Intelligent System Control of the Vessel Executive Devices Redundant Structure

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Abstract

The article examines the issues of optimal control of vessels with redundant structures of executive devices on the example of an offshore vessel with two stern azimuth control devices (ACD) and a bow thruster. Known technical solutions for optimal control of redundant structures in the aviation, space, marine and other industries. The nearest technical solutions in the shipping are dynamic positioning systems (DP-systems) of manufacturers Navis, Marine Technologies, Rolls Royce, Transas, Consberg. The main purpose of such systems is to maintain the vessel in a given position with the help of active control during work (drilling, cable laying, cargo overloading, etc.). The main components of DP-systems are: sensors for measuring the absolute and relative position of the vessel (DGPS and Reference Systems), on-board computer with software and redundant structures of executive devices. Redundant structures in DP-systems are used to increase the reliability of the automated system. The article developed a method of using redundant structures also for optimization of control processes. The purpose of the work is to automate and optimize the processes of controling vessels with redundant structures of executive devices. On the example offshore vessel with two stern ACD and a bow thruster, optimal controls are considered that ensure: minimum energy consumption for performing DP operations, maximum control forces in the channels of longitudinal and lateral movement, which are used to move away from the platform in the presence of a downwind, as well as reconfiguration of redundant structures. The results of the experiment showed that the optimization of control processes allows to reduce energy consumption by (35–50) % and increase the control forces of the structure in the channels of longitudinal and lateral movement. At the same time, the additional load on the calculation cycle of the on-board controller, caused by the solution of optimization problems, is 25–50 ms, which is within (2.5–5) %.

Keywords

Intelligent system, optimal control, redundant structure, aim function, mathematical modeling

1. Introduction

The issues of reducing energy and fuel consumption on vessels, as well as related issues of reducing emissions and improving the environment are particularly relevant today [1]. The ways of solving these issues are different, but most often structural solutions [2], hydrodynamic solutions [3], sails [4] or advanced power plants are used for this purpose. Traffic optimization and fuel savings are also possible due to proper route planning, psychological preparation, use of decision support systems, ergatic [5] and automated systems with automatic control modules [6–8]. According to the authors, the most promising direction for the next 10–15 years, before the appearance of fully robotic vessels, is the development and implementation of automated systems with automatic control modules. Human functions in such systems are reduced only to starting the automatic module and monitoring its

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operation, which significantly reduces the share of manual control of the vessel, the influence of the human factor on control processes, contributes to reducing the number of accidents and disasters [9]. Manual control of the vessel is extremely suboptimal, it can lead to unacceptable deviations of controlled parameters, increased fuel consumption, increased loads on the hull and even destruction of the hull during a storm. Articles [10–12] are devoted to the study of loads on the vessel's hull. An example of an automatic module in an automated system, which is used on almost all vessels today, is the autopilot. Platform supply vessel (PSV) / Offshore Support Vessel (OSV), Diving Support (DSV's) and ROV Support Vessels, Drill Vessels, Cable Lay and Repair Vessels, Pipe Laying Vessels, Dredgers, Crane Barge or Crane Vessel, Rock Dumping Vessels, Passenger Vessels, Specialist – Semi-submersible Heavy-Lift Vessels, Mobile Offshore Drilling Units / Vessels (MODUs), Shuttle Tanker, Floating Production, Storage and Offloading unit or FPSO Vessels, Naval Vessels and Operations, which are subject to increased reliability requirements, accuracy and maneuverability, equipped with more advanced dynamic positioning systems (DP-system). The DP-system includes high-precision means of measuring absolute (DGPS systems) and relative (Reference systems) position, redundant structures of active control, on-board computer system and automatic control modules [13, 14]. Today, vessels with DP-system have the highest degree of automation of traffic control processes. Redundant control structures have redundancy, that is, the number of independent controls is greater than the number of degrees of freedom to be controlled. This makes it possible to increase not only the reliability of the structure of executive devices, but also to use redundancy to increase the efficiency of control processes, for example, reducing the energy costs of moving the vessel, due to the organization of movement without drift, with less hydrodynamic resistance, increasing the resulting control forces and torque due to optimal redistribution control of individual executive devices within the structure itself. There are known methods of using redundancy in the aviation industry, for example, to reduce the vibration of a helicopter propeller [15], in the welding industry, for example, to control the movement of a welding torch [16], etc.

