Intelligent system for reconfiguring the redundant structure of ship actuators without disturbance

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Abstract

The object of the research is the processes of automatic reconfiguration of the redundant structure of actuators to another aim function without creating disturbing forces and torques. Traditionally, redundant structures have been used to increase the reliability of the control system. At the same time, control redundancy also allows you to optimize control processes and increase the efficiency of the control system. For different aim functions, the settings of redundant structures are different. When the aim function changes, the structure is reconfigured, which is accompanied by the emergence of disturbing forces and torques. The work has developed a reconfiguration method (the "zero motion" method), which allows you to reconfiguration of the structure without disturbing forces and yaw moment. The results obtained are explained by using the on-board computer of the control system to determine the controls for reconfiguring the structure to a new aim function, by solving an optimization problem with equalities and inequalities in the on-board computer. Constraints of the equalities type allow finding control of reconfiguration of the structure that do not create disturbing forces and yaw moment, and constraints of the inequality type take into account the physical limitations of the parameters of the structure and controls. The developed method allows for optimal tuning (reconfiguration) of the structure against the background of the main functional task. The performance and efficiency of the developed method were verified by mathematical modeling in the MATLAB environment. The results obtained are reproducible and can be used in the design of automatic control systems for redundant structures of ship actuators.

Keywords

Intelligent systems, navigation safety, automated systems, redundant control, redundant structure reconfiguration

1. Introduction

Reducing fuel consumption, reducing emissions of pollutants into the environment, and preserving the environment are important issues today [1]. There are various ways to solve these issues, among which the main ones can be distinguished: improving power plants; using design solutions [2-4]; using hydrodynamic solutions [5]; using wind energy [6]; optimal route planning and divergence [7]; using decision support systems, ergatic systems [8]; automation of control processes [9-11] and reducing the impact of the human factor [12, 13]; optimizing control processes [14-16]; using redundant control structures [17], etc. Traditionally, redundant control structures were used to increase reliability [18-20]. Later, they began to be used to optimize control processes in space, aviation, and other sectors of the national economy [21, 22].

Redundant control structures are also widely used in modern ships. They are most common in ships with dynamic positioning systems. Redundancy of control means that the number of independent controls exceeds the number of degrees of freedom to be controlled. Typically, for most modern ships, the number of degrees of freedom to be controlled is three (longitudinal motion, lateral

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motion, and angular motion in the yaw channel). The number of independent controls varies from ship to ship.

Independent are controls that create non-collinear force and torque vectors. Thus, the control of the bow and stern thrusters of a vessel located at the same distance from the center of rotation is independent, since the same deviations of the telegraphs create the same force vectors, but different torque vectors. The control of several bow (or stern) thrusters located at the same distance from the center of rotation cannot be considered independent, since the same deviations of the telegraphs create the same force vectors and the same torque vectors.

For conventional single-screw vessels, the number of independent controls is two (power plant telegraph deviation and rudder deviation), and the control redundancy is $RC = 2 - 3 = -1$ For vessels with a bow or stern thruster, the number of independent controls is three (power plant telegraph deviation, rudder deviation, bow or stern thruster telegraph deviation) and the control redundancy is $RC = 3 - 3 = 0$. For vessels with bow and stern thrusters, the number of independent controls is four (power plant telegraph deviation, rudder deviation, bow thruster telegraph deviation, stern thruster telegraph deviation) and the control redundancy is $RC = 4 - 3 = 1$. For vessels with two stern azipods, the number of independent controls is four (the thrust force and the propeller angle of the first azipod, the thrust force and the propeller angle of the second azipod), and the control redundancy is $RC = 4 - 3 = 1$.

Redundant control structures are most widely used in dynamic positioning systems and are used on passenger ships, military ships, platform support ships, pipelayers, cablelayers, anchor winders, and other ships that have special requirements for maneuverability and reliability [23, 24]. Fig. 1 shows exclusive photos of the anchor handling tug AHT Jascon 11 (IMO 9386847) and its stern azipods, provided by the co-author of the article, deep sea captain O. M. Tovstokoryi.

Figure 1: Anchor handling tug AHT Jascon 11 (IMO 9386847) and its stern azipods.

