MODELS OF REMOTE CONTROL OF AN UNMANNED VESSEL MOVEMENT

V. E. Bolnokin(1), A. F. Kaperko(2), S.A. Sorokin(3)*

[(1)] Mechanical Engineering Research Institute of the Russian Academy of Sciences (IMASH RAN), Moscow; [(2)] National research University Higher School of Economics, Moscow; [(3)] Computing System Research and Development Institute (NIIVK, JSC), Moscow
Russian Federation

* Corresponding Author, e-mail: vitalybolnokin@yandex.ru

Abstract: Algorithms for remote control of the vessel's movement using the data of the global satellite positioning system and ensuring the achievement of a given goal with the required accuracy have been developed and investigated. The algorithms take into account the accidental effects on the vessel of external factors that determine the deviation of the vessel from the designated course.

Key words: remote control, vessel's movement, GPS, accidental effects, external factors.

1. INTRODUCTION

The need for remote control systems of various types and purposes of marine and river transport vehicles is associated, for example, with the need to carry out rescue operations in difficult weather conditions, when there is a real danger to the life of rescuers, or with the need to conduct a vessel on a difficult course.

Another area of application of such systems may be the management of small vessels when unloading large vessels in coastal shallow water zones in the absence of equipped berths. This is quite an urgent problem in cases of a coastal port area, which has a complex coastal relief, where the construction of berths is an expensive and difficult task, and the delivery of necessary goods is often possible only by sea.

In addition, the field of application of remote control of unmanned vessels are special areas related to ensuring the performance of special functions and tasks of state security.

Modern vessels and navigation systems are being put into operation, ensuring an increase in traffic volumes, as well as improving navigation safety.

2. PROBLEM STATEMENT

In general, the complex of the ship's remote motion control system consists of subsystems:

- control of the ship's program motion along a given trajectory (route),
- autonomous control that implements adaptive parrying and correction of deviations from program trajectories and control in abnormal conditions.

The general block diagram of the remote control system of an unmanned vessel is shown in Figure 1.

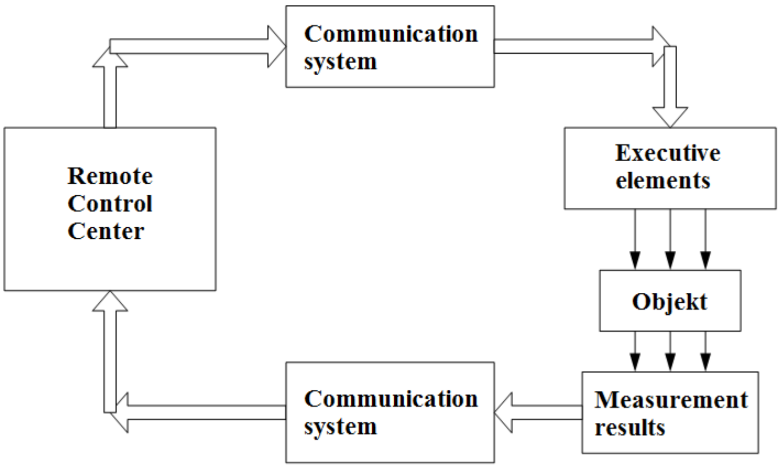

Fig. 1. The general block diagram of the remote control system of an unmanned vessel

At the same time, the control of the vessel is based on the available information about its position and coordinates, as well as environmental parameters.

Currently, in the theory and practice of design, construction and operation of marine and river transport vehicles, a wide range of navigation systems using various physical principles is used.

Such systems include satellite navigation systems, for example, GPS, GLONASS systems [1-4], which allows you to determine the coordinates of the vessel with high accuracy. The use of such systems in navigation greatly facilitates the work of ship management and increases the efficiency and quality of management decisions. Since the use of such systems is based on the use of modern means of communication and computer technology, new opportunities for ship management also appear.

One of such possibilities is the use of remote control systems.

The advantages of this type of management are due to a number of reasons, among which are:

• a fairly simple implementation of remote control systems and their low operational cost, compared to ships, which are controlled by highly qualified and with the use of complex automatic navigation systems by the crew;

• the possibility of a reasonable reduction in the requirements for the level of navigational training of the crew of a controlled vessel;

• possibility of group management of several vessels from one control center;

• safety of management personnel, as they are located at the onshore control center.

