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USING REDUNDANT CONTROL TO OPTIMIZE CONTROL TORQUE

The object of research is the process of automatic control of the redundant structure of the vessel's executive devices for extreme rotation in the yaw channel. Traditionally, redundant structures have been used to improve the reliability of automated control systems and the maneuverability of vessels. At the same time, control redundancy can also be used to optimize control processes, thereby reducing fuel consumption, increasing control forces and moments, and reducing the time required to perform operations. This allows gaining advantages in movement over vessels not equipped with optimization modules. The paper considers the optimal management of the redundant structure of an offshore vessel, which ensures the rotational movement of the vessel around the center of rotation with the maximum angular velocity. As well as simultaneous maintenance of a given position or movement in the longitudinal and lateral channel, taking into account control restrictions. This problem is reduced to a nonlinear optimization problem with nonlinear and linear control constraints. The method, algorithmic and software of the module of extreme rotation of the vessel with a redundant structure of executive devices have been developed. The workability and efficiency of the developed method, algorithmic and software are verified by mathematical modeling in the closed circuit «Control Object – Control System». The results of the conducted experiment showed that the use of optimal control allows, in comparison with traditional methods of splitting controls, to increase the control moment and angular speed of rotation by 1.5–2 times. The obtained opportunities are explained by the use of a mathematical model of the redundant control structure and the optimization procedure for calculating optimal controls in the on-board computer of the automated system. The developed method can be used on vessels, provided it is integrated into the existing automated system of the on-board computer with an open architecture, to increase the capabilities of automatic traffic control.

Keywords: *navigation safety, human factor, intelligent vehicles, automated system, optimal controls, automatic control module.*

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1. Introduction

Today, there is a tendency to equip vessels with an excess number of active control devices, in order to increase the reliability of the control system and improve maneuverability. At the same time, redundant control structures allow additionally to optimize control processes. Therefore, the development of methods for controlling redundant structures, which allow to further optimize the processes of controlling the movement of vessels, is an urgent scientific and technical task.

Many works of various scientists are devoted to the study of the use of redundant control. In particular, work [1] considered the issue of the distribution of thrust of the engine of an autonomous underwater vehicle between the reserve numbers of thrusters, which were used to increase the reliability of the control system as a whole due to failures. It is proposed to distribute the engine traction force using the presented control distribution scheme. The efficiency of the method is confirmed by computer simulation.

In [2], a method of controlling the angular position of the space vehicle using the redundant structure of force gyroscopes is proposed. The use of redundant control allowed the authors not only to increase the reliability of the control system as a whole, but also to optimize the processes of control and unloading of power gyroscopes.

In [3], the issue of controlling the minimum-redundant structure of the spacecraft's flywheels during their unloading is considered. A method and control algorithms have been developed that ensure asymptotic stability of the unloading process. The efficiency of the method and the features of the unloading process were investigated using the example of the controlled angular movement of the spacecraft in the process of three-axis orbital orientation.

In order to reduce angular velocity measurement errors and accelerate aircraft, work [4] proposed to use several micro-inertial measuring devices (gyroscopes) to build a redundant measurement system. An optimal Kalman filter was used to combine the signals of individual devices and improve the measurement accuracy. In order to optimize the geometric arrangement of the non-orthogonal array, noise correlation was used. Two different structures of the conical configuration of the non-orthogonal lattice for 4, 5, 6, 8 gyroscopes were developed and analyzed. The obtained results showed that for a system of 4 gyroscopes, the noise of the redundant measurement system can be reduced by approximately 2.5–3.5 times.

In work [5] the issue of safe interaction between a robot-manipulator and a person is considered. A new path planning method for spherical wrist manipulators where the number of manipulator joints is redundant is proposed. Such redundancy is used to optimize the movements and dexterity of the robot. An intuitive parameterization of the angular motion of the end effector is presented, which separates the rotation of the third joint of the wrist from the rest of the angular motions. Unlike classical approaches, the collision avoidance algorithm takes into account the entire surface of the manipulator, increasing human safety. Time and frequency domain analysis demonstrated that the developed path planner, in addition to better parameterization of redundant tasks, is able to successfully execute simulated paths and avoid obstacles.

