Development of Computer-based Remote Technologies and Course Control Systems for Autonomous Surface Ships

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Summary
Recently, more and more researches aimed at the development of automated and autonomous ships are appearing in the scientific environment. One of the main reason is the need to solve the problems of safe navigation and reducing accidents due to human factor, as well as the ever-increasing problem associated with the lack of qualified maritime personnel. Development of technologies based on application of artificial intelligence also plays important role, after all for realization of autonomous navigation concept and enhancement of ship automatic maneuvering processes, advancement of maneuvering functions and elaboration of specific algorithms on prevention of close quarter situations and dangerous approach of ships will be required. The purpose of this work is the review of preconditions of occurrence of the autonomous ship navigation conception, overview of introduction stages and prospects for ship remote control based on unmanned technologies, analysis of technical and intellectual decisions of autonomous surface ships, main research tendencies. The research revealed that the technology of autonomous ship navigation requires further development and improvement, especially in terms of the data transmission protocols upgrading, sensors of navigation information and automatic control systems modernization, which allows to perform monitoring of equipment with the aim of improving the functions of control over the autonomous surface ship operation.
Keywords:
Autonomous ship, remote control technologies, ship navigation, course steadiness.

1. Introduction

The process of adaptation of software, electronic control systems, optical and digital monitoring devices, as well as satellite communication devices for autonomous ships are among the tasks that require research and solution development. Reliable and safe functioning of such ships in autonomous mode requires development of models and methods of ensuring their accident-free operation for both ship movement process and improvement of automatic control systems of their motion and course steadiness. Numerous scientists devoted their work to the implementation of autonomous ship technology and the principles of functioning of on-board control systems for autonomous ships. Autonomous ship navigation and its influence on safety rules and standards in the industry, specifics of autonomous ships operation were studied in [1-4]. Methods of safety management during operation of remotely piloted vessels are presented in [5,6]. [7-9] investigated the use of infrared vision as a support system during mooring, and studied the methods of controlling an autonomous ship and the problems that arise during their operation. Works devoted to implementation of the concept of autonomous navigation, autonomous shipping, within the limits of solving tasks of finding the optimal and safe route of an autonomous ship, the navigation of an autonomous ship along the planned route, preserving seaworthiness and control of deviation from the route [10-15]. Other topics [16-21] are devoted to research of the basis for ensuring safe operation of ships and analysis of the system-theoretical structure of ship safety management. Thus, the identification of ways to implement the concept of unmanned ships in the context of electronic and autonomous navigation among the current tasks, which require further research.

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2. Autonomous ship concept overview

Maritime transport is a derivative of the commodity demand, the main purpose of which is to support trade, business and commercial relations on different scales, both global and domestic. According to recent estimates, 89.5% of world trade is due to the use of maritime transport. According to UNCTAD data, in 2020, the size of the global merchant fleet grew by 3% and included 99,800 vessels with a total tonnage of more than 100 gross tons. Throughout the next year 2021 this growth trend continued. As of the middle of 2021 the capacity was 2.13 billion tons of deadweight. But it is worth adding that the volume of shipments decreased considerably, partly due to the isolation regime caused by the pandemic and due to the defective workforce, which made adjustments to the work of the maritime industry. Among the vessels put into operation the main part was represented by bulk carriers, followed by oil tankers and container ships. In conditions of limited supply of ships owners and operators also bought more old ships, which caused prices to grow. In 2021, the pace of ship recycling increased, although it remains low compared to previous years. Also during the year, orders for new vessels decreased by 16%, demonstrating a continuation of the downward trend seen in previous years. At the beginning of 2021, the shipping companies responded to freight capacity defects with a sharp increase of new orders, especially for container carriers, which reached the highest level of orders in the last two decades. Also similar indicators of orders for the construction of gas carriers. Accordingly, the increase in the number of the world fleet is inevitable to the growth of demand for qualified maritime personnel, the problems of supplying them extremely urgent. According to the latest statistics, in 2021 the deficit of officers on merchant ships will already be 26,240, while for the previous five years it was projected at 16,500.

