Automatic Optimal Control of a Vessel with Redundant Structure of Executive Devices

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Abstract. The article considers the issues of automatic control of the vessel movement with a redundant control structure. Redundant structures are now widely used on all vessels with a dynamic positioning system to improve control efficiency (accuracy, maneuverability, reduce energy consumption and emissions), reliability and environmental safety. A brief review of the literature on the use of redundant structures to improve control efficiency is made. In open sources, the authors have not found solutions that improve the efficiency of the control by using redundant structures of actuators. Therefore, it was concluded that the development of such systems is relevant. Several schemes for splitting control into executive devices of a redundant structure, including an optimal splitting scheme, are considered. A comparative analysis of the considered splitting schemes with the optimal one is carried out. Comparative analysis showed that the use of optimal control of the redundant structure of actuators allows increasing the accuracy of dynamic positioning by (20–40)%, depending on the direction of the created control, as well as reducing fuel consumption by (30–100)%, which determines its advantages over known solutions. The mathematical and software support for an automatic optimal control system with redundant control has been developed. The operability and efficiency of the mathematical and software support were tested in a closed circuit with a control object in the MATLAB environment. The conducted experiments confirmed the operability and efficiency of the developed method, algorithms and software and allow to recommend them for practical use in the development of vessel control systems with redundant control structures.

Keywords: Redundant control structures · Optimal control · Splitting scheme · Control quality criterion · Mathematical models

1 Introduction

Currently a large number of vessels such as Platform supply vessel (PSV)/ Offshore Support Vessel (OSV), Diving Support (DSV's) and ROV Support

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Vessels, Drill Ships, Cable Lay and Repair Vessels, Pipe Laying Ships, Dredgers, Crane Barge or Crane Vessel, Rock Dumping Vessels, Passenger Vessels, Specialist - Semi-submersible Heavy-Lift Vessels, Mobile Offshore Drilling Units/Ships (MODUs), Shuttle Tanker, Naval Vessels and Operations [1], operate under risk conditions, therefore there are increased requirements for reliability, accuracy and maneuverability. To meet these requirements, the control systems such vessels, which is called a dynamic positioning system (DP-system), are equipped with high-precision measuring devices that allow determining with high accuracy the absolute position of the vessel (DGPS systems), or the position relative to another object (Reference systems), redundant control structures that ensure reliability in control, on-board computer complex and software for the automation of control processes [3–7,11,20,21]. These vessels have the greatest degree of control processes automation in order to minimize the influence of the human factor. Human factor is the weakest link in the vessel control system [18,19,23,25,26]. Manual control of the vessel is extremely suboptimal, it can lead to unacceptable deviations of the controlled parameters, increased fuel consumption, increased loads on the hull and even destruction of the hull in a storm. The work [8,9,17] is devoted to the measurement of loads. The issues of improving control efficiency through the use of automated systems have also been considered by the authors earlier. So, in article [29] there were considered the issues of increasing reliability due to automatic detection and parrying of failures, in articles [33] there were considered the issues of automatic divergence with many targets, including maneuvering ones and in article [32] there were considered the issues of increasing the control accuracy due to the use of the meter mathematical model in on-board controller. Control redundancy is typically used to improve reliability. At the same time, redundancy in control can also be used to increase the efficiency of the control system [30]. To ensure three-dimensional controllability simultaneously in the channels of longitudinal, lateral and rotational movements, the minimum required number of independent controls should be $U = 3$. At the same time, on many transport vessels the number of independent controls is $U = 3$ (the angle of the telegraph and the angle of the stern rudder). On such vessels, one stern rudder is used for sequential development of lateral and angular deviations (first, lateral deviation is worked out by changing the course, then the course itself is worked out). In the presence of external influences, such vessels move along a trajectory with a drift angle, which leads to additional fuel consumption. The use of schemes with sufficient $U = 3$ control already makes it possible to increase the reliability (due to the use of an additional rudder) and the quality of control (due to the possibility of keeping the vessel on the route with a zero drift angle, reducing the hydrodynamic drag, saving fuel, reducing emissions, preservation of the environment).

The object of the research is the processes of the vessel automatic optimal control with redundant structure of executive devices.

The subject of the research is the method, algorithms and software of the vessel automatic optimal control system with redundant structure of executive devices.

The purpose of the research is to improve the efficiency of automatic vessel control with a redundant structure of executive devices.

2 Problem Statement

Figure 1 shows a control scheme of the considered redundant structure.