In [6], a new method for optimizing five-axis milling using the redundant degree of freedom of a six-axis industrial robot is proposed. An optimization model of the excess degree of freedom was created, which allows minimizing the cutting noise at the limit depth, taking into account the limitations of the performance of the robot movements. The experimental results of milling showed that the proposed method of optimizing robotic milling with an excess degree of freedom allows avoiding regenerative cracking and improving the quality and efficiency of processing.

In work [7], the issue of using redundant control for planning and optimizing the trajectory of the welding torch in various complex environments is considered. A method of solving complex planning problems using efficiency strategies (heuristic domain sampling strategy, collision checking strategy) has been developed, which ensures the passage of the weld in hard-to-reach places. The experiment confirmed that the developed method allows not only to avoid collisions with obstacles in various complex environments, but also to optimize the angle of the welding torch according to the established criterion.

The user manual [8] describes three modern dynamic positioning systems: Navis, Marine Technologies, and Rolls Royce, which work with redundant actuator structures. The mentioned systems allow: automatically maintaining the given position of the vessel; maintain a given course; make linear movements between the specified points, or make a movement around the turning pole; to warn the shipmaster about the associated risks.

The aim of research is to use redundant control to increase the control torque in the yaw channel. In comparison with known analogues, this will allow the vessel to turn in conditions of greater wind or current resistance, increase the angular speed of rotation, and reduce the turning time.

2. Materials and Methods

The object of research is the process of automatic control of the redundant structure of the vessel's executive devices for extreme rotation in the yaw channel. The research used a systematic approach, analysis and synthesis, methods of numerical optimization with constraints, methods of the theory of automatic control, numerical integration, and conducting an experiment. Hardware and software were also used: a personal computer with the Windows 10 operating system and the MSOffice 2016 application package; MATLAB environment with application software; software developed by the authors for the modules of the control object, control system, sensors, external influences, etc.

3. Results and Discussion

Fig. 1 shows the vessel control scheme. The control scheme under consideration uses two Azimuth Control Devices (ACD) and one Bow Thruster (BT). ACD_1 coordinates in the $OX_1Y_1Z_1$ $(-a, -b, 0)$ coordinate system associated with the vessel. Coordinates ACD_2 $(-a, b, 0)$, coordinates BT $(c, 0, 0)$. ACD_1 creates a stop force:

$$\mathbf{P}_1 = (P_1\cos\alpha_1, P_1\sin\alpha_1, 0),$$

where P_1 – the modulus of the screw stop force; α_1 – the angle of rotation $\mathbf{P}_1$ of the vector around the OZ_1, ACD_2 axis creates a stop force:

$$\mathbf{P}_2 = (P_2\cos\alpha_2, P_2\sin\alpha_2, 0),$$

where P_2 – modulus of the screw stop force; P_2 – angle of rotation $\mathbf{P}_2$ of the vector around the OZ_1 axis, BT creates a force.

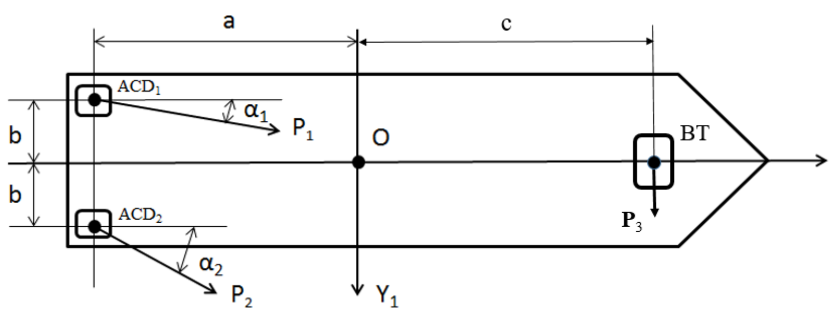

Fig. 1. Vessel management scheme

The screw stop force module P_1 and rotation angle α_1 ACD_1, the screw stop force module P_2 and rotation angle α_2 ACD_2, the stop force module P_3 are limited to the ranges:

$$\begin{cases} |P_1| \le P_{ACD}^{\max}, \\ |\alpha_1| \le \pi, \\ |P_2| \le P_{ACD}^{\max}, \\ |\alpha_2| \le \pi, \\ |P_3| \le P_{BT}^{\max}. \end{cases} \tag{1}$$

Using the available controls P_1, α_1, P_2, α_2, P_3, it is necessary to provide the maximum control torque in the yaw channel.

