ISSN: 3067-8366
Research Article
Journal of Environmental Science, Sustainability, and Green Innovation

Development of Principles for Controlling Autonomous Surface Vessels of Inland Waterway Navigation

Sokolov Sergey Sergeevich[1], Solyakov Oleg Vladimirovich[2], & Yakunchikov Vladimir Vladimirovich[3]*

1Doctor of Technical Sciences, Associate Professor, Vice-Rector of RUT (MIIT), +79217872892, Russia.
2Associate Professor, Associate Professor of the Department of Operation of Water Transport, Academy of Water Transport, RUT (MIIT), +79112586110, Russia.
3Associate Professor, Director of the Scientific and Educational Center for Maritime, Inland Waterway Transport and Autonomous Navigation Technologies of the Russian University of Transport (MIIT), +79165568993, Russia.

***Corresponding author:** Yakunchikov Vladimir Vladimirovich, Associate Professor, Director of the Scientific and Educational Center for Maritime, Inland Waterway Transport and Autonomous Navigation Technologies of the Russian University of Transport (MIIT), +79165568993, Russia.

Submitted: 09 June 2025 **Accepted:** 17 June 2025 **Published:** 23 June 2025

https://doi.org/10.63620/MKJESSGI.2025.1018

***Citation:** Sergeevich, S. S., Vladimirovich, S. O., & Vladimirovich, Y. V. (2025). Development of Principles for Controlling Autonomous Surface Vessels of Inland Waterway Navigation. J Environ Sci & Sustain & Green Innov, 1(2), 01-10.*

Abstract

The relevance of developing control systems for autonomous inland waterway vessels is noted. In order to develop an algorithm for the movement of an autonomous surface vessel operating on inland waterways (IWW), typical navigation tasks are considered for its automatic control system: determining the vessel's position, straight-line movement, circulation, divergence and overtaking, mooring, emergency maneuvering, interaction with other traffic participants. The analysis is based on the provisions of the Rules for the Navigation of Vessels on Inland Waterways of the Russian Federation and educational literature.

The methods of interaction between an autonomous vessel and a conventional navigator, the limitations and prospects of this technology are considered separately.

To construct a block diagram of the algorithm for maneuvering an autonomous inland waterway vessel, a number of foreign publications and methods for the movement of autonomous vessels were analyzed.

The main operations of navigation on inland waterways are considered. Based on the analysis of foreign and national sources, a consolidated algorithm for performing maneuvers of autonomous surface vessels (ASV) is proposed.

Keywords: Autonomous Shipping, Autonomous Ship Control System, Formalization of Navigation Operations.

Introduction

The rapidly developing new water transport mode – autonomous – requires new control systems. For inland waterways, these tasks are only just beginning to be developed.

The aim of the study is to determine the algorithm for diverging and overtaking inland waterway vessels for use in automatic control systems for inland navigation.

The authors set the main objectives of the study, such as to consider the main maneuvers when moving the ANS in accordance with the Rules of Navigation of Vessels on Inland Waterways of the Russian Federation (PPVVP), formalize recommendations on passing and overtaking for the self-propelled guns of autonomous surface vessels.

Today, technologies and methods for managing marine autonomous surface vessels (MAS) already exist and are being actively developed abroad and in Russia, whereas river navigation has a number of specific features and limitations.

In particular, when passing at sea, a large area is used for the maneuvering of ships, which allows for any given safety margin, whereas in narrow passages and on the river this margin is practically non-existent.

When operating a vessel in such an environment, precision control of course and speed, limited by strict time limits, begins to play a role.

In addition, both traditional (conventional) vessels with a live crew on board and new autonomous vessels will coexist on the water for a fairly long time. At the same time, the movement and maneuvers of autonomous vessels must not only ensure safety, but also comply with the requirements of the PPVVP and the expectations of ordinary navigators.

In other words, the automation must control the vessel in accordance with the main task of navigation as carefully, with an excessive reserve in distances and intervals, as a young navigator. It is known that the task of navigation is to deliver a vessel from point A to point B in the least (or specified) time ($\tau \rightarrow$min), or at the lowest fuel consumption (bT$\rightarrow$min), in accordance with the PPVVP, while ensuring the required level of safety of navigation on inland waterways (IWW).

Research Results

Let us consider typical maneuvering tasks that are solved when ships move along inland waterways.

Vessel Positioning

For safe operation, it is necessary to accurately determine the position of the vessel relative to the fairway (CF).
AIS is used today to determine the location of conventional vessels.

For autonomous vessels (AS), the task of determining the vessel's location can also be assigned to AIS, with mandatory duplication. In this case, the position of the autonomous vessel is determined:
- according to GNSS GLONASS/GPS data as part of two ship receivers (to increase accuracy); when GNSS receivers are located at the bow and stern ends, it is possible to determine the orientation of the vessel in space; it should be noted that the error in positioning obtained from GNSS GLONASS/GPS signals can reach significant values, in some cases local failures may be observed, which does not allow an autonomous vessel to be limited exclusively to GNSS sensors;
- according to radar data;
- integration of data obtained from a strapdown inertial navigation system (SINS);
- a technical vision system of an autonomous vessel, which allows the use of a mechanism for precise reference to known "permanent" coastal objects and geographic landmarks.

