TRANSNAV
http://www.transnav.eu
the International Journal
on Marine Navigation
and Safety of Sea Transportation
Volume 16
Number 3
September 2022
DOI: 10.12716/1001.16.03.18

# Autonomous Ships Concept and Mathematical Models Application in their Steering Process Control

O. Melnyk, O. Onishchenko, S. Onyshchenko, A. Voloshyn, Y. Kalinichenko, O. Rossomakha, G. Naleva & O. Rossomakha
*Odesa National Maritime University, Odesa, Ukraine*

ABSTRACT: Advances in computer systems and innovative technologies along with their implementation into the shipping industry not only enabled efficient data exchange between the ship and the shore, but also created a single integrated information network linking all participants of the process and all elements of the maritime sector. Development of the concept of autonomous ships and automated control facilities for their functionality became the next stage in the evolution of innovations. The process of software adaptation, additional electronic steering systems, optical and digital means of monitoring as well as satellite communication facilities for autonomous ships are among the tasks which require search and development of the solutions. Provision of reliable and safe functioning of such ships in the autonomous mode requires development of models and methods for ensuring their accident-free navigation both in relation to the process of ships divergence and improvement of automatic steering systems of movement and course steadiness. In the given work, the analysis of realization of the crewless navigation and possibility of ship automatic movement control systems advancement on the basis of application of mathematical model for the purpose of enhancement of process of the autonomous ship steadiness on the set course is proposed.

## 1 INTRODUCTION

Maritime transport recently has evolved into one of the prospective industries for the application and development of information technologies. Conventional conservative foundations of the industry manifested in long cycles of ship design and operation and, as a result, expensive telecommunication infrastructure based mainly on satellite technologies at a time when transmission of large volumes of information online has already become the main criterion of commercial relations efficiency. The world merchant fleet, seaports and shipping companies, national and international regulators, seafarers and personnel engaged in international shipping and transportation had limited information exchange.

For many centuries, the shipping industry has relied on the knowledge and experience of seafarers who were the crew of the ships. Today, however, autonomous technology is ready to restructure the maritime sector using unmanned craft, meaning ships with no physical presence of crew. Small-unmanned vessels have already begun to operate, while the technology for larger vessels is still at the developmental stage. The maritime industry is about to change with the advent of the autonomous navigation concept and it is necessary to assess how this approach will shape the future of the industry and how it can be used most effectively. Certainly, the design and construction of autonomous ships will have an impact on ship operating processes, shipbuilding projects, port infrastructure operations, interfaces, regulatory and legislative frameworks.

Automation will change the onshore elements of shipping, starting with ship maintenance and cargo handling and ending with ship insurance as well as changes to a large number of international conventions and codes.

Many works are devoted to the functioning of onboard control systems of an autonomous vessel. Thus operational stability under impulse course control of a vessel considered in [5,6]. In [7, 27, 28, 29] the study of using infrared as docking aid system for boat, autonomous ship steering techniques and the difficulties of their operation studied. Works devoted to the concept of autonomous ship, issues of autonomous maritime navigation, that is, the task of finding the optimal and safe route of autonomous ship in the absence of the crew and the task of movement of autonomous ship on the constructed route with preservation of seaworthiness and control of deviation from the route in [8-13]. Autonomous shipping and its impact on regulations, technologies, and industries, new technology trends in the design of autonomous ships. [1,2]. Safety management in remotely controlled vessel operations in [14]. Papers [16,20,22] devoted to identifying research directions of a remotely-controlled merchant ship by revisiting her system-theoretic safety control structure and development the method to identify task-based implementation paths for unmanned autonomous ships. General safety issues for maritime transport considered in [17,23,24,26]. The Impact of Autonomous Ships on Safety at Sea studied in [25]. Work [15,22] researches implications of autonomous shipping for maritime education and training. Regulatory documents concerning autonomous ship navigation presented in [3,4,21].

Thus, the analysis of the presented works causes necessity of address to the given research problem from the aspect of additional studying of problems of autonomous navigation and searching for tools of increase the efficiency of steering control of the given ships by use of mathematical models improving steerability of ships. It is necessary to note, that some provisions stated here are of analytical character and do not exclude possibility of the further investigation of such actual subject of research.