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The control forces and moment of the structure shown in Fig. 1 can be written in the form:

$$\begin{cases} P_x = P_1\cos\alpha_1 + P_2\cos\alpha_2, \\ P_y = P_1\sin\alpha_1 + P_2\sin\alpha_2 + P_3, \\ M_z = P_1\cos\alpha_1 b - P_1\sin\alpha_1 a - P_2\cos\alpha_2 b - P_2\sin\alpha_2 a + P_3 c, \end{cases} \quad (2)$$

where P_x – longitudinal controlling force of the structure; P_y – lateral control force of the structure; M_z – controlling moment of the structure in the yaw channel.

As can be seen from system (2), the structure of two stern azipods with a nose thruster has five controls P_1, α_1, P_2, α_2, P_3, which provide the necessary forces and moment to maintain a given movement or position. So, there is a redundant control structure with a redundancy of 5–3=2.

Let's use the existing redundancy to solve the task of optimizing the control moment $|M_z| \to \max$. To ensure the maximum positive control moment $M_z \geq 0$, let's use the objective function:

$$f(P_1,\alpha_1,P_2,\alpha_2,P_3) = -P_1\cos\alpha_1 b + P_1\sin\alpha_1 a + \\ + P_2\cos\alpha_2 b + P_2\sin\alpha_2 a - P_3 c, \quad (3)$$

and control restrictions:

$$\begin{cases} P_x = P_1\cos\alpha_1 + P_2\cos\alpha_2, \\ P_y = P_1\sin\alpha_1 + P_2\sin\alpha_2 + P_3, \end{cases} \quad (4)$$

and to ensure the maximum negative control moment $M_z \leq 0$, let's use the objective function:

$$f(P_1,\alpha_1,P_2,\alpha_2,P_3) = P_1\cos\alpha_1 b - P_1\sin\alpha_1 a - \\ - P_2\cos\alpha_2 b - P_2\sin\alpha_2 a + P_3 c, \quad (5)$$

and control constraints (4), which provide the required longitudinal force P_x and the required lateral force P_y. Linear control constraints (1) must also be taken into account.

Thus, the task is reduced to the optimization of the nonlinear objective function (3) or (5) with nonlinear (4) and linear constraints (1), which must be performed in real time at each step of the on-board computer.

The longitudinal force P_x and the lateral force P_y used in constraint (4) are found from the proportional-integral-differential controller (PID controller) equations:

$$\begin{cases} P_x = k_1(V_x - V_x^*) + k_2(X_g - X_g^*) + k_3\int (X_g - X_g^*)dt, \\ P_y = k_4(V_y - V_y^*) + k_5(Y_g - Y_g^*) + k_6\int (Y_g - Y_g^*)dt, \end{cases} \quad (6)$$

where V_x, V_y – measured longitudinal and lateral velocities of the vessel; V_x^*, V_y^* – set (program) longitudinal and lateral speeds of the vessel; V_x^*, V_y^* – measured longitudinal and lateral position of the vessel in the basic coordinate system; V_x^*, V_y^* – given longitudinal and lateral position of the vessel in the basic coordinate system; k_1, k_2, k_3, k_4, k_5, k_6 – gain coefficients of the PID controller.

The workability and effectiveness of the method of using redundant control to optimize the control torque are verified by mathematical modeling in the closed loop «Control System – Control Object» created in the MATLAB environment. The fmincon(*) MATLAB nonlinear optimization function was used to determine optimal controls.

