehensive approach combining technological innovations with new safety standards, personnel training, and regulatory framework development [3].

Analysis results indicate that future of maritime transport will be determined by degree of successful integration of intelligent technologies into traditional navigation systems. Particular importance is acquired by development of hybrid systems combining advantages of various AI approaches for achieving maximum efficiency, safety, and environmental friendliness of maritime transport.

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CHAPTER 7

Analysis of modern underwater navigation and design capabilities of underwater cargo vessels

Anastasiia Zaiets

Abstract

The aim of the study is to analyze the advantages and disadvantages of modern navigation methods for autonomous underwater vehicles and their groups, including the use of neural networks, and to determine their development prospects; as well as to enhance the effectiveness of deep-sea surveying and the execution of various underwater operations through the use of advanced mathematical support for autonomous underwater vehicles; the development of underwater space in the interests of maritime freight transport as such, which increases the carrying capacity of existing sea transport routes, increases energy efficiency and reduces the risks of freight transport, provided there is no negative impact on the movement of the vehicle by wind, surface waves and drift currents.

The challenges of developing a control system for autonomous underwater vehicles have been examined. A new architecture of mathematical support for the control system of autonomous underwater vehicles is proposed, which incorporates both hierarchical and behavior-based control structures. This significantly expands the capabilities of these vehicles, enabling them to solve tasks of various classes under the constraints of onboard computational network resources.

Within the proposed architecture, a behavior-based approach is applied at different levels of the functional hierarchical control system. A methodology is substantiated for constructing a tactical-level agent library based on the functional decomposition of the target task class. The structure of an agent has been developed and studied; it includes a local environmental model, tools for planning actions based on this model, and mechanisms for analyzing the utilized information to assess the agent's operational effectiveness.

Examined the development of underwater space in the interests of maritime freight transport as such, which increases the carrying capacity of existing sea transport routes, increases energy efficiency and reduces the risks of freight transport,

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provided there is no negative impact on the movement of the vehicle by wind, surface waves and drift currents. It is proposed to create an extensive system of cargo transportation in the underwater space as an alternative to conventional shipping. It is established that underwater data transmission based on lasers and radio waves is effective for data transmission only in conditions where the underwater transport vessel moves in the near-surface layer of the ocean.

Keywords

Underwater space, autonomous underwater vehicle, hydroacoustic systems, navigation, cargo transportation, behavioral architecture, hierarchical architecture.

7.1 Introduction

In the 21st century, the rapid growth of global trade, increasing congestion of major maritime routes, and the need to reduce the environmental impact of sea transport are driving the search for innovative solutions in maritime logistics. One of the most promising directions that is increasingly attracting the attention of researchers and engineers is the use of underwater cargo vessels as a new class of transport platforms. What only a few decades ago seemed purely futuristic is now being considered a potentially viable solution for transporting strategically important cargo, particularly in conditions of military conflict, sanctions pressure, restricted shipping, or harsh climatic zones.

The development of modern underwater navigation requires a comprehensive analysis – both from the perspective of navigational technologies and from the standpoint of structural implementation of such vessels. Key challenges include optimizing hull design to minimize resistance during submersion, ensuring reliable energy supply, maximizing cargo capacity, and maintaining stability and safety.

It is also worth highlighting that, in the context of geopolitical instability, piracy threats, and restrictions on movement in certain maritime zones, underwater cargo vessels may become a critical strategic asset – both in the commercial and defense sectors.

7.2 Analysis of modern methods and prospects for the development of underwater vehicle navigation

Over the past decade, the development of commercially available, high-accuracy navigation sensors with high update rates – such as Doppler sonars, optical gyroscopes, and inertial measurement units (IMUs) – has significantly complemented traditional underwater sensors like acoustic positioning systems, magnetic compasses, and pressure-based depth sensors.

Long baseline (LBL) systems, in which the vehicle triangulates its position using acoustic ranges from a network of surveyed transponders, and ultra-short baseline (USBL) systems, which use sonar arrays to determine both the range and bearing to the vehicle, are now routinely used in underwater navigation.

External acoustic positioning systems are employed by underwater vehicles to triangulate their position based on range or a combination of range and bearing information between the vehicle-mounted transceiver and multiple external acoustic transponders. A key advantage of these systems lies in their minimal demands on the vehicle's size and power consumption when compared to other navigation techniques. However, unlike some onboard navigation systems, certain types of external acoustic systems require the deployment of seabed-mounted transponders in the operational area [1].

In such systems, the vehicle calculates its distance to each transponder by measuring the time-of-flight of an acoustic signal and estimating the speed of sound in the water column between the vehicle and the transponder. The availability of directional information depends on the geometry of the transponder array. Three primary geometric configurations are used in external acoustic navigation systems: short baseline (SBL), ultra-short baseline (USBL), and long baseline (LBL) [2].

The first developed type of external acoustic system was the **short baseline (SBL)** positioning system, which was primarily used for tracking or navigating underwater vehicles over short distances. These systems consist of a single transponder or transducer mounted on the underwater vehicle and an acoustic network typically installed on the hull of the support vessel.

In the 1970s, **ultra-short baseline (USBL)** navigation systems were developed as a simplified alternative to SBL systems. USBL systems can operate either from the underwater vehicle or its host vessel. USBL systems operating from an AUV (autonomous underwater vehicle), sometimes referred to as inverted USBL systems, enable the AUV to navigate relative to the location of a single external acoustic transponder [3].

Fundamentally, **long baseline (LBL)** navigation systems operate similarly to inverted SBL systems, but differ in that their external transponders are deployed independently in the ocean, rather than being mounted on the hull of a support vessel or on a deployable frame. Typical LBL systems involve deploying between four and twelve acoustic transponders, depending on the mission requirements, although the system can function with as few as two transponders.

An alternative computational algorithm for AUV navigation using an LBL system is based on the Kalman filter (KF). The Kalman filter combines data from onboard sensors with prior knowledge of their inaccuracies and a dynamic model of the system's state-space to provide real-time state estimations.

Despite the cost and time required to deploy and manage the acoustic transponders, LBL navigation systems remain the standard for low-cost deep-sea vehicle operations.

Doppler velocity log (DVL) navigation: the development of high-frequency multibeam Doppler sonars, which can measure bottom velocities with an accuracy of 0.3% or better and an update rate of up to 5 Hz, allows researchers to obtain velocity measurements for navigation near the seabed (within 18–100 meters). This has enabled the development of numerous Doppler-based navigation techniques, including those used to improve state estimation in inertial navigation systems (INS) [4].

NARX-RKF integrated navigation algorithm (nonlinear autoregressive with eXogenous input model with robust Kalman filter): according to recent analyses, navigation parameters are interrelated, and sensor bias is closely linked to external environmental conditions and the vehicle's motion state. Errors in the strapdown inertial navigation system (SINS) evolve according to specific patterns, and the overall navigation status error is strongly correlated with the vehicle's movement history data.

NARX-RKF includes a DVL fault prediction module based on the NARX model and an integrated navigation loop using the robust Kalman filter (RKF). The NARX model can use output data from the inertial navigation system to predict DVL output when it is interrupted, and it employs the RKF for integrated navigation [5].

Inertial navigation. Inertial measurement units (IMUs) offer excellent capabilities for navigation without external references. However, their power consumption (ranging from 12 to 30 V) and cost (often exceeding 100,000 USD) have until recently limited their widespread use in civilian oceanographic vehicles. Typically, IMUs are used together with Doppler velocity measurements and positioning data from GPS or acoustic navigation systems to correct IMU measurement errors. IMUs are often used in high-precision surveys and when vehicles are deployed under ice sheets or in the mesopelagic (mid-depth) zone.

Dead reckoning (DR) and **inertial navigation systems (INS)** are fundamental navigation methods. In both systems, the vehicle receives an initial position and then uses onboard sensor data to continuously update its estimated position.

In DR navigation, the vehicle's speed is integrated over time to estimate its movement path. However, this method provides only an approximate estimate of forward velocity and does not take into account the effects of currents or drift.

Global navigation satellite systems (GNSS) use signals from satellites orbiting the Earth to determine the geographical position of an object on the Earth's surface. The most well-known and widespread GNSS is GPS (Global positioning system). However, GPS signals in the radio frequency range are blocked by seawater, which means they cannot be directly received by deeply submerged ocean vehicles.

Trajectory estimation using diffusion-based observers. This approach is proposed for estimating the trajectory of an underwater vehicle primarily using gyro-Doppler measurements (velocity measurements) and an acoustic positioning system (horizontal positioning). The method relies on the use of diffusion observers, which, unlike traditional state observers, are capable of processing entire segments of a system's trajectory at once [6].

A common solution for group AUV navigation is the use of asynchronous LBL with bottom or surface responder beacons (RBs). This navigation method is based on measuring the response time of a beacon to an outgoing signal from the underwater vehicle. It is assumed that a set of RBs (at least two) is present in the operational area, no more than 10–15 kilometers from the underwater vehicle. By triangulating the received time delays of the beacon responses, the distance from the RBs to the AUV is determined.

In implementing such an approach for group AUV navigation, a key issue arises – the need to allocate the acoustic communication channel to each AUV in the group at an optimally defined frequency to determine its position.

The navigation algorithm for an AUV group within the THESAURUS project uses USBL data and is based on a Kalman filter (KF) that accounts for the specific features of network communication organization. This method is suitable for autonomous underwater vehicles because it does not require any external assistance other than a single seabed station. The core idea is to use mutual acoustic measurements between the vehicle and the single seabed station – the AUV initiates an acoustic query to the seabed station and measures the range between the two units, as well as the bearing of the seabed station relative to the AUV in the AUV's reference frame. Then, the seabed station calculates the bearing of the AUV relative to itself and transmits this information back to the AUV using a similar acoustic device.

Group navigation algorithms based on inter-AUV distance information.

There exists a leader AUV, which determines its position with high accuracy. Other vehicles in the group estimate their positions using onboard navigation sensors and refine those estimates based on distance measurements to the leader AUV. In study [7], a group autonomous navigation system (GANS) with a mobile base is described. In this case, several expensive AUVs equipped with high-precision navigation systems act as beacons for other, simpler and less expensive AUVs.

7.3 A promising structure of mathematical support for autonomous underwater vehicles for surveying sea depths

Autonomous underwater vehicles (AUVs) are a safe and effective means for exploring ocean depths and performing search and survey tasks such as rescue operations, bathymetric measurements, oceanographic and ecological monitoring, as well as mine countermeasures. AUVs can also be used to carry out complex research missions, including automatic inspection of underwater communications, detection of sources of environmental pollution, and anomaly identification [8].

A key challenge lies in the insufficiency of existing methods for task description and control system architectures in general, as well as their software, particularly for survey-related tasks.

Let T represent the set of tasks for seabed survey and underwater operations. Thus, the problem is to decompose the set of tasks T into subtasks T_i, where i belongs to some index set I, in such a way as to optimize the efficiency of solving these tasks. Let $F(T)$ represents a function that estimates the overall complexity of solving a set of tasks T. The goal is to find the optimal schedule $T = \bigcup_{i \in I} T_i$, which minimizes the complexity function $F(T)$, taking into account internal connections and the optimal functional decomposition of the target class of tasks.

Currently, hierarchical, behavioral, and hybrid software architectures are used for control systems in mobile robots. For a more detailed analysis of these architectures, certain requirements are imposed on the information and control systems (ICS) of AUVs: reduction of computational resource usage, resolution of conflicts between different goals, utilization of information from various sensors, reliability, the possibility of incremental functionality expansion, ease of use, and a wide range of implementation options [9].

The hierarchical architecture is knowledge-based and includes an accurate symbolic representation of the surrounding environment. Decisions are made based on formal reasoning, which is one of the advantages of this architecture.

In the behavioral architecture, the control process is divided based on the desired external manifestations of the robot's actions. The robot's behavior is formed from operations executed by independent elements (behaviors or agents). Each behavior is directed towards achieving a specific goal, and its response is based on real-time sensor data.

When developing an architecture for AUVs, it is essential to consider requirements for minimizing resource usage, flexibility, and the ability for sequential expansion. A three-level functional distribution model characteristic of goal-oriented behavior architecture was adopted as the basis for development. This approach allowed the clear definition of explicit tasks for AUVs at the top level while simultaneously meeting resource requirements and enabling stepwise extension [10]. The term "agents" is used to specify the tactical level of behavior. The general structure of the developed software control system for the AUV is shown in **Fig. 7.1**.

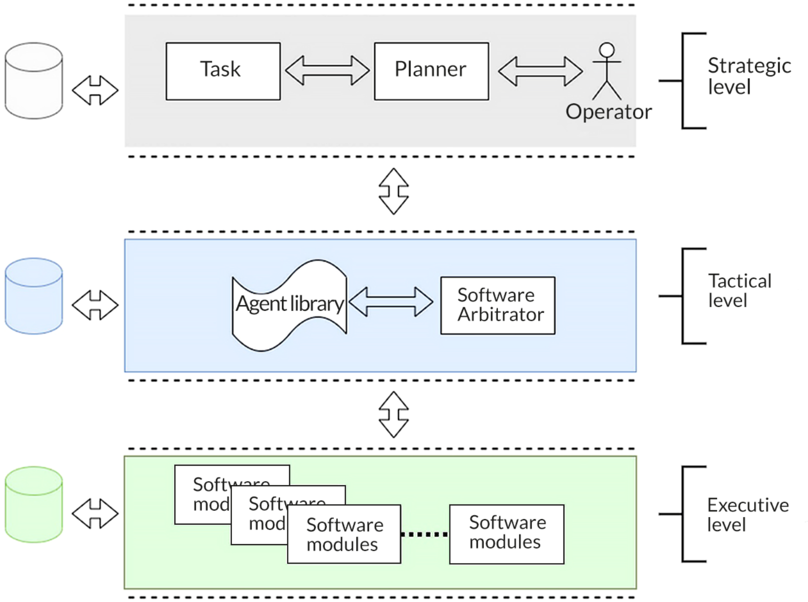

Fig. 7.1 Hybrid three-level architecture of the AUV software system

The system consists of three levels: executive, tactical, and strategic.

The executive level is responsible for controlling the robot's movement and executing reflex functions. The design of this level allows it to perform all functions dependent on the hardware of a specific robot and provides a hardware-independent interface for interaction with the tactical level.

The tactical level is used to organize the execution of the next task set by the strategic level. It directly manages the modes and goals of the executive level. To achieve this, a set of agents and an arbiter are located at this level, where the arbiter maintains the control structure of the agents to solve the current task.

The strategic level of the hierarchy is represented by a task program that contains a description of the current AUV mission objectives. To systematize the achievement of these objectives, a planner is generally used.

Interaction between system components occurs based on a client-server model or through the use of abstract interfaces implemented on the developed software platform, which supports event-driven and publish-subscribe mechanisms.

The tactical level of the system consists of a set of agents, each responsible for solving a specific aspect of the task (**Fig. 7.2**). The input parameters for each agent include the task description received from the strategic level, as well as the necessary data from the executive level. The output parameter is a stream of imperative commands for the executive level.

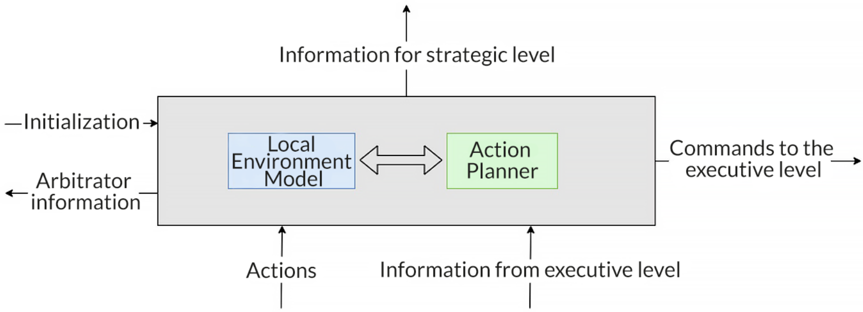

Fig. 7.2 Agent-based structure of the tactical level

The collection of agents is formed so that any task within the target class can be solved by a combination and collaboration of several elements from the collection. The list of agents is passed to the tactical level along with their activation conditions. Thus, the tactical level's task reduces to creating, ensuring the operation of, and terminating the specified group of agents.

An agent can be in one of several states:

1. Active: the agent maintains the model of the external environment in an up-to-date state and forms command lists for the executive level.

2. Passive: the agent maintains the model of the external environment in an up-to-date state but does not generate control commands.

3. Error state: the agent reports to the strategic level that it cannot perform its functions. This state occurs due to erroneous input data or failure of the executive devices controlled by the agent.

The arbiter ensures non-conflicting execution of agents. To do this, based on the assigned task (i.e., the list of agents), it organizes the specified agents into a multilayer control structure (forming layer 0). The priorities of each agent are implicitly set at the strategic level based on task nesting. To the resulting control structure, an additional fixed layer 1 with higher priority is added (**Fig. 7.3**), which serves to organize the response to events unrelated to mission execution (e.g., handling telecontrol commands). Thus, the initial plan can be refined by agents from layer 1 when unplanned situations arise.

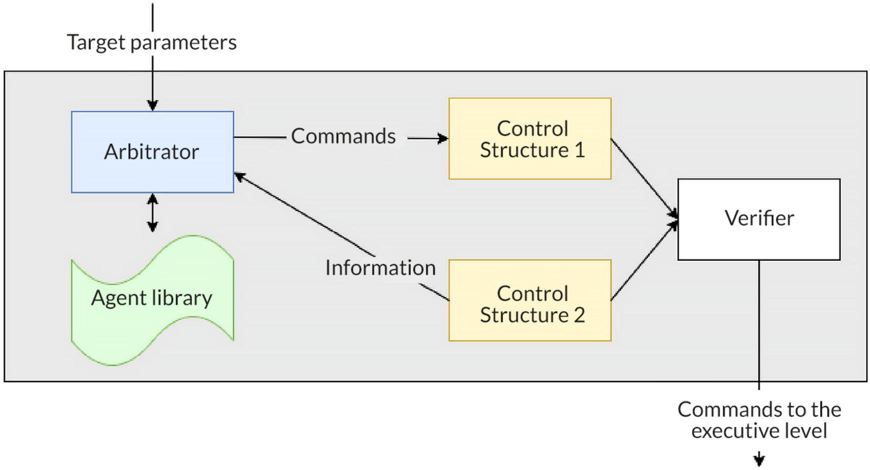

Fig. 7.3 Organization of the tactical level

The tactical level of the system contains an environment model that can be updated during operation by gathering information from the AUVs. This allows for more effective adjustment of target points while moving.

For the task of surveying artificial extended objects (AEO), a set of agents has been developed to ensure the execution of a full cycle of survey operations. These agents include:

1. Typical coverage of the water area with a network of courses.
2. Detection and tracking of AEOs using various AUV detection systems.
3. Re-survey of previously inspected objects.
4. Surveying foreign objects detected during the survey.
5. Return to base.

The indicator of the presence of AEO based on the data of the *n*-th AUV detection system at time *t* is the value p_t^n, which accumulates estimates of the probability of the existence of contacts preceding the current time point

$$p_t^{\sum n} = k^n p_{t-1}^{\sum n} + p_t^n, \tag{7.1}$$

where $p_t^{\sum n}$ – total value of contacts up to a certain point in time *t* for the subsystem *n*; k^n – damping coefficient for the subsystem *n*.

A multi-level structure of the tactical level is used to organize the survey of artificial extended objects (AEO). The structure consists of three management levels (**Fig. 7.4**):

1. Implementation of the desired trajectory.
2. Survey of the AEO.
3. Survey of foreign objects located near the AEO.

These levels are sequentially activated (and suppress the lower ones) as AEOs and foreign objects in their surrounding area are detected.