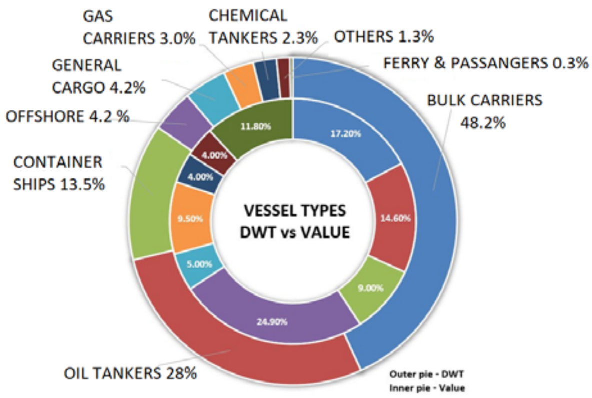

Fig.1 World merchant fleet by ship type

Since the end of the last century, there has been a correspondent development of maritime technologies, which somehow will change the classical understanding of the shipping system and together with this the organization of the ship handling process. At the moment, there are three major indicative trends, which will determine the future course for digitalization of the shipping industry, namely smart technologies, which will be able to control all ship systems, green technologies in ship operations that will improve environmental standards and the emergence of pilotless or crewless ships. With this in mind, active research and development, including demonstration experiments, are being carried out in various countries of the world these days with the aim of practical use of prototype ships, which are more commonly known as Maritime Autonomous Surface Ships (MASS), i.e. unmanned autonomous ships. In spite of some differences in the level of interest of each country, the purpose of research and development in the field of MAAS can be classified as the development of measures to improve the safety of ship operation as well as to reduce the pressure on the ship's crew. In parallel to these tasks, the idea of using such ships as a response to the shortage of seafarers is also evident. Other trends include reduction of environmental impact and cost of ship operation. The above can be summarized in four key concepts, namely:

a) widespread implementation of new achievements of scientific and technological progress;

b) the predicted lack of qualified personnel for the maritime industry;

c) intention to decrease human factor's influence as much as possible in order to effectively ensure maritime safety;

d) shipowner’s concern to reduce crew expenses.

All these factors led to the appearance and rapid development of an entirely new type of vessel in terms of management principles - maritime autonomous surface ships.

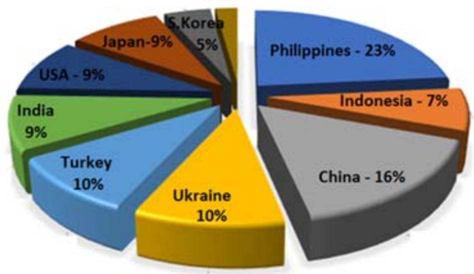

Fig.2 Share of merchant marine officers in the world labor market

The official definition of the terminology MAAS and its meaning, which is used at the present stage, may differ, since the definition of MAAS is still under study by the International Organization for Standardization. However, it is necessary to understand the concepts and define the definitions of automated ship, autonomous ship and unmanned ship.

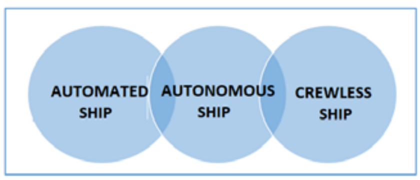

Fig.3 - Basic types of unmanned ships

Automated ship means a conventional ship in which any type of automatic control function is used in the course of operations, through which it is able to carry out navigational passages without direct human control, but by means of equipment associated with navigating, steering and propulsion of the ship.

Autonomous ship, which means a kind of automated ship, which is equipped with an object detection system around with help of number of sensors, capable to ascertain the level of danger of the objects according to the presence of the risk of collision. As well as algorithms for taking actions in the form of a maneuver to avoid a collision, if such a hazard exists, and to return to the desired course after completing the evasive maneuvers, which can be done automatically without human intervention. Currently, the ship's course control system and maintaining specified course does not have a coherent function of detecting objects and preventing obstacles, therefore the automatic steering system, which includes this coherent function, became an important feature of such ships along with further development of the technology in this field. However, this technology concerns only the ships, which are designed with the functions that ensure the operations performance, which are connected with the control process without human intervention, disregard the presence of the crewmembers on board, who able to perform ship maneuvering.