The authors [25, 26] show that redundant control structures can be used not only to increase the reliability, but also the efficiency of the control system (reducing fuel consumption, increasing control forces and torques, reducing maneuvering time, etc.). This is achieved by numerical optimization in the on-board computer of the control system of the selected aim function, taking into account restrictions such as equalities and inequalities on control. Different aim functions that optimize different efficiency indicators (fuel consumption, control forces and torques, time to perform operations, etc.) correspond to different structure settings. When the aim function changes, the structure is reconfigured, which causes disturbing forces and torques. In some cases, this is unacceptable, for example, during dynamic positioning operations.

The object of research is the processes of automatic reconfiguration of the redundant structure of actuators to another aim function without creating disturbing forces and torques.

The subject of the research is models and methods for automatically reconfiguring the redundant structure of actuators to another target function.

The purpose of the research is to increase the efficiency of the control system (reducing energy consumption, increasing control forces and torques, reducing the time to perform operations) by optimally adjusting the redundant structure to the appropriate aim function and early reconfiguring the structure to another aim function without creating disturbing forces and torques.

2. Related works

Optimization of control processes is used in various industries and has been studied in the works of many authors.

Thus, in the article [27] the issues of a spacecraft landing optimization on a planet are considered, taking into account the constraints on engine thrust and descent trajectory. The minimization of energy consumption is taken as the aim function. The form of Max-Min-Max or Max-Singular-Max of optimal control is proved for the first time, the obtained result is extended to control problems taking into account the influence of the atmosphere.

In [28], the Kulbit maneuver was considered to create a library of maneuvers with optimal controls. Using the change of variables and penalty functions, the optimal control problem with a free final state and time was transformed into an optimal control problem with a fixed final state, which can be solved using the minimum principle. The results of mathematical modeling showed that the developed method allows solving the problem of optimal control in terms of speed in the Kulbit maneuver.

The method of mooring autonomous surface vessels using modified mechanics (rope) is considered in [29]. Simulation of mechanically modified mooring processes on board plays an important role. The contribution of the article is the correction of rope sag, which is achieved using a smooth penalty function and a linear complementary solution.

In article [25], the optimal control of the redundant structure of the vessel's actuators, which ensures the rotational motion of the vessel around the center of rotation with maximum angular velocity, and simultaneously maintaining a given position or motion in the longitudinal and lateral channels, taking into account control constraints, is considered. The problem is reduced to a nonlinear optimization problem with linear and nonlinear control constraints. Models and methods of extreme rotation with a redundant structure of actuators are developed. The performance and effectiveness of the method are verified by mathematical modeling in a closed-loop scheme "Control object - control system".

Recommendations for practical maneuvering of a vessel with two stern azipods are given in [30]. Recommended control means for implementing several fixed modes. Taking into account that these modes are implemented manually, the azipod angles in all modes are chosen as multiples of 45 degrees, with the exception of some modes of fast movement to the left (fast movement of the vessel to the port side) and fast movement to the right (fast movement of the vessel to the starboard side).

In [31], an optimal control problem for a wide class of stochastic systems is investigated, inspired by the energy harvester model. The stochastic noise in the system is caused by mechanical oscillations, while the reward function is the average power obtained from them. The authors use control theory tools to develop optimal solutions in a perturbed regime close to the steady state. The results obtained showed that the considered approach allows the development of protocols that perform better than any possible solution with constant resistance.

In article [32], the issues of optimal control using an extended mathematical model of the control object are considered. The extended mathematical model includes: a universal motion stabilization system; a model of the control object; a reference model with a free control vector. The optimal control problem is formulated in a classical form, when control is a function of time. The proposed method was tested by a computational experiment on a model of spatial motion of a quadcopter and a group of two-wheeled mobile robots with a differential drive. The experimental results showed that the universal stabilization system provides stabilization of the motion of objects along optimal trajectories that are not known in advance, but obtained as a result of solving the problem with an improved model.

In article [33], a mathematical model of dengue virus transmission in different regions through humans and mosquitoes was developed. The authors developed an optimal strategy that uses information campaigns, safety measures and health interventions in dengue fever areas as influences on the intensity of the virus spread. Using mathematical modeling and optimal control methods, optimal strategies for influencing the spread of the epidemic were determined. Numerical modeling was performed in the MATLAB environment and cost-effectiveness coefficients were determined. Analysis of the obtained results revealed cost-effective strategies that consist of: protecting risk groups; preventing contact between infected people and mosquitoes; using quarantine facilities as the most powerful methods for controlling the spread of the virus.