At the same time, the fundamental principle of the implementation of remote control of ships is the use of high-precision navigation support systems, which, at present, can only be implemented using satellite navigation systems.

Thus, the purpose of this work is to study the system and algorithms of remote control of ships based on the use of satellite navigation systems.

3. OVERVIEW OF EXISTING SOLUTIONS

Modern approaches and methods of solving the problem of research and design of remote control systems for water vehicles of various purposes and types are interdisciplinary and are based on modern technologies of the theory of automatic control systems, information processing, and the use of satellite navigation systems. The current state of the problem is given in [1-3, 5].

Numerous works have been devoted to the development of the composition, structure and algorithms of remote control systems for ships, we note, first of all, works [1, 4, 6-8], where much attention is paid to the problems of using, processing and optimizing information coming from satellite navigation systems [1-3, 6].

GLONASS/GPS technology includes there are three key components: space, control and user. GLONASS/GPS are used to determine coordinates using systems called satellite radio navigation systems (SRNS).

This definition applies to both GPS and GLONASS systems. Satellites constantly broadcast radio navigation signals containing data on their position and time, as well as special codes. The coordinates of the vessel are found using GLONASS/GPS equipment.

Works [1, 4, 6] describes the basic principle of operation, which consists in comparing the periods between the time of receiving signals from satellites by equipment on the ship and the time of sending these signals.

Here is also an algorithm for the operation of the satellite navigation system of ships, in the so-called differential mode, which is used to better determine the location of the vessel.

The differential mode is implemented using a special receiver called a base station.

In [6], an algorithm is described by which the known coordinates of the vessel are compared with those calculated using special processing algorithms. The computer of the base station makes changes, which are transmitted to the skippers via communication channels.

Among the ways of implementing the differential method, of which the following can be distinguished today:

- differential navigation systems based on code measurements are based on the principle of measuring and processing imaginary long distances. Their error in determining the location of the vessel ranges from fractions of a meter to several meters;
- systems of differential navigation by pseudo-phase measurements provide the determination of the coordinates of the vessel with very high accuracy.

In general, it can be stated that during the use of the satellite navigation system, it has proven its reliability and high accuracy.

But increasing its efficiency and expanding its application areas requires the use of special mathematical methods and computational tools for processing large amounts of information.

The works [3, 7-11] describe the principles of operation, algorithms and computer implementation of the ship's autonomous auto pilots (auto steering) installed on board the ship and solving the problem of direct control of the ship along the program trajectory, obstacle avoidance, control in a confined space, in conditions of external disturbances, lack of complete information about the coordinates of the ship, etc., including in cases of managing groups of vessels operating in the same area.

Solving the problem of remote control of a vessel in conditions of incomplete information requires the use of modern effective methods of adaptive systems and neural network technologies, which is discussed in [3-5, 9].

4. MAIN RESULTS

In remote control systems, as a rule, the use of automatic control and control facilities located on board the vessel is limited. All data is transmitted and processed in digital form, which ensures reliable transmission and high accuracy of data presentation. The structure of the digital remote control system is shown in Fig. 1.

Due to the intensive use of communication channels, the remote control system should use control algorithms that require a minimum amount of information for transmission and processing, and allow for the necessary calculations to be carried out quickly enough [3, 4, 12].

The purpose of controlling the movement of the vessel is either to reach a point with set coordinates with a given accuracy, or to guide the vessel along a given route.

The control is carried out on the basis of data on the coordinates of the vessel obtained using a satellite navigation system. After receiving the coordinates from the vessel, the coastal control station calculates the control parameters that are transmitted to the vessel. The control can be carried out both in fully automatic mode and in automated mode, when the parameters can be adjusted by the operator. Having received the control parameters, the vessel moves in accordance with them, and after the time of the control step has elapsed, it again transmits its coordinates to the control station, Figure 2.