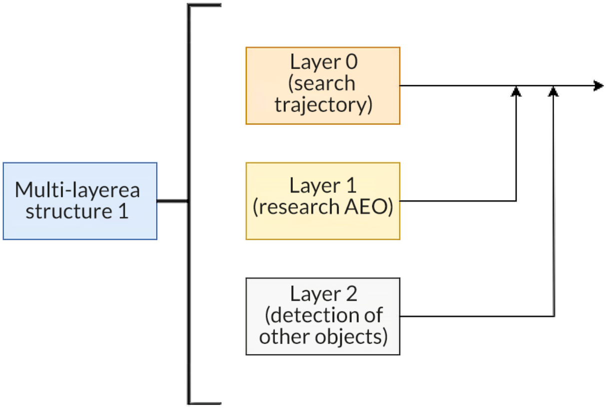

Fig. 7.4 Multi-level structure used for AEO inspection

The executive level of the control system is implemented as a reactive interpreter of the command stream from the tactical level. It interacts with the tactical level via an interface that includes messages and commands of various types (such as movement control, onboard equipment management, and provision of measured parameters).

According to the adopted methodology, at the executive level, tasks controlling identical actuators are combined into a multi-level control structure with precedence (dominance), as shown in **Fig. 7.5**. This structure includes:

– standard movement;

– movement correction (the choice between two options is determined by the goals set by the tactical level);

– reflex actions of the control system and emergency response.

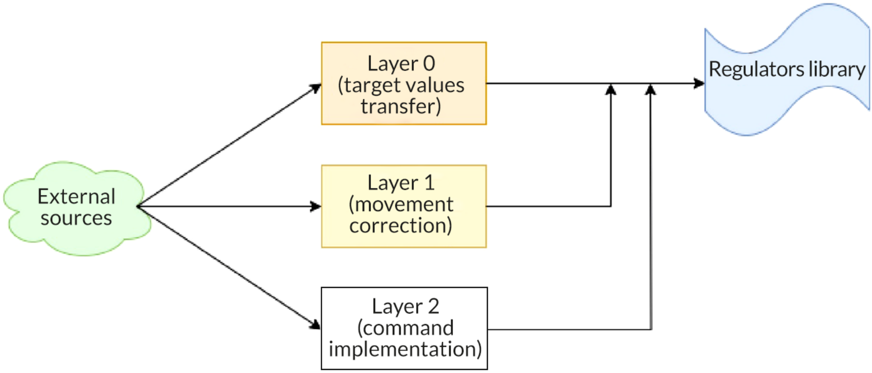

Fig. 7.5 Multi-level behavior structures of the executive level

The practical implementation consists of the following stages (**Fig. 7.6**):

1. Initially, the process of developing an agent library can be started, using the concepts of functional decomposition of the target class of tasks. This may include creating the program architecture, algorithms, methods of integration, and testing.

2. After developing the agent library, it requires testing in various scenarios and tasks related to deep-sea surveys and underwater operations. This includes verifying the operation of individual agents, their interactions, and compliance with declared functions and requirements.

3. Following testing, there may be a need for optimization or improvement of the library's performance. This may involve refining algorithms, increasing execution speed, improving accuracy, or expanding agent functionality.

4. Since the goal is to apply this library in real conditions, further plans include implementing it in underwater vehicle systems for real-world testing. This will allow evaluation of the library's effectiveness and suitability in practice.

5. After successful development, testing, and optimization, it is important to document all steps and results. This may include writing technical reports, articles, or publishing in scientific journals for sharing with the community of researchers and specialists in the field.

Fig. 7.6 Structure of the practical implementation process of the declared objective

Such a cycle can help improve the efficiency of solving deep-sea survey tasks and conducting underwater operations by leveraging advanced mathematical support for autonomous underwater vehicles.

7.4 Concepts of the development of a civil network system of underwater traffic control

Unlike conventional shipping, the sufficient efficiency of traffic control in the underwater space is due to the still unsolved tasks of providing reliable communication, processional positioning, identification of submarines, warning of navigational obstacles. It should be noted that traffic management of the future system of underwater transport corridors will be created taking into account the modern experience of developed maritime countries. First of all, this is the experience of building the information layer of the network-centric system of underwater warfare (underwater positioning and underwater communication) and the sensor layer (illumination of the underwater situation, recognition of underwater targets). The implementation of the mentioned military experience into the civilian system will not be burdened by the specific problems of covert and anonymous use of underwater positioning and communication, may not meet the requirements of invulnerability to means of destruction, may not have a system of recognition of "home-foreign". The engines of underwater vehicles should not be silent, the hydrodynamics of the hull should not provide extremely high speed, and their hull should not be designed for diving to a depth of 6000 m.

Due to this, the cost of civilian underwater vehicles will be many times lower compared to submarines. The large number of submarine collisions with each other should not be alarming, because the reason for these incidents is the noiselessness of their movement. Preventing the collision of underwater vehicles is solved very simply and effectively by installing on them hydroacoustic beacons in the sound range of 1–20 kHz with a range of up to 10–15 km. In addition, the installation of an acoustic beacon with an individual acoustic signature on each vehicle will ensure the operation of the underwater AIS segment.

The means of identification of underwater moving objects are considered by the authors of the work, which describes the tactical and technical characteristics of an AIS-type system that can simultaneously track several underwater objects with the necessary spatial and temporal resolution, demonstrating a realistic trajectory of movement [11]. The acoustic tracking system, designed for long-term tracking, thanks to the solar panel and is based on the principle of trilateration. The algorithm of the difference in the arrival time of the acoustic signal is used to determine the 2D/3D location of the moving object (three receivers provide 2D positioning, and four – 3D positioning). It should be noted that the creation of an extensive system of cargo transportation in the underwater space, in terms of traffic control, requires the development and implementation of the so-called information and sensor layers – permanent network infrastructure - along shipping routes. This is due to the fact that the existing systems of radio communication and satellite geodesy do not work in the underwater space, or have significant limitations. An analogue of the civilian system that will need to be created is a military network-centric navigation and communication system (**Fig. 7.7**), which was put into service in the US Navy in 2005.

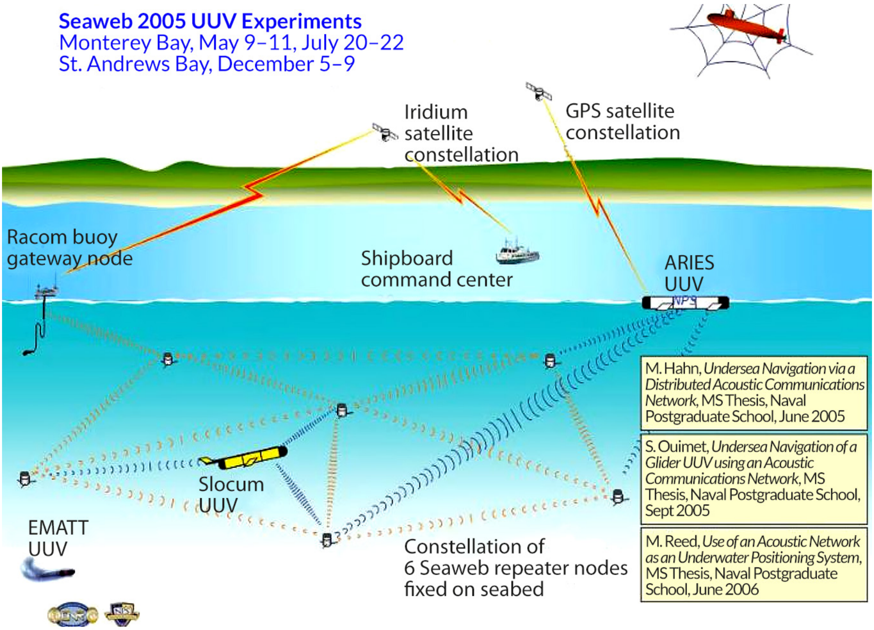

Fig. 7.7 Scheme of bottom infrastructure of underwater positioning

Control of movement in the underwater space is connected with informational and sensory provision of situational awareness of the artificial intelligence of an autonomous unmanned underwater vehicle: own current coordinates; the coordinates of surrounding vessels, which are a navigational hazard and are determined based on the data of the vehicle's own active hydroacoustic system; communication, to transmit commands and exchange data between the underwater vehicle and the shore traffic control center. The coastal center for controlling the movement of ships in the underwater space needs to be provided with data on: current coordinates of the submarine according to AIS data; the current technical condition of the vessel and its navigation equipment. Providing underwater communication and positioning is solved by several methods. In underwater space, hydroacoustics dominates, because the range of propagation of radio and optical electromagnetic waves is limited to the first tens of meters. The minimum range of hydroacoustic communication is 1–2 km, and in deepsea areas, if there is a hydroacoustic waveguide, it exceeds 100 km [12].

In hydroacoustics, data exchange is carried out only in the sound and infrasound frequency ranges, because ultrasound propagates anisotropically and over a distance of no more than 1 km. The modern technical level of the speed of hydroacoustic communication and the volumes of transmitted information are sufficient for the successful control of the movement of underwater vehicles, that is, for the exchange of navigational information and the transmission of commands.

Theoretically, calculating the arrival time of the signal from the source to the receiver is extremely difficult. This is due to the fact that the trajectories of acoustic rays are strongly transformed on the complex topography of the bottom and that the sound wave, moving from one horizon to another, changes the speed of movement in accordance with the VSSD. Errors in distance measurement by acoustic methods should not be considered significant, depending on the paths along which the acoustic signal propagates and on changes in the speed of sound along these paths. The maximum error can be up to $3 \pm 0.3\%$.

Due to acoustic shadow zones, signal transmission may not occur between the transmitter and receiver installed at a certain distance and at a certain depth, which disrupts communication and underwater positioning. It is immediately possible to say that the specified problem is solved both mathematically and technically. Technically, this problem is solved by using a vertical antenna array instead of one acoustic receiver on the seabed. The characteristics of the vertical antenna array are known. For data exchange at a frequency of 10 kHz, the distance between the hydrophones should be 1.5 m, which corresponds to 10λ (where λ is the length of the acoustic wave) based on the frequency of 10 kHz [12].

The mathematical solution consists in calculating the spatial position of the acoustic shadow zones, ranging and bearing errors. The calculation algorithm is known. In the work [13] sonograms from sound sources placed in the conditions of the real relief of the seabed are given. It is shown that circles of an acoustic shadow with radii of approximately 7 and 15 km are created around the source of the acoustic signal (**Fig. 7.8**).

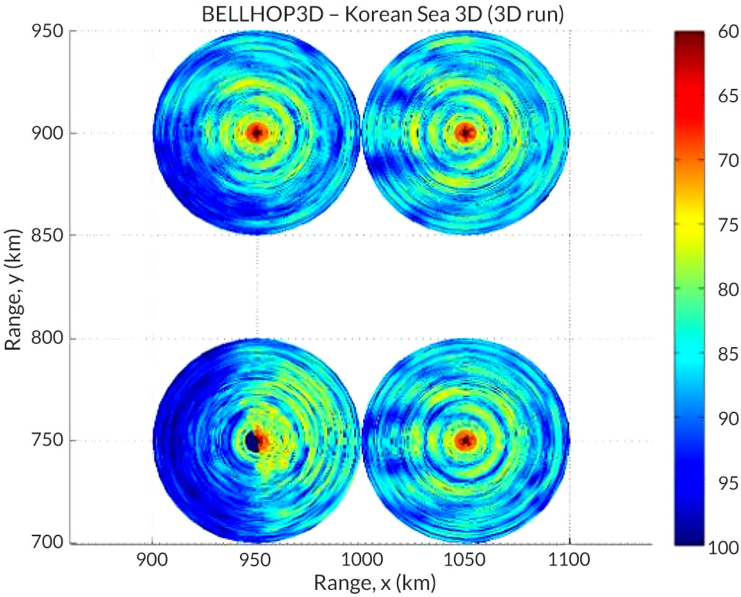

Fig. 7.8 Scheme for calculating spatial losses of an acoustic signal

The spatial position of the acoustic shadow zones depends exclusively on the features of the vertical distribution of sound speed in water. The vertical distribution of sound speed is determined by measurements, but it is very difficult to do technically. Another solution is the use of the acoustic tomography method. Our department conducts research in this direction. The latest article published in the direction of acoustic tomography has a title "Acoustic tomography algorithm for determining the spatial isotropicity of the hydroacoustic field".

One of the primary characteristics of the marine environment is the speed of sound, which very sensitively reflects its smallest changes. Moreover, this characteristic is integral. It inseparably characterizes the state of the system, which is formed by a whole complex of influences and reactions to them. Acoustic tomography is based, among other things, on the sound irradiation of the marine environment and the analysis of the received signal for the purpose of evaluating changes in its characteristics after passing through the water space. Changes in the characteristics of the acoustic signal can occur for annual reasons, one of which is spatial changes in the vertical distribution of sound speed. As a result of theoretical research in the direction of passive acoustic tomography, using the methods of modeling the refraction of acoustic waves, a new type of quantitative characteristics of the acoustic field was determined for the first time. The principle of determining the appropriate reference characteristic of the acoustic field is proposed, on the basis of which the basis for creating algorithms for restoring the vertical distribution of sound speed is developed. The algorithm for determining the reference characteristic, including, includes the calculation of acoustic energy losses, which is translated into the frequency domain to determine the positive extremum of the amplitude spectrum and the calculation of the reference characteristic of the regional acoustic field in the time domain. One of a number of algorithms for determining the spatial isotropy of the vertical sound speed distribution has been adapted. The implementation of the specified algorithm of passive acoustic tomography will provide ship sonar with input data for depth determination, which will increase the safety of navigation.

In this way, the technologies for determining the spatial characteristics of the sound speed distribution have been developed and are continuously being improved. Analysis of volume refraction calculations allows to determine periodic manifestations of acoustic shadow zones. Circles with good (red color) and bad (blue color) transmission of the acoustic signal are formed by the isotropic sound speed field. blue "spots" – zones of poor acoustic signal transmission are formed by the isotropic component of the sound velocity field. Sectors of no acoustic signal transmission are formed by the interaction of the acoustic field and the topography of the seabed. In **Fig. 7.9** shows the scheme for calculating the trajectory of acoustic rays propagating in the direction of the continental slope [13]. The given calculation scheme explains why in **Fig. 7.8**, zones of sector-type acoustic shadow appear around the emitter of the acoustic signal.

That is, the coordinates of the zones of the acoustic shadow can be determined by calculations. Under the conditions of refraction of acoustic rays in the horizontal plane, bearing determination errors occur. It also happens in areas with significant slopes of the seabed [13, 14].

The article [9] gives an example of the deployment of an underwater hydroacoustic data exchange network with an area of approximately 500 km^2 (**Fig. 7.10**). The diagram shows the acoustic relay network of underwater communication, consisting of 100 stations.

Fig. 7.11 shows that the underwater acoustic communication channel is time-varying. In addition to the distortion of acoustic signal beams due to refraction, multibeam is generated by the formation of numerous interactions of sound with the surface and seabed. This is especially evident in shallow water. Multipath slows communication by creating a delay in sound propagation. In addition, an acoustic signal, which characteristics change along the propagation path leads to the

Doppler effect, which is associated with an increase in the dispersion of changes in the frequency of the acoustic signal. Due to sound reflection from the bottom and surface, the distance measured by acoustic methods is always greater than the actual distance. This effect should not be overestimated. Theoretically, it is very difficult to calculate the arrival time of the signal from the source to the receiver. This is due to the fact that the trajectories of acoustic rays are strongly transformed on the complex relief of the bottom and that the sound wave, moving along the trajectory of its own movement, changes the speed of movement. The measured distance errors by acoustic methods, depending on the trajectories along which the acoustic signal propagates, and on changes in the speed of sound along the specified trajectories, can be up to $3 \pm 0.3\%$.

Thus, it can be stated that some problems of underwater communication are solved by technical means, some are taken into account by mathematical modeling. Some problems have not been solved and there are limitations in the propagation of an acoustic signal under water. Such limitations are determined by determining the bit error rate (BER).

Fig. 7.12 shows that the determination of the range of the communication relay station is calculated by determining the intersection of the actual constant BER value with a threshold value of BER of 2%.

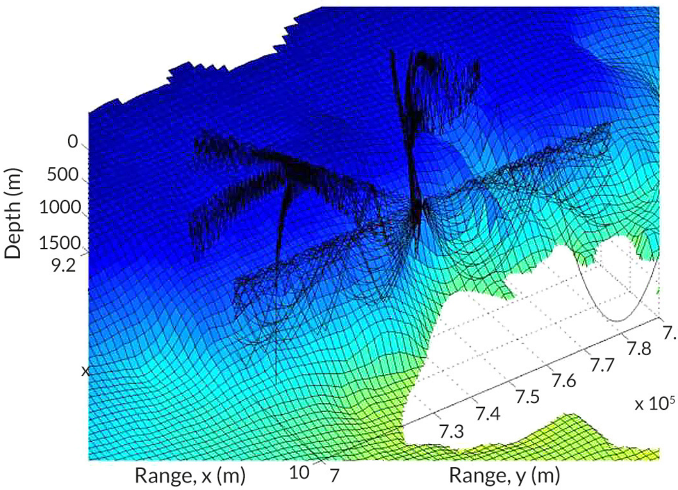

Fig. 7.9 Scheme for calculating the trajectory of acoustic rays propagating in the direction of the continental slope

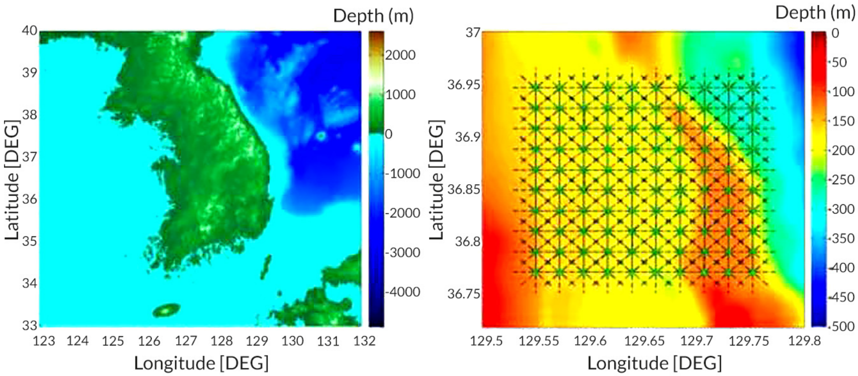

Fig. 7.10 The map and scheme of the acoustic relay network of underwater communication, as the basis of mathematical modeling

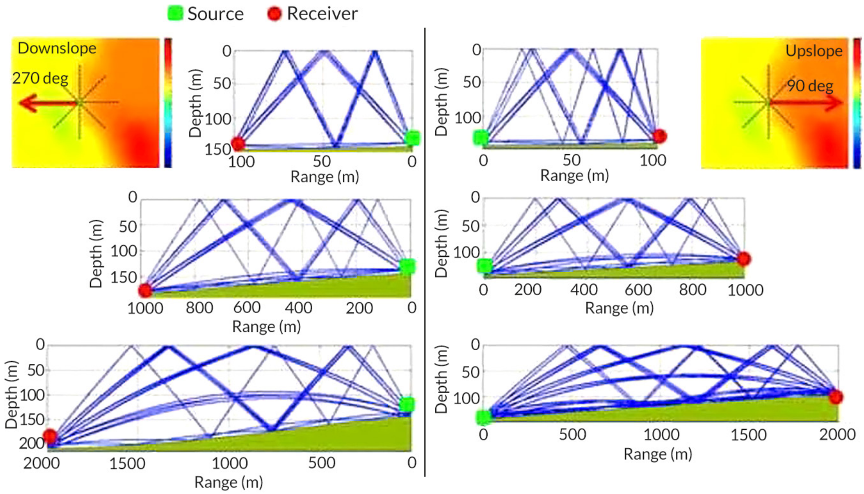

Fig. 7.11 Results of calculations of acoustic ray trajectories for azimuthal angles 270° and 90°

A reliable data exchange system requires real-time communication with high data rates and low error rates. **Fig. 7.13** shows the simulation results of the optimal deployment of the underwater data exchange network for two different seasons. Certain quantitative characteristics are defined. The distance between each sensor node and its neighboring sensor nodes corresponds to the minimum communication threshold. The level of communication coverage for February was estimated at 85.2%, which is higher than in August (estimated at 80.6%).