Below is the procedure-function of the Rsysctr12 module, which provides the calculation of optimal controls. In line 3 of the function procedure, the global variables Px, Py, Mz are declared to enable their transfer to the nonlinear constraints file @nonlcon5. In lines 5–12, the geometric characteristics of the vessel, the coordinates of the installation of executive devices, and the program values of the movement parameters are transferred from the array to physically understandable variables:

```
1  function [u,intDx,intDy,intDpsi,dcl]=
   =Rsysctr12(xn,u,intDx,intDy,intDpsi,cc);
2  % модель системи керування;
3  globalPxPyMz;
4  clb=clock;
5  Vmax=cc(4);
6  Pmax=cc(6);
7  L=cc(8);
8  B=cc(9);
9  a=L/2;
10 b=B/2;
11 c=L/2;
12 xz(1:12)=cc(46:57);
13 Vnxg=xn(1)*cos(xn(9))–xn(2)*sin(xn(9));
14 Vnyg=xn(1)*sin(xn(9))+xn(2)*cos(xn(9));
15 k(1)=50.0;
16 k(2)=1.0;
17 k(3)=0.0;
18 k(4)=50.0;
19 k(5)=1.0;
20 k(6)=0.0;
21 k(7)=50;
22 k(8)=1;
23 k(9)=0.0;
24 Dx=xn(10)–xz(10);
25 intDx=intDx+Dx;
26 Dy=xn(11)–xz(11);
27 intDy=intDy+Dy;
28 Dpsi=xn(9)–xz(9);
29 intDpsi=intDpsi+Dpsi;
30 sig1=k(1)*Vnxg+k(2)*Dx+k(3)*intDx;
31 sig2=k(4)*Vnyg+k(5)*Dy+k(6)*intDy;
32 sig3=k(7)*xn(6)+k(8)*Dpsi+k(9)*intDpsi;
33 Px=-3000*sig1;
34 Py=-3000*sig2;
35 Mz=-5000000*sig3;
36 if flag=5;
37 A=[];
38 b=[];
39 Aeq=[];
40 beq=[];
41 lb=[-Pmax,-pi,-Pmax,-pi,-0.25*Pmax];
42 ub=[Pmax,pi,Pmax,pi,0.25*Pmax];
43 fun=@(u)–u(1)*cos(u(2))*B/2+
   +u(1)*sin(u(2))*L/2+u(3)*cos(u(4))*B/2+
   +u(3)*sin(u(4))*L/2–u(5)*L/2;
44 u=fmincon(fun,u,A,b,Aeq,beq,lb,ub,@nonlcon5);
45 end
46 end
```

Lines 13–14 calculate the projections of the vessel's velocity vector on the axis of the base coordinate system. In lines 15–23, the gain coefficients of the PID controller are set. In lines 24–29, current deviations and integrals of current deviations in the control channels (longitudinal, lateral and angular movements) are determined. Lines 30–35 define the forces and moments in the control channels that are necessary to maintain a given movement or position. In lines 36–46, the settings of the nonlinear optimization procedure (lines 37–42), the objective function (line 43), and the actual call of the objective function (line 45) and the definition of optimal controls are specified.

Fig. 2 shows the graphs of changes over time in the parameters of the vessel's state vector in the process of rotation under the action of an extreme control moment in the yawing channel, where:

- Vx [m/s] – longitudinal speed of the vessel;
- Xg [m] – longitudinal movement of the vessel;
- Vy[m/s] – lateral speed of the vessel;
- Yg [m] – lateral movement of the vessel;
- Wz [degrees/s] – angular speed of rotation of the vessel in the yawing channel;
- Psi [degrees] – course of the vessel;
- P1 [n] – ACD_1 screw stop force;
- alfa1 [degrees] – rotation angle of ACD_1;
- P2 [n] – ACD_2 screw stop force;
- alfa2 [degrees] – rotation angle of ACD_2;
- P3 [n] stop force BT;
- En – integral indicator of energy consumption for turning the vessel.