Also, a significant gain in accuracy is possible by comparing the parameters of the situation with data obtained from a previously created database - a "digital twin" of the water area.

Interaction of the Navigator with Traffic Participants

When vessels pass each other both in narrow passages and in open water, as well as during overtaking and other maneuvers, one of the most important means of ensuring safety and alerting navigators is VHF radio communication.

All registered vessels must comply with the requirements of the IWPR regarding the use of appropriate light and sound signals, as well as the requirements of the Radio Regulations for the Mobile Service and the Mobile-Satellite Service on Inland Waterways.

Thus, paragraph 71 of the PPVVP states: "in the event of a malfunction of the VHF radio communication installation, the vessel/train may only move to the nearest point for repair of radio-electronic equipment."

It is clear that ship radio communication today remains a mandatory requirement for navigation on inland waterways.

Ship Control by a Navigator

To create a vessel control algorithm, we will consider typical navigation maneuvers, where we will distinguish two types of movement:
- uniform movement along the route (movement at a given speed along the CX axis with compensation for the impact of the external environment, adequate maneuvering to ensure safe divergence from other road users, and overtaking them);
- uneven movement along the route (acceleration, braking, maneuvering, including emergency maneuvering).

Uniform Movement Along the Course or Lane of the Fairway
- for the GDP, the rotation frequency of the screws n is selected, corresponding to the economic course (bT $\rightarrow$ min), or the value of the propeller speed to ensure the traffic schedule / minimize travel time ($\tau \rightarrow$min), however, it must be possible to adjust the speed taking into account local navigation conditions to "safe speed" values, which may be significantly lower than the criterion speed values;
- the ship's steering gear is shifted by an amount equal to the required compensation for external conditions / drift and drift angle. The rudder (rudder) shift angle is calculated using a special method.

Change of Course (turn)

- the radius is calculated, as well as the start and end point of the maneuver (depending on the inertial and hydrodynamic characteristics of the vessel/train and ensuring the safety of the maneuver under given sailing conditions, including taking into account the running lane);
- when reaching the starting point of the turn, the steering gear

is shifted to a value corresponding to the required turning radius under the given sailing conditions;
- when controlling exclusively with rudders in narrow waters, it is usually necessary to perform a “holding” maneuver in advance upon reaching a specified value of the angular velocity of turn (depending on the maneuvering characteristics of the vessel/train and ensuring the safety of the maneuver under the specified sailing conditions);
- when controlling the propulsion system (at low speeds, when mooring, possibly in combination with thrusters (PU)) it is possible to reduce the rotation speed or pitch of the propeller;
- on open water the turning radius of the AN can be increased, which reduces the energy costs of the maneuver with a slightly increased maneuver time.

Discrepancy

Narrow divergence is one of the most difficult maneuvers, so let's look at it in more detail2:

“If it is impossible to ensure the specified zone along the width of the shipping channel, it is necessary to reduce the speed of the vessel, down to the minimum.

When the distance to the oncoming vessel is 2-3 hull lengths, both vessels vigorously put the rudder to the right and come closer to the edge of the canal. It is impossible to approach the edge of the canal in advance, at a large distance between the vessels, since it is difficult to keep the vessel close to the edge for a long time. At the moment when the stems of the vessels are level, the rudder is shifted to the left in order to move the stern and begin moving along the oncoming vessel, simultaneously increasing the rotation frequency of the propeller. The vessels round each other, making a smooth turn to the left. When the bow approaches the beam of the midship of the other vessel, the rudder is shifted to the right in order to prevent the stern from moving towards the edge of the canal. Due to the interaction of hydrodynamic forces between the vessels and each vessel with the shore, both vessels tend to turn to the left.

The skippers should control the movement of the vessels, but not prevent them from turning smoothly to the left. As soon as both vessels pass each other cleanly, they will again enter the channel axis. The movement must be assisted by the rudder and, upon entering the channel axis, the vessel must be held on the set course.

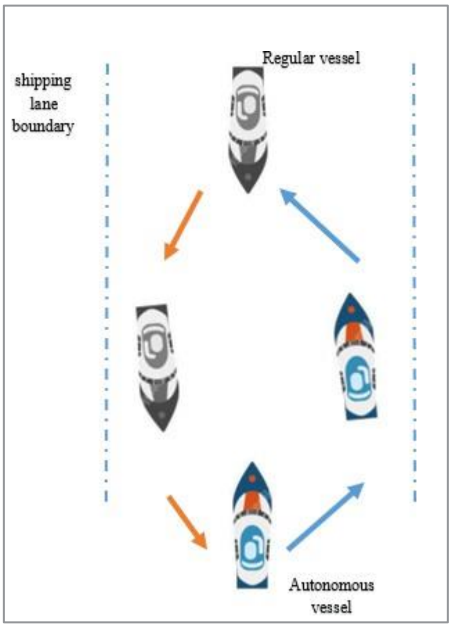

Figure 1(a): Divergence in narrowness.