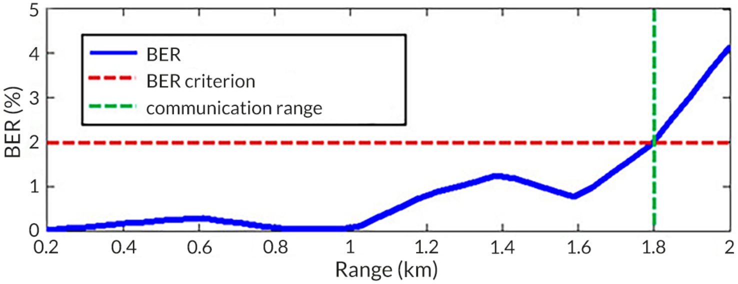

Fig. 7.12 Example of BER variation as a function of range

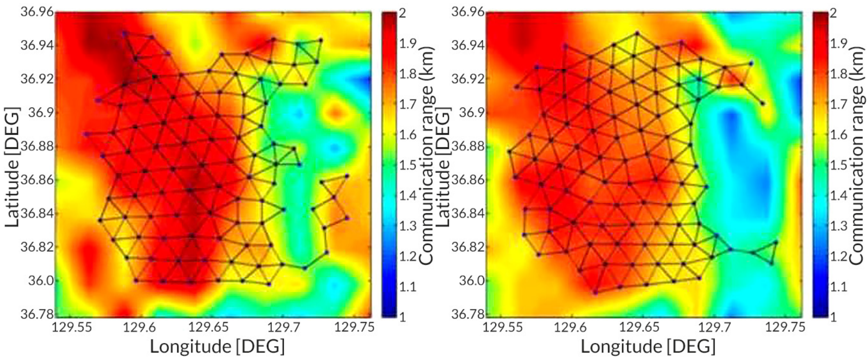

Fig. 7.13 Simulation results of the optimal deployment of an underwater data exchange network using 100 sensor nodes

Prospects for the creation of hybrid acoustic and electromagnetic systems are considered in the work [15]. In principle, data exchange in the interests of ship control and positioning can be carried out by acoustic (mechanical) waves in the sound frequency range, lasers (coherent electromagnetic waves) in the optical wavelength range of 400−600 nm, and radio waves at frequencies of 30−300 MHz. The results of the comparison of the specified underwater communication technologies are given in the **Table 7.1**.

The best underwater data exchange in terms of speed and volume of transmitted information is provided by laser methods. In second place is radio communication in the microwave range and in third place is the hydroacoustic communication channel.

The advantage of data transmission in the radio range is that, unlike laser and acoustic methods, radio waves propagate freely through the interface between the ocean and the atmosphere [16].

Table 7.1 The results of the comparison of the specified underwater communication technologies

Parameter	Acoustic	RF	Optical
Attenuation	Distance and frequency dependent (0.1–4 dB/km)	Frequency and conductivity dependent (3.5–5 dB/m)	0.39 dB/m (ocean) 11 dB/m (turbid)
Speed	1500 ms^{-1}	2.3×10^8 ms^{-1}	2.3×10^8 ms^{-1}
Data rate	kbps	Mbps	Gbps
Latency	High	Moderate	Low
Distance	More than 100 km	< 10 m	10–150 m (500 m potential)
Bandwidth	1–100 kHz	MHz	150 MHz
Frequency band	10–15 kHz	30–300 MHz	5×10^{14} Hz
Transmission Power	10 W	mW–W	mW–W

As an example of the prospect of combining military and civilian technologies, it is possible to cite a possible prospective hybrid of military communication systems "Tactical Underwater Network Architecture" [17], and civil underwater acoustic communication systems [18] and systems of hydroacoustic automatic identification of the movement of underwater targets [11].

The first system, which is an alternative to unreliable hydroacoustic underwater communication, involves the installation of autonomous surface buoys with radio receivers and radio transmitters (surface buoys under water connected by a fiber optic cable) solves the problem of reliable data transmission (traffic control). The second system provides for the installation of sonar devices on surface buoys, which provides protection of the surface system from saboteurs to the underwater vehicle and simplified underwater positioning. The third system involves retrofitting surface buoys with an acoustic vertical antenna array to provide additional underwater hydroacoustic communication of an underwater vehicle with surface radio communication buoys. The fourth system involves the additional use of an antenna array as a noise deflector. the noise direction finder is used as an element of underwater AIS to passively track the trajectory of an underwater vehicle equipped with a hydroacoustic emitter with an individual acoustic signature.

7.5 Conclusions

A new architecture has been proposed for the control system of an autonomous underwater vehicle, which incorporates both hierarchical and behavioral control structures. This significantly expands the capabilities of the AUV, allowing it to solve tasks of various classes under the constraints of limited computational resources of the onboard computing network.

Within the proposed architecture, a behavioral approach is applied at different levels of the functional three-tier control system architecture. The control structures at the executive level have a fixed composition, while variable structures are formed at the tactical level based on a developed library of agents.

An approach to building the tactical-level agent library is justified based on the functional decomposition of the target class of tasks. The robot's actions are formulated in terms of agents that form the library, which provides a foundation for creating declarative missions. The agent structure has been developed and studied, including a local environment model, tools for action planning based on this model, and analysis of the utilized information to assess the agent's operability.

This gives reason to believe that sea transportation of cargo under water will become a reality in the near future. An underwater transport fleet will be built just as quickly. Unlike conventional ships, which are difficult to design, designing a fleet of unmanned underwater vehicles will not take much time, because simplified technologies for the construction of military submarines and LDUUVs will be involved. The experience of creating bottom network bottom positioning and communication systems based on the hydroacoustic principle of action should be applied in combination with systems operating on other physical principles. Microwave radio communication directly between an underwater vehicle in an underwater position and satellite means of communication certainly has prospects. There are prospects for laser communication, which is unsurpassed in the speed and volume of information transmission and the real time scale.

Research has demonstrated the necessity to improve the control systems of autonomous underwater vehicles as more complex tasks beyond simple search and survey operations are undertaken. There is a pressing need to expand the range of solvable task classes.

Accordingly, in the course of further scientific investigations, the author is prepared to focus efforts on the recognition and classification of search objects and situations occurring in the underwater environment, detection of emerging trends in the operational situation, and modeling the behavior of certain objects that may pose danger or threat.

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CHAPTER 8

Meteorological and hydrographic support of energy-saving maritime transport

Georgiy Tomchakovsky

Abstract

This section is dedicated to a comprehensive analysis of meteorological and hydro-navigational support as a key factor in optimizing maritime routes and reducing energy consumption in commercial shipping. The role of satellite technologies, automated monitoring platforms (in particular, ARGO drifters and wave glider-type gliders), numerical ocean circulation models, monsoon forecasting, and gravimetric variations in ensuring navigational safety and enhancing route planning efficiency is assessed. It is demonstrated that the integration of navigational and meteorological data allows avoidance of areas with high resistance, storm risks, or abnormal waves, leading to reductions in fuel consumption and emissions. Special attention is given to the analysis of gravitational anomalies in the Indian Ocean region and their influence on monsoon processes, which are critically important for ocean voyage planning. Technological and organizational approaches are proposed for the development of integrated hydro-meteorological support systems for maritime transport, aimed at lowering fuel consumption and supporting the sustainable development of marine transportation.

The section explores the complex interplay of meteorological, hydro-navigational, and geophysical factors that define the conditions for energy-efficient navigation within the Indian Ocean monsoon circulation zone. Particular focus is given to the influence of spatiotemporal variations in Earth's gravitational field (Δg) and geoid shape deformations on atmospheric structure, sea level, and seasonal wind activity. Evidence is presented showing the synchronization between annual Δg harmonics and the phases of monsoon circulation, providing a basis for a new paradigm of hydro-meteorological forecasting based on satellite data from GRACE and AVISO+.

It is shown that such gravitational and geoidal anomalies may serve as reliable indicators of changes in air mass and marine conditions prior to the formation

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of classical barometric gradients, opening new possibilities for long-term voyage planning.

The materials of this section are interdisciplinary in nature and are intended for professionals in the fields of shipping, navigation, hydro-meteorology, oceanography, and applied geophysics. The proposed approaches form a foundation for the development of integrated systems that ensure energy-efficient shipping within the global maritime transport network.

Keywords

Maritime transport, hydro-navigation, ARGO drifters, gliders, satellite altimetry, oceanographic data, monsoon circulation, hydro-meteorological support, energy-efficient navigation, ship route optimization, Earth's gravitational field.

8.1 Introduction

The modern maritime transport system is undergoing a transformation driven by the challenges of the global energy crisis, the need to reduce greenhouse gas emissions, and increasing safety requirements in navigation. One of the key tools for achieving energy efficiency in maritime transport is the implementation of an integrated meteorological and hydro-navigational support system, which is capable not only of monitoring the current state of the marine environment but also of providing predictive data for adaptive route management.

According to research, fuel consumption during sea voyages can be reduced by up to 10–15% solely through the optimization of vessel routes based on weather conditions, currents, waves, and wind patterns [1]. Such optimization is only possible if the ship's navigational system is integrated with high-precision meteorological models, digital nautical charts, and global oceanographic data exchange platforms.

The search for new ways to reduce fuel costs, voyage time, and environmental impact requires a fundamental transformation of navigational support systems. Particular emphasis must be placed on improving methods of meteorological and hydro-navigational support for shipping – especially in open-sea operations and when crossing variable hydro-meteorological zones.

One of the fundamental directions in this context is the development of digital, dynamic routing systems that adapt to changing weather conditions, ocean currents, wave heights, and the spatiotemporal structure of oceanographic variability. These parameters are critical in determining ship resistance, the risk of accidents, and ultimately the overall efficiency of maritime transportation.

8.2 The role of hydro-meteorological forecasting in enhancing the energy efficiency of maritime transport

The availability of accurate hydro-meteorological forecasts along a vessel's route enables not only the avoidance of hazardous areas (such as cyclones, storms, or fog zones), but also the optimization of the vessel's trajectory by accounting for ocean currents, wave patterns, and wind direction. For instance, avoiding headwinds exceeding 10 m/s can reduce fuel consumption by up to 15–20% per day of navigation.

The informational support for such decisions is made possible through the integration of data from multiple sources, including satellite-based altimetry and gravimetry, forecasts of wind, currents, wave height, as well as data collected from ARGO buoys, wave gliders, and drifting platforms.

Moored buoys (**Fig. 8.1**) are a vital component of modern ocean observation systems. These are stationary platforms anchored to the seafloor by means of mooring systems. Their primary advantage lies in their ability to conduct long-term, continuous measurements at a fixed point in the ocean.

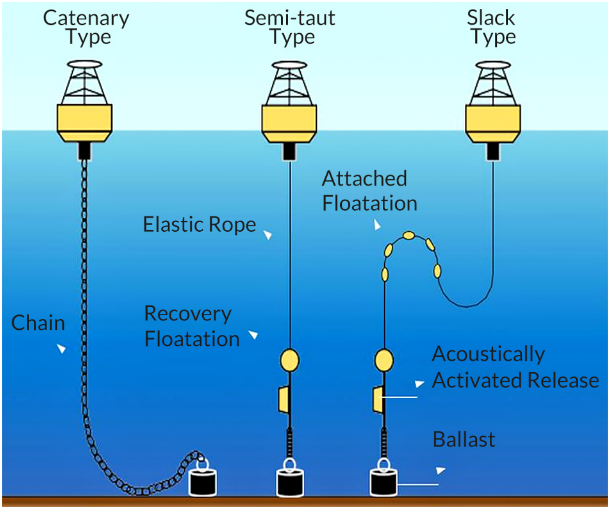

Fig. 8.1 Types of moored buoys

The use of moored buoys for oceanographic research began in the 1960s. One of the first major projects was the Barbados Oceanographic and Meteorological Experiment, conducted in 1969. This experiment involved the deployment of a network of moored buoys in the tropical Atlantic to study ocean-atmosphere interactions.

A significant milestone in the development of moored buoy systems was the launch of the tropical ocean global atmosphere (TOGA) program in the late 1970s [2]. Within this program, a network of buoy stations was established across the tropical Pacific Ocean to investigate the El Niño phenomenon. This network, known as TAO (tropical atmosphere ocean), was later expanded to include other regions of the World Ocean [3].

Modern moored buoys are equipped with a suite of sensors designed to measure a variety of parameters:

− meteorological (air temperature, humidity, atmospheric pressure, wind speed and direction);

− oceanographic (temperature and salinity at various depths, current speed and direction);

− wave characteristics (wave height, period, and direction).

The main advantages of moored buoys include the ability to perform long-term observations at a fixed location, measure parameters at different depths, provide high measurement accuracy, and transmit data in real time.

However, moored buoys also have several drawbacks, such as high installation and maintenance costs, limited spatial coverage, and vulnerability to damage (from storms, vandalism, or collisions with vessels).

In addition, some buoys are equipped with sensors to monitor biogeochemical parameters, such as chlorophyll concentration, dissolved oxygen, and seawater pH.

A key feature of modern buoy stations is their capability to transmit data in real time via satellite communication channels. This allows timely access to oceanic and atmospheric information. For instance, TAO buoys transmit data every hour and are used for operational weather forecasting and monitoring conditions in the tropical Pacific Ocean.

Modern moored buoys can operate autonomously for extended periods (up to a year or more) thanks to energy-efficient electronics and power systems based on solar panels and other renewable energy sources. For example, ATLAS buoys (autonomous temperature line acquisition system), used in the TAO array, can function without maintenance for up to 12 months.

Oceanic drifters (drifting buoys) are an important supplement to the network of stationary moored buoys. Their primary advantage lies in the ability to cover large ocean areas at relatively low energy costs.

The history of using drifters for oceanographic research dates back to the 19th century, when so-called "message-in-a-bottle" techniques were employed to study currents. However, a true breakthrough came in the second half of the 20th century with the development of satellite communication and positioning systems.

Modern drifters are autonomous platforms that move freely with ocean currents [4]. They are equipped with sensors for measuring sea surface temperature, salinity, and atmospheric pressure. Some models are also capable of profiling temperature in the upper ocean layers.

A typical drifter design includes (**Fig. 8.2**):

1. A surface buoy equipped with a GPS antenna and satellite communication system.

2. A subsurface "drogue" or sea anchor to ensure the drifter moves with the surrounding water masses.

3. Sensors for measuring temperature, salinity, and other parameters.

An important feature of drifters is the presence of a positioning system (typically based on IRIDIUM or GPS) and data transmission via satellite communication channels. This allows for tracking the trajectory of the buoy's movement and obtaining real-time information on ocean currents.

The large-scale deployment of drifters began with the U.S. coastal ocean dynamics experiment (CODE) in the 1980s [5]. This experiment provided unique data on water circulation in coastal regions.

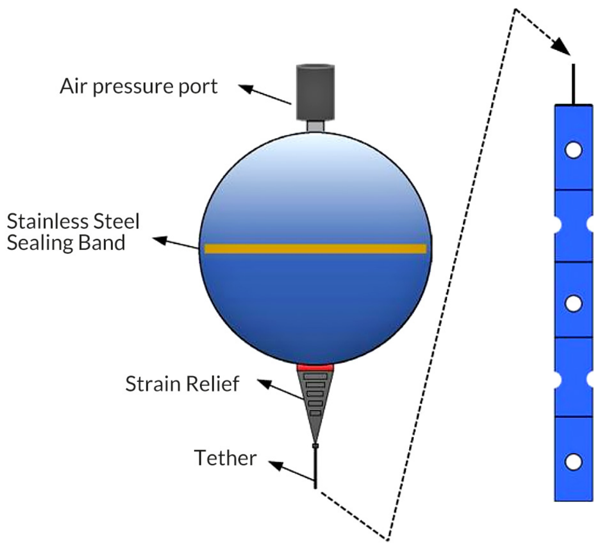

Fig. 8.2 Drifting buoy

Initially, the global network of drifting buoys consisted of several thousand units. One of the prominent initiatives is the global drifter program (GDP), which maintains a network of approximately 1,500 drifters evenly distributed across the world's oceans. These buoys supply operational data to weather services, oceanographic centers, and maritime search and rescue systems.

However, the most significant milestone in the development of the global ocean observation system was the establishment of the ARGO program (**Fig. 8.3**). This program involves the deployment of a network of autonomous drifting buoys capable of measuring vertical profiles of temperature and salinity down to depths of 2,000 meters. Currently, the ARGO program includes over 4,000 active buoys, providing global coverage of the world's oceans.

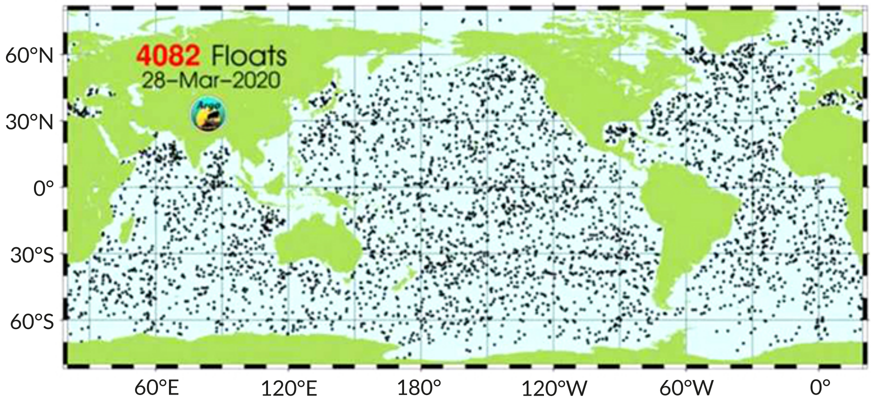

Fig. 8.3 ARGO drifter network scheme

Drifter data are widely used for validating satellite measurements and numerical ocean models. They are particularly valuable for studying surface ocean circulation, including large-scale currents, eddies, and frontal zones.

Special attention should be given to autonomous gliders, which represent a new class of ocean observation platforms. One of the most successful examples of such systems is the wave glider, developed by liquid robotics (**Fig. 8.4**).

The wave glider uses ocean wave energy for propulsion, converting the relative motion between the ocean surface and the calmer subsurface waters into forward movement. Solar panels supply power to onboard electronics, sensors, and communication systems. This hybrid energy system allows the vehicle to operate for several months without the need to return to base.