For comparison, Fig. 3 shows the graphs of changes over time in the parameters of the vessel's state vector in the process of rotation under the action of the control moment, formed using equal-vector (non-optimal) control.

As can be seen from the above graphs, the angular speed of rotation of the vessel under the action of suboptimal equal-vector control of the redundant structure after 100 s is 7 deg/s. The angular speed of rotation of the vessel under the action of the optimal moment after 100 s is 15 deg/s, which is more than 2 times higher than the speed obtained using known, non-optimal solutions. From the En(t) graphs, it is also clear that the power consumption during extreme driving also increases.

Fig. 2 provides graphs of changes over time in the parameters of the vessel's state vector in the process of rotation under the action of an extreme control moment in the yawing channel.

Fig. 3 shows graphs of changes in parameters of the vessel's state vector in the process of rotation under the action of suboptimal control.

The obtained result of increasing the control moment, speed of rotation and reducing the time for turning the vessel is explained by the optimization of the control moment in the redundant structure [9].

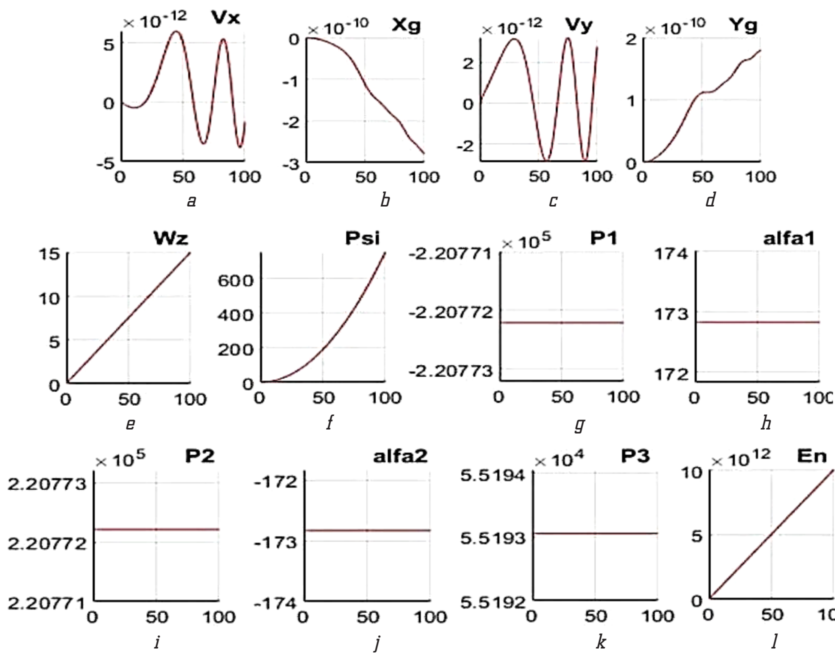

Fig. 2. Graphs of changes over time in the parameters of the vessel's state vector during rotation under the action of an extreme control moment in the yawing channel: *a* – longitudinal speed of the vessel; *b* – longitudinal movement of the vessel; *c* – lateral speed of the vessel; *d* – lateral movement of the vessel; *e* – angular speed of rotation of the vessel in the yawing channel; *f* – course of the vessel; *g* – force of the stop of the screw ACD_1; *h* – rotation angle ACD_1; *i* – force of the stop of the ACD_2 screw; *j* – rotation angle ACD_2; *k* – force of the stop BT; *l* – integral indicator of energy consumption for turning the vessel