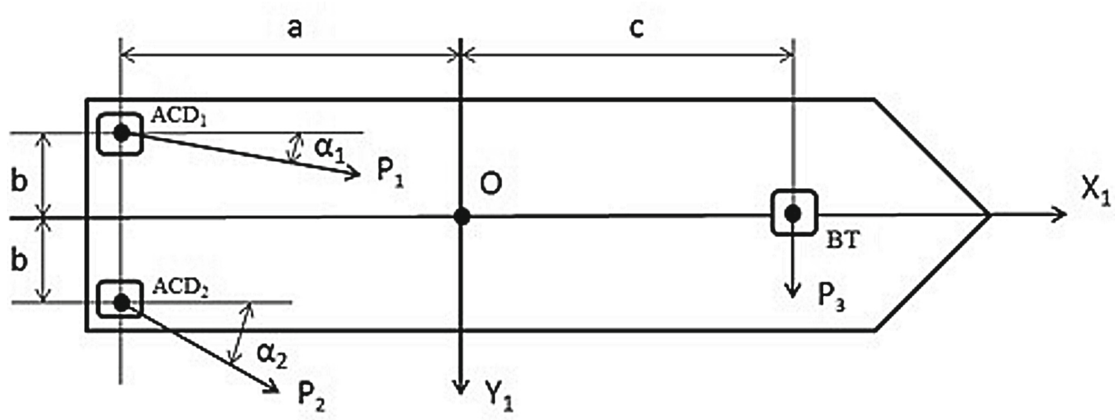


Fig. 1. Control scheme of the considered redundant structure

It is required to find such control parameters $P_1, \alpha_1, P_2, \alpha_2, P_3$, that would ensure the optimization of the control quality function (1) in the presence of control constraints (2) and (3).

$$Q(P_1, P_2, P_3) \Rightarrow opt. \tag{1}$$

$$\vec{U} = \vec{f_u}(P_1, \alpha_1, P_2, \alpha_2, P_3) \tag{2}$$

$$|P_1| \leq P_1^{max}, |P_2| \leq P_2^{max}, |P_3| \leq P_3^{max}, |\alpha_1| \leq \pi, |\alpha_2| \leq \pi, \tag{3}$$

where $Q(\bullet)$ is the quality control function, $\vec{U}(P_x, P_y, M_z)$ is the vector of required control forces and moments in control channels, $\vec{f_u}(\bullet)$ is the mathematical model of the control structure, P_1, P_2 is the thrust force of the screw of the first and second ACD, respectively, α_1, α_2 is the rotation angle of the first and second ACD respectively, P_3 is the bow thruster force.

3 Literature Review

The article [27] discusses the issues of restoring the operability of the tracking system, in the event of random undefined failures of the executive mechanisms, using backup drives. Random undefined failures of actuators, the time of failure, the nature and values of which may not be known, pose serious problems in the design of feedback control, since such failures can introduce large structural and parametric uncertainties. An overview of tracking systems with adaptive compensation of failures is given, which allow efficient use of redundancy. Methods for solving these problems are proposed, based on the use of direct or indirect approaches of adaptive control for direct adaptive compensation of drives failures without explicit detection of failure, for fast and effective restoration of the system's performance.

In [12], the issues of parrying failures in an active radial magnetic bearing tightly connected to a redundant support structure are considered. A strategy of fault tolerance control by reconfiguring the magnetic flux in order to keep the bearing force constant is proposed. Using the FSS (Fault State Series) to describe the fault condition of the drives, a current sharing index rule has been developed to address various fault conditions. A fault-tolerant control model has been created to test the generation of electromagnetic force in rigidly coupled standby support structures after failure of the actuators. The simulation results showed that the fault-tolerant control strategy makes it possible to stabilize the rotor rotation in the event of failure of some of the actuators.

The article [14] discusses the issues of creating a fault-tolerant steering system to improve the reliability of unmanned underwater vehicles. To implement fault-tolerant control, redundancy control strategies and algorithms are used. The analysis carried out by the authors showed that the reliability of the control system, in which the strategy and redundancy control algorithms are used, is significantly better than the traditional configuration.

The article [16] explores methods for control redundancy of electro-hydraulic drives based on fuzzy aggregation, Mamdani fuzzy logic rules and the theory of fuzzy neural networks. Fault identification and isolation as well as system recovery are performed by combining fuzzy clustering with Mamdani fuzzy control, fuzzy neural network and redundancy control. The methods proposed in the article allow solving the problem of erroneous judgments, as well as avoiding undefined states in the system.

The article [22] explores a new approach to the distribution of the forces of an autonomous underwater vehicle (AUV) engine. Typically, the number of actuators in the AUV is more than the minimum required to achieve the required movement. The possibilities of using an excessive number of actuators to parry faults during operation are studied. The scheme for the resolution of redundancy is presented, which allows the formation of the necessary support forces to create the desired movement. These support forces are used by the on-board AUV controller to create the required motion. The results of computer simulation confirm the efficiency of the proposed scheme.