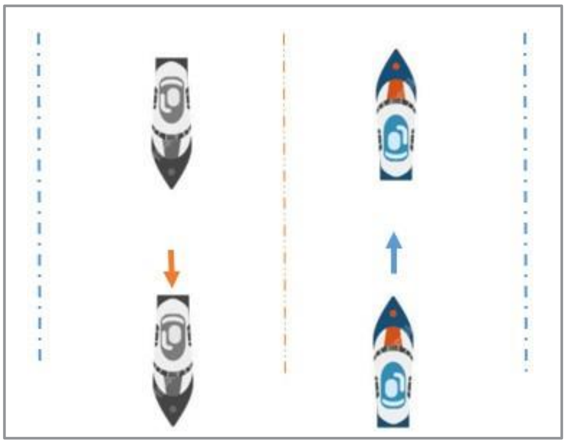

Figure 1(b): Divergence in wide water – in the SRD [done by the authors].

If one of the vessels delays its movement to the left during the divergence and remains at the right edge of the canal after the other vessel passes, the influence of the shore effect (repulsion of the bow and attraction of the stern) can sharply deviate it to the left and even turn it across the canal. In order to prevent a turn to the left, it is necessary to hold the vessel with the rudder in a timely manner, up to the point of shifting the rudder to the right side, and to assist with the operation of the engine until the vessel reaches the canal axis."

In this case, the divergence algorithm can be formalized as follows:

- radio notification of your location and maneuver when approaching a narrow area/turn/section with limited visibility;
- agreement with an oncoming vessel to carry out a divergence maneuver;
- when vessels approach within line of sight (at least 500 m) or in response to a signal from another vessel, the corresponding light signal is switched on, in accordance with the requirements of the PPVVP;
- propeller speed - does not change or increases to the level necessary to ensure the necessary controllability in the event of an excessively dangerous approach;
- when passing in narrow passages - minimal deviation of vessels from each other, only to prevent the influence of dangerous hydrodynamic effects (suction);
- deviation from an oncoming vessel in a narrow passage (Fig. 1a) to ensure safety; or when passing in wide water (Fig. 1b) – movement in one's own lane in the traffic separation system (TSS); in this case, the steering gear is shifted to perform a maneuver to ensure a safe passing distance. If necessary, a maneuver of "holding" and (turning) the stern away from the oncoming vessel is performed.
- When passing dangers on the water, a minimal deviation of course from the obstacle is allowed, only to prevent a collision.

Overtaking (Passing)

- agreement with the overtaken vessel on overtaking (autonomous vessels communicate with each other using a digital protocol, communication between the AS and human-controlled vessels using a special message exchange protocol). If the overtaken vessel responds negatively, overtaking is prohibited.
- Providing appropriate maneuvering instructions.

Overtaking Vessel (ANS)

- the overtaking vessel usually moves closer to the CX axis if local navigation conditions permit; the deviation and the permissible distance from the CX are determined by the navigator;
- when vessels approach each other at a distance of direct visibility (at least 500 m), the overtaking vessel makes a request to overtake (usually on the left side of the overtaken vessel); if the request is confirmed, subsequent overtaking is carried out;
- the rotation speed of the propellers - to ensure safe navigation, it can be increased to full speed;
- When overtaking, the navigator must determine and maintain a safe approach distance from the vessel being overtaken.

Overtaken Vessel (ANS)

- when vessels approach each other within line of sight (at least 500 m), in response to another vessel's request to overtake, if such a maneuver is agreed upon, the side on which overtaking will be carried out is confirmed;
- reduces the propeller speed to reduce its own speed by agreement with the overtaking vessel (usually n is reduced by 25%; in the case of poor visibility or dangerous approach, the overtaking vessel may be allowed to pass by reducing the propeller speed until it stops completely);
- when overtaking, the navigator must determine and maintain a safe approach distance from the vessel being overtaken;
- The steering gear is shifted to the required value to ensure a safe overtaking distance.

Maneuvering to Avoid a Collision when an Obstacle to Traffic is Suddenly Detected

- the possibility of dangerous approach to an obstacle is calculated when only the rudders are controlled, and when both the rudders and the propellers are controlled. If necessary, in addition to the rudders, afterburner/reversal of the propeller rotation direction is performed;
- the steering controls are shifted in such a way as to ensure the performance of a maneuver to bypass an obstacle, taking into account the provision of a safe distance from the obstacle;
- If available and possible at low speeds, it is possible to use steering devices.

Departure from the Berth / Lifting Anchor

- radio announcement of your maneuver before starting to move towards the CX;
- the rudder is shifted to ensure movement along a trajectory that ensures a safe exit to the CX (if possible, in open water, at acute angles of up to 30°).
- the rotation frequency of the propellers increases smoothly until the set speed is reached .