3. Methods and materials

As noted above, redundant structures of actuators allow not only to increase the reliability of the control system, but also its efficiency. To confirm this conclusion, the authors conducted mathematical modeling in the MATLAB environment to determine the optimal controls of the redundant structure with two stern azipods ACD_1, ACD_2 and a bow thruster BT, shown in Fig. 2.

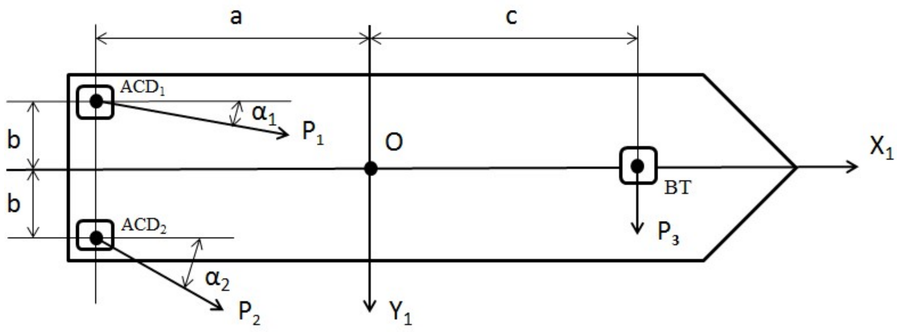


Figure 2: Redundant control structure

The given structure has control redundancy $RC = 5 - 3 = 2$, where 5 is the number of independent controls (propeller thrust force P_1 and the rotation angle α_1 of the first azipod ACD_1, propeller thrust force P_2 and the rotation angle α_2 of the second azipod ACD_2, propeller thrust force P_3 of the bow thruster BT), 3 is the number of freedom degrees to be controlled (longitudinal movement, lateral movement and angular movement in the yaw channel).

Table 1 presents the results of mathematical modeling for the aim function $Q_1 = P_1^2 + P_2^2 + P_3^2 \to \min$ that minimizes energy consumption for a given control (P_x, P_y, M_z). The data in Table 1 were obtained for the given range of azipod control forces $|P_1| \le 1, |P_2| \le 1$, $|\alpha_1| \le \pi, |\alpha_2| \le \pi$.

Table 1
Results of mathematical modeling for aim functions Q_1

(P_x, P_y, M_z)	P_1	P_2	α_1	α_2	P_3	Q_1
(1;0;0)	0,5	0,5	0	0	0	0,5
(0,866;0,5;0)	0,465	0,438	15,87	16,73	0,247	0,47
(0,5;0,866;0)	0,35	0,315	38,79	43,95	0,428	0,40
(0;1;0)	0,255	0,254	83,94	96,09	0,494	0,37
(-0.5;0,866;0)	0,316	0,35	136,09	141,19	0,428	0,41
(-0,866;0,5;0)	0,433	-0,5	-179,92	-30,08	0,25	0,5
(-1,0,0)	0,5	-0,5	-179,92	-0,11	0	0,5
(0,0,1)	-0,006	-0,007	83,03	96,67	0,013	0,000254

The first column of the table shows the given control vectors that the redundant structure creates. The control vector $(P_x, P_y, M_z) = (1;0;0)$ means that the structure creates a force $P_x = 1$ along the longitudinal axis, a lateral force $P_y = 0$, and a yawing moment $M_z = 0$.

The second and third columns show the screw thrust force of the first P_1 and second P_2 azipod, respectively.

The fourth and fifth columns show the rotation angles of the first $\alpha_1[dg]$ and second $\alpha_2[dg]$ azipods.

The sixth column shows the thrust force of the bow thruster screw P_3.

The seventh column shows the value of the aim function Q_1 corresponding to the minimum energy consumption for the given control vectors.

Table 2 presents the results of mathematical modeling for the aim functions $Q_2 = P_x \to \max(\min)$, $Q_2 = P_y \to \max(\min)$, $Q_2 = M_z \to \max(\min)$ which optimize the control forces and yaw moment of the structure along the coupled coordinate system (CCS) axes. The data in Table 1 are obtained for the range of the azipod control forces $|P_1| \le 1, |P_2| \le 1$, $|\alpha_1| \le \pi, |\alpha_2| \le \pi$