A crewless (pilotless) ship is a ship on which crewmembers are not physically present and which, in its turn, is a type of automated ship. This type of vessel is either equipped with the functions of the above-mentioned autonomous vessel which performs ship's operations based on commands for maneuvering the ship, which are transmitted from a human operator, located in a remote location by means of satellite communication facilities. It should be emphasized, that even though the designation of this type of vessel means unmanned (although this terminology is gradually being abandoned), it can carry passengers. In addition, taking into account the possibility of loss or interruption of communication with the remote control center, it can be assumed that this type is going to be fitted with autonomous ship functions. A ship that is not equipped with autonomous navigational functions, but is controlled remotely by transmitting navigational commands related to the operation of its control systems, can also be categorized as an unmanned ship, provided that there are no seafarers on board, who can perform maneuvering operations.

3. Specifics of the MAAS management process

The shore-based control station is the center of remote ship control, one of the most important components, which also has some peculiarities in the process of these technologies trials. As an analogue of the dispatching center, this value-added element plays a major role in the process of transforming autonomous ship technology to the reality. Collecting meteorological and navigational data as well as other information on navigational safety and monitoring the operational condition of the ship, her systems and the status of the engine room, enabling operating the ship remotely using satellite technologies, including emergencies. The system is also capable of accompanying the ship and controlling it during port operations with full use of land-sea communication channels, providing support at any moment of time.

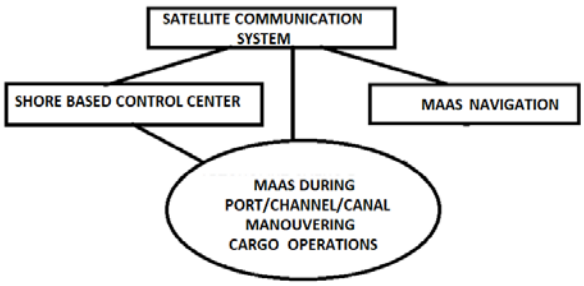

Fig.4 - Scheme of MAAS process control

The MAAS handling and steering systems that are already installed on many existing ships are examples of automated steering functions. The ship that performs maneuvering using these functions is also an automated steering ship. As described above, an autonomous ship and unmanned ship also use automatic steering functions and, therefore, are types of automated ship which implement the following functions: steering according to the set course at a certain speed, avoidance of obstacles, perform evasive maneuvers, increasing or decreasing speed, transition from the navigation to the anchorage mode, from the anchorage mode to the navigation mode, mooring operations while in port.

Probably the most important problem in current environment of dense ship traffic is improvement of collision avoidance technologies or evasive maneuvers during navigation, where the first issue is the function of detecting obstacles on the MAAS route. This detecting function is not limited only to identifying other ships, but also includes ships that are not moving relatively to the water (not under command), ships with restricted maneuvering ability, etc., as well as fishing boats other floating objects. In this case, the task is to evaluate the differences in the order of priority depending on the situation of the encounter and the conditions of the navigation, and accordingly to determine the algorithms for the unique approach of a dangerous convergence or collision. Therefore, the development of systems that use artificial intelligence (AI) is being carried out in many countries on the basis of technologies for identifying obstacles. Currently, a system is being developed for evaluating the obstacles that need to be identified and the obstacles that do not need to be identified, but in the future it is expected that automatic identification will be possible, therefore the minimum function of avoiding an obstacle should be identification of the obstacle and stopping the ship immediately before it encounters the obstacle. Regarding automated ship mooring and unmooring process, the maneuvering process can be simplified by providing suitable berths for automated vessels. It is quite clear that control of the ship's route is carried out with the help of installed video surveillance cameras, which provide the functions necessary for controlling the MAAS operation.

4. Modelling of MAAS course stabilization system

Reduction of running time costs through the development and implementation of more accurate steering control systems and maintaining the ship on the set course, as well as reduction of hull and wheel braking action are still among the topical tasks. Many technical and research centers are developing automatic steering systems for use on remotely piloted autonomous ships, which will be used in navigation systems and systems of steering control and vessel course stabilization within the limits of computerization of the MAAS steering process. These systems use the automatic system for ship steering underway, including maneuvering algorithms in accordance with the International Regulations for Preventing Collisions at Sea (COLREG). The system has three modes: steering mode, heading mode and joystick control. The autopilot is programmed in such a way that the ship always remain at a specific route. For full-scale tests small displacement ships are chosen as modeling objects, the steering system of which is equipped with a low-inertia, electrically operated rotary device. In this device practically absent limitation on frequency of wheel rotation, which allows to create highly efficient systems of ship automatic steering on the set course, in which the maximum angle of rotation of the wheel is 35 degrees.