The article [15] considers the issues of unloading the excess structure of the spacecraft flywheels in the Earth's magnetic field. A key feature of the work is the use of arbitrary parameters in the general solution of an indefinite system of linear algebraic equations as additional control parameters. For the minimally redundant flywheel structure and magnetic moments of the unloading system, control algorithms are synthesized that provide asymptotic stability of the solution of model equations describing the motion of the flywheel. The performance of the proposed algorithms and the features of the process of unloading the flywheels are investigated by the example of the controlled motion of a spacecraft while maintaining a three-axis orbital orientation.

In [13], the issues of planning the movement of the welding torch are considered. The angular redundancy that exists during the welding process is taken into account to plan and optimize the welding torch path by minimizing the angular cost of the torch. Some strategies for improving the efficiency of the proposed method are also considered, such as the heuristic sampling strategy, which is used to control scheduling, the collision checking strategy, which is used to improve the efficiency of collision checking. The proposed method is very effective in solving complex problems of motion planning, for example, in a welding environment, where the weld is located in various difficult environments. The results of the performed experiments showed that the proposed method can find not only a possible collision-free path, but also optimize the angle of the torch burner with an increase in the number of iterations.

The work [2] provides recommendations for practical maneuvering of a vessel with two stern ACDs. Recommended controls for implementation of several fixed modes are considered: sailing slow ahead, sailing full ahead, sailing slow astern, sailing full astern, turning to port, turning to starboard, turning the stern to port, turning the stern to starboard, normal stopping, emergency crash stop, turning on the spot to port, turning on the spot to starboard, walking the vessel slowly to port, walking the vessel fast to port, walking the vessel slowly to starboard, walking the vessel fast to starboard. Taking into account that these modes are implemented manually, the angles of the ACD setting in all modes, except for the modes walking the vessel fast to port and walking the vessel fast to starboard, are selected as multiples of 45°.

The article [30] discusses the issues of automatic control of the vessel's movement using excessive control, which allows to organize the movement of the vessel without a drift angle, to reduce the hydrodynamic resistance and fuel consumption. Issues of reducing energy consumption and fuel economy on board, as well as related issues of reducing emissions and improving the environment are especially relevant at the present time. Mathematical, algorithmic, and software have been developed for an on-board controller simulator of a vessel's motion control system with excessive control, the operability and efficiency of which has been verified by numerical simulation in a closed circuit with a mathematical model of the control object.

The article [31] discusses the issues of mathematical support of the Information and Risk Control System for the offshore vessel operating in high risk areas near oil or gas platforms, other large moving objects. Vessels operating in high-risk areas are equipped with dynamic positioning systems and excessive control, which allows to increase the reliability, maneuverability and quality of control. Minimally excessive control structure with two stern Azimuth Control Devices is considered. To dispensation redundancy, three control splitting algorithms were considered, analytical expressions for control splitting were obtained. There was carried out a comparative analysis of the considered splitting algorithms between themselves and the prototype according to the minimum - criterion. A comparative analysis showed that the splitting algorithm used in the prototype are special cases of the considered algorithms for dispensation redundancy. Operability and efficiency of the algorithmic and software of the vessel control system operating in high risk areas, verified by mathematical modeling at imitation modeling stand.

As can be seen from the above review, control redundancy is mainly used to increase the reliability of actuators [12,14–16,22,27], optimize motion using the example of a welding torch [13], increase maneuverability using the example of a vessel with ACD in manual control mode [2] and automatic control mode [30,31].

In open sources, the authors have not found an automatic control system for the movement of a vessel with a considered redundant structure, which would optimize control. Therefore, the development of such systems is an urgent scientific and technical task.

4 Materials and Methods

The mathematical model $\vec{f_u}(\bullet)$ of the control structure (2), in projections on the axis of the related coordinate system, has the form

$$P_x = P_1 \cos\alpha_1 + P_2 \cos\alpha_2, \tag{4}$$

$$P_y = P_1 \sin\alpha_1 + P_2 \sin\alpha_2 + P_3, \tag{5}$$

$$M_z = P_1 b \cos\alpha_1 - P_2 b \cos\alpha_2 - P_1 a \sin\alpha_1 - P_2 a \sin\alpha_2 + P_3 c. \tag{6}$$

