Unmanned Navigation Development Prospects Based on Structural Analysis of Automated Vessel Control System

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Abstract. The reduction of vessel crew counts and increased automation have been observed in marine and river vessels for several decades. These processes are based, firstly, on the development of modern technology and, secondly, on the urge to reduce the so-called human factor, which is recognized today as one of the key causes of water transport emergencies. It is expected that unmanned navigation will help reduce operational costs, increase the carrying capacity of vessels, and reduce the impact of the human factor on the safety of navigation. This, in its turn, requires the development of a reliable and safe automated control system for unmanned vessels. This article aims to assess the development prospects of unmanned navigation based on the structural analysis of such systems. In the first part of this article, the authors review the classification of control systems depending on the degree of vessel autonomy and the generalized structure of the unmanned vessel control system. In the second part, the authors review the control system structure for a remote-control unmanned vessel and that for an autonomous unmanned vessel.

1. Introduction
In 1899, Nicola Tesla, a Serbian scientist and inventor presented a miniature ship controlled by radio signals to the public at an exhibition in Madison Square Garden. This was essentially the first prototype of an unmanned vessel, although it did not cause much interest in the public at the time. Today, over 100 years later, we can indicate a significantly greater interest in unmanned navigation and water transport digitalization [1-10]. The reduction of vessel crew counts and increased automation have been observed in marine and river vessels for several decades. These processes are based, firstly, on the...
development of modern technology and, secondly, on the urge to reduce the so-called human factor, which is recognized today as one of the key causes of water transport emergencies. Today, 60-80% of all water transport emergencies are attributed to this factor, and the losses in this sector incurred due to the human factor daily are estimated at 1.5 million US dollars.

Currently, navigation companies are struggling to reduce the impacts of the human factor on the safety of navigation through personnel training, re-training, and certification, as well as the introduction of crew action control systems. These activities are associated with significant costs for ship owners, therefore they are interested in the reduction of crews and the development of ship automatics. In its utmost development, this idea must result in a transition to unmanned navigation based on the operation of self-piloted vessels.

It is expected that unmanned navigation will help reduce operational costs, increase the carrying capacity of vessels, and reduce the impact of the human factor on the safety of navigation. This, in turn, requires the development of a reliable and safe automated control system for unmanned vessels. This article aims to assess the development prospects of unmanned navigation based on the operation of self-piloted vessels.

In the first part of this article, the authors review the classification of control systems depending on the degree of vessel autonomy and the generalized structure of the unmanned vessel control system. In the second part, the authors review the control system structure for a remote-control unmanned vessel and that for an autonomous unmanned vessel.

2. The structure of the control system for unmanned vessels

To start assessing the development prospects of unmanned navigation, we must understand what it is like [11].

Unmanned navigation is a water transportation concept based on the idea of using unmanned vessels. The International Maritime Organization (IMO) refers to unmanned vessels as MASS (Maritime Autonomous Surface Ships). According to the definition provided by the IMO in May 2018, an unmanned vessel (MASS) is a vessel that may function without the participation of humans up to a certain degree. At the same time, vessel autonomy classification was proposed:

- Vessels with automated processes and decision-making support systems, with a crew onboard to activate and operate onboard systems and functions.
- Remote-control manned vessels;
- Remote-control unmanned vessels;
- Fully autonomous vessels, whose onboard control systems can make decisions and select a course of actions independently.

Thus, vessels with various degrees of automation require different control systems. A control structure (CS) is a dynamic system formed by several systems interacting in control processes, including the control or command system (CS) and the controlled object (CO). Control is a process in which one object changes the state of another object by a series of deliberate impacts [12]. Within the control structure, the command system generates deliberate impacts, and the controlled object receives them. If the control system can operate without the direct participation of humans, it is referred to as an automated control system. This type of system is used for fully autonomous vessels.