It is known that to any technical (technologically effective and functional) closed loop stabilization system completely certain requirements are demanded - satisfaction of the set static properties and dynamics (quality of transients). For systems of ship automatic control on the set course astatism of the second order (on the set point and on perturbation), and also the minimum time of transients at the maximum overregulation, not exceeding 5 %. At realization of these properties, system of course stabilization of MAAS is maximum effective at a wide range of external perturbations. The controller synthesis for this type of course stabilization systems is based on an open-loop transfer function of the control system consisting of the product of transfer functions of the controller, steering unit model, ship model and the synchronous link sensor (e.g., gyroscope with standardized electrical output signals). The structure of the closed-loop system will be characterized by the transfer function, which describes its properties inclusively with the synthesized controller. The preliminary identification of the parameters of the object allows us to take these parameters of the transfer functions of the stabilization system for modeling.

The design model of the steering drive takes into account the limitation of the output signal 35 degrees.

a) Ship model (MAAS) under nominal operating conditions of the ship:

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

Where s – operator Laplace, ω – angular frequency of MAAS, $H(\omega) = \nu_1|\omega|\omega + \nu_2\omega^3$ – is a non-linear function of the angular rotation frequency of the vessel. The coefficients ν_1 and ν_2, included in the phrase H(s) practically do not change depending on the ship's state of loading. Therefore they are considered constant for any conditions of vessel operation (ν_1 = - 0,016; ν_2 = 0,0014).

b) Signal of negative feedback (gyroscope):

$$W_{NF}(s) = 1{,}0/(0{,}1s + 1) \quad (2)$$

c) Wind and wave disturbances:

Disturbances (φ_{DIST}), which deviate the ship's course from the set value (φ_{NOM}), can be described by the sum of three sinusoidal signals of different amplitude, frequency and phase:

$$\varphi_{DIST}(t) = \sum_{i=1}^{3} sin(\Omega_i t + \phi_i), \quad (3)$$

where Ω_i – angular frequency, a ϕ_i – phase shift of the perturbations.

d) PID-controller (proportional-integral-differential controller);

To synthesize the properties of the system for stabilizing the ship's course, the parameters of the PID controller are taken constant for sufficiently large changes in the transfer function $W_{NOM}(s)$. This solution is considered reasonable, because if the robustness study of the system proves that the designed system does not have the required performance indicators (statics and dynamics), then more complex, e.g. adaptive, controllers must be used. Further need to synthesize a controller based on the synthesis of reduced logarithmic amplitude and phase frequency characteristics (LAFF) - Bode diagrams. The condition for quality of functioning of the closed system is fulfillment of conditions for Bode diagrams of the disconnected system:

- overriding of the synthesized LAFF characteristics in the amplitudes at single frequency slope - 40 dB/dec;
- frequency shift at 20 dB/dec of sufficient length (one octave left-hand and right-hand frequencies of the break);
- a phase margin of at least 20 degrees.

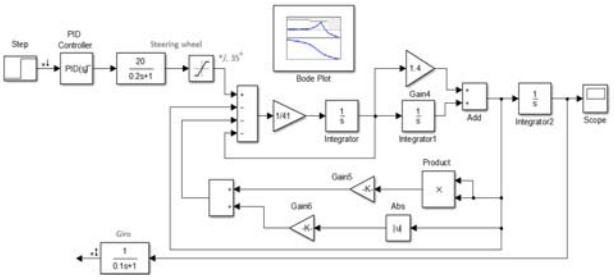

Fig.5 Schematic of the open loop stabilization system (for the synthesis of the PID controller)

If we look at (1), we will see the presence of intrinsically nonlinear coefficients in H(s). The synthesis of the PID controller of the control system is extremely complicated. We proceed with synthesis of parameters for setting of the PID-controller (taking into account limitation of the control signal at 10 V) for the above-listed transfer functions of the ship, the steering machine and the bell-communication sensor. When setting up the PID-controller, the following requirements for the closed system are specified: overcontrolling not more than 1,5 sec with the minimum time of the override process (Fig.6).