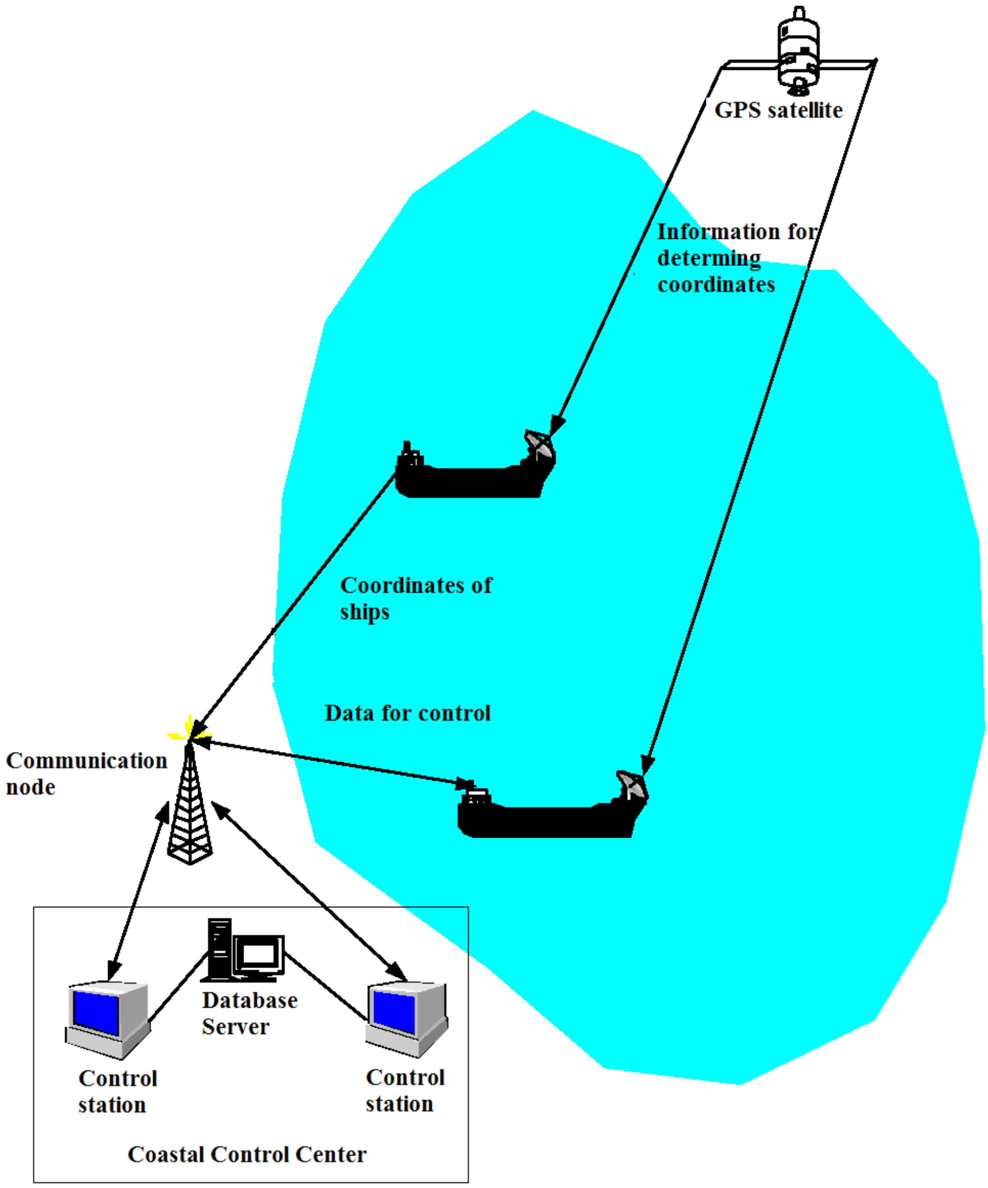

Fig. 2. Structure of the ship traffic remote control system

It is taken into account that various factors influence the vessel during its movement (wind, currents, waves, etc.), therefore, there is a deviation from the specified trajectory of movement and at the end of the control step the vessel can come to a point whose coordinates deviate from the calculated ones. It should be noted the specifics of the control system, which is taken into account when developing control algorithms:

• the on-board computer has the necessary capabilities for processing satellite signals, generating signals to the ship's actuators, counting the duration of the control step (it is possible to implement control and counting time intervals by other means, for example, by the ship's crew);

• the parameters of the vessel's engine (power) and the characteristics of the vessel (dimensions, weight, etc.) provide for the possibility to abandon the consideration of inertia during movement;

• the navigation system allows you to determine the coordinates of the vessel with the required accuracy;

• the time of calculations and data transmission is considered to be sufficiently small, which eliminates the delay;

• the coastal control station has the ability to control several vessels at the same time.