Table 2
Results of mathematical modeling for aim functions Q_2

(P_x, P_y, M_z)	P_1	P_2	α_1	α_2	P_3	Q_2
$(P_x \to \max; 0;0)$	1	1	0	0	0,0	2
$(P_x \to \min; 0;0)$	-1	-1	0	0	0,0	-2
$(0; P_y \to \max;0)$	1	1	26,76	153,28	0,5	1,4
$(0; P_y \to \max;0)$	1	1	-26,76	-153,28	-0,5	-1,4
$(0;0; M_z \to \max)$	1	0,865	-30,08	179,92	0,5	55,77
$(0;0; M_z \to \min)$	-1	0,865	-30,08	0	-0,5	-55,77

The first column of the table shows the specified control vectors that the redundant structure creates. The control vector $(P_x, P_y, M_z) = (P_x \to \max;0;0)$ means that the structure creates the maximum force along the longitudinal axis $P_x \to \max$, the lateral force $P_y = 0$, and the yawing moment $M_z = 0$.

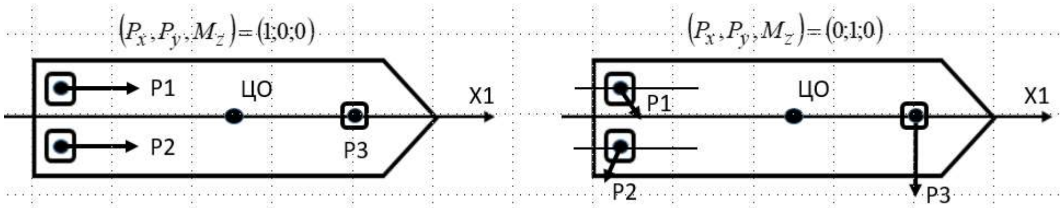
The second and third columns show the screw thrust force of the first P_1 and second P_2 azipod, respectively.

The fourth and fifth columns show the rotation angles of the first $\alpha_1[dg]$ and second $\alpha_2[dg]$ azipod, respectively.

The sixth column shows the thrust force of the bow thruster screw P_3.

The seventh column shows the value of the aim function Q_2 when implementing the given control vectors.

Fig. 3 shows the optimal control vectors of azipods according to the data in Table 1, which provide minimal energy consumption for the given control vectors.



a) **b)**

Figure 3: Optimal azipod control vectors that provide minimal energy consumption for given control vectors

Fig. 4 shows the optimal control vectors of azipods according to the data in Table 2, which provide extreme control.

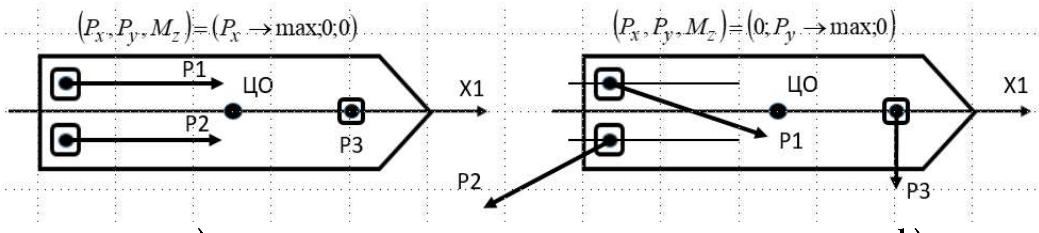


Figure 4: Optimal azipod control vectors that provide extreme control

As can be seen from the data in the tables and the figures, the optimal settings of the structure (the positions of the azipod control vectors) depend on the aim function and differ from each other. When the aim function changes (for example, from minimum energy consumption to extreme control, or vice versa), the redundant structure will begin to retune to the new aim function, which will lead to the appearance of disturbing forces and yaw moments during the retuning. To minimize the disturbing effect, the authors proposed to use the "zero motion" method, which provides retuning of the structure without disturbing forces and yaw moments.

3.1. The "zero-movement" method

Let us write down the mathematical model of the redundant structure of two stern azipods with a bow thruster, shown in Fig. 2

$$\begin{cases} P_x = P_1 \cos\alpha_1 + P_2 \cos\alpha_2 \\ P_y = P_1 \sin\alpha_1 + P_2 \sin\alpha_2 + P_3 \\ M_z = P_1 b \cos\alpha_1 - P_2 b \cos\alpha_2 - P_1 a \sin\alpha_1 - P_2 a \sin\alpha_2 + P_3 c \end{cases}, \quad (1)$$

where P_x is the total control force of the structure along the OX_1 axis of the coupled coordinate system,

P_y is the total control force of the structure along the OY_1 axis of the coupled coordinate system,

M_z is the total yaw moment of the structure about the OZ_1 axis of the coupled coordinate system.