## 2 MATERIALS AND METHODS

In recent years, there has been a growing interest in the concept of Maritime Autonomous Surface Ships (MASS) in the international maritime community. A number of well-funded initiatives have been and continue to be undertaken in several countries. The Nordic countries, mainly Norway and Finland, are at the forefront of this activity. The Asia-Pacific countries, which are actively involved in the maritime business, both in shipbuilding and in the operation and chartering of fleets, are also showing considerable interest. Increased interest from commercial organizations is predicted in the mid- and long-term perspective. According to BIS Research, a market analysis firm, the estimated global revenue from the emerging autonomous vessel market is expected to be $3.48 billion by 2035. Much of this work is focused on the types of shipping in which both commercial and research organizations see the greatest promise.

According to experts, in the future the volume of maritime trade will grow, respectively, the number of ships needed to transport goods will grow, as well as the number of seafarers needed to operate these ships. At the same time, the global shipping industry is already facing a shortage of qualified maritime professionals. At the heart of this problem is the growing unattractiveness of maritime professions, especially for new generations, and to some extent it is caused by the inherent problem of lack of full communication, detachment from family, high degree of isolation from social life, which accompanies work on a seagoing vessel as well as all hardships and difficulties of this profession, weather conditions, specificity of time zones, etc. The growing trend in recent years to reduce the speed of ships, based on environmental standards and requirements and economic considerations, is further increasing the length of a ship's voyage, and consequently the time that seafarers spend at sea.

Considering the above mentioned factors, the unmanned offshore autonomous surface vessel is a certain way out of the situation where, as mentioned above, the prevalence of a growing shortage of qualified personnel due to the unattractiveness of the job and the expected growing demand for seafarers, primarily due to the increasing volume of international maritime trade. As a result, on the one hand, it can reduce the expected pressure on the seafarers' labor market, because it will allow, at least partially, to reduce the labor intensity of ship operation. On the other hand, routine tasks on board will be automated, and only complex but interesting navigational and technical work will be transferred from the ship to a shore-based operations center, making the "seafarer" job more attractive and at the same time shore-based. In addition, economic and environmental benefits are expected with the introduction of unmanned shipping.

Many governments, realizing the importance of developing and deploying high technology, are increasingly investing in targeted technology development for autonomous ships, with the goal of taking a significant share of the global market for such ships in the foreseeable future. Projects are being developed to build ships that meet the "third degree" of the four degrees of autonomy defined by the IMO Maritime Safety Committee in its assessment of regulatory requirements for MASS. For example, degree three describes a ship that does not require crew on board and is operated remotely, although noting the fact that seafarers may be required on board for regulatory purposes at an early stage of development, which would be degree two autonomy. Degree four is a fully autonomous and unmanned vessel, capable of making its own decisions and determining its own course of action shown in Figure 1.

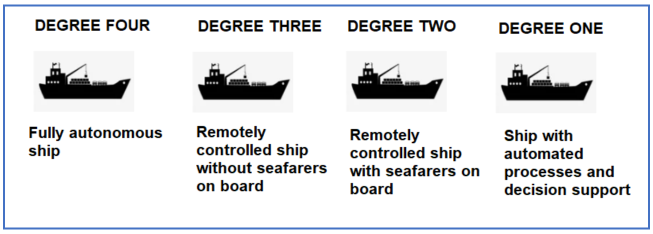


Figure 1. Degrees of MASS autonomy defined by the IMO

Project teams are already being set up everywhere to develop the core technologies needed for autonomous ships and to lay the groundwork for early commercialization of new systems by demonstrating their capabilities in real-world environments by the end of 2025. The goal of these projects is to replace actions that currently involve crew decision-making with autonomous systems that integrate artificial intelligence (AI), Internet of Things (IoT), Big Data and sensors. Experts' estimate that once these systems are in place, up to 22% reduction in ship operating costs can be achieved through fuel savings due to improved routing and maintenance optimization. The goal of such projects is to focus on development in four main areas: creating an intelligent navigation system, creating automated decision-making systems, promoting international standardization of technology and conducting a test program of medium-sized merchant ship models that are capable of operating autonomously.