In our case, it is possible to use the average time or the average number of steps to achieve the goal as criteria for the quality of management.

However, there are cases when it is only necessary to achieve a given goal.

Restrictions on the speed of movement of the vessel, restrictions on the duration of the control interval (step), restrictions on the distance traveled by the vessel in one control step can act as restrictions when making management decisions.

We introduce the following notation:

X_0, Y_0 – coordinates of the starting point of the vessel along the abscissa and ordinate axes;

x_k, y_k - the real coordinates of the vessel along the axes at the end of the k-th control step;

X, Y – coordinates of the ship's moving target along the axes;

v_{xk}, v_{yk} – calculated components of the vessel's speed along the coordinate axes at the k-th control step;

t_k is the duration of the k–th control step (the interval of the control step);

h_{xk}, h_{yk} are the control coefficients along the coordinate axes at the k-th control step;

Δ_{xk}, Δ_{yk} are the values of the vessel's drift (deviation) along the coordinate axes at the k–th control step (random variables), $\Delta_{xk} = x_k - (x_{k-1} + t_k v_{xk})$, $\Delta_{yk} = y_k - (y_{k-1} + t_k v_{yk})$. The random variables Δ_{xk}, Δ_{yk} are mutually independent of each other and in k.

The case of simple control is investigated, when the impact of external factors on the vessel is taken into account as an independent random variable that determines the magnitude of the coordinate demolition of the vessel at each step. At the same time, for each coordinate, you can write equations that allow you to calculate the control at each step, depending on the actual coordinates obtained at the end of the previous step:

$$x_k = x_{k-1} + t_k v_{xk} + \Delta_{xk},$$

$$y_k = y_{k-1} + t_k v_{yk} + \Delta_{yk},$$

where

$$t_k v_{yk} = (Y - y_{k-1}) / h_{yk},\ t_k v_{xk} = (X - x_{k-1}) / h_{xk},\ t_k v_{yk} = (Y - y_{k-1}) / h_{yk},$$

$$x_0 = X_0,\ \ y_0 = Y_0,\ \ t_k = (\sqrt{\frac{(X - x_{k-1})^2}{h_{xk}^2} + \frac{(Y - y_{k-1})^2}{h_{yk}^2}}) / v_k,\ \ \frac{h_{xk} v_{xk}}{h_{yk} v_{yk}} = \frac{X - x_{r-1}}{Y - y_{k-1}}.$$

The coefficients x_k, y_k are used to ensure the speed limits of the vessel.

It is proved that if $h_{xk} = n_x \geq 1$ and $h_{yk} = n_y \geq 1$ and $|\mathbf{M}\{\Delta_{xk}\}| \leq z_x < \infty$, and $|\mathbf{M}\{\Delta_{yk}\}| \leq z_y < \infty$, then for $k \to \infty$ the sequence $\mathbf{M}\{x_k\}$ and $\mathbf{M}\{y_k\}$ converge and inequalities are valid for their limits:

$$\lim_{k\to\infty}(\mathbf{M}\{x_k\}) \leq X + z_x n_x,$$

$$\lim_{k\to\infty}(\mathbf{M}\{y_k\}) \leq Y + z_y n_y$$

The obtained result shows that the proposed control algorithm can lead to deviations from the goal depending on the values n_x, n_y and average values of random variables Δ_x, Δ_y. However, if $\mathbf{M}\{\Delta_x\} = \mathbf{M}\{\Delta_y\} = 0$, this algorithm allows you to ensure the necessary accuracy of achieving the goal.