Mooring/Anchoring

- radio notification of your maneuver when approaching the pier;
- when approaching a berth/berthing area, the rotation speed of the propellers is smoothly reduced to the minimum safe level, allowing the vessel to maintain maneuverability;
- the movement of a vessel without a PU to the berth is usually carried out at an acute angle relative to the berth. If the vessel has a PU, it is possible to use them near the berth, up to and including moving alongside;
- the angle of the shift / the law of change of the angle of the shift and the control of the PU is selected in such a way as to ensure the most parallel position possible of the side of the vessel and the wall of the berth when touching the berth at speeds of up to 0.1 m/s;
- When anchoring, the speed of the vessel at the moment of anchor release must also not exceed the safe speed (selected by the navigator).

Table 1: Qualitative indicators* of control actions for an inland watercraft in calm water, light wind and a current speed of no more than 4 km/h

Name of the maneuver	Propeller speed control	Steering control
Uniform movement along the route	n= nnom or n= neconomy of running	Angle of transfer $\Theta = \beta$drift
Change of course when reaching a turning point on the route	does not change	Re-laying Θ, taking into account the need for obsession
Discrepancy	does not change / decreases tonmin	Rudder shift maneuver to provide a distance to prevent "sticking"
Overtaking another vessel	n= nmax	
Overtaking another vessel	n< nnom	
Departure from the pier	n $\rightarrow$nnom	Course for shipping lane according to the situation
Mooring	n $\rightarrow$nmin	A maneuver by shifting the rudders to ensure a touchdown speed of no more than 0.1 m/s
Emergency maneuvering	n $\rightarrow\pm$ nmax	Rudder shift maneuver Θ $\rightarrow$max to ensure minimal divergence from the obstacle

*Determining quantitative indicators for each vessel requires separate model and full-scale tests.

Interaction of ANS with Traffic Participants
If, in addition to the ANS, there are traditional vessels on the SS, it is necessary to ensure that radio communication requirements are met, for which purpose it is necessary to have a special communication system on board the AS.
This could be an intelligent automatic responder (similar to a voice assistant) with the ability to recognize and synthesize speech, for communication between the AI ANS and a live captain or shore specialist.
Let us propose a variant of such a solution.

Autonomous Ship - Conventional Ship / Shore Communication
Currently, voice intelligent chatbot technologies are actively developing, for example, in the solution from SberTypical voice bot capabilities include:
- human voice recognition;
- imitation of speech;
- analysis of the obtained data and decision making;
- conducting a full-fledged dialogue in a given area of knowledge.

Speech Recognition
The ability to hear and understand a person is the main task of the program. End2End technologies are used for this.

Speech Synthesis
The prepared answer is converted into speech. High-quality audio tracks read by a speaker or synthesized speech are used.

One of the signs of successful generation of natural speech is a result when it is impossible to distinguish artificial speech from synthesized speech by ear. For this, proven speech service platforms are used.

Decision Making
The generated information enters a trained system with a multitude of scenarios, on the basis of which further decisions are made.

Once configured, such a chatbot can be used as an AI vessel answering machine for dialogue with captains of other vessels and VTS dispatchers.

Autonomous Vessel-to-Autonomous Vessel Communication
For two ANS, this may be a system of messages using a special certified protocol.

Since communication between AI of autonomous vessels will not require a speech flow, the ANS of vessels will communicate with each other using a flow of AIS data with instructions for divergence (interaction), according to a specialized protocol. In this case, logging of information exchange and its transmission to the shore in real time will be mandatory.

Automatic Vessel Control
To construct a control algorithm for an autonomous vessel, existing control algorithms for sea vessels, including autonomous ones, were analyzed [1-10].

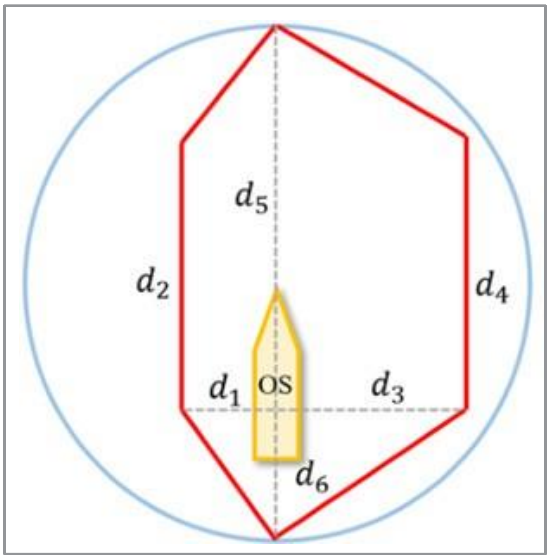

Figure 2: Safety domain for the MASS vessel

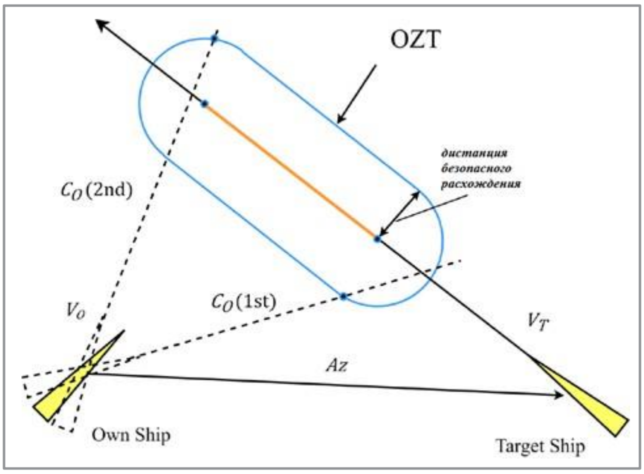

Figure 3: Implementation of the collision avoidance algorithm [6] where OZT (Obstacle Zone by Target) is the target obstacle zone