System (1), which contains three equations, includes five unknowns (independent controls $P_1, \alpha_1, P_2, \alpha_2, P_3$), i.e., the control redundancy is $RC = 5 - 3 = 2$. We will use these two redundant controls to tune the structure.

At the moment of changing the aim function, the redundant structure (1) is in a position that provides the extreme value of the current aim function $Q_1(P_1(0), \alpha_1(0), P_2(0), \alpha_2(0), P_3(0))$. The final position of the structure must provide the extreme value of the new aim function $Q_2(P_1(T), \alpha_1(T), P_2(T), \alpha_2(T), P_3(T))$. It is necessary to solve the problem of reconfiguring the structure from a state determined by the aim function $Q_1(P_1(0), \alpha_1(0), P_2(0), \alpha_2(0), P_3(0))$ to a state determined by the aim function $Q_2(P_1(T), \alpha_1(T), P_2(T), \alpha_2(T), P_3(T))$ without disturbing forces and yaw moments during the reconfiguration.

Let's consider several optimization problems.

- optimization of the structure's energy consumption against the background of the implementation of the main functional task.

$$\begin{cases} Q_1 = P_1^2 + P_2^2 + P_3^2 \to \min \\ P_1 \cos\alpha_1 + P_2 \cos\alpha_2 - P_x^* = 0 \\ P_1 \sin\alpha_1 + P_2 \sin\alpha_2 + P_3 - P_y^* = 0 \\ P_1 b \cos\alpha_1 - P_2 b \cos\alpha_2 - P_1 a \sin\alpha_1 - P_2 a \sin\alpha_2 + P_3 c - M_z^* = 0 \end{cases} \tag{2}$$

In this case, the aim function Q_1 ensures the minimization of energy consumption, and the equality-type constraints ensure that the structure creates the necessary controls P_x^*, P_y^*, M_z^* to maintain the position or the given maneuvering.

- optimization of the longitudinal strength of the structure and creation of the necessary lateral force and yaw moment

$$\begin{cases} Q_2 = |P_x| \to \max \\ P_1 \sin\alpha_1 + P_2 \sin\alpha_2 + P_3 - P_y^* = 0 \\ P_1 b \cos\alpha_1 - P_2 b \cos\alpha_2 - P_1 a \sin\alpha_1 - P_2 a \sin\alpha_2 + P_3 c - M_z^* = 0 \end{cases} \tag{3}$$

- optimizing the lateral force of the structure and creating the necessary longitudinal force and yaw moment

$$\begin{cases} Q_3 = |P_y| \to \max \\ P_1 \cos\alpha_1 + P_2 \cos\alpha_2 - P_x^* = 0 \\ P_1 b \cos\alpha_1 - P_2 b \cos\alpha_2 - P_1 a \sin\alpha_1 - P_2 a \sin\alpha_2 + P_3 c - M_z^* = 0 \end{cases} \tag{4}$$

- optimization of yaw moment and creation of the necessary longitudinal and lateral force

$$\begin{cases} Q_4 = |M_z| \to \max \\ P_1 \cos\alpha_1 + P_2 \cos\alpha_2 - P_x^* = 0 \\ P_1 \sin\alpha_1 + P_2 \sin\alpha_2 + P_3 - P_y^* = 0 \end{cases} \tag{5}$$

Also, when performing optimization (2)-(5), it is necessary to take into account physical constraints on the parameters of structures such as inequalities.

$$\begin{cases} |P_1| \le P_{ACD}^{\max}, |P_2| \le P_{ACD}^{\max}, |P_3| \le P_{BT}^{\max} \\ |\alpha_1| \le \pi, |\alpha_2| \le \pi \end{cases} \tag{6}$$

To transition from one of the current optimal states of the structure to one of the following optimal states defined by systems (2)-(5):