Among other advantages of crewless navigation are increased safety of navigation and reduction of the number of crew on board or improvement of the existing traditional ship management system. The crew receives timely information for decision-making and support from qualified shore personnel; the shipping company receives the opportunity to control everything that happens on the vessel, optimize its movement and promptly influence decisions; ship owners, insurance companies, and maritime administrations receive unprecedented transparency and reliability of information on vessel movement and condition.

In addition to increased safety and elimination of human factor in ship control, introduction of remote control is beneficial due to cheaper ship design, increased tonnage and, above all, lower operational costs for the crew. It is expected that the introduction of MASS global use may take several decades: first companies will use remotely piloted vessels with reduced crew numbers, then fully autonomous vessels will emerge. While companies are developing new designs, testing models in test pools and field-testing individual models in real-world environments, some experts acknowledge that autonomous vessels will not become widespread in the foreseeable future, and their use will be very limited. It is difficult to disagree with such a restrained assessment, because it is based on the developers' awareness of a huge number of difficulties, which the operation of autonomous ships will inevitably face.

Worth to point out that use of autonomous vehicles has already found its place in many land modes of transport including passenger transportation as an example of automated subways, logistics self-propelled transporters or automated guided vehicles in container terminals, there are also very broad approaches to the concepts of autonomous management of objects in modern aviation. Consequently, autonomous control can also be seen as an opportunity for the maritime transport industry to address competitiveness, safety and sustainability issues.

Modular control systems and communications technology will enable wireless monitoring and control functions both on and off the ship, so unlike a remote ship, where control tasks are performed by a remote control facility such as a human operator ashore, an automated ship is equipped with advanced decision support systems on board independently, without the intervention of a human operator.

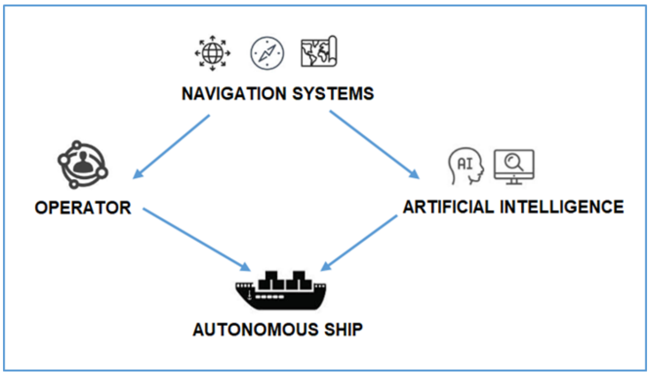


Figure 2. Monitoring functions and MASS decision support.

According to the experts involved in the MUNIN project, which aims to combine both typical alternatives into a coherent concept based on the symbiosis of automated and remote ships, the development of autonomous ships mainly relies on automatic and fully deterministic ship control functions. However, to detect problematic situations, such as unexpected objects at sea, bad weather conditions or dangerous close-quarter situations, risk assessment of collision, different sensor systems will be required to be equipped inside the ship hull. In the event of unforeseen situations, the autonomous control module will be activated, which will try to make corrections and remedy the situation within the given limits. If the onboard system is unable to perform these functions, it will request support from a remote operator or initiate a safe state transition procedure in the event that the shore-based operator is unavailable for some reason. If properly implemented, this approach to MASS autonomy will reduce the need for constant human supervision while maintaining a high and well-defined level of safety. The main challenge, however, will be to establish sensor systems so that all relevant hazardous situations can be reliably detected and appropriately accounted for.

## 3 RESULTS AND DISCUSSION

Frequently the task of autonomous ship motion control is reduced to the task of course stabilization. The automatic course control system contains: course controller, which can be either classical or intelligent or adaptive. The system also includes a feedback sensor (e.g. gyrocompass) and a control object - a steering gear itself and a seagoing ship.) According to IMO Resolution A.751(18), where necessity of use of mathematical models of a vessel at the decision of practical tasks of management lying in the field of safety of navigation and increase of efficiency of ship course steadiness on the set course is shown, we consider application of the simplified mathematical models of a vessel in comparison with model of an autonomous vessel. Steadiness is the ability of a vessel to maintain a set course or to maintain a set direction of straight motion without deviating from it.