To calculate the accuracy and convergence rate, it is obtained that

$$| X - \mathbf{M}\{x_k\} | = | (x_0 - X)(\frac{n_x - 1}{n_x})^k + z_x n_x - z_x n_x (\frac{n_x - 1}{n_x})^k |.$$

The time required for k steps at the same speed v_x of the vessel is estimated by the formula:

$$T_k = (X - x_0)\frac{n_x^k - 1}{n_x^{k+1} - n_x^k} + \frac{1}{v_x}\sum_{r=1}^{k-1}\frac{\Delta_{k-r}}{n_x^r} \leq (X - x_0)\frac{n_x^k - 1}{n_x^{k+1} - n_x^k} + \frac{z_x}{v_x}(\frac{n_x^{k-1} - 1}{n_x^k - n_x^{k-1}}).$$

A modification of the algorithm is investigated, which takes into account that the deviation, as a rule, is proportional to the duration of the control step: $\Delta_x(t) = u_x t$ and $\Delta_y(t) = u_y t$. Then:

$$x_k = x_{k-1} + t_k v_{xk} + t_k u_{xk},$$

$$y_k = y_{k-1} + t_k v_{yk} + t_k u_{yk},$$

where $t_k v_{xk} = (X - x_{k-1}) / h_{xk}$, $t_k v_{yk} = (Y - y_{k-1}) / h_{yk}$.

It is proved that if $h_{xk} = n_x \geq 1$, $h_{yk} = n_y \geq 1$ and $|\mathbf{M}\{u_x\}| = d_x$, $|\mathbf{M}\{u_y\}| = d_y$, then, at $|\frac{d_x}{v_{xr}}| < 1$, $|\frac{d_y}{v_{yr}}| < 1$ and for any r, the sequences $\mathbf{M}\{x_k\}$, $\mathbf{M}\{y_k\}$ converge at $k \to \infty$ and their limits are equal:

$$\lim_{k\to\infty}(\mathbf{M}\{x_k\}) = X,\ \lim_{k\to\infty}(\mathbf{M}\{y_k\}) = Y.$$

The control algorithm is investigated, which introduces corrections to the motion parameters depending on the demolition at the previous control step:

$$x_k = x_{k-1} + t_k v_{xk} + \Delta_{xk},$$

where

$$y_k = y_{k-1} + t_k v_{yk} + \Delta_{yk},\ t_k v_{xk} = (X - x_{k-1}) / h_{xk} - \Delta_{xk-1},$$

$$t_k v_{yk} = (Y - y_{k-1}) / h_{yk} - \Delta_{yk-1}.$$

It is proved that if $h_{xk} = n_x \geq 1$, $h_{yk} = n_y \geq 1$ and $|M\{ \Delta_{xk}\}| = z_x < \infty$, $|M\{\Delta_{yk}\}| = z_y < \infty$, then for the sequence $M\{x_k\}$ and $M\{y_k\}$ converge and the limits are equal:

$$\lim_{k\to\infty}(\mathbf{M}\{x_k\}) = X,\ \lim_{k\to\infty}(\mathbf{M}\{y_k\}) = Y.$$

From the results obtained for the algorithms under consideration, the convergence of sequences x_k, y_k on average of the order of 2, because $\lim_{k\to\infty}\mathbf{M}\{|x_k - X|^2\} = \lim_{k\to\infty}\mathbf{M}\{(x_k - X)^2\} = 0$, $\lim_{k\to\infty}\mathbf{M}\{|y_k - Y|^2\} = \lim_{k\to\infty}\mathbf{M}\{(y_k - Y)^2\} = 0$, if there are limits $\lim_{k\to\infty}\mathbf{M}\{x_k\} = \mathrm{X}$, $\lim_{k\to\infty}\mathbf{M}\{y_k\} = \mathrm{Y}$.

It follows that for all algorithms.

Thus, three different remote control algorithms are investigated and their convergence is shown. In general, to account for unpredictable external impacts on the vessel, it is effective to use modern approaches based on the principles of fuzzy logic and adaptive control [3, 5, 9, 13, 14].

5. CONCLUSION

The analysis of systems and methods of automatic control of the vessel's movement was carried out, which made it possible to identify the basic principles of remote control systems, the specifics of their operation and advantages over traditional control systems.