- we determine the optimal setting of the structure $\mathbf{X}(0) = \left(P_1(0), \alpha_1(0), P_2(0), \alpha_2(0), P_3(0)\right)$ for the current aim function by solving the optimization problem with constraints of the equalities type (2)-(5) and inequalities type (6);
- we determine the optimal setting of the structure $\mathbf{X}(T) = \left(P_1(T), \alpha_1(T), P_2(T), \alpha_2(T), P_3(T)\right)$ for the next objective function;
- we write the equation of the line that passes through the points $\mathbf{X}(0)$ та $\mathbf{X}(T)$

$$\frac{\mathbf{X}(t) - \mathbf{X}(0)}{\mathbf{X}(T) - \mathbf{X}(0)} = \frac{t - t_1}{t_2 - t_1} \tag{7}$$

and find $\mathbf{X}(t)$

$$\mathbf{X}(t) = \mathbf{X}(0) + \mathbf{k}t - t_1\mathbf{k}\,, \qquad (8)$$

where $\mathbf{k} = \dfrac{\mathbf{X}(T) - \mathbf{X}(0)}{t_2 - t_1}$. Equation (8) allows us to obtain predicted structure states during reconfiguration, but does not guarantee zero disturbing forces and yaw moments.

- for this we solve the optimization problem

$$\begin{cases} Q = (P_1 - P_1(t))^2 + (\alpha_1 - \alpha_1(t))^2 + (P_2 - P_2(t))^2 + (\alpha_2 - \alpha_2(t))^2 + (P_3 - P_3(t))^2 \to \min \\ P_1 \cos\alpha_1 + P_2 \cos\alpha_2 = 0 \\ P_1 \sin\alpha_1 + P_2 \sin\alpha_2 + P_3 = 0 \\ P_1 b \cos\alpha_1 - P_2 b \cos\alpha_2 - P_1 a \sin\alpha_1 - P_2 a \sin\alpha_2 + P_3 c = 0 \end{cases} \qquad (9)$$

The aim function of the system (9) ensures the smallest deviations of the structure state parameters from predicted ones, and the constraint of the equalities type ensures absence of disturbing forces and yaw moments.

4. Experiment

The performance and effectiveness of the “zero motion” method proposed by the authors was verified by mathematical modeling in the MATLAB environment using the example of a redundant structure of two stern azipods with a bow thruster, Fig. 1.

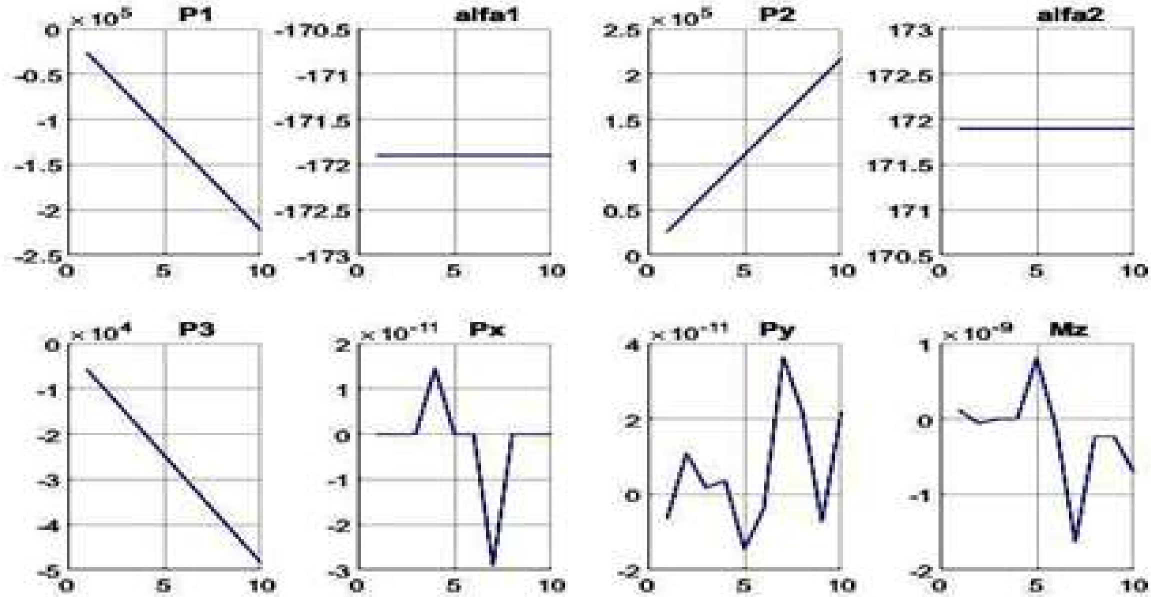


Figure 5: Structural reconfiguration result by “zero motions” method

The transition from the initial value of the structure $P_1(0) = 0$, $\alpha_1(0) = 0$, $P_2(0) = 0$, $\alpha_2(0) = 0$, $P_3(0) = 0$ to the target function of the maximum lateral force of the structure $Q_2 = P_y \to \max$ was modeled. The simulation results are shown in Fig. 6 in the form of graphs of changes in time of the thrust force P_1 and the rotation angle α_1 of the first azipod, the thrust force P_2 and the rotation angle α_2 of the second azipod, the thrust force P_3 of the bow thruster. The values of the total longitudinal force P_x, total lateral force P_y, and total yaw moment M_z of the structure are also given.