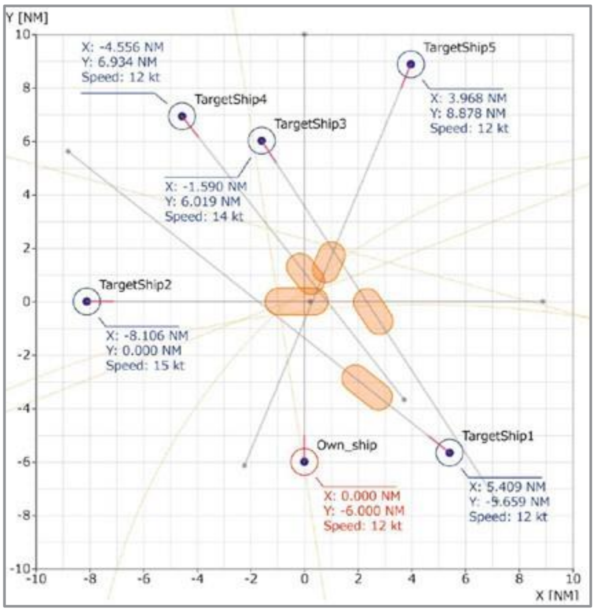

Figure 4: Implementation of the collision avoidance algorithm. Continuous action space model (target scenario for ships)

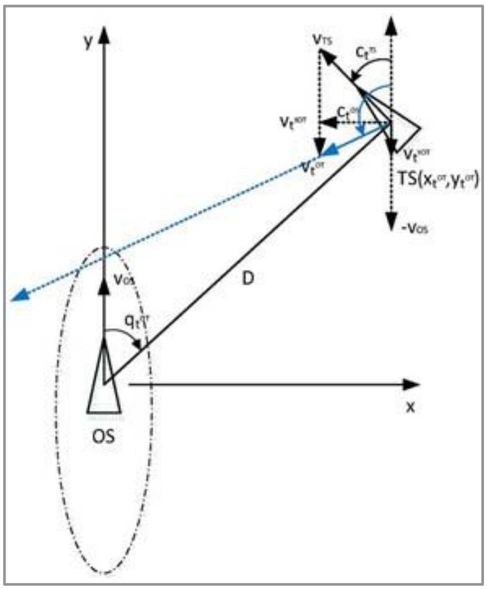

Figure 5: Schematic diagram of collision assessment Research Center for Intelligent Transportation Systems, Wuhan University of Technology, China

From the analysis of the indicated works it is evident that for the MANS in one form or another the concept of a "safety zone" is introduced, which has the form of an ellipse with the center of gravity coinciding with the center of gravity of the vessel and exceeding the dimensions of the vessel by 2-5 times along the main axes.

A number of works are devoted to collision risk assessment, considered, for example, in [8]. These methods include trajectory clustering, graph method, extremely short-term trajectory prediction method, xG-Boost method, time series modeling and multi-criteria forecasting.

The work is devoted to the application of an encoder-decoder model with an attention mechanism for predicting a collision along a trajectory based on AIS data.

In an algorithm of the method for identifying risks when ships navigate complex waterways is presented, which consists of two procedures: determining the type of vessel and classifying the risk of collision, rice.6.

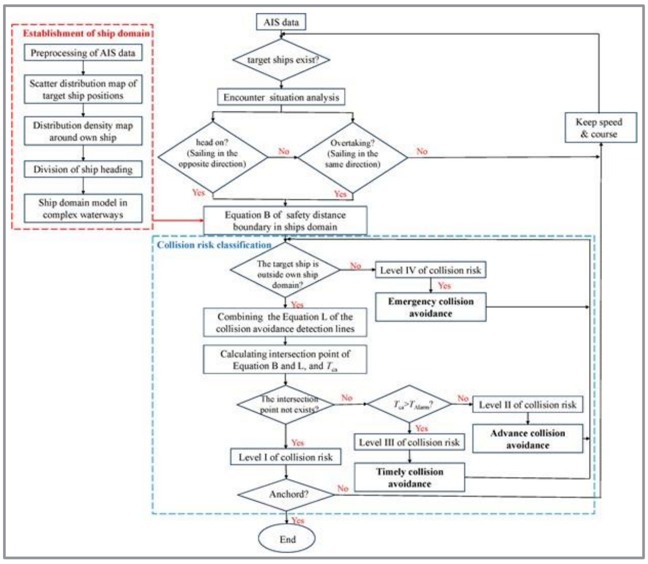

Figure 6: Block diagram of the collision risk assessment method.