As well known the steadiness is an element of one of the ship's basic seaworthiness - controllability. Steadiness on set course also determines how long the vessel will remain on the same course without having to change the position of wheel by any steering devices. Ship's course steadiness achieved by steering gear is called operational steadiness. The number of rudder flips per unit time required to maintain the ship on course with a given accuracy. This value is usually calculated by the equations of ship dynamics controlled by proportional regulator in the absence of perturbations. When an external disturbing force tends to change a vessel's heading angle, an unguided ship may be unsteady, therefore, when upon termination of this disturbance, the ship does not return to any straight course, but enters circulation, or it becomes asymptotically unsteady, that is, when the ship returns to a straight course with a new heading angle. Thus, an unguided vessel is not steady on course, since in both cases, manual steering and other controls by the operator or automatic motion control systems are required to return to the original course. Steadiness on course is evaluated either from the vessel's equations of motion, or from the results of a test model or a full-scale vessel. In the first case, course steadiness is determined by direct criteria developed on the basis of the theory of system steadiness, in the second case - by indirect indicators, which are controllability diagram or yaw parameters of the vessel (periods and amplitudes of angular speed, course angle and angles of controlling elements).

Many technical and research centers are developing new steering systems for use on remotely piloted and controlled autonomous vessels, which will be used in navigation systems and ship motion control systems to computerize the process of steering an autonomous vessel. Such systems use an autopilot to control a ship underway, which includes evasive maneuvers in accordance with the International Regulations for Preventing Collisions at Sea (COLREG). The autopilot has three modes: tracking mode, heading mode and joystick slow steering. In "tracking mode", the system steers the ship along a pre-agreed route. If the ship detects another vessel to be avoided, the autopilot switches to "course mode" which allows to perform the necessary maneuvers to evade the other ship by changing the ship's course. The autopilot returns to "course mode" after the other ship is avoided. When the joystick function is activated, the controls and propulsion equipment are set to maneuver at low speed, allowing systems to be operated with the joystick, for example, to maneuver the vessel alongside a berth. The autopilot is programmed to ensure that the vessel always remains within the specified distance of the planned route. If these limits are exceeded, the autopilot issues a warning and remote control is cancelled.

The staging of full-scale experiments on maneuvering of seagoing ships and processing of their results are subordinated to the main task - estimation of parameters of the selected ship model. This is a complex task, especially considering that the model itself is usually non-linear. Therefore when solving this problem, there is an intention to simplify the model without loss of behavioral features inherent to a real object, which was proposed by Nomoto, who proposed using the simplest ship controllability model, containing only two parameters.

It should be noted, that a number of international conferences on the use of experimental pools recommended the use of simplified mathematical models of the ship, built based on models developed by Nomoto. Nonlinear Nomoto model of the second order proved itself well enough in practice. This model is described by a differential equation:

$$T1{\cdot}T2\left(d2\omega/dt2\right) + \left(T1 + T2\right)\left(d\omega/dt\right) + \omega + H\left(\omega\right) = \\ = K{\cdot}\alpha r + KT3\left(d\alpha r/dt\right) \tag{1}$$

where:
$\omega$ – ship angular velocity; $H(\omega) = v1|\omega|\omega + v2\omega3$ – nonlinear function of angular velocity; $T1$, $T2$, $T3$, $K$, $v1$, $v2$ – time and design parameters identified by maneuvering experiments; $\alpha r$ – rudder angle.

One of the solutions to the problem of identification of the parameters $T1$, $T2$, $T3$, $K$, $v1$, $v2$ of equation (1) is presented in [29].

Analytical solution of (1) is quite difficult, but, in general, when solving the problems of ship control, it is not necessary. It is connected with the fact that in control problems synthesis of controllers is performed on the basis of not only performance criteria, but also steadiness. That is why (1) makes sense to solve numerically with subsequent representation as a system of equations in Cauchy form. In this case, the transition to the structural representation of (1), which allows, for example, in Matlab/Simulink to synthesize regulators, is straightforward. One of the structural descriptions of (1) in Matlab/Simulink is shown in Figure 3.