As can be seen from the graphs above, during the structure reconfiguration interval $0 \le t \le 10$, the positions of the thrust force of the first and second azipods and the bow thruster change, but the total longitudinal force, total lateral force and total jaw moment of the structure remain close to zero, which confirms the operability of the developed method.

A program fragment of the “zero-movement” algorithm in the MATLAB environment is shown in Fig. 6.

```
beq = [];
lb = [-Pmax,-pi,-Pmax,-pi,-0.25*Pmax];
ub = [Pmax,pi,Pmax,pi,0.25*Pmax];
fun = @(u)-u(1)*sin(u(2))-u(3)*sin(u(4))-u(5);

u=[0,0,0,0,0];
u = fmincon(fun,u,A,b,Aeq,beq,lb,ub,@nonlcon6);
u1(1:5)=u(1:5);

u=[0,0,0,0,0];
fun = @(u)-u(1)*sin(u(2))-u(3)*sin(u(4))-u(5);
u = fmincon(fun,u,A,b,Aeq,beq,lb,ub,@nonlcon4);
u2(1:5)=u(1:5);
for j=1:5
k(j)=(u2(j)-u1(j))/TRec;
end

while t<=tmax
A = [];
b = [];
Aeq = [];
beq = [];
lb = [-Pmax,-pi,-Pmax,-pi,-0.25*Pmax];
ub = [Pmax,pi,Pmax,pi,0.25*Pmax];
for j=1:5
u0(j)=u0(j)+k(j)*dt;
end
fun = @(u)(u(1)-u0(1))^2+(u(2)-u0(2))^2+(u(3)-u0(3))^2+(u(4)-u0(4))^2+(u(5)-u0(5))^2;
u = fmincon(fun,u,A,b,Aeq,beq,lb,ub,@nonlcon7);
Fx=u(1)*cos(u(2))+u(3)*cos(u(4));
Fy=u(1)*sin(u(2))+u(3)*sin(u(4))+u(5);
Momz=u(1)*cos(u(2))*B/2-u(3)*cos(u(4))*B/2-u(1)*sin(u(2))*L/2-u(3)*sin(u(4))*L/2+u(5)*L/2;
```

Figure 6: Program fragment of the "zero movements" algorithm

5. Discussion

The method of "zero motions" has been developed - reconfiguration of redundant structures of ship actuators without disturbing forces and yaw moments. The results obtained are explained by the use of an on-board computer, finding controls for reconfiguring the structure without disturbing forces and yaw moments by solving an optimization problem with equalities and inequalities-type constraints in the on-board computer. Equalities-type constraints allow finding control for reconfiguring the structure without disturbing forces and yaw moments, and inequalities-type constraints take into account physical constraints on the structure and control parameters. Known methods for controlling redundant ship structures do not use reconfiguration of structures. The "zero motions" method developed by the authors for reconfiguring redundant structures of actuators without disturbances requires the presence of an on-board computer and can be used only in automated/automatic control systems. The results obtained are reproducible and can be used in the design of mathematical support for automated/automatic vessel movement control systems with redundant control structures.

Further research may be related to the assessment of the effectiveness of the "zero motion" method for various redundant structures.

6. Conclusion

A method of "zero movements" has been developed - automatic reconfiguration of redundant structures of the vessel's actuators to another aim function without disturbances. This is achieved by using an on-board computer, solving an optimization problem in the on-board computer to find structure controls that transfer it to a new optimal position without disturbing forces and yaw moments, which allows using reconfiguration against the background of the current functional task, reducing the time for preparation for the next functional task. Known methods of controlling redundant structures do not use optimization of the structure and its reconfiguration to a new aim function.

The theoretical value of the results obtained lies in the development of a method for automatic reconfiguration of the redundant structure of the actuators to a new aim function without disturbances.

The practical value of the results obtained lies in verifying the operability and effectiveness of the developed method by mathematical modeling, reducing the time for preparation for the next operations.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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