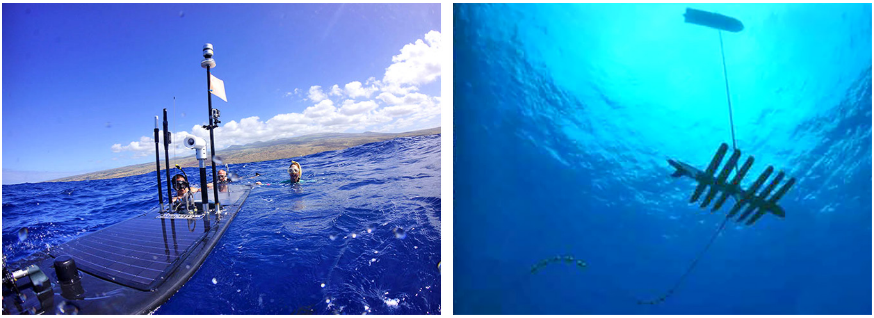

Fig. 8.4 Wave glider unmanned surface vehicle

The wave glider is equipped with a wide range of sensors:

− meteorological and oceanographic instruments;

− seismic sensors for detecting earthquakes and tsunamis;

− video cameras and acoustic systems;

− environmental monitoring systems.

Gliders provide valuable data from hard-to-reach areas of the ocean and enable long-term observations with minimal operational costs. They are particularly effective for studying mesoscale processes and monitoring changes in the oceanic environment.

Satellite technologies play a key role in modern ocean observation systems. They provide data with global coverage and high temporal resolution.

The history of satellite ocean observation began in the 1960s with the launch of the first meteorological satellites. However, a true breakthrough occurred during the 1970s and 1980s with the development of dedicated oceanographic satellites.

The main types of satellite sensors used for ocean studies include:

− radiometers, which measure sea surface temperature;

− altimeters, which determine sea surface height;

− scatterometers, which measure wind speed and direction near the surface;

− spectroradiometers, which assess ocean color (for evaluating chlorophyll concentration).

Satellite altimetry is one of the most important methods of ocean remote sensing [6] (**Fig. 8.5**). It allows the measurement of sea surface height with an accuracy of a few centimeters. Based on these data, sea level anomalies, geostrophic currents, and wave parameters can be determined. The principle of satellite altimetry is based on measuring the time it takes for a radar pulse to travel from the satellite to the ocean surface and back. Knowing the exact coordinates of the satellite makes it possible to calculate the sea surface height. Modern altimeters, such as those onboard the JASON satellite series, provide sea surface height measurements with an accuracy of 2–3 cm.

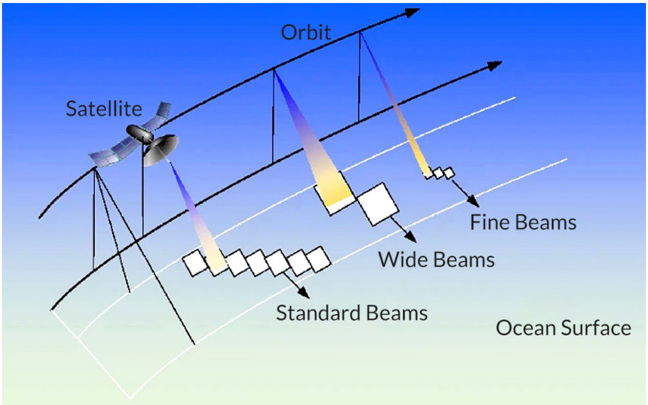

Fig. 8.5 Remote sensing via satellite

An important aspect of satellite measurements is the need to account for multiple sources of error, such as atmospheric interference, satellite orbit inaccuracies, and others. To address this, advanced data processing algorithms have been developed.

Modern satellite systems are capable of measuring the following ocean parameters:

– sea surface temperature (accuracy: 0.3–0.5°C);
– surface salinity (accuracy: 0.2–0.4 psu);
– sea surface height (accuracy: 2–4 cm);
– near-surface wind speed (accuracy: 1.5–2 m/s);
– wave height (accuracy: 0.5 m or 10%);
– chlorophyll concentration (accuracy: 30–50%).

A key direction in satellite technology development is the deployment of satellite constellations, which enhances the spatial and temporal resolution of measurements. An example is the JASON system for altimetric measurements, which includes multiple satellites operating in orbit simultaneously.

Main advantages of satellite methods:

– global coverage;
– high observation frequency;
– capability to collect data from remote and hard-to-access areas;
– long-term measurement stability.

Limitations of satellite methods:

− limited spatial resolution;

− atmospheric influence on measurements;

− complexity of calibration and data validation;

− high cost of satellite development and launch.

An analysis of the current state of ocean observation technologies makes it possible to outline the main directions for their further development.

Improvement of sensors and measuring systems. This will increase the accuracy of observations and expand the range of measurable parameters. A promising direction involves the development of new types of sensors, including chemical and biological sensors for ecosystem monitoring.

Advancement of power supply systems for autonomous platforms. The use of more efficient renewable energy sources, such as solar panels, will extend the autonomous operating time of buoys and drifters. For example, systems are being developed that harness wave energy to power buoys.

Improvement of communication and data transmission systems. This will enable the transfer of larger data volumes in real time. Promising solutions include next-generation satellite communication systems and the development of underwater acoustic networks for data transfer.

Development of new types of ocean observation platforms. A promising area is the creation of autonomous underwater vehicles such as gliders, capable of long-term missions with minimal energy consumption. These vehicles can travel thousands of kilometers and periodically surface to transmit data.

Enhancement of data processing and analysis methods. The application of machine learning and artificial intelligence will enable more efficient processing of the large volumes of data generated by different observation systems. This is especially important for integrating multisource data and identifying complex interrelations in ocean processes.

Integration of various observation systems into a unified global network. This will provide a more comprehensive and accurate view of the ocean's state. A key step in this direction is the creation of a global ocean observing system that combines data from different national and international programs.

A promising direction is the development of coastal observation systems that integrate various types of sensors – from bottom-mounted stations to radar systems. These systems provide detailed information about coastal zone processes, which is crucial for managing coastal resources and ensuring maritime safety.

International cooperation plays a vital role in the advancement of ocean observation technologies. An example is the global ocean observing system, which unites the efforts of many countries in building a comprehensive monitoring network for the world's oceans.

The formation of monsoonal circulation, driven by changes in the Earth's gravitational field, provides a unique foundation for long-term meteorological forecasting in the Indian Ocean region. The use of high-precision satellite data on Δg variations (from GRACE) and sea level (from AVISO+) makes it possible to identify the sinusoidal nature of changes underlying climatic seasonality.

These periodic phenomena have direct practical significance for the transportation sector. Incorporating them into route planning models enables proactive avoidance of high wave activity zones, reducing fuel consumption by minimizing resistance from strong winds and rough seas; optimal scheduling of voyage start and end times, synchronizing operations with the most energy-efficient navigation conditions; adaptive adjustment of vessel draught and engine performance settings based on expected atmospheric pressure and sea state values.

Thus, hydro-meteorological forecasting based on fundamental physical and geophysical patterns is a key factor in the energy-efficient operation of maritime vessels.

8.3 Climatic features of the Indian ocean region and navigational risks

The tropical zone of the World Ocean, particularly the northern part of the Indian Ocean, is characterized by relatively stable solar insolation and the absence of significant barometric gradients, which contributes to the formation of persistent trade winds. However, during the summer months (June–August), strong southwesterly monsoon winds develop, reaching speeds of up to 14 m/s, generating waves as high as 7 meters. These conditions significantly complicate navigation, increase fuel consumption, and elevate risks for vessels and crews.

For effective energy-efficient maritime navigation, it is critically important not only to forecast the onset and end of the monsoon season but also to understand the underlying physical mechanisms that drive monsoonal circulation. This knowledge allows vessel routes to be adapted to expected weather scenarios, thereby reducing fuel consumption and enhancing navigational safety.

The Indian Ocean region – particularly its northern sector is a unique maritime area in terms of climatic conditions, exhibiting a pronounced seasonal variability of atmospheric processes. The main climate-forming factors are monsoonal circulation and the complex interaction between oceanic and atmospheric systems, amplified by geophysical factors such as variations in the Earth's gravitational field and geodynamic deformations.

For most of the year, the region is dominated by trade winds – steady and predictable winds that create a stable navigational environment. However, during the summer period (June–September), the southwest monsoon prevails, bringing strong wind-driven waves, storms, and powerful currents. Sea states can reach 6–7 meters in wave height, with wind speeds of 12–14 m/s. Such conditions considerably complicate vessel operations and, crucially, lead to increased fuel consumption due to added resistance and maneuvering efforts.

The lack of accurate long-term forecasts regarding the onset, peak, and termination of the monsoon season forces vessels to select conservative routes, increasing bunker fuel expenditures, voyage duration, and diminishing the efficiency of global logistics chains.

In this context, hydro-meteorological forecasting serves as a critical tool for ensuring energy-efficient maritime transport. Its role is not only to provide warnings about adverse weather conditions but also to deliver detailed analytics regarding:

– expected changes in wind and wave fields;

– sea surface temperature and convective activity;

– seasonal shifts in circulation systems (monsoons, cyclones);

– upwelling and downwelling currents that influence vessel draught and speed.

The application of accurate forecasts in navigational planning allows for optimizing ship routes considering meteorological factors, reducing excess fuel consumption by avoiding wave-prone zones and headwinds, and improving cargo handling efficiency by coordinating port operations with available safe approach windows.

Particular attention should be given to incorporating satellite altimetry and gravimetry data into forecast models. These allow for predicting not only atmospheric conditions but also deeper physical and geodynamic changes (Δg) that precede or accompany monsoonal activity. This opens the possibility for long-term, annual cyclic forecasts, which can be used in strategic fleet operations and voyage planning for large vessels.

In summary, the Indian Ocean region requires the integration of traditional hydro-meteorological support with modern satellite and geophysical forecasting systems to achieve maximum energy efficiency in maritime transport.

This approach enables not only cost reduction but also a significant decrease in greenhouse gas emissions, aligning with the IMO's strategic environmental goals.

The formation of monsoonal circulation has long been a subject of debate among meteorologists, climatologists, and oceanographers. The classical scientific approach has centered around two main hypotheses: the thermal hypothesis and the dynamic hypothesis, which for centuries have served as the foundation for constructing synoptic models and forecasts.

The original "thermal hypothesis" of monsoons, first proposed by Edmund Halley in 1686, interpreted the monsoon system as a large-scale land-sea breeze driven by differential heating between the continent and the ocean. This concept formed the foundation for further development by other climatologists, who described monsoonal circulation as a component of a large-scale thermal system. However, modern research – particularly the work by Wang et al. – demonstrates that while land-sea thermal contrast plays a role, it is insufficient to fully explain the complexity of monsoonal behavior [7]. Their study highlights the crucial importance of seasonal migration of the Intertropical Convergence Zone, planetary circulation patterns, and energy redistribution processes. These dynamics go far beyond the explanatory scope of the classical thermal model and are essential for achieving the level of forecasting precision required for modern energy-efficient maritime routing.

An alternative to the thermal concept was the dynamic hypothesis, introduced in the 20th century. This approach views the monsoon as a heat engine operating between two sources with different thermal capacities – the ocean and the landmass. It emphasizes not only the temperature gradient but also the movement of air masses under the influence of Coriolis forces, orography, Earth's rotation, hydraulic effects, and convective processes [8].

The expansion of the dynamic approach was made possible through the work of researchers such as Lineykin, Gandina, Khromova, and Riehl, who proposed considering cross-equatorial flows, the influence of orographic barriers (notably the Himalayas), and the dynamics of the upper troposphere. For example, the formation of jet streams plays a crucial role in the initiation of monsoons.

Taken together, the classical hypotheses have enabled the formulation of a general understanding of the monsoon phenomenon. However, they do not provide the necessary levels of precision, spatial coverage, or seasonal validation required by the maritime sector in the face of climate change and the growing need for energy efficiency.

From a maritime transport perspective, classical hypotheses of monsoonal circulation formed the foundation for the first operational forecasting models used by marine meteorological services. However, the limited accuracy of these models forces operators to incorporate larger speed and fuel reserves into voyage planning, implement redundant routing in cases of expected unstable weather, and avoid transits through certain zones under conditions of uncertainty.

Such measures are in direct conflict with the principles of modern energy efficiency. Therefore, it is essential to supplement classical models with new parameters – such as gravitational variability and satellite-derived geoid deformation data, which are analyzed in the following sections.

8.4 Geophysical factors of monsoonal circulation formation in the context of hydro-meteorological support for energy-efficient shipping

Modern science is increasingly focusing on the study of fundamental geophysical factors that influence global atmospheric circulation, particularly the formation of monsoons. One of the most significant of these factors is the spatio-temporal variability of the Earth's gravitational field (Δg). This phenomenon is directly related to mass exchange and deformation processes within the mantle, tectonic activity, and the deep internal structure of the Earth.

In the Indian Ocean region – especially in the Arabian Sea – extreme negative anomalies in gravitational acceleration are observed. These anomalies vary throughout the year and exhibit a clear annual periodicity (**Fig. 8.6**). It is known that the air mass over the region loses hydrostatic equilibrium under the influence of decreasing Δg, which leads to a reduction in the weight of the atmospheric column and, consequently, to the formation of wind flows even in the absence of a pronounced barometric gradient [9].

Alongside gravitational variations, changes in the shape of the geoid lead to fluctuations in sea level ranging from several tens of centimeters or more. These variations have substantial practical implications for forecasting storm surges and set-down phenomena, adjusting vessel draft, and evaluating additional resistance to motion caused by elevated wave activity.

Satellite altimetry (AVISO+) and gravimetry (GRACE) data confirm a statistically significant correlation between seasonal changes in Δg and sea surface height in the Goa region. A 15-year analysis yielded a correlation coefficient of $R = 0.73$ between Δg and sea level.

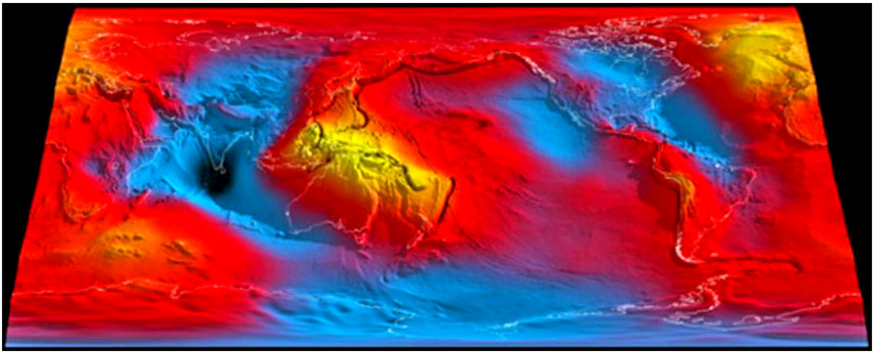

Fig. 8.6 Map-scheme of the Earth's gravitational field

Incorporating gravitational variability into hydro-meteorological support systems enables the development of multi-annual forecasts of circulation activity with a high degree of reliability. This offers several practical advantages for energy-efficient navigation, including:

– the ability to define seasonal "windows" for transit through monsoon zones with minimal fuel consumption;

– dynamic route adjustments based on geoid topography changes and associated hydrodynamic conditions;

– forecasting areas of potentially unfavorable sailing conditions even before atmospheric instability manifests.

Scientific research confirms that gravitational anomalies in the Indian Ocean region are neither accidental nor isolated. They originate from deep Earth processes, particularly the ascent of hot mantle material beneath the African tectonic plate. This mantle plume, moving northeastward, causes a geoid depression in the Indian Ocean region and thereby disrupts traditional models of atmospheric statics [10].

Understanding these processes lays the groundwork for the creation of a comprehensive navigational analytics system that accounts not only for surface meteorological conditions but also for planetary-scale geophysical parameters. This is especially important for planning voyages of large-tonnage vessels, forecasting prolonged periods of poor navigation conditions, and assessing the feasibility of routes in terms of fuel efficiency.

Thus, hydro-meteorology in the 21st century holds the potential to evolve from a local synoptic science into a global, physics- and gravity-based forecasting discipline. This new paradigm integrates satellite Δg data, geoid deformation models, conventional wind, wave, and precipitation forecasts, and digital atmospheric and ocean circulation models.

Such an integrated approach enables the design of flexible and precise maritime routes that are not only safe but also optimized in terms of fuel consumption – a critical requirement for modern shipping amid global climate challenges and mounting pressure to reduce CO_2 emissions.

8.5 Synchronization of Δg variations and seasonal monsoon dynamics: implications for energy-efficient shipping

One of the most compelling indications of the gravitational nature of monsoonal circulation is the clear seasonal synchronization between changes in gravitational acceleration (Δg) and the dynamics of atmospheric processes within monsoon climate zones. Thanks to high-precision satellite observations (GRACE, AVISO+), quantitative data have confirmed that the most significant Δg variations occur on an annual cycle, precisely aligned with the onset and cessation of both the summer and winter monsoons (**Fig. 8.7**).

In the region of India's western coast (Goa), an analysis of the time series of Δg and sea level variations for the period 2002–2017 revealed the following:

– an annual periodicity in the spectra of both parameters;

– a high level of coherence (0.96) between seasonal fluctuations of Δg and the shape of the geoid;

– a phase shift of 18°, indicating a stable and predictable lead of one variable over the other [11].

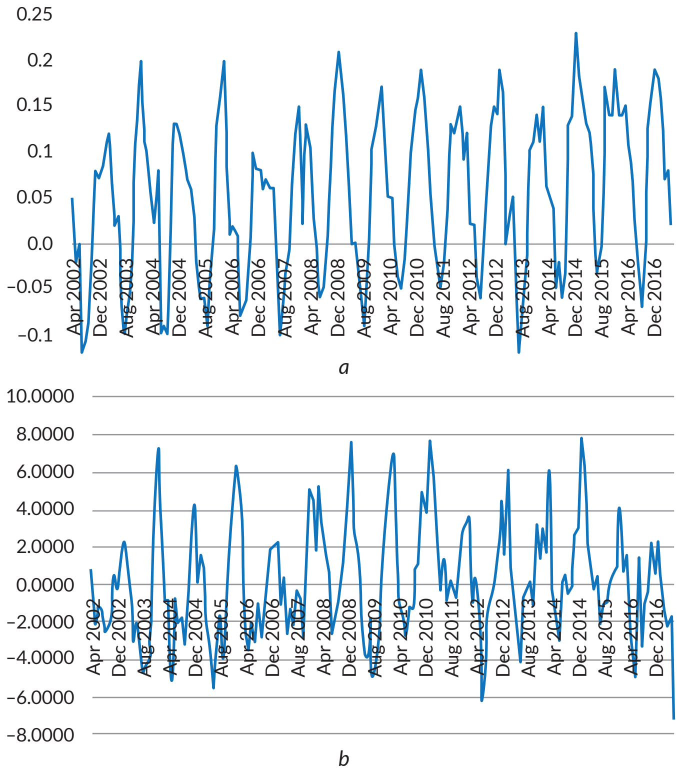

Fig. 8.7 Temporal variations of (*a*) geoid shape and (*b*) gravity in the area of the Western Coast of the Indian Peninsula (Goa Province, India)

These results make it possible to develop a predictive model in which the detection of a Δg change can serve as an early indicator of the upcoming strengthening or weakening of monsoon winds.

When gravitational acceleration decreases in a given region, the weight of the atmospheric column also decreases. This causes local disruptions in hydrostatic equilibrium without the necessary formation of a barometric gradient. In response, the atmospheric system activates self-regulation mechanisms through the movement of air masses, resulting in wind flows – monsoons.

During the summer monsoon period, Δg shows a negative anomaly that stimulates the inflow of air from the ocean toward the land. In winter – conversely – Δg increases, the weight of the air grows, and winds form in the opposite direction. Thus, Δg acts as a physical trigger for monsoon exchange, in much the same way that temperature activates thermal convection.