As can be seen from Eqs. (4)–(6), for the implementation of control actions P_x, P_y, M_z in the channels of longitudinal, lateral and rotational motions, respectively, there are five control parameters $P_1, \alpha_1, P_2, \alpha_2, P_3$, that is, the control redundancy for the considered control structure is $5 - 3 = 2$. Redundancy in control means the availability of free control parameters that can be used to optimize control processes. Below we will consider optimal controls of the considered redundant structure for the following control quality functions:

$$Q_1(P_1, P_2, P_3) = P_1^2 + P_2^2 + P_3^2 \Rightarrow min, \tag{7}$$

Quality control function (7) minimizes power consumption.

$$Q_2(P_1, P_2, P_3) = |P_x| \Rightarrow max, \tag{8}$$

The quality control function (8) implements the maximum control action in the positive or negative directions of the axis OX_1, respectively, which allows to create the maximum speed of longitudinal movement and reduce the time for longitudinal movement.

$$Q_2(P_1, P_2, P_3) = |P_y| \Rightarrow max, \tag{9}$$

The control quality function (9) implements the maximum control action in the positive or negative directions of the axis OY_1, respectively, which makes it possible to create the maximum speed of lateral movement and reduce the time for lateral movement.

$$Q_2(P_1, P_2, P_3) = |M_z| \Rightarrow max, \tag{10}$$

The control quality function (9) implements the maximum control torque around the axis OZ_1 in the positive or negative directions, respectively, which allows to create the maximum angular rotation speed in the yaw channel and reduce the turnaround time.

Unfortunately, it is not possible to obtain an analytical solution to the considered optimization problem. Therefore, further study of the structure was carried out by numerical methods in the MATLAB environment. For this, the numerical optimization procedure optimtool of the Optimization Toolbox library was used.

The results of optimization of the control quality function $Q_1 = P_1^2 + P_2^2 + P_3^2$ for various values of the vector of control actions $\vec{U}$ are presented in Table 1.

Table 1. Optimization results of the control quality function $Q_1 = P_1^2 + P_2^2 + P_3^2$

Num	$\vec{U}$	P_1	P_2	α_1	α_2	P_3	Q_1
1	(1;0;0)	0,5	0,5	0	0	0	0,5
2	(0,866;0,5;0)	0,465	0,438	15,87	16,73	0,247	0,47
3	(0,5;0,866;0)	0,35	0,315	38,79	43,95	0,428	0,4
4	(0;1;0)	0,255	0,254	83,94	96,09	0,494	0,37
5	(−0.5;0,866;0)	0,316	0,35	136,09	141,19	0,428	0,41
6	(−0,866;0,5;0)	0,433	−0,5	−179,92	−30,08	0,25	0,5
7	(−1,0,0)	0,5	−0,5	−179,92	−0,11	0	0,5
8	(0,0,1)	−0,006	−0,007	83,03	96,67	0,013	0,000254

The results of optimization of the control quality functions $Q_2 = P_x, Q_2 = P_y, Q_2 = M_z$ are presente in Table 2. The table also shows the values of the function Q_1, which can be used to estimate the energy consumption of the structure for the formation of the control vector $\vec{U}$.

To compare the obtained characteristics of the optimal control scheme with the characteristics of other control schemes, several other schemes should be considered. Equal-vectorus control scheme. To implement this scheme, we use two additional constraint equations $P_2 = P_1$ and $\alpha_2 = \alpha_1$ (the vector of the screw force ACD1 is equal to the vector of the screw force ACD2). Taking into account additional constraint equations, the system of Eqs. (4)–(6) takes the form

$$P_x = P_1 \cos\alpha_1 + P_1 \cos\alpha_1 = 2P_1 \cos\alpha_1 \tag{11}$$

Table 2. Optimization results of the control quality functions $Q_2 = P_x$, $Q_2 = P_y$, $Q_2 = M_z$

Num	$\vec{U}$	P_1	P_2	α_1	α_2	P_3	Q_2	Q_1
1	($P_x \Rightarrow max$;0;0)	1,00	1,00	0,00	0,00	0,00	2,00	2,00
2	($P_x \Rightarrow min$;0;0)	−1,00	−1,00	0,00	0,00	0,00	−2,00	2,00
3	($P_y \Rightarrow max$;0;0)	1,00	1,00	26,76	153,28	0,5	1,4	2,25
4	($P_y \Rightarrow min$;0;0)	1,00	1,00	−26,76	−153,28	−0,5	−1,4	2,25
5	($M_z \Rightarrow max$;0;0)	1,00	0,865	−30,08	179,92	0,5	55,77	1,998
6	($M_z \Rightarrow min$;0;0)	−1,00	0,865	−30,08	0,00	−0,5	−55,77	1,998

$$P_y = P_1 \sin\alpha_1 + P_1 \sin\alpha_1 = 2P_1 \sin\alpha_1 + P_3 \tag{12}$$

$$\begin{aligned} M_z &= P_1 b \cos\alpha_1 - P_1 b \cos\alpha_1 - P_1 a \sin\alpha_1 - P_1 a \sin\alpha_1 + P_3 c \\ &= -2P_1 a \sin\alpha_1 + P_3 c. \end{aligned} \tag{13}$$