A. E. Sazonov, the founder of the scientific tradition of mathematical, algorithmic, programmatic, and hardware support of automated control systems for ships, described the control system for unmanned vessels as comprising 4 parts [13]: the CO, the CS, the metering system, and the executive system (Figure 1).
As we can see from the chart, any unmanned vessel control system operates based on the following principle: the control part (automated control system or the operator) sets the control goal and objectives and, using control laws (commands), sends them to the executive part (engines, rudder mechanisms, etc) that make control impacts on the controlled object (vessel). The controlled object changes its state, and this change is registered by the metering part. The data obtained is sent as feedback to the control part that calculates adjustments and generates new control commands. It is a generalized description, and the details will vary depending on the degree of autonomy of the vessel.

3. Structure type analysis

As we mentioned above, the IMO identified 4 types of control systems depending on the degree of autonomy. We are not reviewing the first type in this article as it has nothing to do with unmanned vessels. The second and third types differ insignificantly by the possibility of controlling the vessel's propulsion system from onboard, therefore they can be reviewed together. Within this work, we focus on the control systems for remote-control unmanned vessels (RCUMV) and those of fully autonomous unmanned vessels (AUMV). While searching for the information, we found out that there are currently no uniform approaches to the design of the specified control systems.

Many Russian and foreign researchers [14] focused on the use of information technology to facilitate navigation including A.E. Sazonov (the mathematical and programmatic support of automated ship control systems), S.V. Smolentsev (the bases control system design for ships), S.V. Rudykh (monitoring and control systems for auxiliary and engineering vessels), I. G. Malygin, V.I. Komashinsky (the problems of transport system construction), D. A. Skorokhodov (integrated vessel control systems), Ch. Liu, (automated vessel control systems), M. Höyhtyä (autonomous control systems, satellite communications), E. Topp (remote control systems), R. Polvara (computer vision systems), A.A. Sikarev (fixed radio communications systems). However, they do not consider the approaches to the designing of the remote control systems for unmanned vessels.

The Technology Level and Development Trends of Autonomous Shipping Means [15] by V. Karetnikov, E. Olkhovik, A. Ivanova, and A. Butsanets demonstrates that control systems for unmanned vessels are being developed nowadays but the majority of the developments in this sector belong to private companies. Since their projects are commonly limited to unique prototypes, their control systems are also unique and tailored for the specific parameters of the prototypes. Since the developers are trying to keep their trade secrets, the structures of control systems designed for different projects are generally unavailable to the public. However, there are some research works [14,16] that present the structure of the control system for a remote-control unmanned vessel (RCUMV) and that for a fully autonomous unmanned vessel (AUMV). Figure 2 shows an example of an RCUMV control system design.
Figure 2. The structure of an RCUMV control system.

Following this chart, the generalized structure of an RCUMV control system should include 5 components:

1) Operator's workplace. We assume that one operated in the on-shore control center can control the vessel instead of the entire crew. The advantage of this approach is that it makes it easier to monitor the physical and psycho-emotional state of the skipper and replace them to avoid dangerous situations due to operator fatigue. The operator's workplace must have the following equipment:
   - The control module that would send control signals to the processing module on the vessel over the radio channel, which would then send them to the propulsion system to change the vessel's state.
   - The communications module for the data exchange between the operator and the navigation pilot and the VTS operator in real-time. This module will also receive the data collected by the processing module of the vessel from the sensor module and the visualization module. We expect that this will provide the operator with comprehensive information on the state of the controlled vessel, as well as the objects surrounding it in the same water zone.
   - The authentication module to exchange digital authentication keys with the authentication and control system server to prevent unauthorized access to vessel control.