2. Related works

The issue of control processes optimization using redundant structures was previously considered by many authors. So, in work [17], the issue of increasing the reliability of magnetic bearings in structures with redundancy, due to the reconfiguration of the structure in case of failure of some components, is considered. The bias current coefficient is one of the key coefficients in the fault-tolerant control of magnetically levitated bearings. The authors have developed a method for optimizing the bias current coefficient in a redundant structure. By means of a mathematical analysis of the range of variation of the bias current coefficient, the existence of the optimal solution was proved, and the model of electromagnetic force, load current and bias current coefficient was established. Algorithms for finding the optimal solution are developed for two types of optimization tasks, according to fault-tolerant control of magnetic bearings.

The work [18] considers the issues of creating a control system for Autonomous Surface Vessels (ASV), which could ensure the safe and accurate performance of tasks in wind, current and waves. A new controller design topology based on a combination of Successive Loop Closure and optimal control is presented. This topology allows you to create reliable autopilots based on the Proportional-Integral-Derivative (PID) controller. Controllers are tuned based on the obtained results of optimal control, which ensures minimization of model uncertainties. The operability and efficiency of the method was tested on a mathematical model of a real ASV vessel with 3 degrees of freedom (DoF model). The simulation results showed that the PID controller tuned according to the proposed method is able to operate under various parametric uncertainties, demonstrating reliability and applicability for various prototype scenarios.

In work [19] there were considered issues of nonlinear optimal control of a jib cranes used on vessels. The dynamic jib crane model was linearized by Taylor series expansion around the operating point, which was recalculated at each control step. To calculate the gain factor of the regulator feedback channel, the Riccati algebraic equation was solved. The proposed nonlinear approach to optimal control provides fast and accurate tracking of jib cranes variable states with moderate fluctuations of input control signals. The stability of the control scheme is proven by Lyapunov method.

In work [20], to create a library of aviation maneuvers with optimal controls, the Kulbit maneuver is considered. With the help of variable substitution methods and the imposition of a penalty function, the optimal control problem with a free terminal state and free terminal time is transformed into unconstrained optimal control problem with a fixed terminal state, based on the minimum principle. The optimization algorithm is presented. The modeling results showed that the proposed method can solve the problem of time-optimal control in Kulbit maneuver.

The work [21] considers the mooring maneuver of autonomous surface vessels (ASVs) using modified mechanics, which is chosen as a rope. The low speed of the vessel when mooring significantly reduces the maneuverability, and the wind and waves enhance this effect. For ASVs, on board simulation of mechanically modified mooring processes plays an important role. The contribution of this article to the development of methods for mooring ASVs using modified mechanics is to take into account rope slack. This is achieved in two ways: using a smooth penalty function, as well as a linear complementary solution.

In article [22], the optimization problem of the vertical descent of a spacecraft during a planetary landing is studied, taking into account the limitations on the glide path and engine thrust. As a criterion of optimality, the function of energy consumption minimization was adopted. For the first time, the form of Max-Min-Max or Max-Singular-Max optimal control using the Pontryagin maximum principle was proved, the obtained result was extended to control problems taking into account the influence of the atmosphere. It is shown that the singular structure does not appear in extended control problems. The optimal trajectory for a specific task is theoretically analyzed and it is shown that there is no more than one contact or limited interval on each Max or Min arc.

The article [23] discusses the creation of a fault-tolerant steering system to increase the reliability of unmanned underwater vehicles. The authors' analysis showed that the reliability of the control system, which uses the redundancy control strategy and algorithms, is significantly better than the traditional configuration.