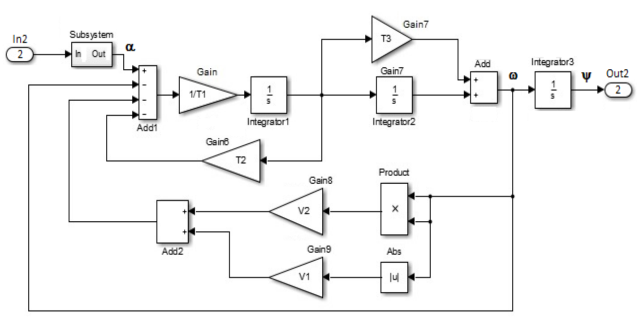


Figure 3. Structural description of proposed model

Block diagram of the ship's course stabilization system is presented on Figure 4;

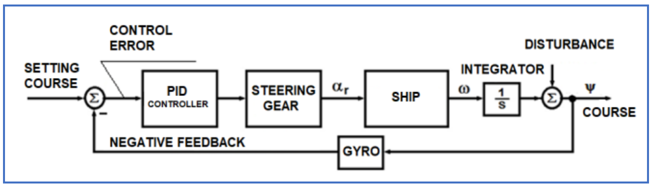


Figure 4. Block diagram of the ship's course stabilization system

A vessel with a displacement of 640 tons was selected as a modeling object. In the steering system of which a low-inertia electric rudder turning device is installed. In this device, there is practically no restriction on the rudder turning frequency, which makes it possible to create highly efficient auto-rudder systems. The maximum rudder angle is 35 degrees.

A given system's structure is characterized by a transfer function that describes its properties. The performed identification of the parameters of expression (1) allows us to accept the following parameters of transfer functions of the stabilization system for modeling.

1. Steering gear;

$$W_{SG}(s) = \frac{20}{0,2s+1}. \quad (2)$$

The structural model of the steering gear (Fig. 5) takes into account the limitation of the output signal ±35°.

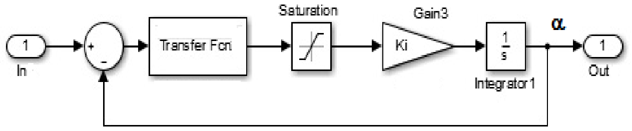


Figure 5. Structural model of steering gear

2. Ship;

At nominal operating conditions of the ship:

$$W_{NOM}(s) = \frac{1,4s+1}{41s^2+14s+[1+H(s)]}. \quad (3)$$

The coefficients *K*, *v1*, *v2*, included in the expression *H(s)*, practically do not change depending on the ship's loading status. Therefore, they are assumed to be constant for any ship operating conditions ($K = 0,93$, $v_1 = -0,016$, $v_2 = 0,0014$). Modeling of the nonlinear transfer function WNOM(s) is based on the structural diagram shown in Figure 3;

3. Negative feedback;

$$W_{NF}(s) = \frac{1,0}{0,1s+1}. \quad (4)$$

4. Wind-wave disturbances;

Perturbations that deviate ship's course from the set value can be described by the sum of three or four sinusoidal signals of different amplitude, frequency and phase.

5. PID – controller (Proportional-integral regulator);

To evaluate the properties of the ship's course stabilization system, the PID parameters are assumed constant for sufficiently large changes in the transfer function WNOM(s). Synthesis of tuning parameters of PID controller with output signal limitation at level ◎10 is performed for the above mentioned transfer functions of ship, steering machine and feedback sensor. The following requirements for PID controller tuning are put forward: overshoot not more than 1.5 with minimum transient time. For these conditions and WNOM(s), the transfer function of the PID controller has the following tuning parameter values.

$$W_{PID}(s) = P + I/s + D\frac{N}{1+N/s}, \quad (5)$$

Proportional component: P = 0,013, integral component I = 0,0016 c-1, differential component: D = 0,08 c, filtration factor: N = 0,9.