Incorporating Δg monitoring into navigation and meteorological analysis enables:

– forecasting changes in wind direction and speed several weeks in advance;

– predicting sea level at ports of arrival and departure;

– identifying in advance the periods when transit through monsoon zones would be excessively costly or dangerous;

– integrating the annual cycle of Δg variations into fleet route planning and voyage scheduling, thereby optimizing fuel use.

Since Δg fluctuations are globally synchronized phenomena and have a planetary nature (their influence can be simultaneously observed in the American, African, and Asian monsoon regions [12]), they can be employed for unified strategic planning of global shipping. This opens new opportunities for interregional coordination of logistic routes (for example, synchronization of cargo flows between the Indian Ocean and the South China Sea), the development of seasonal global maps of maritime risk and energy consumption, and the enhancement of decision support systems (DSS) for navigators.

As shown in previous sections, gravity field variations in the Indian Ocean region are often linked to geodynamic activity of the African tectonic plate (**Fig. 8.8**). In particular, compression of the plate in 2001–2002 was accompanied by the emergence of an anomalous weather phenomenon – nighttime condensation of water vapor over the Sahara Desert, associated with large-scale moisture transport [13].

These geophysical processes have long-term implications for fleet energy consumption. For example, the 2002 drought in India (**Fig. 8.9**) was a consequence of changes in Δg, which disrupted the usual monsoon circulation. This led to alterations in ocean currents, wind patterns, and sea levels, resulting in prolonged voyage durations, increased fuel consumption, and the need for emergency route adjustments.

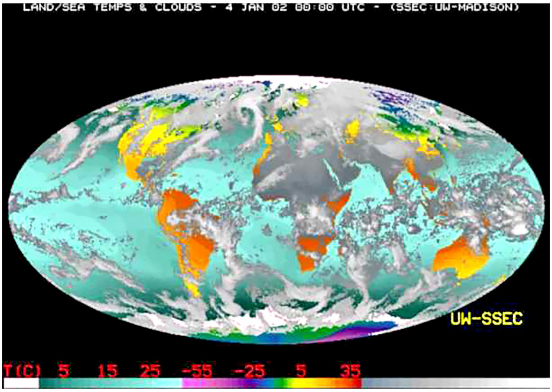

Fig. 8.8 Depiction of the compression process of the African plate during extreme geodeformations (13.11.2001–18.01.2002)

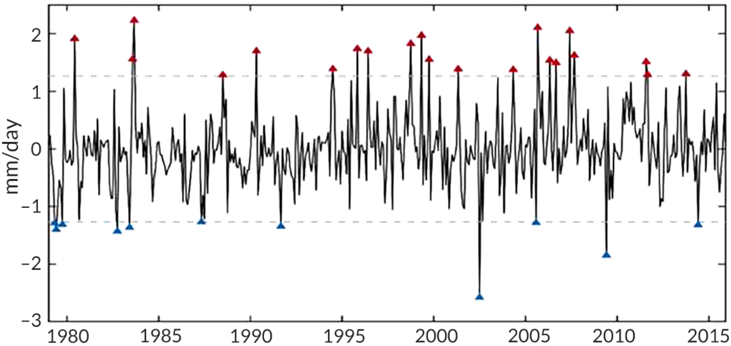

Fig. 8.9 Monthly-averaged daily precipitation in India (dotted lines represent 2 standard deviations) within the rectangular zone 10°N–30°N and 60°E–95°E

The use of satellite altimetry (AVISO+) and gravimetry (GRACE) enables the development of highly accurate synchronized models of gravitational variations and geoid changes that affect both the ocean and the atmosphere. For instance, in the Goa region, a strong correlation has been recorded between the annual harmonics of Δg and sea level (R = 0.73).

Such data make it possible to implement automated alerts for the onset and end of the monsoon season, dynamically adjust routes in response to predicted storm surges or water withdrawals, and model the most energy-efficient trajectory based on forecasted sea state, atmospheric pressure, and gravitational field conditions.

8.6 Altimetry and gravimetry: a new paradigm in hydro-meteorological analysis

Satellite altimetry (AVISO+) enables highly accurate measurement of sea level height, taking into account the influence of wind, atmospheric pressure, and ocean currents. In contrast, gravimetry (GRACE) provides unprecedentedly precise information on variations in the Earth's gravitational field (Δg), which indirectly reflect processes occurring in the Earth's interior and changes in the mass balance of the atmosphere and hydrosphere (**Fig. 8.10**).

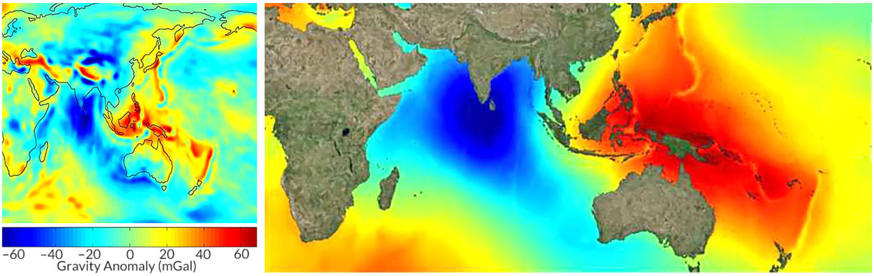

Fig. 8.10 Maps of Earth's gravity field anomalies (mGal) and geoid shape anomalies, i.e., mean sea level (m)
Source: [14]

Unlike classical meteorological models, which have temporal limitations of 5–7 days and require frequent updates, gravitational signals exhibit stable annual periodicity. This allows the development of long-term predictive scenarios for route planning.

Integrating AVISO+ and GRACE data into hydro-navigational support systems enables the following:

– forecasting the development of surge and seiche currents along coastlines and in narrow straits, which is essential for optimizing vessel speed and draft;

– detecting sea level anomalies prior to storm onset, allowing for preemptive reduction of hull and main engine loading;

– calculating optimal port and strait entry windows, minimizing energy consumption during maneuvering;

– identifying critical navigational points where decreased Δg signals a potential drop in atmospheric pressure and, consequently, increased storm activity.

A major advantage of satellite technologies is their global coverage, including remote oceanic areas where traditional meteorological stations are either absent or operate with low spatial resolution. This enables high-precision monitoring of monsoon activity in open-sea areas (e.g., between the Somali Current and the Indian subcontinent). It also makes it possible to create regional maps of forecasted gravitational instability, facilitating weather prediction weeks in advance and integrating data from multiple satellite missions to build robust multiparametric models for marine navigation.

Data from AVISO+ and GRACE satellite missions can already be integrated into the following systems:

– ECDIS (electronic chart display and information systems);

– SPOS (ship performance optimization system);

– Voyage optimization platforms (e.g., Wärtsilä, StormGeo, etc.).

This integration allows shipmasters and logistics planners to model the most energy-efficient routes in real-time based on sea state and expected currents, to adjust sailing speed according to forecasted wave height and pressure, and to modify route waypoints to avoid hazardous or high-resistance areas.

In conclusion, the use of satellite data is not only a tool for enhancing the accuracy of meteorological forecasts but also a key component of energy-efficient voyage management. It directly impacts fuel consumption, voyage completion times, and the overall environmental footprint of maritime transport.

8.7 Conclusion

First and foremost, it should be noted that modern ocean monitoring systems are based on the integrated use of various technologies, including both autonomous buoy stations and satellite remote sensing systems of the ocean surface. This integration ensures the acquisition of high spatial and temporal resolution data on ocean conditions.

Moored buoys play a key role in conducting long-term observations at fixed points in the ocean. Their data are indispensable for calibrating satellite measurements and validating numerical models. Ocean drifters, in turn, provide a cost-effective means of collecting data on temperature, salinity, and currents across large areas. The global drifter network has become a critical component of operational oceanography, particularly valuable for studying surface ocean circulation.

Satellite technologies offer unique opportunities for global coverage and high observation frequency. They enable the measurement of a wide range of parameters, including sea surface temperature, sea surface height, wind speed, and chlorophyll concentration. Satellite data are indispensable for studying large-scale processes in the ocean but have limited spatial resolution and require complex algorithms for data processing and interpretation.

The conducted study allows drawing several important conclusions regarding the impact of gravitational anomalies in the Indian Ocean region on the formation of monsoon circulation and the consequences of this phenomenon for maritime fuel consumption. The annual periodicity of Earth's gravitational field in the Arabian Sea region (Δg) is synchronized with seasonal variations in the geoid shape, which alters the weight of the atmospheric air column and, consequently, initiates or terminates monsoon winds. This provides a foundation for long-term weather forecasting.

Recorded sea level anomalies that contradict expected results based on wind effects (storm surges or seiches) indicate the presence of alternative mechanisms of barometric gradient formation. These mechanisms have a gravitational origin and must be taken into account when calculating the optimal balance of ship draft, speed, and propeller regime.

For the first time, a high level of coherence (0.96) between the annual harmonics of Δg and the geoid shape has been confirmed. This opens up prospects for the creation of a comprehensive navigational-predictive system that integrates hydrometeorological, satellite, and geophysical data. Geodynamic processes beneath the African plate have an indirect influence on meteorological conditions in the Indian Ocean, creating the need for transcontinental analysis of satellite information to accurately model the navigational environment.

The proposed approach may form the basis for a new generation of energy-efficient maritime navigation management systems, which will consider not only local weather conditions but also fundamental factors that shape global atmospheric circulation.

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CHAPTER 9

Development of a system for assessing navigational and energy safety on inland waterways

Nataliia Dolynska

Abstract

An approach to the development of an integrated system for assessing navigational and energy safety on the inland waterways of Ukraine is considered, taking into account current challenges and sustainable development trends. Special attention is given to energy efficiency as a key criterion in the planning, monitoring, and management of navigation. A system architecture is proposed, based on the use of sensor networks, analytical models, river information services (RIS), and digital navigation tools. The main system components are defined, which ensure the reduction of energy consumption, the enhancement of vessel traffic safety, and the optimization of logistical processes. The results of an analysis of the current state of infrastructure are presented, and the necessity of creating a unified information environment to support real-time decision-making is substantiated. Conclusions are drawn regarding the feasibility of implementing such a system as an element in the transition to environmentally safe and energy-efficient waterborne transport.

The developed assessment system for navigational safety enables an increased level of safety on the inland waterways of Ukraine through the integration of modern monitoring technologies and data analysis tools. The implementation of this system will contribute to more effective risk management in navigation and improved economic efficiency of water transport.

The proposed strategies and directions have proven to be essential for improving the efficiency and safety of navigation. The research confirms the need to integrate modern technologies, cooperate with river information services, account for environmental aspects, and ensure active participation of all stakeholders to achieve continuity and safety on inland waterways. The final conclusions support the necessity of creating and implementing comprehensive strategies aimed at optimizing port areas to achieve sustainable development and improve the competitiveness of inland water transport routes.

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Keywords
Digital technologies, inland waterways, navigational safety, energy efficiency of navigation, information and navigation systems, river information services.

9.1 Introduction

In the context of current environmental challenges and the urgent need to reduce fuel and energy resource consumption, the development of energy-efficient navigation management systems for inland waterways is becoming increasingly relevant. Shipping, being one of the most energy-intensive modes of transport, has significant potential for improving efficiency through route optimization, speed regulation, vessel operation modes, and enhanced navigational support.

On inland waterways (IWW), where infrastructural constraints, shallow waters, variable hydrological conditions, and high traffic density create additional challenges, ensuring navigational safety must be combined with achieving a high level of energy efficiency. Traditional approaches to navigation safety have primarily focused on collision risks, accidents, or traffic stoppages. However, in the transition toward a climate-neutral economy, it is essential to integrate an energy component into the safety assessment system – one that considers fuel consumption, energy expenditure for maneuvering, schedule efficiency, and the impact of external factors.

The development of an integrated system for assessing navigational and energy safety on inland waterways involves the creation of a methodology that enables objective and dynamic analysis of the water route condition and vessel energy consumption in real time. This system should be based on modern digital technologies, including satellite navigation, AIS, RIS systems, and algorithms for intelligent data analysis and risk forecasting.

In the current conditions of increasing traffic load on Ukraine's inland waterways, the issue of improving the efficiency of navigational information support becomes particularly important. Fairways, as the main arteries of inland water transport, require constant monitoring and timely notification to navigators about changes in the navigational situation, hydrological conditions, and potential hazards. The effective operation of navigational information services is not only the foundation of safe navigation but also a key factor in improving vessel energy efficiency.

The implementation of intelligent monitoring systems, digital data exchange platforms, and automated visualization and analysis processes using AIS, Inland ECDIS, IoT sensors, and satellite navigation significantly reduces fuel consumption, minimizes delays, and optimizes routes. This contributes not only to safety but also to the reduction of harmful emissions – an essential part of the "green transport" policy and sustainable development agenda.

9.2 Peculiarities of developing a navigation safety assessment system for inland waterways

Navigation safety on Ukraine's inland waterways is critically important not only for the preservation of human life and environmental protection but also as a foundation for ensuring efficient, reliable, and energy-saving navigation. In the context of post-war reconstruction of Ukraine's transport infrastructure, it is necessary to improve navigation safety assessment systems to prevent accidents and reduce risks to navigation.

Ukraine's inland waterways have significant development potential, but the low level of navigation safety limits their use. The main risk factors include outdated infrastructure [1], insufficient navigational equipment on vessels [2], and the absence of an integrated monitoring system [3]. Therefore, developing a modern architecture for a navigation safety assessment system is an urgent need [4], which will contribute to more effective navigation management.

In the current context of energy instability, rising fuel and energy costs, and ecological challenges, it is important not only to ensure safe vessel movement but also to evaluate the efficiency of that movement in terms of energy consumption, environmental impact, and time expenditure. Excessive maneuvering, port delays, route inconsistencies, and a lack of energy-optimal planning increase fuel consumption and harmful emissions. This creates an objective need for the development of an integrated system for assessing both navigational and energy safety, which will reduce risks and simultaneously improve the energy efficiency of all components of the navigation process.

The relevance of this study is driven by the continuous growth of freight traffic on waterways, the need to ensure uninterrupted and safe vessel movement in ports, and the necessity to reduce the environmental impact on inland water resources. This makes the study and implementation of modern strategies and technologies for optimizing water areas and ensuring sustainable navigation development especially important.

The developed architecture and identification of the key components of a navigation and energy safety assessment system for Ukraine's inland waterways should serve as a decision-making tool for operators, dispatchers, and governing bodies.

It will help enhance navigational safety, ensure stable energy consumption, optimize logistics chains, and minimize environmental impact.

To achieve this goal, the following tasks must be addressed:

1. Analysis of existing navigation safety assessment systems and identification of their shortcomings.

2. Development of the architecture for an integrated navigation safety assessment system.

3. Identification of the system's key components, including sensor networks, data processing tools, analytical algorithms, and visualization means.

4. Testing of the system prototype under real operating conditions.

The architecture of the proposed navigation and energy safety assessment system (**Fig. 9.1**) is based on the principles of digital transformation of transport infrastructure, integration with traffic management platforms, analytical mechanisms for evaluating energy consumption and risk, and adaptive response to changes in the navigation environment. The system is intended to provide a comprehensive approach to inland waterway management, simultaneously accounting for technical safety indicators and the energy efficiency of navigational decisions.

An innovative architecture for the navigation safety assessment system has been developed to enhance the accuracy of monitoring the navigational environment, automate the processing of information on potential risks, and provide timely notifications to operators and vessel pilots.

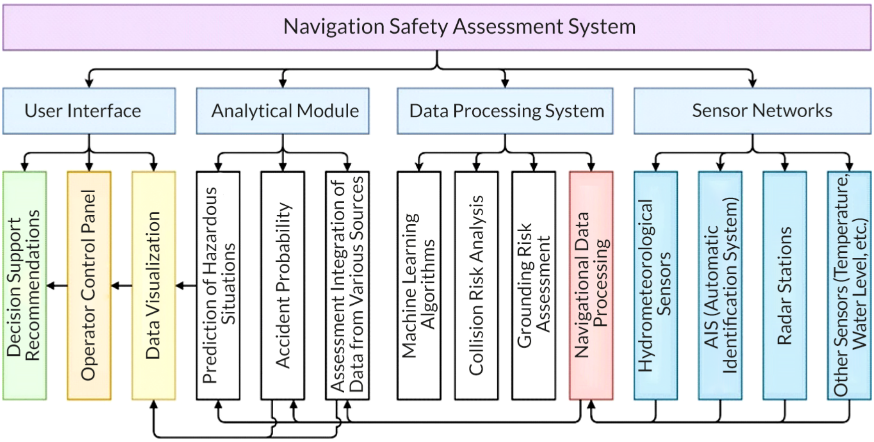

Fig. 9.1 Architecture of the navigation and energy safety assessment system for inland waterways

The system is built on the principles of integrated data collection, analysis, and visualization, utilizing artificial intelligence technologies and modern sensor solutions. It is capable of adapting to real-time changes in the navigation situation, considering both safety and energy efficiency parameters of vessel movement. The main components of the architecture have been defined:

1. Sensor networks.

The sensor network is the primary source of input information for the system. It includes:

− hydrometeorological sensors that record wind speed and direction, air and water temperature, atmospheric pressure, water level, currents, and waves. These data allow forecasting changes in hydrological conditions, which is especially important for safe navigation in shallow or unstable bottom terrain conditions;

− AIS (automatic identification system) stations that provide automatic tracking of vessel movement parameters (course, speed, location), enabling the creation of an accurate traffic picture in the fairway;

− radar and hydroacoustic systems, including coastal radars and echo sounders, which provide obstacle detection, identification of non-AIS objects, and monitoring of fairway depth.

2. Data processing system.

The information collected by sensors is sent to a computing module where it is processed using machine learning algorithms. The system is capable of:

− automatically classifying high-risk situations (e.g., crossing courses, failure to maintain safe distance, approaching shallow areas);

− detecting atypical vessel behavior patterns that may indicate potential threats;

− taking into account weather and hydrological conditions when assessing navigation safety.

3. Analytical module.

This component performs situational analysis and forecasting. Statistical modeling and neural network computing methods are applied to:

− predict hazardous scenarios (collisions, grounding, navigation in low visibility conditions);

− determine the optimal trajectory considering the minimization of water resistance, fuel consumption, and time spent in risky zones;

− support real-time decision-making.

4. User interface.

A centralized control panel displays information in a user-friendly visual format:

− interactive maps visualizing navigation conditions, risks, forecasts, and recommendations;

– alert notifications regarding changes in conditions or threats;

– customizable dashboards for dispatchers, vessel pilots, and analysts;

– reporting modules for further analysis and operational optimization.

During prototype testing in real operational conditions, it was found that the accuracy of navigation situation assessment increased by 35% compared to traditional monitoring systems. This improvement allowed for a reduction in incidents related to risky maneuvers; enhanced proactive traffic management; decreased fuel consumption through the selection of energy-efficient routes; and reduced environmental impact on inland waterways.

Optimization of the creation of operational water areas in ports on inland waterways is a strategically important direction for ensuring uninterrupted, safe, and energy-efficient navigation [5]. In conditions of increasing traffic, the need to reduce fuel consumption, and compliance with environmental standards, the issue of rational planning and management of water areas becomes especially relevant. At the same time, this process cannot be isolated – it requires close integration with RIS, which provide real-time navigational support [6]. Below are the key steps and considerations fundamental to achieving comprehensive optimization:

1. Hydrographic surveys. A primary condition for effective planning of operational water areas is conducting detailed hydrographic surveys, which include:

– high-precision mapping of riverbeds, identification of bottom features, depths, widths, and potential obstacles;

– creation of digital models of the bottom and shoreline used for further 3D modeling of operational zones;

– regular monitoring of changes in bottom morphology, enabling the detection of shoaling, sedimentation, and the need for dredging works.