From Eq. (13), taking into account Eqs. (11) and (12), we find

$$M_z = -P_y a + P_3(a + c),$$

where do we find

$$P_3 = \frac{M_z + P_y a}{(a + c)}. \tag{14}$$

After dividing Eq. (12) by Eq. (11), we find

$$\alpha_1 = \arctan(\frac{P_y - P_3}{P_x}), \tag{15}$$

$$\alpha_1 = \alpha_2. \tag{16}$$

From Eq. (11), or Eq. (12), we find

$$P_1 = \frac{P_x}{2\cos\alpha_1}, \tag{17}$$

$$P_1 = \frac{P_y - P_3}{2\sin\alpha_1}, \tag{18}$$

$$P_2 = P_1. \tag{19}$$

Equations (14)–(19) make it possible to determine the control parameters that implement the vector of the required control action $\vec{U} = (P_x, P_y, M_z)$.

Table 3 shows the control parameters and functions $Q_1 = P_1^2 + {P_2}^2 + {P_3}^2$ for the equal-vectorus control.

Equal-modulus control scheme with orthogonal vectors. In this case, the additional constraint equations have the form $P_2 = P_1, \alpha_2 = \alpha_1 + \frac{\pi}{2}$ (the force of the

Table 3. Control parameters and functions Q_1 for the equal-vectorus control

Num	$\vec{U}$	P_1	P_2	α_1	α_2	P_3	Q_1
1	(1;0;0)	0,5	0,5	0	0	0	0,5
2	(0,866;0,5;0)	0,45	0,45	16,10	16,10	0,25	0,468
3	(0,5;0,866;0)	0,33	0,33	40,89	40,89	0,433	0,406
4	(0;1;0)	0,25	0,25	90,00	90,00	0,50	0,375
5	(−0.5;0,866;0)	−0,33	−0,33	−40,90	−40,90	0,433	0,40
6	(−0,866;0,5;0)	−0,45	−0,45	−16,10	−16,10	0,25	0,469
7	(−1,0,0)	−0,5	−0,5	0,00	0,00	0,00	0,5
8	(0,0,1)	0,00622	0,00622	−90,00	−90,00	0,0124	0,000232

ACD1 screw is equal to the ACD2 screw force in magnitude and is perpendicular to it).

Taking into account additional constraint equations, the system of Eqs. (4)–(6) can be represented in the form

$$P_x = P_1 \cos\alpha_1 - P_1 \sin\alpha_1, \tag{20}$$

$$P_y = P_1 \sin\alpha_1 + P_1 \cos\alpha_1 + P_3, \tag{21}$$

$$M_z = P_1 \cos\alpha_1 (b-a) + P_1 \sin\alpha_1 (b-a) + P_3 c, \tag{22}$$

We multiply Eq. (21) by (b-a) and subtract it from Eq. (22)

$$M_z - P_y(b-a) = P_3 c - P_3(b-a),$$

where do we find

$$P_3 = \frac{M_z - P_y(b-a)}{a-b+c}. \tag{23}$$

Add and subtract Eqs. (20) and (21)

$$P_y + P_x = 2P_1 \cos\alpha_1 + P_3,$$

$$P_y - P_x = 2P_1 \sin\alpha_1 + P_3.$$

From the last equations we find

$$\alpha_1 = \arctan\left(\frac{P_y - P_3 - P_x}{P_y - P_3 + P_x}\right). \tag{24}$$

$$\alpha_2 = \alpha_1 + \frac{\pi}{2}. \tag{25}$$

From Eqs. (20) and (21) we find

$$P_1 = \frac{P_x}{\cos\alpha_1 - \sin\alpha_1}, \tag{26}$$

or

$$P_1 = \frac{P_y - P_3}{\cos\alpha_1 + \sin\alpha_1}, \tag{27}$$

$$P_2 = P_1. \tag{28}$$

Equations (23)–(28) make it possible to determine the control parameters that implement the vector of the required control action $\vec{U} = (P_x, P_y, M_z)$ in equal-modulus control with orthogonal vectors.

Table 4 shows the control parameters and functions $Q_1 = P_1^2 + {P_2}^2 + {P_3}^2$ for equal-modulus control with orthogonal vectors.