2) The controlled object (RCUMV) must be equipped with the following:
   - The processing module that receives control signals from the operator's control module over the radio channel.
   - The sensor module that identifies surface objects that can be dangerous for the UMV and sends the data about them to the operator's workplace via the UMV processing module. Besides, the sensors help control the state of vessel systems and mechanisms. Therefore, they must measure not only the standard technical parameters of the equipment but also such indirect parameters as noise and vibration levels and the presence of water and smoke in engineering rooms.
   - The visualization module that visualizes the control processes by displaying 3D models of UMV surroundings based on the data collected by sensors and radars, as well as a set of surveillance cameras broadcasting live.
   - The propulsion system that includes the main engines, the steering unit, and the auxiliary thrust units.
   - The authentication module.

3) Navigation pilot radio channel;
4) VTS operator communications radio channel;
5) The channel for the authentication key transmission between the UMV and the authentication and control server, and between the operator's workplace and the authentication and control server.

The system uses several radio channels for the data exchange between the operator and the RCUMV, as well as the communications with the navigation pilot and the VTS operator. Therefore, it is necessary to secure these channels: the data transmitted over them must be confidential, complete,
and accessible. Besides, the channel must have a sufficient bandwidth and interference immunity. Besides, it is also necessary to prevent potential collisions.

The work [16] suggests the following design of the CS for AUMV (Figure 3):

In this system, unlike the previous type, the main UMV control functions are carried out by the autonomous navigation system controller operating 2 key systems:

1) Mooring and anchoring system. This system controls anchor windlasses and mooring mechanisms near the mooring wall. These mechanisms should be designed so that they do not require the participation of humans in mooring.

2) The positioning, navigation, and time system that comprises the compass, the global satellite navigation system, the inertial unit, and the speed log.

3) Navigation circumstances information system. This system uses the data from the positioning system and, like in the previous type of CS, it comprises an array of sensors and radars that search for objects that can be dangerous for the vessel, identify them and collect as much data (position with respect to the UMV, distance, speed, dimensions, heading, etc) as possible and then send these data to the next system.

4) Collision prevention system. As we mentioned before, one of the key problems in automation and UMV deployment is the reduction of the human factor impacts on navigation safety. Therefore, this system is deemed very promising. To create such a system, it is necessary to solve the problem of ‘training’ UMV to safely pass other vessels so that if there is a risk of passing too close to other vessels they could perform predictable and safe maneuvers to prevent further approaching. Besides, this system must prevent low-water stranding of UMV. The correctness and response speed of this system will depend on the correct operation of the navigation circumstances information system sensors.

5) Lighting system. This system is used to control the watch, navigation, running, and mooring lights of UMV.

6) Reporting and communications system. This system is used to diagnose the state of the UMV and send the data to its controller and on-shore system.

7) Weather monitoring and interpretation system. This system is used to collect weather data and send them to the route planning system.

8) Route planning system This system uses the data from the weather monitoring system, etc (e.g. depth and current maps) to construct the shortest and safest route. Together with the collision prevention system, it controls the dynamic positioning system.

9) Dynamic positioning system. This system is controlled by the route planning and collision prevention systems, and it adjusts the speed and heading of the UMV using the main engines, the steering system, and the thrusters.

As we can see from the charts, CS for UMV are complex and require the use of innovative technical solutions. Today, this problem receives a lot of attention in Russia. It is considered in the Marinet action plan of the National Technological Initiative [17] that was approved by the Presidential Council for Economic Modernization and Innovative Development of Russia on October 16, 2015. This plan stipulates the development of the following sectors:
Digital navigation (e-Navigation),
Oceanic resource development technologies,
Innovative shipbuilding technologies,
Human capital,
Legal framework.

For instance, the Marineo project, a Skolkovo Fund resident launched in late 2015, develops automated navigation route plotting systems.

Apart from Marineo, there is a project for the creation of a pilot e-Navigation zone and e-Navigation hardware. The goal of this project is to develop and produce hardware components and commercial products based on them to implement the concept of e-Navigation in real life.