Explanation of the algorithm: "When the position data (from AIS, radar or fusion of their data) of own ship and target ship are collected in real time. By determining whether the target ship is within the ship type, whether the collision risk detection line crosses the safety distance boundary of own ship, and whether the time to the intersection point between the collision risk detection line and the safety distance boundary of the ship type is sufficient, the collision risk level is estimated, forming a method for rapid identification of the risk of collision of ships in complex waterways."

Also, in the work direct quantitative recommendations are given: "according to research conducted with experienced sailors and Wen's research, the safe distance between one's own vessel

and a target vessel sailing ahead in the same direction is about 200 m on the Yangtze River” [7].
Collision prevention algorithms are varied; among the latest developments, one can note an algorithm for a large number of vessels in a closed water area, developed by the Department of Ship Automation at the Maritime University of Gdynia [10].

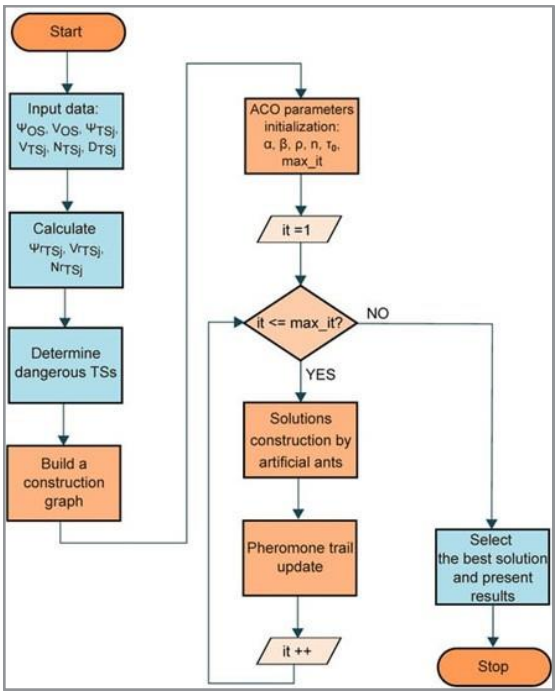

Figure 7: Block diagram of the ant colony optimization algorithm for preventing ship collisions

Dangerous target ships are considered to be target ships whose courses intersect with the course of their own ship and the point of intersection of the trajectories of both ships located in the observation zone. For each of these objects, the algorithm calculates the distance of its ship from the intersection point and the time after which its ship will arrive at the intersection point.
Based on the results of the analysis, for inland waterway vessels we will adopt a safety zone equal to 2 hull lengths and 2 hull widths on each side.

Generalized Algorithm for Ship Maneuvering
Based on the conducted analysis, as well as the results of, we propose a generalized algorithm for performing maneuvers by an autonomous VVT vessel [11-18].
Once the vessel has started moving, the automatic navigation system receives data from:
- a navigational cartographic system that meets the requirements of the national river register;
- GNSS sensors;
- ship radar;
- machine vision systems;
- other awareness sensors.

Based on the data, a 2D surface of the water area is constructed with the boundaries of the shipping channel, a depth map (if a digital twin is available), and objects in the water area.
The objects are analyzed, classified, their safety zones (ZZ) are constructed, and their speeds and accelerations are assessed.
Analysis and prediction of the trajectories of objects in the water area is carried out to determine the probable intersection of the ZB.

If the vessel's ZB does not cross other zones, then movement continues along the specified route trajectory.

In the case of a calculated collision, it is determined whether a moving or stationary object falls within the ZB.

If the object is stationary, an evasive maneuver is performed by turning the rudder, for which a trajectory is calculated that satisfies the minimum action condition; the time of movement along the new course is also calculated, after which the vessel's course is changed.

In the case of a moving target, the target is classified and, if it is a normal vessel, an attempt is made to contact its captain. If successful, the onboard AI specifies the divergence (overtaking) maneuver – by course and/or speed, after which a new propeller speed and/or a new course and maneuver time are calculated and set.

The maneuver is then carried out until it is completed, after which the course is returned or a transition to a new course occurs according to the plotted trajectory; the vessel’s movement continues.