Table 4. Control parameters and functions Q_1 for the equal-modulus control with orthogonal vectors

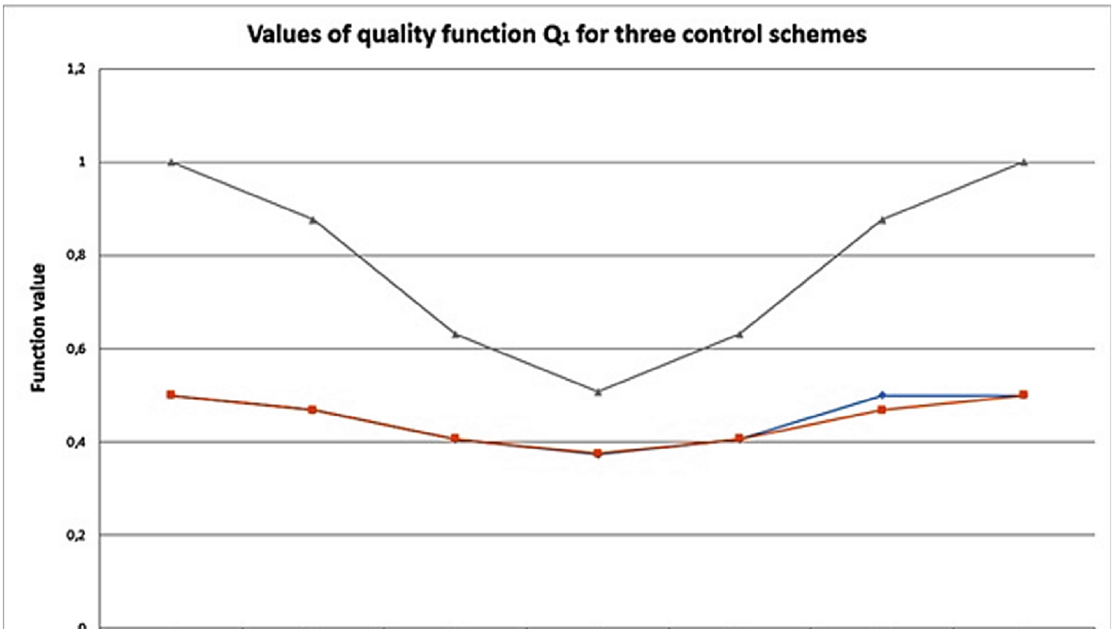
Num	$\vec{U}$	P_1	P_2	α_1	α_2	P_3	Q_1
1	(1;0;0)	0,707	0,707	−45,00	45,00	0,00	1,00
2	(0,866;0,5;0)	0,644	0,644	−26,99	63,01	0,218	0,877
3	(0,5;0,866;0)	0,494	0,494	−0,72	89,28	0,378	0,63
4	(0;1;0)	0,398	0,398	45,00	135,00	0,437	0,51
5	(−0.5;0,866;0)	−0,494	−0,494	−89,28	0,72	0,378	0,631
6	(−0,866;0,5;0)	−0,644	−0,644	−63,01	26,99	0,218	0,877
7	(−1,0,0)	−0,707	−0,707	−45,00	45,00	0,00	1,00
8	(0,0,1)	0,00	0,00	45,00	135,00	0,014	0,000196

Figure 2 shows the quality functions Q_1 for three control schemes (Row 1 - optimal control, Row 2 - equal-vectorus control, Row 3 - equal-modulus control with orthogonal vectors).

As can be seen from Fig. 2, the function $Q_1 = P_1^2 + {P_2}^2 + {P_3}^2$, obtained for the optimal and equal-vector control, practically coincide for all values of the control action $\vec{U} = (P_x, P_y, M_z)$. This means that the power consumption of the redundant structure under equal-vectorus control is practically equal to the power consumption of the redundant structure under optimal control with a quality function $Q_1 = P_1^2 + {P_2}^2 + {P_3}^2$.

At the same time, the function $Q_1 = P_1^2 + {P_2}^2 + {P_3}^2$, obtained for the equal-modulus control with orthogonal vectors scheme is located above the previous functions, which means more power consumption for this control scheme. So, for the vector of control action $\vec{U} = (0, 1, 0)$, the excess of energy consumption, in comparison with the optimal control scheme, is $\Delta Q_1 = 36, 2\%$, and for vectors of control actions $\vec{U} = (1, 0, 0)$ and $\vec{U} = (-1, 0, 0)$ the excess of energy consumption, in comparison with the optimal control scheme, is $\Delta Q_1 = 100\%$.

Figure 3 shows the quality functions Q_2 for three control schemes (Row 1 - optimal control, Row 2 - equal-vectorus control, Row 3 - equal-modulus control with orthogonal vectors).