It is shown that the implementation of such systems requires modern means of communication and data processing, as well as control algorithms based on a limited amount of information about the state of the vessel.

The structure of the remote control system has been developed, including a satellite navigation system, a coastal control center, computer information processing facilities and a database with cartographic information. The system provides the ability to control several vessels, the use of automatic and automated control modes.

REFERENCES

[1] Matveev A. A., Kuznetsov V.N., Gaskarov V.D. Review of technical means and methods of satellite navigation of ships. *Bulletin of the Admiral S. O. Makarov State University of the Sea and River Fleet*, No 1 (vol. 35), 2016, pp. 207-214.

[2] Pırtı A., Yucel M.A. Evaluating Repeatability of RTK (GPS and Galileo/GPS) performance in the analysis of points located in areas with and without obstructions. *Reports on Geodesy and Geoinformatics*, No 1 (vol. 113), 2022, pp. 11-20.

[3] Bolnoкin V.E., Uy D.V., Manh D.X. *Adaptive control for group of ships (fuzzy logic approach)*, Vietnam, Haiphong, National Maritime University printing company, 2007, 244 p.

[4] Frolov V.N. Technologies of unmanned navigation. *Transport of the Russian Federation*. No 4 (vol. 2018), 2018, pp. 17-21.

[5] Bolnokin V.E., Mutin D.I., Ngo Anh Tuan, Povalyaev A.D. Models of adaptive control system design for nonlinear dynamic plants based on a neural network. *Automation and Remote Control*, No 3 (vol. 76), 2015, pp. 493-499.

[6] Nyrkov A.P., Vaygandt N.Y. Data integrity control in the transport monitoring. *Journal of University of Water Communications*, No 1 (vol. 2013), 2013, pp. 54-61.

[7] Niyu H., Lu Yu., Savva N., Surdas A. Energy-efficient trajectory planning algorithm for unmanned ground vehicles. *Ocean engineering*, No 1 (vol. 161), 2018, pp. 308-321.

[8] Rujian Ya., Sho P., Han-bin S., Yong-Jie P. Development and tasks of an unmanned marine vehicle. *Journal of Marine Science and Applications*, No 4 (vol. 9), 2010, pp. 451-457.

[9] Bolnokin V.E., Ho D. Lok. *Adaptive control based on fuzzy controllers and neural network technology,* Yelm, Scientific Book, 2012, 280 p.

[10] Xie J., Wang H., Li P., Meng Y. *Satellite Navigation Systems and Technologies*, Springer, 2021, 399 p.

[11] Wright, G.R., Intelligent Autonomous Ship Navigation using Multi-Sensor Modalities. *TransNav*, No. 3 (vol. 13), 2019, pp. 503-510.

[12] Romansky R. Program Environment for Investigation of Micro-level Computer Processing. *International Journal on Information Technologies and Security,* No.1 (vol. 13), 2021, pp. 67-76.

[13] Savyanavar A.S., Ghorpade V.R. Node Classification Model for On-the-fly Computing Based Mobile GRIDS Using Rough Set Theory, *International Journal on Information Technologies and Security,* No.3 (vol. 13), 2021, pp. 15-26.

[14] Chauhan S., Gupta N.L. Quantum Dialogue Protocol Using Six Qubit Cluster States with Optimal Superdense Coding, *International Journal on Information Technologies and Security,* No.4 (vol. 13), 2021, pp. 83-98.

Information about the authors:

Vitalii Evgenievich Bolnokin – Dr. Sci (IT), professor, professor of Mechanical Engineering Research Institute of the Russian Academy of Sciences (IMASH RAN), Moscow, areas of scientific research – system analysis, optimization, simulation of complex objects

Alexey Fedorovich Kaperko – Dr. Sci (IT), professor, general designer of National research University Higher School of Economics, areas of scientific research – information technology, computer networks, reliability modeling and engineering

Sergey Alexandrivich Sorokin, Dr. Sci (IT), general designer of Computing System Research and Development Institute (NIIVK, JSC), areas of scientific research - information technology, computer networks, reliability modeling and engineering

Manuscript received on 14 July 2022