4. Conclusion
In the first part of this article, the authors reviewed the classification of control systems depending on the degree of vessel autonomy and the generalized structure of the unmanned vessel control system. In the second part, the authors reviewed the control system structure for a remote-control unmanned vessel and that for an autonomous unmanned vessel. Even though the development of unmanned vessels began in the mid-twentieth century, it saw a significant growth interest over the last five years. The interest from the state is a crucial factor for this sector. Today, researchers are interested in solving specific technical problems, and a large number of advances relate to the creation of specific systems and mechanisms to be installed on unmanned vessels. At the same time, more generalized conceptual problems like the development of a standard control system structure for unmanned vessels are often left unattended. Of the two unmanned vessel control system options reviewed in this article, the first one could be used more extensively in internal waterways, and the second one could be more useful at sea.

5. References
[1] Sokolov S, Glebov N, Novoselov R, Chernyi S Database problems of maritime transport industry on high load platform MATEC Web of Conferences 239
[2] Koroleva E, Sokolov S, Filatova E Digitalization as a method of implementation EEU transit potential E3S Web of Conferences 138
[3] Iskanderov Yu M, Gaskarov V D, Doroshenko V I 2021 Multi-agent model of an integrated ship control system Bulletin of the State University of Marine and River Fleet named after Admiral S.O. Makarov vol. 11 5 pp 831-841
[4] Koroleva E, Sokolov S, Makashina I, Filatova E 2021 Digital maritime container terminal - An element of digitalization of container transportation systems E3S Web of Conferences 203
[5] Nyrkov A P, Sokolov S S, Karpina A S, Chernyakov A V, Gaskarov V D Cluster-type models in the logistics industry International Journal of Engineering and Technology(UAE) 7(1) pp 39-43
[6] Nyrkov A, Shnurenko A, Sokolov S, Chernyi S, Korotkov V 2021 The effective optimization methods of port activity on the basis of algorithmic model International Journal of Electrical and Computer Engineering 7(6) pp 3578-3582
[7] Reshnyak V, Sokolov S, Nyrkov A, Budnik V 2021 Inland Waterway Environmental Safety Journal of Physics: Conference Series 1015(4)
[8] Sokolov S S, Alimov O M, Trubacheva Y A, Katorin Y F, Goloskokov K P 2018 Providing security for virtual infrastructures based on an integrated mechanism Proceedings of the 2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering, EIConRus 2018 pp 132-135
[9] Sokolov S S, Alimov O M, Ivleva L E, Vartanova E Y, Burlov V G 2018 Using unauthorized access to information based on applets Proceedings of the 2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering, EIConRus 2018 pp 128-131
[10] Sokolov S S, Alimov O M, Golubeva M G, Burlov V G, Vikhrov N M 2021 The automating process of information security management Proceedings of the 2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering, ElConRus 2018 pp 124-127

[11] Unmanned navigation, BES tadviser.ru: inf. portal url: https://www.tadviser.ru

[12] Vagushchenko I L, Tsymbal N N 2002 Automatic ship traffic control systems 2nd ed., Rev. and add (Odessa: Latstar) p 310

[13] Rodionov A I, Sazonov A E 1992 Automation of navigation. 3rd ed., Rev. and add. (M.: Transport) 192

[14] Butsanets A A 2020 Organization of a remote control system for an unmanned technical fleet to ensure navigation on inland waterways: [Text] dis ... .. cand. those. Sciences: 05.22.19: protected 02.16.2021: approved. 11/24/2020 (St. Petersburg) 189

[15] Karetnikov V, Ol'Khovik E, Ivanova A, Butsanets A 2020 Technology Level and Development Trends of Autonomous Shipping Means International Scientific Conference on Energy Management of Municipal Facilities and Sustainable Energy Technologies Vol 1258 AISC pp 421-432

[16] Chaala M, Bandaa O, Glomsrudb J, Basneta S, Hirdarisa S, Kujalaa P 2021 A framework to model the STPA hierarchical control structure of an autonomous ship Safety Science Vol 132 (Cover date: December 2020) Article 104939

[17] About us marinet.org: inf. portal URL: https://marinet.org/ru/about/