	1	2	3	4	5	6	7
Row1	0,5	0,469078	0,404909	0,373577	0,40554	0,499989	0,5
Row2	0,5	0,468750002	0,406250005	0,375000001	0,40624999	0,468749988	0,5
Row3	1	0,876986092	0,630958273	0,507944352	0,63095825	0,87698607	1

Fig. 2. Quality functions Q_1 for three control schemes

As can be seen from the presented results, the function Q_2 obtained for the optimal control scheme is greater than the function Q_2 obtained for the other two schemes. This means that the optimal control scheme is capable of developing maximum control actions greater than the other two schemes. Thus, the maximum transverse control action $\vec{U} = (0; P_y \Rightarrow max; 0)$ (position 4 in Fig. 4) developed by the optimal control scheme is greater on $\Delta Q_2 = \dfrac{1,4-1,15}{1,15} 100\% = 21,7\%$ than the maximum control action developed by the equal-modular control scheme with orthogonal vectors and on $\Delta Q_2 = \dfrac{1,4-1,00}{1,00} 100\% = 40\%$ more than the maximum control action developed by the equal-vector control scheme.

The maximum longitudinal control action $\vec{U} = (P_x \Rightarrow max; 0; 0)$ (positions 1 and 7 in Fig. 4), created by the optimal control scheme, is larger on $Q_2 = \dfrac{2,0-1,4}{1,4} 100\% = 42,8\%$ than the maximum longitudinal control action created by the equal-modular control scheme with orthogonal vectors and coincides with the maximum longitudinal control action created by the equal-vector control scheme.

Thus, in the mode of maintaining maximum positioning accuracy (control quality function Q_2), the use of optimal control of the redundant structure will increase the maximum control actions by $(21.7 - 42.8)\%$, depending on the direction of the created action, and by about the same decrease dynamic positioning error. At the same time, in the fuel economy mode (control quality function

Fig. 3. Quality functions Q_2 for three control schemes

Q_1), the use of optimal control will reduce fuel consumption by $(36.2 - 100)\%$, depending on the direction of creating a control action to compensate for external disturbances.

5 Experiment, Results and Discussion

The problem of finding the optimal control $P_1(n), \alpha_1(n), P_2(n), \alpha_2(n), P_3(n)$ at the n - computation step is reduced to solving the problem of minimizing the control quality function (7) in the fuel saving mode or maximizing the control quality functions (8)–(10) in the mode of maximum positioning accuracy, in the presence of constraints such as equalities (4)–(6) and inequalities (3). This optimization problem should be solved in the on-board controller of the control system in real time, therefore, the time for its solution should not be large and should be placed in on-board controller cycle with the time for solving other tasks. For nonsmooth functions, more complex global optimization methods are used, for example [10,24,28]. In our case the control quality functions (7) or (8)–(10) are smooth, the search for the optimal solution does not present much difficulty and can be carried out in a small number of iterations. To further reduce the search time for the optimal solution $P_1(n), \alpha_1(n), P_2(n), \alpha_2(n), P_3(n)$ at the $n-$ computation step, it is proposed to take the optimal solution $P_1(n-1), \alpha_1(n-1), P_2(n-1), \alpha_2(n-1), P_3(n-1)$ from the previous computation step as an initial approximation.

To solve the optimization problem, the function

$$fmincon(@fun, \vec{x}0, \vec{A}, \vec{b}, \vec{A}eq, \vec{b}eq, \vec{l}b, \vec{u}b, @nonlcon)$$

was selected from Optimization Toolbooks library, where

$@fun$ is the link to file with optimization function (7) or (8) – (10),

$\vec{x}0$ is the initial approximation vector,

$\vec{A} = []$ is the matrix of the inequalities type linear constraints system, is absent,

$\vec{b} = []$ is the right-hand side vector of the inequality type linear constraints system, is absent,

$\vec{A}eq = []$ is the matrix of the equality type linear constraints system, is absent,

$\vec{b}eq = []$ is the right-hand side vector of the equality type linear constraints system, is absent,

$\vec{l}b = [-P_1^{max}, -\pi, -P_2^{max}, -\pi, -P_3^{max}]$ is lower bound vector,

$\vec{u}b = [P_1^{max}, \pi, P_2^{max}, \pi, P_3^{max}]$ is upper bound vector,

$@nonlcon$ is the link to a file of the equalities type nonlinear constraints (4)–(6).