Methods of controlling the redundant structure of electrohydraulic drives based on fuzzy aggregation, Mamdani fuzzy logic rules, and the theory of fuzzy neural networks are investigated in [24].

The manual [25] contains recommendations for practical maneuvering of a vessel with two stern azimuth control devices (ACD). Recommended controls for implementing multiple fixed modes are reviewed. Taking into account that these modes are implemented manually, the ACD angles in all modes are selected as multiples of 45 dg, except for the modes of fast movement to the left (walking the vessel fast to port) and fast movement to the right (walking the vessel fast to starboard). A design with two aft ACD can occur when the bow and stern thrusters fail due to sand or silt clogging. In addition, this design is the last "frontier" that provides three-dimensional control of the vessel, so it is particularly interesting.

The user manual [26] describes three modern dynamic positioning systems: Navis, Marine Technologies, and Rolls Royce.

As can be seen from the examples of the considered solutions, optimal control and redundant structures are used in various branches of the national economy; aviation industry [20], space industry [22], vessel industry [18, 19, 21, 23] and others [17, 24]. At the same time, the authors did not find known solutions for automated vessel movement control systems that allow, due to the redundancy of executive device structures, to reduce energy consumption, increase control forces and moments, and rearrange the redundant structure from one aim function to another. Such tasks arise, for example, during long-term dynamic positioning, when it is advisable to: a) minimize the energy consumption of the structure for maintaining the position; b) maximize the lateral control force for departure from the platform, in the presence of a strong downwind; c) maximize the longitudinal control force for the fastest longitudinal movement; d) configure the structure to perform the next task against the background of the current task, for example, to quickly move away from the platform in a downwind, after the end of dynamic positioning operations. Therefore, the development of automatic modules for optimal control of redundant structures to ensure the above-mentioned capabilities is an urgent scientific and technical task.

The object of research is the processes of automatic optimal control of redundant structures of the vessel's executive devices.

The subject of research is methods, algorithmic and software modules for automatic optimal control of redundant structures of the vessel's executive devices.

The purpose of the study is to reduce energy consumption during dynamic positioning, increase control forces and moment in the yawing channel and, due to this, reduce the risks of piling on the platform during departure, in the presence of downwind.

3. Methods and materials

Figure 1 shows the scheme of redundant control of the OSV vessel

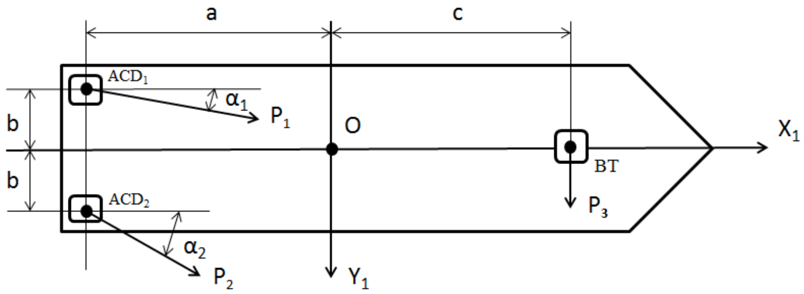

Figure 1: Scheme of redundant control of the OSV vessel

The coordinate system OX1Y1Z1 related to the vessel is located at the center of rotation of the vessel O, the axis OX1 lies in the diametrical plane of the vessel, parallel to the vessel 's deck and directed to the bow of the vessel. The axis OY1 is perpendicular to the diametrical plane of the vessel and is directed towards the starboard side. The axis OZ1 complements the system OX1Y1Z1 to the "right". The redundant control structure includes the first ACD1 whose coordinates are $(-a, -b, 0)$, the second ACD2 whose coordinates are $(-a, b, 0)$, and the bow thruster BT whose coordinates are $(c, 0,0)$. The ACD1 creates a propeller thrust vector $\boldsymbol{P_1} = (P_1 cos\alpha_1, P_1 sin\alpha_1, 0)$as control limitations $|P_1| \leq P_{ACD}^{max}$, $|\alpha_1| \leq \pi$. ACD2 creates a propeller thrust vector $\boldsymbol{P_2} = (P_2 cos\alpha_2, P_2 sin\alpha_2, 0)$as control limitations $|P_2| \leq P_{ACD}^{max}$, $|\alpha_2| \leq \pi$. The bow thruster BT creates lateral force $\boldsymbol{P_3} = (0, P_3, 0)$ and has control limitations $|P_3| \leq P_{BT}^{max}$.