Such studies form an objective basis for designing efficient working zones, minimizing vessel downtime, and avoiding unnecessary maneuvering, which directly impacts the reduction of fuel consumption.

2. Navigation modeling. It is noted that the use of navigation modeling software to simulate vessel movements and interactions in the water area is a highly advisable measure that defines the scale of the chosen technical solution. The model selection should be based on justified maximum vessel dimensions, for example, the "Dnipro-Max" type [7]. These simulations allow the formation of an energy-efficient configuration of the water area, reducing the number of maneuvers, decreasing vessel dwell time in the port, and optimizing logistical chains.

3. Environmental impact assessment. Any changes to the configuration of port water areas must comply with current environmental standards. The impact of dredging and construction works on the local ecosystem, particularly on biodiversity,

water quality, and bottom sediments, is assessed. The project for modernizing existing or creating new hydraulic structures must convincingly demonstrate compliance with environmental regulations and measures to minimize negative effects. These steps help reduce the ecological footprint of navigation, contributing to the achievement of green transport goals in Ukraine.

4. Stakeholder involvement. It is particularly recognized that engaging all relevant stakeholders, including port authorities, shipping companies, environmental agencies, and local communities, and incorporating their considered input can help shape the optimization plan and ensure it meets the needs of all parties. Involving these stakeholders ensures transparency of the process and the formation of a balanced development model.

5. River information services (RIS). A general overview of RIS is provided, emphasizing the importance of integrating hydraulic and hydrographic institutions with RIS systems that deliver real-time information about river conditions, traffic, and weather [8]. This data is critically important for optimizing the use of water areas and ensuring safe navigation. Integrating RIS with the design and operation of water areas enables the implementation of intelligent vessel traffic management systems, which are key to reducing fuel consumption, lowering emissions, and improving navigational safety.

6. Vessel traffic management. One of the key components for ensuring the effective functioning of operational water areas in ports is the implementation of modern vessel traffic management systems. Such systems are designed to optimize traffic both within the port zone and along the entire inland waterway segment. They should be based on the use of data from River Information Services, providing access to hydrographic, meteorological, and navigational information in real time. This may include traffic control, movement monitoring, and automated reporting systems integrated with radar surveillance and Inland ECDIS. Thanks to these systems, it is possible not only to reduce the risks of collisions and delays but also to optimize fuel consumption by minimizing idle time and rationally distributing traffic flows.

7. Dredging and maintenance. Regular dredging operations and maintenance of water areas are integral to maintaining an adequate level of navigational safety. In inland waterways, where water level fluctuations and sediment dynamics can significantly alter depths, these measures must be planned and based on up-to-date hydrographic data [8]. This approach not only enhances safety but also ensures a stable traffic regime, contributing to energy savings by reducing the need for maneuvering and delays.

8. Safety measures. Navigational safety is a priority component in the planning and operation of operational water areas. The main elements of the safety system

should ensure clear vessel orientation in space, especially under challenging weather or night conditions. Such measures include:

– installation of navigational aids – buoys, lateral marks, signal lights, lighthouses – which must comply with IMO international standards;

– equipping these objects with sensors and connection to RIS, allowing automatic updates on their status, position, and functionality;

– providing backup power supply and redundant control systems to guarantee the stability of navigational infrastructure in emergency situations;

– integration of these aids into digital navigation systems significantly improves response times and reduces the risk of accidents.

9. Technology integration. Enhancing the efficiency of port water area management is also impossible without the active implementation of innovative digital solutions such as AIS (Automatic Identification System), IoT sensors, and satellite navigation to improve the efficiency and safety of port operations. These technologies can provide real-time data for decision-making. They increase transparency, speed of response to changing conditions, and the overall level of safety and energy efficiency of vessel movements.

10. Emergency response planning. To improve readiness for crisis situations, a clearly developed emergency response system is necessary. The provided sample emergency response plan considers a wide range of potential incidents, including vessel collisions, fuel spills, fires, groundings, and meteorological anomalies. It defines interaction algorithms between port services, RIS, local authorities, emergency rescue teams, medical institutions, and emergency services. The response plan must include operational alerting tools, including digital channels, mobile applications, and automated notifications. Regular drills and system tests should be scheduled to enhance staff preparedness.

Such an integrated approach to safety management not only reduces risks but also strengthens the overall resilience of port infrastructure to extraordinary situations.

11. Compliance with regulatory requirements. One of the fundamental conditions for the successful implementation of optimization measures for operational water areas is ensuring their compliance with current national and international regulatory frameworks. Particular attention is given to the implementation of provisions related to energy efficiency in shipping. Specifically:

– national standards (DSTU, sectoral regulations) should take into account modern requirements for reducing energy consumption during vessel maneuvering within water areas, including through optimization of dimensions, speeds, and operating conditions;

– international norms (e.g., IMO energy efficiency design index (EEDI) and energy efficiency operational indicator (EEOI)) must be incorporated into the criteria for evaluating the efficiency of port infrastructure optimization;

– regulatory environmental compliance implies the integration of solutions that reduce fossil fuel consumption, shorten vessel waiting times, and promote electrification of port facilities.

Thus, compliance with legal requirements is not only a legal necessity but also a foundation for implementing systematically coordinated energy-efficient solutions into navigational infrastructure.

12. Monitoring and evaluation. Sustainable development of inland waterways requires a continuous cycle of monitoring and adaptive optimization of water area functionality. Energy efficiency here acts not only as an outcome but also as a key evaluation criterion. Continuously monitor and assess the performance of optimized water areas and make adjustments as necessary. This should be an ongoing process to adapt to changing conditions and requirements.

13. Key monitoring approaches include establishing energy consumption indicators, such as average fuel consumption per unit of cargo during port entry or passage through channels; using digital monitoring tools – flow sensors, fuel meters, AIS data – to record waterway loads and predict congestion; and employing machine learning to identify patterns in energy consumption changes depending on navigation conditions and the impact of implemented measures.

Regular adjustments of traffic schemes and navigational infrastructure parameters (depth, width, waiting zones) should also be carried out based on data about energy overconsumption or traffic slowdowns.

As a result, this approach enables improvements not only in technical and logistical efficiency but also achieves significant reductions in energy consumption within the transport cycle.

14. Environmental development. Modern optimization of inland waterway transport infrastructure is impossible without considering principles of environmental sustainability and energy efficiency. It is emphasized that the optimization process takes into account the environmental friendliness of dredging methods, the energy efficiency of infrastructure, and the reduction of environmental impact. Modernization of water area infrastructure should focus on energy saving – for example, installing LED lighting, energy-efficient pumping stations, and energy recovery systems in locks. Emissions from vessel berthing should be minimized by developing shore-to-ship power supply infrastructure (cold ironing) and encouraging the use of vessels with hybrid or electric propulsion systems. Environmental impact assessments of optimization measures should consider not only biodiversity and water quality but

also their contribution to reducing CO_2, NO_x, and SO_x emissions, as criteria for energy-efficient modernization.

Such environmental and energy integration ensures not only safe and economically advantageous operation of water areas but also compliance with the "green logistics" strategy adopted at European and global levels.

Thus, optimizing the creation of operational water areas in ports on inland waterways is a complex and multifaceted process. It requires the integration of various technologies and systems, consideration of environmental and safety factors, and cooperation with multiple stakeholders. Interaction with River Information Services is crucial for real-time decision-making and ensuring safe and efficient navigation.

The developed system for assessing navigational and energy safety aims not only to enhance the safety level of shipping on Ukraine's inland waterways but also to achieve a higher level of energy efficiency through the integration of modern monitoring technologies, digital data processing, and analytical forecasting. Its implementation allows for more rational risk management in navigation processes and reduction of energy losses, which directly impacts the economic feasibility and environmental sustainability of water transport.

The proposed strategies and technical solutions have proven effective in improving shipping productivity, reducing fuel consumption, minimizing environmental impact, and ensuring safe vessel passage. The conducted research highlights the urgent need for a comprehensive approach to energy-saving navigation management, which includes integration with river information services, use of digital charts, predictive algorithms, and involvement of all participants in the logistics chain.

Final conclusions emphasize the necessity to develop and implement energy-efficient strategies for managing port water areas and waterway routes, which will form the basis for sustainable development, increased competitiveness of inland waterways, and achieving green transport goals in Ukraine.

9.3 Improving the efficiency of navigational information services for fairways

In the context of transforming water transport towards more sustainable and energy-efficient operational models, the role of navigational information services (NIS) is increasingly important not only for ensuring safety but also for enhancing the energy efficiency of shipping on inland waterways. Optimizing vessel trajectories, reducing time spent in channels, minimizing stops, and limiting maneuvering in complex hydrological conditions are directly linked to the quality, accuracy, and timeliness of navigation information provided by fairway services [9].

In the post-war recovery of Ukraine's transport infrastructure, improving the NIS efficiency takes on strategic significance. Timely updating of cartographic information, dynamic reporting on fairway conditions, water levels, the presence of obstacles, or changes in navigation regimes contributes to decision-making that allows pilots to select the most energy-efficient routes. The use of digital technologies, automated monitoring systems, and data analytics creates the conditions for minimizing fuel consumption, reducing operational costs, and lessening environmental impact.

River information services (RIS) are aimed at enhancing the safety, efficiency, and environmental friendliness of inland navigation on the path toward its development as a sustainable mode of transport [10]. RIS face the following specific tasks:

− to make inland navigation reliable, planned, and transparent as part of a multimodal transport chain;

− to strengthen navigation safety by reducing the number of accidents and incidents related to vessel movement and cargo transport, providing information for legal compliance and statistics;

− to increase traffic and transport efficiency by optimizing the use of waterway capacity and vessel cargo capacity, improving the performance of ports and terminals, managing water transport chain resources through information exchange among vessels, locks, bridges, terminals, and ports, thereby lowering transportation costs, reducing fuel consumption, and increasing RIS user awareness of the current situation;

− to promote environmental safety of transportation by reducing harmful impacts on the environment.

Ukraine's inland waterways have significant development potential, but low navigation safety limits their utilization. Therefore, the fairway service aims to ensure the safe passage of vessels to their destinations.

The objective of this study is to develop effective methods and identify key components of the fairway service provision system. To achieve this, it is essential to understand that one component of RIS services is the fairway information service, which provides geographic, hydrological, and administrative data on waterway infrastructure and fairways within the RIS zone, necessary for users to plan voyages, execute them, and monitor their progress. Information transmission about fairways is one-way: it is sent from shore services to vessels or from shore services to the offices of interested parties.

The fairway service collects, processes, and provides the following information:

− the status of navigational aids on inland waterway sections;

− depths and dimensions of the navigable channel;

– obstacles present on the fairway;
– restrictions under bridges and in locks;
– meteorological conditions on various sections of the waterway;
– ice conditions on the fairway;
– electronic charts of fairway sections.

Improving the efficiency of marine navigational information services for fairways is critically important to ensure shipping safety and optimize traffic in water areas.

One key area for improving the efficiency of fairway navigational information services is upgrading their technical equipment. Implementing modern navigational and hydrographic equipment allows for timely, accurate, and reliable information delivery to pilots about navigation conditions, which, in turn, helps reduce risks, minimize delays, and improve the energy efficiency of vessel movement.

Modern satellite positioning systems (GPS), combined with AIS, enable real-time precise determination of a vessel's location with high accuracy and transmission of this information to shore services [11]. This allows more effective coordination of vessel traffic, avoidance of congestion on certain fairway sections, reduction of downtime, and support for choosing optimal routes with minimal fuel consumption. Together with centralized dispatch control systems, this enables dynamic route planning that accounts for changing conditions and reduces emissions by avoiding inefficient maneuvering.

Timely updating of hydroacoustic equipment – radars, echo sounders, and multibeam sonar systems – ensures accurate determination of fairway depths, detection of underwater obstacles, shoals, and seabed changes. High precision of such measurements is especially important for vessels with deep drafts or when navigating critical sections with limited dimensions. Clear knowledge of available depth promotes route selection with minimal grounding risk, accident avoidance, and consequently, increased safety and energy efficiency in shipping [12].

Modern solutions in the integration of navigational data enable the combination of information from various sources – GPS, AIS, meteorological stations, hydrographic sensors, video surveillance cameras, automated water level and current monitoring systems. Such integrated systems create a unified visualization dashboard for operators, traffic controllers, or ship captains, providing comprehensive real-time analysis of the navigational situation. This ensures timely decision-making, avoidance of unexpected maneuvers, and reduced fuel consumption through smoother and more predictable course and speed management.

Automation of processes within navigational information services for fairways forms the basis of modern, efficient, and safe shipping management. Its implementation reduces personnel workload, shortens response times to changes in navigational conditions, and provides more accurate risk forecasting [13]. Additionally, automated solutions contribute to increased energy efficiency by minimizing idle time, optimizing routes, and vessel speeds.

The implementation of digital chart systems such as ECDIS (electronic chart display and information system) provides access to continuously updated data on depths, fairways, navigational warnings, weather conditions, and obstacles. These charts integrate data from GPS, AIS, meteorological stations, and hydrographic sources, forming an up-to-date real-time navigational picture. This enables vessels to avoid hazardous areas, plan movements considering depths and currents, and reduce fuel consumption through optimized course, speed, and travel time.

Automated vessel traffic services (VTS) play a critical role in coordinating traffic in complex or congested sections of inland waterways. VTS provide surveillance, control, forecasting, and rapid response to conflict situations. With the introduction of analytical modules and predictive algorithms, such systems can detect potential route conflicts, recommend optimal passing maneuvers, identify risk zones, and generate energy-efficient trajectories, minimizing unnecessary movements and abrupt speed changes.

Automated fairway control through remote monitoring involves installing hydrometric sensors, surveillance cameras, thermal imagers, and other real-time data collection tools at strategically important waterway locations. These systems continuously monitor water levels, currents, wind speed, obstacle presence, status of floating navigation aids, and technical infrastructure (bridges, locks, etc.). Collected data is automatically processed and integrated into a unified decision-support system, enabling prompt response to navigational changes and preventing inefficient use of energy resources by vessels.

Reliable, timely, and efficient communication is a key element of modern inland waterway traffic management systems. In the context of energy efficiency, improving communication infrastructure helps avoid delays, inefficient maneuvering, and idle time, directly reducing fuel consumption and emissions.

Traditional VHF/UHF radio systems are supplemented by modern digital channels that provide higher quality voice and data transmission. The implementation of the global maritime distress and safety system (GMDSS) standards, including simplified versions for river navigation, ensures continuous and reliable communication among vessels, traffic control centers, locks, and ports. Multichannel communication systems capable of transmitting not only voice but also text and graphical messages improve the speed of information exchange and support faster decision-making regarding routes or changes in navigational conditions.

Integration of vessels and shore-based services into a single information network is facilitated by the deployment of broadband data transmission networks. In particular, the use of satellite communication channels enables continuous information exchange even in remote or poorly covered areas, such as isolated river sections or mountainous regions. This capability is especially critical for navigation safety and prevention of unscheduled stops or emergency situations that may lead to excessive energy consumption. Additionally, such networks allow centralized monitoring and coordination of a large number of vessels in real time.

Fairway information services increasingly rely on automated warning systems capable of sending real-time alerts to captains about changes in hydrographic or meteorological conditions. These systems notify about sediment shifts, shoaling, rising water levels, current changes, fog, storm warnings, and more. This allows captains to adjust routes or speeds proactively, avoiding accidents and optimizing energy use.

Contemporary challenges in inland water transport require not only technical upgrades but also fundamental transformations in the ways navigational information is exchanged, processed, and stored. In conditions of high traffic density, variable hydro-meteorological factors, and the need for energy-efficient vessel traffic management, optimizing information flows plays a crucial role. The goal is to create a system that ensures fast, reliable, and efficient data transmission and analysis among all transport process participants.

Information interoperability between stakeholders – ports, traffic control centers, vessels, locks, meteorological services – is a necessary prerequisite for efficient navigation. Implementation of unified data formats (e.g., IALA S-100, XML, JSON) and standardized communication protocols enables seamless interaction between information systems. This reduces the likelihood of delays, data processing errors, and information duplication, thereby contributing to reduced time and fuel consumption during maneuvering and route planning.

Integration of intelligent systems takes traffic management to a new level. Using large volumes of historical and real-time data, machine learning algorithms can predict fairway traffic loads, identify bottlenecks, congestion, or potential hazard zones. For example, based on analysis of vessel traffic frequency, depth, current speed, and weather conditions, dynamic recommendations can be generated for the most optimal route with minimal water resistance and risk of delays. Such recommendations can be automatically transmitted to vessel onboard systems or traffic controllers, significantly enhancing navigation energy efficiency.

Centralized cloud platforms provide convenient access to up-to-date information for all users regardless of their location. Data on depths, movement restrictions, current lock situations, weather conditions, warnings, and recommendations can be updated and delivered in real time via unified protocols. Cloud architecture also simplifies system scalability, backup, software updates, and cybersecurity measures. Moreover, these platforms facilitate the implementation of the digital twin concept for fairways, where each river segment is virtually modeled and analyzed for more precise situation forecasting.

The physical infrastructure of fairways plays a crucial role in ensuring the safety and efficiency of navigation. Its current condition directly affects the navigational situation, vessel transit speeds, and fuel consumption levels. Wear, instability, or inadequacy of infrastructure leads to additional maneuvers, speed reductions, delays, or even accidents, which significantly reduce the energy efficiency of the transportation process. Therefore, a systemic approach to improving elements of fairway infrastructure is of paramount importance.

To enable timely detection of changes in seabed configuration, sedimentation, emergence of obstacles, or shifting sandbanks, it is necessary to implement regular and automated monitoring of water areas.

For this purpose, the following technologies are recommended:

– drones equipped with high-precision cameras and LIDAR sensors, capable of aerial photography and mapping of coastal areas;

– autonomous surface and underwater vehicles (USV/ROV) capable of real-time hydroacoustic seabed scanning and rapid data transmission to navigation services;

– automated bathymetric charting systems that monitor depth changes dynamically and update navigational databases accordingly.

Such measures help reduce the risks of passage through hazardous zones, avoid forced stops, and prevent routing decisions that lead to fuel overconsumption.

Traditional buoys and navigational marks remain essential visual orientation aids for vessels; however, their functionality can be significantly enhanced through digitalization. Promising directions include:

– equipping buoys with sensors to measure water level, current speed, temperature, and other hydrological parameters impacting navigation;

– connecting navigational aids to centralized monitoring systems via LoRaWAN or LTE/5G networks, enabling prompt data transmission to shore control centers;

– integrating energy-efficient LED lighting with automatic brightness adjustment based on weather conditions and time of day, improving both energy savings and safety.

These initiatives ensure timely notification of crews about changes in the fairway and improve the overall quality of the navigational environment.

The modern paradigm of inland water transport development focuses on digital transformation of logistics processes, notably through the implementation of the Smart Port concept. This high-tech ecosystem integrates digital services for vessel traffic management, infrastructure, cargo turnover, and energy consumption into a unified dynamic environment. Integrating fairway navigation information services with such ecosystems is a crucial step toward enhancing energy efficiency, reliability, and sustainability of inland water transport.

A key condition for achieving effective waterway traffic management is the coordination between vessels, fairway navigation services, and port administration. Ensuring operational data exchange between vessel traffic services (VTS) and port planning platforms enables:

– coordinated vessel approach to ports considering current navigational conditions;

– avoidance of queues and idle time in anchorage areas, leading to reduced fuel consumption and emissions;

– optimized berth allocation, minimizing the need for additional maneuvers.