Figure 4 shows the results of mathematical modeling of dynamic positioning processes in the MATLAB environment in the form of graphs in time of the state vector parameters:

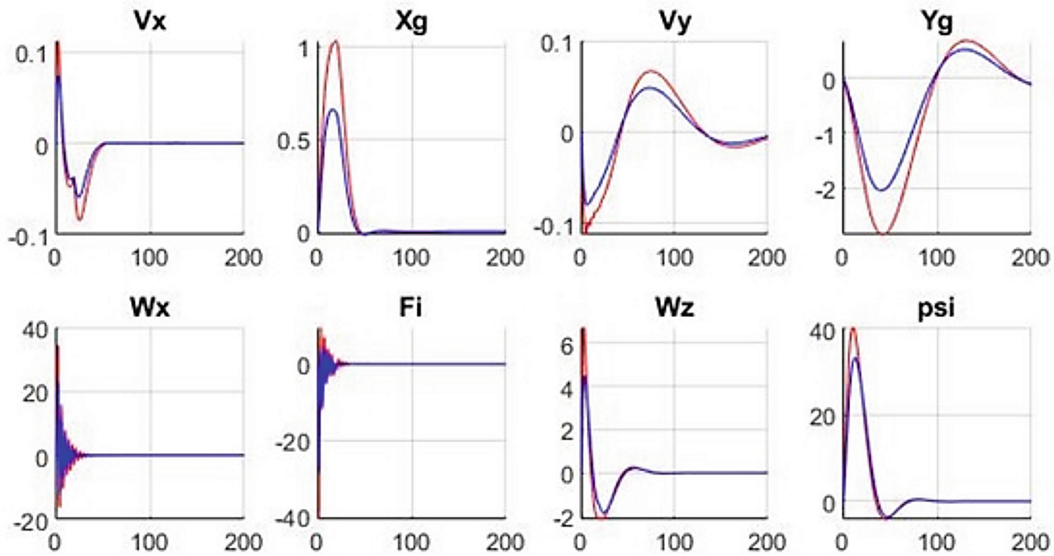


Fig. 4. Results of mathematical modeling of dynamic positioning processes

longitudinal speed V_x, longitudinal displacement X_g, lateral speed V_y, lateral displacement Y_g, angular rate in the roll channel ω_x, roll angle φ, yaw rate ω_z and yaw angle ψ. The blue graphs correspond to the optimal control with the control quality function Q_2, and the red graphs correspond to the equal-module control with orthogonal vectors. In the time interval $(0 - 20)$ s, a gust of wind acts on the vessel at a speed of 20 m/s at an angle of 45° to the diametrical plane, which leads to deviations of the parameters of the state vector from their programmed values. Moreover, the deviation $\Delta X_g = 0,6$ m, $\Delta Y_g = -2,0$ m for optimal control and $\Delta X_g = 1,0$ m, $\Delta Y_g = -3,0$ m for equal-modulus control with orthogonal vectors. Thus, the results of mathematical modeling confirm an increase in the dynamic positioning accuracy in the longitudinal channel on $\delta_x = \dfrac{1-0,6}{1}100\% = 40\%$ and in the transverse channel on $\delta_y = \dfrac{-2+3}{3}100\% = 33\%$ when using the optimal control.

6 Conclusions

The article considers the issues of automatic control of the vessel movement with a redundant control structure. Redundant structures are now widely used on all vessels with a dynamic positioning system to improve control efficiency (accuracy, maneuverability, reduce energy consumption and emissions), reliability and environmental safety.

The Scientific Novelty of the obtained results is that for the first time theoretically substantiated design features of the original automatic system of optimal control of vessel movement with redundant structure of actuators, which are constant, with the on-board controller, automatic measurement of vessel parameters, automatic determination of deviations program values, automatic determination of the required control forces and torque $\vec{U} = (P_x, P_y, M_z)$ to compensate for deviations, automatic determination of optimal control parameters $P_1, \alpha_1, P_2, \alpha_2, P_3$ that provide the required control forces and torque $\vec{U} = (P_x, P_y, M_z)$ and optimization of a given control quality function, automatic implementation of certain optimal control parameters $P_1, \alpha_1, P_2, \alpha_2, P_3$ and provide fundamentally new technical characteristics: positioning of the vessel with optimization of the control quality function, which allows to increase the dynamic positioning accuracy by $(21.7 - 42.8)\%$ and reduce fuel consumption by $(36.2 - 100)\%$, which determines its advantages over known solutions.
The Practical Significance of the obtained results is that the development and implementation in industrial production of the original device - Automatic optimal control system of the vessel with redundant structure of actuators and regulatory documentation on it will provide automatic optimal control of the vessel with redundant structure of actuators, increase dynamic accuracy positioning and reduce fuel consumption.

Further research may involve the transfer of redundant structures to other control quality functions without disturbances.

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