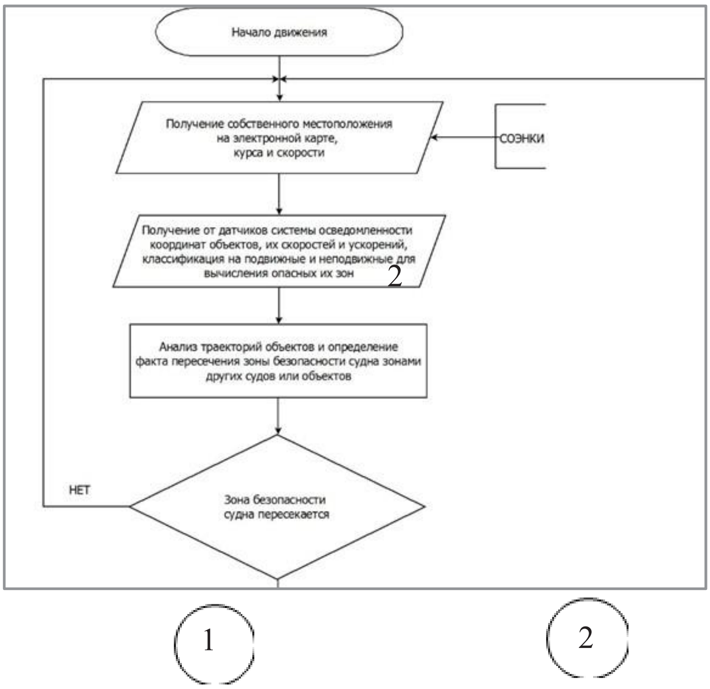

Figure 8: Block diagram of the algorithm for implementing the ANS maneuver [completed by the authors].

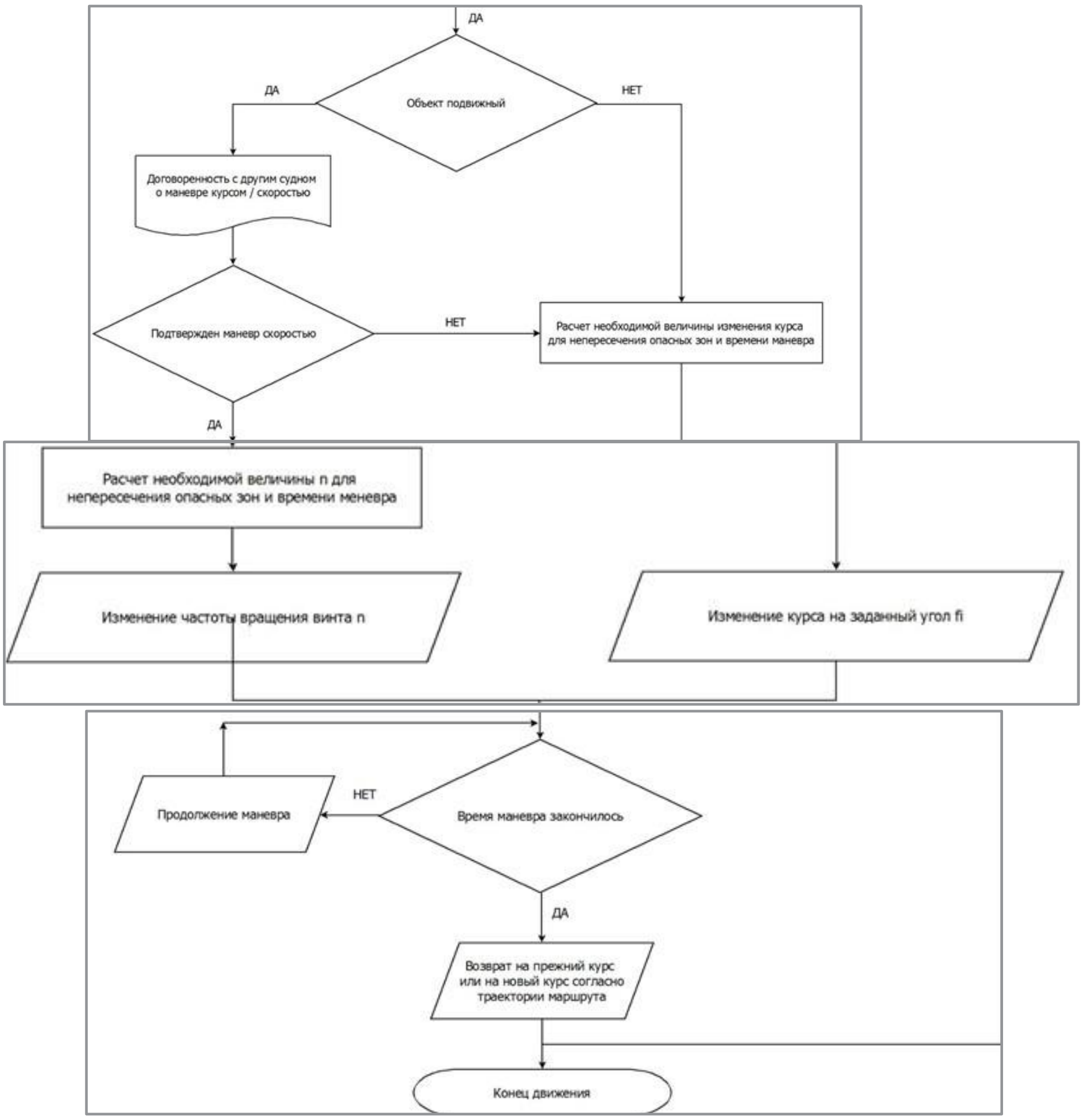

Figure 9: Block diagram of the algorithm for implementing the ANS maneuver (continued).