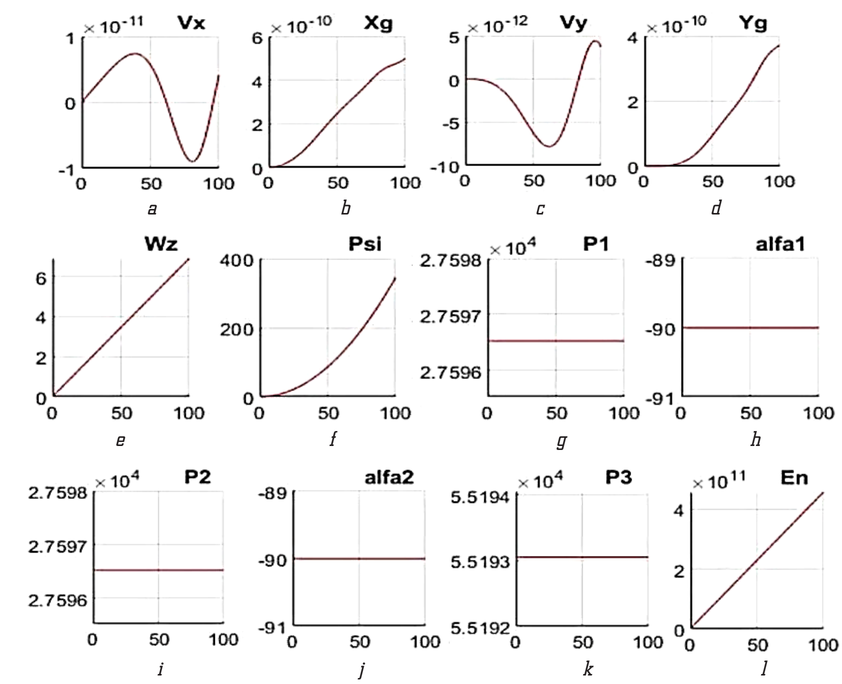

Fig. 3. Graphs of changes in the parameters of the vessel's state vector in the process of rotation under the influence of suboptimal control: *a* – longitudinal speed of the vessel; *b* – longitudinal movement of the vessel; *c* – lateral speed of the vessel; *d* – lateral movement of the vessel; *e* – angular speed of rotation of the vessel in the yawing channel; *f* – course of the vessel; *g* – force of the stop of the screw ACD_1; *h* – rotation angle ACD_1; *i* – force of the stop of the ACD_2 screw; *j* – rotation angle ACD_2; *k* – force of the stop BT; *l* – integral indicator of energy consumption for turning the vessel

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This is achieved by: using an on-board calculator; solving, at each step of the on-board computer, an optimization problem with a non-linear objective function, linear and non-linear control constraints; transfer of optimal controls to the automation of executive devices for testing. In the known solutions used in systems of dynamic positioning of vessels, suboptimal control splitting algorithms are used with a selected splitting law for redundant executive devices, which does not allow for the formation of an extreme control moment. The results of the research can be used in new and existing automated vessel motion control systems [10], provided that an on-board computer with expandable automatic control modules is integrated into the control system. The developed method can be used in automated vessel motion control systems only if there is an on-board computer and an automatic control moment optimization module.

Further research should be directed to the development of other automatic control modules in automated systems in order to increase their efficiency.

4. Conclusions

The mathematical model of the redundant structure and the objective function, which ensures the formation of the extreme moment when solving the optimization problem, is given. Non-linear constraints on optimal control are recorded, which take into account the need for the formation of forces to maintain a given position or movement of the vessel. The equations of the PID controller for determining these forces based on the deviations of the vessel's movement parameters from their programmed values are presented. Algorithmic and software of the automatic control module for the extreme rotation of the vessel in the yawing channel has been developed. The workability and efficiency of the method, algorithm and software are verified by mathematical modeling in the closed circuit «Control system – Control object». The results of the simulation showed that the use of the developed method allows increasing, in comparison with known solutions, the angular speed of rotation by 50–100 %, depending on the swimming conditions. The obtained result is explained by the use of redundant control to optimize the control moment and on-board computer to solve the nonlinear optimization problem in real time. The theoretical significance of the obtained result lies in the development of a method for determining the optimal control of the redundant structure of executive devices that ensure extreme rotation of the vessel in the yawing channel. The practical significance of the obtained result lies in the possibility of applying the developed method in automatic control modules to increase the efficiency of automated systems:

- reducing the influence of the human factor on management processes;
- increasing the reliability of control systems;
- improving the tactical and technical characteristics of control systems (increasing the control moment against external influences, increasing the angular speed of rotation, reducing the maneuver time).

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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