The implementation of a shared information environment based on API integration principles and IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) standards allows construction of efficient logistic routes with predictable energy consumption levels.

The Smart Port ecosystem actively employs IoT devices that provide continuous monitoring of environmental parameters, port infrastructure, and water areas. Integrating fairway navigation services into this network enables:

– monitoring fairway conditions (depths, obstacle presence, water level) via underwater sensors and telemetry-equipped buoys;

– real-time detection of structural wear in hydraulic engineering facilities or soil shifts;

– direct transmission of data to vessel traffic management systems, allowing prompt route adjustments and avoidance of zones with increased energy consumption (e.g., due to strong currents or insufficient depth).

Additionally, IoT devices can be utilized to control lighting parameters, climatic conditions, vibration loads on equipment, and more, contributing to reduced operational costs and improved energy efficiency of the entire infrastructure.

Thus, deep integration of fairway navigation information services with Smart Port digital platforms and IoT technologies forms a new quality of inland waterway management. This approach is based on principles of dynamic adaptation, increased process transparency, and energy consumption optimization at all stages of the logistics chain. It opens broad prospects for implementing green shipping initiatives at the national level.

These measures will enhance the accuracy, speed, and safety of fairway information services, which is critical for modern navigation.

9.4 Conclusion

The results of the conducted study confirmed the importance of implementing a comprehensive approach to energy-efficient navigation management on inland waterways. This approach should be based on integration with river information services, the use of digital navigation tools, predictive models, and effective coordination of actions among all participants in the transport and logistics process.

The summarized conclusions point to the strategic necessity of developing and implementing energy-saving management systems for port water areas and water routes. This will ensure sustainable development, strengthen the competitiveness of inland water transport, and achieve the goals of environmentally friendly ("green") transport in Ukraine.

Modernization of technical equipment not only enhances the overall efficiency of navigation management on inland waterways but also lays the foundation for implementing intelligent transport systems aimed at reducing energy consumption, lowering CO_2 emissions, and realizing the principles of green shipping. Overall, improving communication infrastructure is an integral component of the digital transformation of water transport. It not only increases the overall level of safety and operational efficiency but also creates conditions for sustainable, predictable, and energy-efficient navigation on Ukraine's inland waterways.

Optimization of information flows within navigation services significantly reduces navigational risks, minimizes unnecessary stops or waiting times, and, most importantly, ensures more efficient fuel use through reduced transit times and more precise speed planning. As a result, this leads to lower operational costs, reduced emissions, and an overall improvement of the environmental profile of inland water transport.

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CHAPTER 10

Digital strategies for enhancing the efficiency of cargo ships maintenance

Andrii Holovan

Abstract

This section is dedicated to the systematization of digital solutions in the field of ship maintenance, with a focus on enhancing the reliability of ship equipment, reducing costs, and improving operational performance. The analysis of previous studies and publications is used to identify potential challenges and demonstrate how the application of digital strategies can effectively address them. The section explores modern approaches to implementing digital strategies in the context of systematic maintenance of cargo vessels, outlines the main challenges related to the inefficiencies of traditional maintenance practices, and substantiates the necessity of adopting digital strategies to achieve sustainable shipping objectives.

The emphasis is placed on the integration of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), digital twins, and Big Data to ensure the reliable operation of fleet technical systems. It is justified that the use of digital models not only enhances the safety and efficiency of maintenance processes but also enables significant reductions in fuel consumption through optimized engine load management, early fault detection, and predictive maintenance planning.

A digital strategy development approach is proposed, based on the principles of energy-efficient lifecycle management of ship systems. The potential of virtualized maintenance is analyzed as a means of minimizing resource consumption, human effort, and environmental impact. Examples are provided of digital platforms being implemented to monitor the technical condition of vessels in real time, which allows for increased flexibility in decision-making and reduced downtime. The section also discusses and substantiates optimal parameters for a ship maintenance system based on the use of digital strategies.

Keywords

Digital strategies, energy efficiency, maintenance, cargo vessels, digital twins, artificial intelligence, condition monitoring, parameter optimization, maritime transport, ship systems.

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10.1 Introduction

The issue of ensuring energy efficiency in maritime transport is directly linked to the technical condition of cargo vessels and the effectiveness of their maintenance systems. Given the continuous rise in fuel costs and increasing requirements for greenhouse gas emission reductions, traditional scheduled maintenance methods are becoming inadequate. These methods fail to account for the current condition indicators of onboard systems and do not enable effective responses to changes in technical or navigational contexts.

In contrast, digital technologies – particularly digital twin models, sensor-based monitoring systems, and artificial intelligence – enable the implementation of a new maintenance paradigm, where the priorities are predictiveness, adaptability, and energy efficiency. This approach reduces the risk of emergency stoppages, improves resource utilization, and minimizes vessels' idle time. The focus is not only on technical operability but also on minimizing energy losses caused by the misalignment of mechanical components and systems.

Modern merchant vessels play a crucial role in the global transportation system, enabling the movement of large volumes of cargo worldwide. This imposes high demands on the efficiency and reliability of shipboard equipment. Maintenance systems for cargo vessels are essential for ensuring their functional integrity and operational safety. However, several issues persist concerning the current state of ship maintenance systems. Specifically, the reliability and efficiency of technical maintenance are critical for optimizing operational costs and enhancing the overall performance of maritime transport. Well-defined maintenance system parameters can address these challenges and improve cargo vessel operations.

The operation of the cargo fleet under current conditions is characterized by a high degree of technological complexity, increasing energy costs, stricter environmental regulations, and the need to maintain competitiveness in the global shipping market. In this context, effective maintenance of ship systems is particularly relevant, as it helps reduce repair costs, ensures voyage safety, and lowers overall fuel consumption. Outdated maintenance approaches – focused on scheduled or breakdown-based repairs – do not reflect the actual technical condition of equipment and fail to meet required energy efficiency standards.

Within this framework, digital transformation serves as a key tool for modernizing cargo vessel maintenance systems. Digital technologies such as sensor networks, big data, predictive analytics, digital twin models, and artificial intelligence tools provide new opportunities for real-time technical condition monitoring, failure forecasting, and optimal maintenance planning. Especially important is the implementation of strategies that integrate digitalization with the principles of energy-efficient shipping.

10.2 Development of digital strategies for improving the efficiency of maintenance systems for cargo vessels

In the current context of maritime transport operations, where increasingly stringent requirements are imposed on reducing greenhouse gas emissions and enhancing the energy efficiency of shipping, there is a pressing need to optimize maintenance systems for cargo vessels. Effective management of a ship's technical condition directly affects not only its reliability and safety, but also its energy consumption during operation. This necessitates a comprehensive revision of traditional approaches to service maintenance, incorporating cutting-edge digital technologies that can minimize fuel losses, reduce unplanned downtime, and consequently improve carbon footprint metrics [1].

A wide range of factors – including unplanned breakdowns, idle time due to unexpected repairs, excess fuel consumption resulting from inefficient operation of onboard systems, and the absence of modern condition monitoring infrastructure – contribute not only to financial losses but also to a reduction in the vessel's overall energy efficiency. For instance, improper maintenance planning may result in increased hull resistance, higher auxiliary energy consumption, and decreased efficiency of propulsion systems.

Key challenges that require immediate attention include:

1. Predictability and downtime. The absence of digital early-warning tools leads to operational failures and downtime, which in turn causes elevated fuel consumption, especially in cases of engine restarts or course deviations.

2. Economic and fuel-related costs. Ineffective planning of repairs and maintenance leads to excessive use of resources, including fuel, and underutilization of equipment capacity, ultimately resulting in avoidable fuel expenditures.

3. Technical obsolescence. The use of outdated monitoring and control systems prevents early detection of anomalies in propulsion and power systems, increasing energy losses and reducing the overall operational efficiency of the vessel.

4. Safety and environmental concerns. Equipment failures pose threats not only to crew safety but also increase environmental risks through the release of harmful substances and non-compliance with fuel consumption standards.

5. Lack of systemic coordination. Insufficient integration of information flows between onboard systems and shore-based facilities leads to time and energy losses, as well as poor coordination in resource management, including energy use [2].

In light of these challenges, an effective maintenance system must serve not only as a service tool but also as a means of enhancing a ship's energy efficiency. This is achievable through the implementation of modern digital strategies capable of ensuring reliable vessel performance, minimizing fuel consumption, supporting environmental compliance, and optimizing equipment lifecycle management.

The analysis carried out has demonstrated that a number of key issues in ship maintenance can be addressed through the transformation of maintenance systems with a focus on digital adaptation and energy efficiency:

1. Reduction of delays and stoppages. The use of predictive analytics enables early detection of critical failures, reducing the number of unscheduled stops, optimizing logistics, and minimizing idle time with engines running.

2. Energy-saving maintenance planning. Through the use of digital models, maintenance planning takes into account energy consumption, load periods, and equipment operating modes, thus minimizing fuel expenditure.

3. Optimization of repair costs. By collecting and analyzing operational data, digital systems can accurately determine the optimal timing for replacing components, avoiding both premature and delayed interventions – each of which impacts the vessel's energy performance.

4. Centralized monitoring. Continuous remote monitoring of a ship's energy systems in real time enables rapid response to malfunctions and facilitates the development of a comprehensive database on energy consumption patterns under different operational conditions.

5. Standardized data exchange. The use of unified digital platforms facilitates interaction between onboard subsystems, the engine room, and shore-based technical offices, allowing for synchronized actions and the avoidance of energy waste.

6. Reduced environmental risks. A lower number of technical failures directly contributes to a reduced likelihood of fuel spills, unauthorized emissions, or other breaches of environmental safety regulations.

7. Standardization and transparency. Energy efficiency is no longer treated as a secondary outcome but becomes a core objective of maintenance planning, contributing to improved CII ratings and compliance with MARPOL Annex VI requirements.

Based on the conducted research, a structural-logical scheme for the digital transformation of cargo ship maintenance systems has been proposed, aimed specifically at reducing energy losses. This framework accounts for the full cycle – from data collection to management decisions based on analytics. In particular, the use of digital twins, intelligent diagnostics, and risk visualization allows for energy-balanced management of a vessel's technical condition.

Digital strategies in the context of cargo ship maintenance encompass:

1. Process digitalization, which minimizes human error and improves diagnostic accuracy.

2. Analytical processing of energy system data to identify efficiency trends and changes in performance.

3. Modeling and forecasting, which provide the foundation for making optimal energy decisions.

4. Digital communication with stakeholders, ensuring transparency and coordination between crew, technical teams, and company management.

5. Platform integration, enabling unified control of fuel and technical parameters within a single digital environment.

Thus, the implementation of digital strategies in cargo ship maintenance systems opens up extensive opportunities for cost reduction, enhanced safety, environmental sustainability, and – most importantly – a transition to an energy-efficient paradigm of maritime operations.

In the context of cargo ship maintenance, digital strategies involve the application of digital models, digital shadows, and digital twins (**Fig. 10.1**), combined with data analytics (**Fig. 10.2**, **10.3**), to enhance maintenance efficiency, forecast service requirements, and define optimal maintenance and repair schedules.

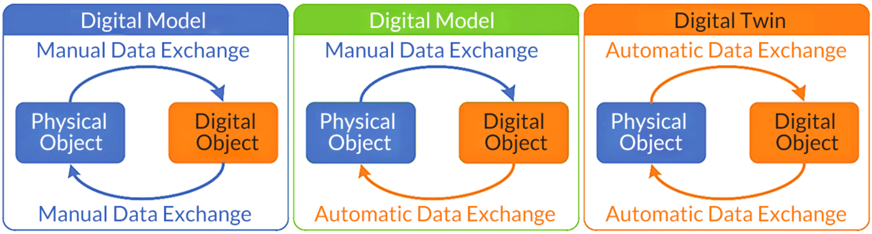

Fig. 10.1 Differences in data topology between digital model, digital shadow, and digital twin

Considering the need to improve the energy efficiency of cargo ship operations, the implementation of advanced digital tools for technical maintenance emerges as a key aspect. One of the most promising directions in this digital transformation is the use of digital representations of ship systems – namely, digital models, digital shadows, and digital twins. These approaches enable real-time monitoring of equipment conditions, reduce the risk of unscheduled shutdowns, help avoid excessive fuel consumption, and optimize the performance of onboard energy systems.

A *digital model* lacks automated data exchange between the physical and digital entities. Data must be manually entered for condition analysis, which limits the system's ability to react promptly to technical deviations that directly affect fuel efficiency – such as malfunctioning main engines or fuel supply systems.

A *digital shadow* offers a one-way data flow from the physical object to the digital environment. This partially supports fuel performance monitoring but does not allow the digital system to influence energy management processes. It follows the "human-in-the-loop" (HITL) principle, where decision-making relies on operator intervention, reducing the level of automation and energy optimization potential.

The most promising solution for improving energy efficiency is the *digital twin*. It provides two-way, real-time automated data exchange, enabling dynamic adjustment of engine parameters, fuel optimization, fault prevention, and condition-based maintenance. Due to the full integration between the physical and digital environments, digital twins significantly contribute to reducing a vessel's carbon footprint [3].

As part of this study, a classification of predictive analytics methods was developed, forming a crucial component of energy-efficient maintenance systems. This classification includes three main categories:

1. Machine learning and intelligent data analysis – these methods identify hidden dependencies between operational parameters and equipment condition. They are especially useful in detecting anomalies in fuel consumption or reductions in power-plant efficiency. Neural networks, clustering techniques, and ensemble models are used to forecast risks of increased fuel usage at early stages [4].

2. Probabilistic models – these incorporate Bayesian logic, probability distributions, and Monte Carlo simulations to account for uncertainty in predicting the lifespan of components that have a direct impact on fuel consumption.

3. Statistical analysis – techniques such as regression, correlation, and variance analysis are used to establish relationships between operational parameters and the frequency of energy-inefficient malfunctions.

The proposed classification offers a structured approach to energy-conscious technical maintenance. It provides the foundation for developing analytical models that not only predict failures but also identify the most fuel- and cost-efficient service strategies, taking into account time, economic costs, and environmental impact.

In conclusion, digital representations – especially digital twins – combined with predictive analytics tools, enable a paradigm shift in managing the technical condition of cargo vessels. This integrated approach ensures long-term energy efficiency, optimized performance, and greater reliability of onboard systems.

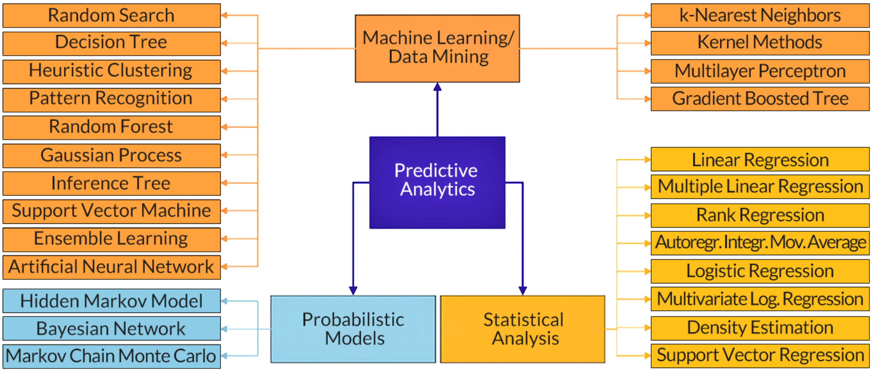

Fig. 10.2 Classification of predictive analytics methods

As part of the study, the role and significance of digital technologies in the maritime transport sector were analyzed in the context of achieving energy efficiency. Particular attention was paid to the use of sensor systems, platforms for monitoring the condition of onboard equipment, and data analytics for predicting equipment failures and optimizing technical maintenance with minimal fuel consumption. These approaches enable timely intervention, reduce the number of emergency stops, prevent energy overconsumption during critical operating modes, and optimize repair logistics with consideration of the vessel's energy parameters [1].

Prescriptive (recommendation-based) analytics plays a particularly important role in energy-efficient management, allowing not only the identification of problems but also the generation of actionable recommendations to improve vessel performance. As part of the study, a classification of prescriptive analytics methods was developed (**Fig. 10.3**), covering six key approaches relevant to the management of ship maintenance with a focus on minimizing energy consumption:

1. Machine learning and intelligent data analysis. These methods support the development of recommendation systems based on large volumes of historical and sensor data. For instance, classification algorithms can identify parameters indicative of future engine efficiency degradation, while clustering can reveal operational regimes with elevated fuel consumption. Such tools are already being integrated into next-generation marine navigation platforms [2].

2. Evolutionary computation. The use of genetic algorithms and optimization strategies enables modeling maintenance tasks as problems of minimizing energy resource use across the entire lifecycle of ship components. These methods are

effective in complex environments with numerous variables and constraints (e.g., port availability windows, predicted wear levels, or expected loads).

3. Simulation modeling. These techniques create digital environments to test the impact of various maintenance scenarios on overall vessel energy performance. For example, simulating the choice between on-the-go or in-port repair allows the prediction of potential energy losses due to reduced propulsion efficiency or engine overheating.

4. Probabilistic models. This approach accounts for high uncertainty levels typical of maritime operations. By incorporating probabilities of equipment failure and operational delays, more flexible maintenance schedules can be developed, reducing unplanned downtime – a key source of fuel overconsumption.

5. Logic-based models. Systems grounded in rule-based or logical constraints allow the enforcement of energy performance standards during service planning. For example, maintenance actions may be triggered only when energy consumption exceeds specified thresholds.

6. Mathematical programming. Optimization techniques help identify the best maintenance schedules that minimize time and resource losses. These approaches take into account both the energy use of each equipment unit and the impact of repair modes on the vessel's overall energy profile.

Thus, the systematic classification of prescriptive analytics methods enables a structured approach to decision-making in the field of ship maintenance, taking into account energy-related constraints. This not only contributes to reducing operational costs but also aligns with contemporary environmental standards in the maritime industry, which emphasize the rational use of resources and the reduction of harmful emissions resulting from inefficient vessel operation.

The developed classification (**Fig. 10.3**) serves as an important tool for organizing and understanding various approaches to prescriptive analytics. It provides a framework for systematizing available methods and selecting the most appropriate ones for solving specific problems.

The classification presented in **Fig. 10.3** holds significant potential in the domain of technical maintenance for cargo vessels. It assists both researchers and practitioners in identifying and applying effective decision-making techniques that enhance vessel maintenance processes and contribute to improved operational efficiency and energy performance.

At the next stage of the study, key aspects were identified that play a crucial role in the development and implementation of digital strategies for maintenance systems of cargo ships, with a focus on energy efficiency. In particular, sensor accuracy and monitoring tools, the adaptability of fault prediction algorithms to specific operational conditions, and energy-conscious resource allocation during maintenance planning were emphasized. The application of energy-efficient solutions helps avoid fuel overconsumption due to delayed repairs or improper equipment operation [5].