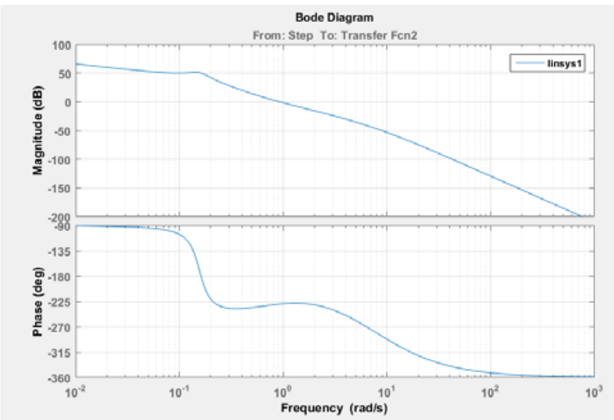

Fig.6 Bode diagram for the disconnected system

If we look at the Bode diagram of the disconnected system (Fig. 6), we will see that the system is unstable and the phase reserve is absent. Let's synthesize the PID-controller by means of Matlab optimization tools. As a result of searching for the controller's settings, we obtain the Bode diagram shown in Fig. 7.

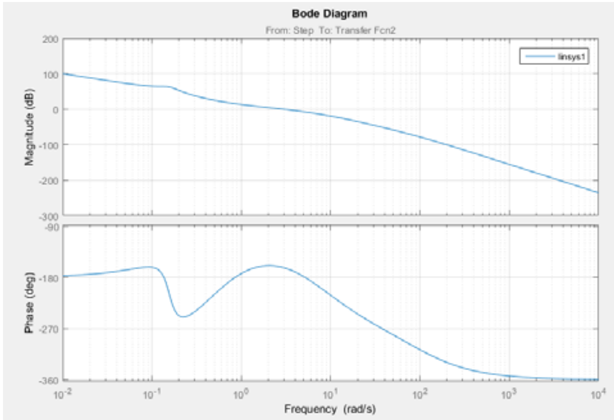

Fig.7 Bode diagram after the process of optimizing the controller settings

From Fig. 7 shows that the phase reserve is close to 20 degrees and the synthesized system is static. Synthesized transfer function of the PID controller has the following values of the adjustment parameters - proportional composition P = 3, integral composition I = 1,5 s^{-1}, differential composition: D = 1 s, coefficient of filtration N = 120.

Fig.8 Dynamics of the closed system when the course is changed by 10 degrees

Fig. 8 shows the results of simulation of the stabilization system when the course is changed by +10 degrees. From this figure we can see that the system meets the specified requirements in terms of speed and overregulation.

Thus, as a result of using this model in the prototypes of MAAS, an increase in the accuracy of course stabilization was demonstrated, which increases by 10-17 % with reduction of rudder shift frequency by 8-12 % and decrease of fuel consumption (for average statistical voyage and average statistical wind and wave impact for the particular navigation area) by 3-7 %.

5. Conclusion

It should be acknowledged that the process of drafting legislation and creating insurance standards for autonomous ships takes more time than the development and implementation of remote control technologies themselves. Nevertheless, first of all the requirements for the minimum required number of personnel on board may be changed, regardless of whether these ships are fully autonomous, the number of crew will be reduced through the introduction of navigation systems equipped with automated devices to prevent ship collision. But at the same time there is a need for software development for the processing of significant amounts of information, analytics and telemetry of possible problems with prototypes, their sensors, engines, The main devices and other features make it possible to predict the time intervals for the necessary replacement of components and mechanics, plan maintenance and as a result, prevent the equipment failure. On the other hand, it is necessary to actively develop activity in the development of standards and regulations, starting at the stage of technology development. It is also necessary to take measures aimed at international standardization, including the consolidation of safety requirements for the implementation of projects of pilotless ships, the development of provisions for insurance and legal provisions in accordance with all international conventions.

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