Thus, as a result of application of this model in prototypes it was demonstrated an increase in accuracy of course stabilization, which increases by 10-17% with rudder shifting frequency decreasing by 8-12% and fuel consumption decreasing (during average statistical voyage and average statistical wind-wave disturbances for the particular navigation area) by 3-7%.

Considering the complexity of navigational conditions, especially in confined waters, the speed of decision-making by the crew on board can determine the safety of the ship. Therefore, in spite of all advantages, automation of ships has its disadvantages. For instance, ships cannot be fully autonomous, as installed equipment needs to be supervised by specialists. For example, the maintenance of video surveillance equipment installed on the ship, which can not always reproduce a clear image to the operator on shore, especially in low visibility conditions or in case of communication failure. In such a case, the presence of qualified personnel on the ship is essential in order to notice the danger and prevent its consequences. The analysis of accidents shows that despite the rapid development of science and technology in the maritime industry, autonomous ships undoubtedly have to comply with the international regulations necessary for the safe operation of ships in different countries and even in maritime areas beyond national jurisdiction. While some aspects of manned vessel regulation may be compatible with unmanned vessels, such as some clauses of the International Safety Management Code (ISM), specific international regulations need to be developed to take into account the specifics of unmanned vessels. It is necessary to create an infrastructure for providing autonomous navigation based on e-Navigation, to develop and implement ship and shore-based autonomous navigation equipment, as well as an autonomous port fleet, and certainly to train specialists for the operation and management of autonomous ships.

## 4 CONCLUSION

As a basis, expected that crewless technology will eliminate the human factor in ships divergence process and allows the system to provide more accurate and uninterrupted information about the location of ships and their movement parameters, including the course steadiness quality. However, it is necessary to pay attention to the combination of such factors as unemployment of not only seamen but also of many educational institutions and training and training centers because the crew will be replaced by robotics. On the other hand, there will be a need for highly qualified service personnel capable to maintain and repair electronic automated control systems and complexes, so there are tendencies for development in this direction. However, overall, automation allows simplifying ship control on the basis of ready-made software solutions.

In the context of the MASS concept, it is not about inventing a new entity, but transforming a set of functions, which are now prescribed to the crew on board in terms of navigation by international and national regulators, and consistently, each of these functions is performed in automatic and remote mode. Due to the implementation of MASS, shipping companies will be able to reduce 15-30% of operating costs. It will also make it possible to cover the shortage of highly qualified seafarers, which now reaches 20% of the required workforce. Application of ship mathematical models for solving practical navigation tasks becomes more and more actual, mainly due to the use of computer technologies in ship navigation systems, as well as innovative methods and technologies in ship navigation and innovative methods and management of an autonomous ship when performing key ship operations under conditions of increased risks.

## REFERENCES


[1] M. Kim, T.H. Joung, B. Jeong, and H S Park. "Autonomous shipping and its impact on regulations, technologies, and industries", Journal of International Maritime Safety, Environmental Affairs, and Shipping (2020) 4.

[2] G. Koikas, M. Papoutsidakis and N. Nikitakos, "New Technology Trends in the Design of Autonomous Ships", International Journal of Computer Applications (2019) 178(25), pp. 4-7.

[3] Development of Canadian Asset Map and Assessment of Global Competitiveness in the Area of Autonomous Surface Ships. (CISMaRT) Canadian Network for Innovative Shipbuilding Marine Research andTraining (2020) 54 p.

[4] DNV GL. A New Inspirational Ship Concept. The ReVolt (2019).

[5] Marine encyclopedic dictionary in two volumes. Vol. 2, Edited by N Isanin (1986) 520 p.

[6] E. Poselenov and A. Preobrazhensky, "Operational stability under impulse ship course control", Scientific problems of water transport (2005) 14, 18-22.

[7] N. Nakarith and P. Iamraksa, "The study of using infrared as docking aid system for boat", In: Proceedings of the ACDT 2015, The 1st Asian Conference on Defense Technology.

[8] J. C. Chong, "Impact of maritime autonomous surface ships (MASS) on VTS operations", World Maritime University Dissertations (2018) Malmo, Sweden.

[9] Z. Pietrzykowski and J. Hajduk, "Operations of Maritime Autonomous Surface Ships",TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation (2019) 13, pp. 725-733.