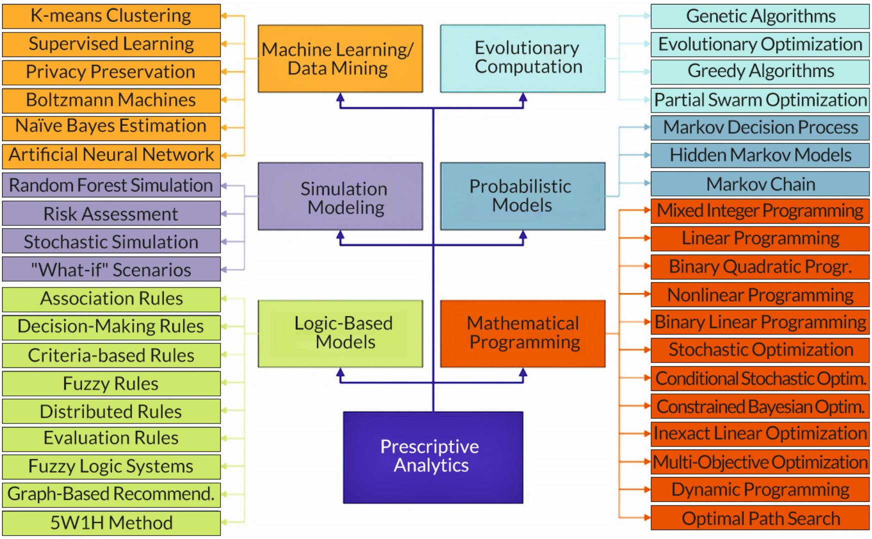

Fig. 10.3 Classification of prescriptive analytics methods

Subsequently, a comparative analysis of two classifications of analytical approaches (**Fig. 10.2, 10.3**) was conducted. The primary objective was to determine how well each classification aligns with the goals of creating a structural-logical scheme aimed at enhancing the energy efficiency of ship maintenance systems through digital technologies. The results of the analysis demonstrated that the classification of prescriptive (recommendation-based) analytics methods is the most relevant. It provides a structured approach to decision-making based on multifactor analysis, enabling not only prediction but also optimization of energy consumption during vessel operation [6].

The choice of this classification (**Fig. 10.3**) is driven by the need for strategic management of the vessel's technical condition, focusing on reducing downtime, fuel loss, and excessive load on main propulsion systems. This approach improves decision-making in favor of energy efficiency and the sustainability of vessel operations.

Based on the obtained findings, a structural-logical scheme for the implementation of digital strategies in the maintenance of cargo ships was developed (**Fig. 10.4**).

It includes the stages of onboard sensor data collection, equipment condition analysis, failure prediction, modeling of maintenance scenarios, and optimal distribution of technical and fuel resources.

The anticipated benefits of implementing this scheme include reduced costs for unplanned repairs, lower fuel consumption due to the maintenance of optimal technical condition, increased energy efficiency of ships, reduced environmental impact, and improved reliability of ship systems. In the long term, such a system can be integrated into platforms such as SPOS, ECDIS, and SmartShip, providing automatic control over equipment energy consumption and technical condition [5, 6].

In the final part of the study, practical aspects of applying this scheme in real operational conditions were explored. The need for algorithm adaptation to various types of ships, as well as further research aimed at reducing prediction errors in equipment condition assessment, is emphasized.

Based on the conducted analysis, the author concludes that the proposed structural-logical scheme can significantly improve the energy efficiency of cargo ship operation, reduce operating costs, and enhance the overall stability of maritime logistics.

The implementation of digital strategies – particularly the concepts of the digital model, digital shadow, and digital twin – combined with prescriptive analytics will contribute to transforming maintenance into an energy-efficient, dynamic system. The main positive outcomes include:

1. Automated monitoring: continuous data streams from sensors allow for timely detection of technical faults that contribute to fuel overconsumption.

2. Detailed digital modeling: enables virtual testing of vessel operating modes and forecasting the consequences of certain technical failures from the perspective of energy use.

3. Maintenance optimization: data analytics helps schedule maintenance during periods of low operational load, reducing unproductive energy consumption.

4. System reliability: timely replacement or repair of components minimizes the risk of efficiency drops in ship engines.

5. Rational resource use: prescriptive analytics optimizes the procurement of spare parts and crew scheduling in accordance with the ship's actual needs.

6. Crew training: the systems can simulate technical fault scenarios and appropriate energy-saving response actions.

Overall, the implementation of digital strategies will enhance predictability, efficiency, and energy savings in the maintenance systems of cargo ships. This approach allows for cost reductions, lower greenhouse gas emissions, and extended service life of ship systems.

10.3 Development of optimal parameters for the maintenance system of cargo ships through digital strategies

In today's world, ships play a key role in the global transportation system by enabling the movement of large volumes of cargo across the globe. This imposes high demands on the efficiency and reliability of shipboard equipment. Maintenance systems for cargo ships are critical for ensuring their proper operation and safety.

However, there are certain problems and challenges associated with the current state of ship maintenance systems. In particular, the reliability and efficiency of maintenance are critical issues for cost optimization and improving the performance of maritime transport. Optimizing the parameters of maintenance systems can address these issues and enhance the functioning of cargo vessels.

In this context, the problem of improving the efficiency and optimizing the maintenance systems of cargo ships through the implementation of digital strategies becomes increasingly relevant. The challenge lies in the fact that maintenance of cargo vessels requires significant expenditure and management of various parameters, including reliability, safety, regularity, and cost.

Firstly, the condition of a cargo ship must meet reliability and safety standards, as well as ensure voyage regularity.

Secondly, maintenance costs must be optimized to reduce overall vessel operation expenses.

Therefore, this study aims to examine the parameters of ship maintenance systems and identify optimal values that ensure maximum efficiency and minimized management costs for cargo vessel operations. Addressing this problem requires the development of digital strategies and methods aimed at improving performance and reducing costs during ship maintenance.

The authors of study [7] emphasize the need to reorganize maintenance and logistics services to improve the economic performance of maintenance systems. Article [8] explores approaches to optimizing maintenance parameters with regular control intervals, considering such criteria as minimizing the unit cost of operations and maximizing the technical utilization rate.

Additionally, the reviewed works suggest that modern digital tools and technologies can optimize the parameters of cargo ship maintenance systems. Shorter maintenance periods for selected equipment groups can enhance the vessel's average reliability at sea with minimal cost [9]. The maintenance system integrates information flow using various maintenance strategies [10]. A hybrid multi-criteria decision-making method is suitable for selecting appropriate maintenance actions for each unit of shipboard technical equipment, systems, and complexes [11].

The analyzed articles collectively highlight the importance of reorganizing maintenance services, optimizing service intervals and threshold values, and applying reliability-enhancing methods to improve cargo ship maintenance systems.

The analysis of existing studies has shown that there are several potential issues that can be addressed through the implementation of digital strategies in cargo ship maintenance systems. Key issues include:

1. Insufficient reliability: improved reliability of shipboard equipment and mechanisms can reduce accident rates and enhance safety at sea.

2. Rising costs: improving the maintenance system can help address increasing maintenance costs caused by unplanned repairs and high expenses for spare parts.

3. Performance enhancement: implementing optimized maintenance parameters can reduce downtime for repairs and extend the vessel's operational life, thereby positively impacting productivity.

4. Reduced environmental impact: effective maintenance can help reduce emissions of toxic substances and enhance the ecological sustainability of ships.

5. Increased competitiveness: since shipping companies operate in a competitive environment, optimizing the maintenance system can provide a competitive edge.

Thus, this Chapter proposes approaches for optimizing the parameters of cargo ship maintenance systems using digital strategies, which can address the aforementioned problems and contribute to enhancing the efficiency and reliability of ships in maritime transport.

The issue of improving the efficiency of cargo ship maintenance systems is highly relevant both at the design stage and during the operational lifecycle. **Fig. 10.4** presents a conceptual scheme of system interaction that forms the basis for enhancing the effectiveness of maintenance systems for cargo vessels through the implementation of digital strategies. These strategies define an integrated approach to solving the challenges of managing and improving the performance of maintenance processes.

The selection of a specific digital strategy for managing the cargo ship maintenance system requires decision-making regarding the choice and implementation of appropriate combinations of digital technologies. This process involves adjusting the maintenance plan in accordance with the selected digital strategy. In this context, the modern integrated system "ShipDiMRO" is utilized to support managerial decision-making.

Consideration of various digital maintenance strategies for cargo vessels takes place with respect to the vessel's lifecycle stage. The selection of a particular strategy is based on approaches to achieving optimal maintenance system parameters, which are reflected in the management processes carried out within the ship maintenance system. The variability in decision-making regarding the optimization of maintenance system parameters arises from the absence of a single universal solution. Choosing the most suitable optimization approach requires analysis from different perspectives and with the use of diverse methodologies, enabling the selection of the optimal course of action under specific conditions.

An analysis of the presented system (as illustrated in **Fig. 10.4**) makes it evident that within the framework of managing the optimal parameters of a cargo ship maintenance system using digital strategies, two essential and interacting components can be distinguished – informational and managerial (executive).

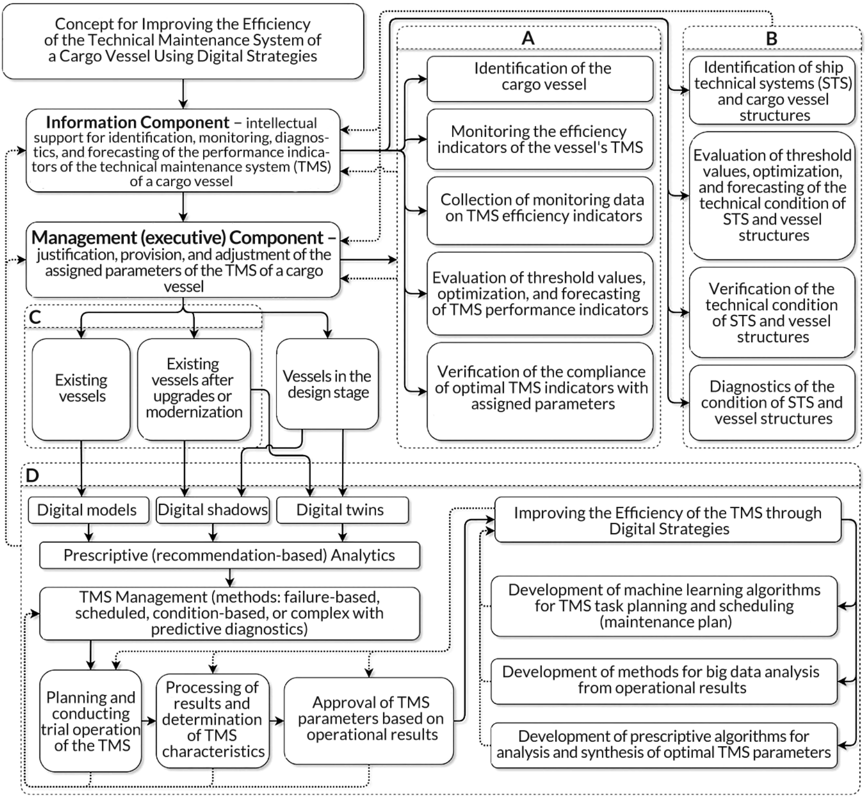

Fig. 10.4 System interaction scheme for improving the efficiency of cargo vessel maintenance systems based on digital strategies

The informational component encompasses remote support for processes of identification, monitoring, diagnostics, and forecasting of both the maintenance system's performance indicators and the technical condition parameters of ship systems, structures, and cargo vessels within the context of an intelligent transport system (ITS).

On the other hand, the managerial (executive) component involves the creation and implementation of digital processes aimed at ensuring the optimal parameters of the cargo vessel maintenance system during operation.

The characteristics of information interaction that emerge within the processes aimed at ensuring the specified performance indicators of a cargo ship maintenance system are presented in **Fig. 10.4** (segments A and B). The processes of managerial (executive) support for the defined maintenance system parameters (segments C and D) are based on information that reflects the actual technical condition of the ship's systems, structures, and the performance indicators of the maintenance system itself – obtained through identification, monitoring, diagnostics, and forecasting (segments A and B). These processes utilize an automated condition monitoring system (ACMS) in combination with the "ShipDiMRO" system, which operates within the framework of the ITS. These procedures involve data collection during monitoring, evaluation of threshold values, and long-term optimization of technical condition parameters and maintenance system effectiveness.

At the final stage of segment A, the system verifies whether the achieved performance indicators of the ship maintenance system meet the pre-established parameters.

The informational component within segment B, in addition to the aforementioned functionalities, includes a broad range of features. These include the assessment of threshold values, optimization and forecasting of the technical condition parameters of the ship's systems and structures, and the ship as a whole. Furthermore, the system evaluates compliance of the current technical condition with the specified maintenance parameters and manufacturer or owner requirements. Notably, the informational layer also includes diagnostic capabilities based on collected data.

Based on the accumulated information in segment A, management of maintenance parameters begins, both for existing cargo vessels (segment C) and for those under design. In segment D, the development of a digital strategy aimed at increasing the maintenance system's efficiency is initiated, depending on the available digital technologies at a particular stage in the ship's life cycle. These technologies may include digital models, digital shadows, digital twins, and prescriptive analytics. A relevant digital strategy for improving maintenance system efficiency is then formed by combining these technologies and is subsequently implemented within a specific management process [12, 13].

Maintenance system management refers to a targeted activity that includes the analysis, justification, provision, and adjustment of maintenance parameters required to meet reliability indicators for ship systems, structures, and the vessel as a whole. This management is carried out regardless of whether a predictive maintenance method, failure-based maintenance, scheduled maintenance, or condition-based maintenance is applied.

The maintenance management process consists of three key sequential stages:

1. Planning and executing controlled operation of the maintenance system.
2. Processing results and defining maintenance system characteristics.
3. Approving the system parameters based on the outcomes of the controlled operation.

During the initial stage – planning and implementation – input parameters are received, which define either a baseline or a modified maintenance system for the cargo ship. Upon completing the control operation period, the next stage begins, where collected results are analyzed and a set of maintenance system characteristics is evaluated. Based on this analysis, the output parameters of the ship's maintenance system are formulated.

The effectiveness of parameter evaluation depends on the performance or quality of the applied software, modern mathematical methods, and the algorithms and programs developed accordingly. The third stage involves substantiating the compliance of the obtained maintenance parameters with the required ones. In the event of discrepancies between parameters revealed during the control operation and the necessary values, a decision is made to correct the parameters. These corrections may involve organizational measures within the shipping company or be implemented through structural or production modifications of technical equipment by the manufacturer.

The existence of feedback at each of the three stages of the maintenance management process makes it possible to adjust and manage the parameters of the cargo ship's maintenance system during controlled operation, bringing them to required values or modifying them to ensure the required reliability indicators are met. If the system meets all requirements, it is adopted as the baseline maintenance system for the respective vessel. This initiative then forms the foundation of the final stage in developing a digital strategy aimed specifically at increasing the efficiency of cargo ship maintenance systems.

During the synthesis of the maintenance system based on operational results, it is crucial to evaluate the parameters of the maintenance system and verify their compliance with the requirements and the defined reliability indicators for the ship's technical components and the cargo vessel as a whole. If the established requirements are not met, a decision must be made to either improve the vessel's design, enhance the organizational aspects and technologies of various maintenance types, or adjust the maintenance system parameters followed by an analysis of their optimality.

The goal of the cargo vessel maintenance system, according to the stated objectives, is to ensure the longest possible period of technical operability, while strictly adhering to safety and service regularity requirements, and achieving this with minimal maintenance costs. In this context, the optimality of the maintenance system parameters can be evaluated by solving one of two problem formulations:

– the first formulation aims to ensure the required probability of remaining in an operable condition while maximizing operational profit;

– the second seeks to achieve a predetermined profit level with the highest possible probability of maintaining operability.

When treated parametrically, the set of solutions for both problems is equivalent, meaning only one problem needs to be solved. However, in the non-parametric variant (with fixed constraints), based on a selected target level of technical operability, it is necessary to find the most economically viable way to ensure this level. This stems from the fact that, under poorly substantiated cost constraints, one may achieve a maximum technical operability indicator that does not meet the actual requirements. Therefore, technical operability, as a more critical metric, should be treated as a constraint, while costs – being a less critical metric – are considered as the objective function. The following sections focus on the first problem formulation.

Improving the efficiency of the maintenance system means increasing the performance and optimizing the processes associated with maintaining and supporting the ship's technical operability. This may include reducing downtime for repairs, lowering the cost of spare parts, and extending the operational lifespan of equipment. All these changes help ensure higher-quality and more cost-effective ship operations.

Performance is a measure of how effectively goals or objectives are achieved. It reflects how well the actual results align with planned or expected outcomes. In the context of ship maintenance, performance may be evaluated based on the number of effective operating hours between maintenance stoppages, repair costs compared to budget, or reduced downtime, among others. An effective maintenance system achieves the highest possible performance with minimal expenditures.

To evaluate the effectiveness of a cargo vessel maintenance system across various stages of its refinement within a shipping company, the performance indicators outlined in Section 1 are used. In addition to the discussed metrics, an integrated indicator of maintenance system performance – the general reliability index (GRI) – may be introduced. This GRI is calculated using existing analytical models based on matrix theory, logical-probabilistic approaches, as well as Bayesian and minimax estimations [14].

To improve the performance of the maintenance system, a continuous process of enhancement of its constituent parameters is essential. One of the strategic directions for increasing efficiency through digital strategies (segment D) is the improvement of control elements across all three stages of the maintenance system management process. This enhancement (segment D) includes the development and implementation of machine learning algorithms in shipping practices for planning the composition and frequency of maintenance activities at the first stage, big data analysis methods for processing operational results at the second stage, and prescriptive algorithms for analyzing and synthesizing optimal maintenance system parameters at the third stage (**Fig. 10.4**).

The outcomes of these improvements are transmitted through feedback loops to both the informational and managerial (executive) components of the process responsible for maintaining the specified parameters and performance indicators of the ship maintenance system.

10.4 Conclusion

As a result of the study, it was established that digital strategies in the field of cargo ship maintenance are capable of radically transforming traditional approaches to equipment servicing and repair. The implementation of digital twins, intelligent data analytics, and predictive maintenance makes it possible to reduce downtime, avoid emergency situations, minimize operational costs, and decrease fuel consumption. This, in turn, contributes to achieving the strategic goals of the International Maritime Organization regarding the reduction of greenhouse gas emissions and the transition to "green" shipping.

Special attention should be paid to the formation of a unified digital platform for managing the technical condition of a vessel, integrating sensor systems, digital models, and optimization tools. Such an approach enables a systematic assessment of energy consumption and the implementation of scenario-based modelling of future repairs in the context of energy use.

At the same time, the full implementation of digital strategies requires modernization of regulatory and methodological support, personnel training, and the creation of a unified information space among shipowners, port services, and technical inspections. Thus, digital technologies become the foundation of energy-efficient technical management of the cargo fleet, which is of critical importance in the context of the ecological transition and the global digitalization of the maritime industry.

The use of digital strategies in cargo ship maintenance systems is a key factor in achieving optimal efficiency and economic benefits in maritime transport and will lead to a number of positive changes and improvements:

1. The study identified that the optimal parameters of cargo ship maintenance systems can be achieved through digital strategies. It was found that the use of digital tools allows for the reduction of downtime for repairs, spare parts costs, and extends the operational life of equipment.

2. The research demonstrated that digital strategies enable the effective assessment of reliability and safety of vessel operations, reducing the risk of technical failures and accidents.

3. The application of digital approaches in the maintenance of cargo ships allows for the reduction of maintenance costs and ensures the efficient operation of vessels.

4. One of the key contributions of the article is the development of a system interaction scheme aimed at improving the efficiency of cargo ship maintenance systems based on digital strategies. This scheme includes the use of machine learning algorithms for maintenance planning, big data analysis for processing operational results, and the development of prescriptive algorithms for analyzing and synthesizing optimal maintenance system parameters. This approach ensures maximum outcomes with minimal costs.

The further use of the results of this study may include their practical application in shipping companies and port institutions. The implementation of digital strategies in the practical maintenance of cargo vessels can lead to a reduction in technical failures, increased productivity, and cost savings. Furthermore, these findings may serve as a basis for future scientific developments in the field of maintenance system optimization, including the development of new digital tools and methodologies.

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