Conclusion

The main operations of navigation are considered, and the qualitative characteristics of the control of the inland waterway propellers of ships are summarized.

Based on the analysis of foreign and national sources, a general algorithm for performing an ANS maneuver is proposed.

To determine the quantitative parameters of navigation maneuvers and numerical algorithms for control systems of autonomous inland waterway vessels, similar to those existing for autonomous sea vessels , further research is needed.

References

1. Aybars Oruc, Gkioulos, V., & Katsikas, S. (2022). Towards a cyber-physical range for the integrated navigation system (INS). Journal of Marine Science and Engineering, 10(1), 107. https://doi.org/10.3390/jmse10010107

2. Kim, J., Park, J., & Cho, K. (2022). Continuous autonomous ship learning framework for human policies on simulation. Applied Sciences, 12(3), 1631. https://doi.org/10.3390/app12031631

3. Cui, Z., Guan, W., Luo, W., & Zhang, X. (2023). Intelligent navigation method for multiple marine autonomous surface ships based on improved PPO algorithm. Ocean Engineering, 287, 115783. https://doi.org/10.1016/j.oceaneng.2023.115783

4. Zhang, X., Wang, C., Jiang, L., An, L., & Yang, R. (2021). Collision-avoidance navigation systems for maritime autonomous surface ships: A state of the art survey. Ocean Engineering. http://researchonline.ljmu.ac.uk/id/eprint/18414/

5. Wang, L., Wu, Q., Liu, J., Li, S., & Negenborn, R. R. (2019). State-of-the-art research on motion control of maritime autonomous surface ships. Journal of Marine Science and Engineering, 7(12), 438. https://doi.org/10.3390/jmse7120438

6. Sawada, R., Sato, K., & Majima, T. (2020). Automatic ship collision avoidance using deep reinforcement learning with LSTM in continuous action spaces. Journal of Marine Science and Technology, 26(1). https://doi.org/10.1007/s00773-020-00755-0

7. Wang, Z., Wu, Y., Chu, X., Liu, C., & Zheng, M. (2023). Risk identification method for ship navigation in the complex waterways via consideration of ship domain. Journal of Marine Science and Engineering, 11, 2265. https://doi.org/10.3390/jmse11122265

8. Zhang, D., Chu, X., Liu, C., He, Z., Zhang, P., & Wu, W. (2024). A review on motion prediction for intelligent ship navigation. Journal of Marine Science and Engineering, 12, 107. https://doi.org/10.3390/jmse12010107

9. Zhao, L., Zuo, Y., Li, T., & Chen, C. L. P. (2023). Application of an encoder–decoder model with attention mechanism for trajectory prediction based on AIS data: Case studies from the Yangtze River of China and the Eastern Coast of the US. Journal of Marine Science and Engineering, 11, 1530. https://doi.org/10.3390/jmse11081530

10. Lazarowska, A. (2024). A comparative analysis of computational intelligence methods for autonomous navigation of smart ships. Electronics, 13, 1370. https://doi.org/10.3390/electronics13071370

11. Piehl, H. P. (2016). Ship roll damping analysis (Doctoral dissertation, Universität Duisburg-Essen). https://duepublico2.uni-due.de/servlets/MCRFileNodeServlet/duepublico_derivate_00043372/Piehl_Diss.pdf

12. Chen, S., Shiotani, S., & Sasa, K. (2013). Numerical ship navigation based on weather and ocean simulation. Ocean Engineering, 69, 44–53. https://doi.org/10.1016/j.oceaneng.2013.05.019

13. Thu, A. M., Htwe, E. E., & Win, H. H. (2015). Mathematical modeling of a ship motion in waves under coupled motions. International Journal of Engineering and Applied Sciences (IJEAS), 2(12), 97–102. https://www.ijeas.org/download_data/IJEAS0212031.pdf

14. Uzunoglu, E. (2011). Numerical and experimental study of parametric rolling of a container ship in waves (Master's thesis, Technical University of Lisbon). https://doi.org/10.1201/b17494-140

15. Ibrahim, R. A., & Grace, I. M. (2010). Modeling of ship roll dynamics and its coupling with heave and pitch. Mathematical Problems in Engineering, 2010, Article 934714. https://doi.org/10.1155/2010/934714

16. Ulusoy, T. (2006). State-space modeling and optimal control of ship motions in a sea state (Master's thesis, Massachusetts Institute of Technology). https://core.ac.uk/download/pdf/4402129.pdf

17. Skjetne, R., Smogeli, Ø. N., & Fossen, T. I. (2004). A nonlinear ship manoeuvering model: Identification and adaptive control with experiments for a model ship. Modeling, Identification and Control, 25(1), 3–27. https://doi.org/10.4173/mic.2004.1.1

18. Kjerstad, Ø. K., & Skjetne, R. (2014). Modeling and control for dynamic positioned marine vessels in drifting managed sea ice. Modeling, Identification and Control, 35(4), 249–262. https://www.mic-journal.no/PDF/2014/MIC-2014-4-3.pdf