[10] I. Kurt and M. Aymelek, "Operational and economic advantages of autonomous ships and their perceived impacts on port operations", Maritime Economics & Logistics (2022) 24.

[11] T. E. Kim, L. Perera, M. P. Sollid, B. M. Batalden, and A Sydnes, "Safety challenges related to autonomous ships in mixed navigational environments", WMU Journal of Maritime Affairs (2022).

[12] L. P. Perera, "Deep Learning Toward Autonomous Ship Navigation and Possible COLREGs Failures", Journal of Offshore Mechanics and Arctic Engineering (2020) 143, 3.

[13] T. E. Kim and S. Mallam, "A Delphi-AHP study on STCW leadership competence in the age of autonomous maritime operations", WMU Journal of Maritime Affairs (2020) 19, pp. 163-181.

[14] K Størkersen, "Safety management in remotely controlled vessel operations", Marine Policy (2020) 130, 104349.

[15] K. Bogusławski, M. Gil, J. Nasur and K. Wróbel, "Implications of autonomous shipping for maritime education and training: the cadet's perspective", Maritime Economics & Logistics (2022) 24.

[16] K. Wróbel, M. Gil and J. Montewka, "Identifying research directions of a remotely-controlled merchant ship by revisiting her system-theoretic safety control structure", Safety Science (2020) 129, 104797.

[17] O. Onishchenko, K. Shumilova, S. Volyanskyy, Ya. Volyanskaya, and S. Volianskyi, "Ensuring Cyber Resilience of Ship Information Systems", TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation 16 (2022), pp. 43-50.

[18] V. Golikov, V. Golikov, Ya. Volyanskaya, O. Mazur and O Onishchenko, "A simple technique for identifying vessel model parameters", In: Proceedings of IOP Conference Series: Earth and Environmental Science 172 (2018), 012010.

[19] C. Kooij and R. Hekkenberg, "A Method to identify Task-based Implementation Paths for Unmanned Autonomous Ships", Maritime Policy & Management, 2021.

[20] C. Kooij, A. Colling and C. Benson, "When will autonomous ships arrive? A technological forecasting perspective", 2018.

[21] IMO MSC.1/Circ.1638 Outcome of the Regulatory Scoping Exercise for the use of Maritime Autonomous Surface Ships (MASS).

[22] T. Miyoshi, S. Fujimoto, M. Rooks, T. Konishi and R Suzuki, "Rules required for operating maritime autonomous surface ships from the viewpoint of seafarers", Journal of Navigation (2022), 75(2), pp. 384-399.

[23] O. Melnyk, S. Onyshchenko and K. Koryakin, "Nature and origin of major security concerns and potential threats to the shipping industry", Scientific Journal of Silesian University of Technology. Series Transport (2021), 113, pp. 145-153.

[24] I. Burmaka, I. Vorokhobin, O. Melnyk, O. Burmaka and S. Sagin, "Method of Prompt Evasive Maneuver Selection to alter Ship's Course or Speed", Transactions on Maritime Science (2022), 11(1).

[25] J. de Vos, R. G. Hekkenberg, A. Osiris and V. Banda, "The Impact of Autonomous Ships on Safety at Sea - A Statistical Analysis", Reliability Engineering & System Safety (2021), 210, 107558.

[26] S. Onyshchenko and O. Melnyk, "Probabilistic Assessment Method of Hydrometeorological Conditions and their Impact on the Efficiency of Ship Operation",

Journal of Engineering Science and Technology Review (2021), 14 (6), pp. 132-136.
[27] Autonomous ship steering system developed. Digital Ship - Digital Energy Journal (2017).
[28] V. Filimonov, "Autonomous ships and the difficulties of their operation", Baltic Lloyd (2020).
[29] Y. Yudin, A. Gololobov and A. Stepakhno, "Method of Parameter Calculation of Mathematical Model of Vessel", MGTU Bulletin (2009), 12, pp. 5-9.
[30] O. Melnyk and S. Onyshchenko, "Ensuring Safety of Navigation in the Aspect of Reducing Environmental Impact, ISEM 2021, LNNS 463, pp. 1-9.