The mathematical model shown in fig. 1 structure will be written in the form

$$\begin{cases} P_x = P_1 cos\alpha_1 + P_2 cos\alpha_2 \\ P_y = P_1 sin\alpha_1 + P_2 sin\alpha_2 + P_3 \\ M_z = P_1 bcos\alpha_1 - P_2 bcos\alpha_2 - P_1 asin\alpha_1 - P_2 asin\alpha_2 + P_3 c \end{cases}, \tag{1}$$

where P_x is the total longitudinal control force of the structure,

P_y is the total lateral control force of the structure,

M_z is the total control moment of the structure in the yaw channel.

System (1) includes five control parameters P_1, α_1, P_2, α_2, P_3. To control the longitudinal, lateral and angular movement of the vessel in the yawing channel, 3 independent controls are required P_x, P_y, M_z, i.e. the redundancy of the structure is $5 - 3 = 2$. We will use these two redundant controls to optimize the control processes and adjust the structure.

3.1. Optimal control of redundant structure

In general, the objective function of the redundant structure control (1) can be written as follows

$$Q(P_1, \alpha_1, P_2, \alpha_2, P_3) \rightarrow extr \tag{2}$$

To find optimal control parameters $P_1, \alpha_1, P_2, \alpha_2, P_3$ that satisfy condition (2) and constraint (1), we will use an optimization procedure similar to $fmincon(*)$ MATLAB

$$fmincon(@fun, \boldsymbol{x}0, \boldsymbol{A}, \boldsymbol{b}, \boldsymbol{A}eq, \boldsymbol{b}eq, \boldsymbol{l}b, \boldsymbol{u}b, @nonlcon), \tag{3}$$

where $@fun$ is a reference to the function (2) being optimized,

$\boldsymbol{x}0 = (P_1(0), \alpha_1(0), P_2(0), \alpha_2(0), P_3(0)$ is the starting vector of control parameters,

$\boldsymbol{A}$ is the matrix of the inequalities type restrictions system, in our case is absent,

$\boldsymbol{b}$ is the vector of the system right parts of the inequalities type restrictions, in our case it is absent,

$\boldsymbol{A}eq$ is the matrix of the equalities type restrictions system, in our case is absent,

$\boldsymbol{b}eq$ is the vector of the system right parts of the equalities type restrictions, in our case is absent,

$\boldsymbol{l}b = [-P_{ACD}^{max}, -\pi, -P_{ACD}^{max}, -\pi, -P_{BT}^{max}]$ is the vector and components of the optimization parameters lower limits,

$\boldsymbol{u}b = [P_{ACD}^{max}, \pi, P_{ACD}^{max}, \pi, P_{BT}^{max}]$ is the vector and components of the optimization parameters upper limits,

$@nonlcon$ is the reference to the system of nonlinear constraints (1).

The optimization procedure (3) allows, using numerical methods, to find controls $P_1, \alpha_1, P_2, \alpha_2, P_3$ that optimize the nonlinear objective function (2), in the presence of nonlinear control constraints (1) and linear control constraints $-P_{ACD}^{max} \leq |\boldsymbol{P}_1| \leq P_{ACD}^{max}$, $-\pi \leq |\alpha_1| \leq \pi$, $-P_{ACD}^{max} \leq |\boldsymbol{P}_2| \leq P_{ACD}^{max}$, $-\pi \leq |\alpha_2| \leq \pi$, $-P_{BT}^{max} \leq |\boldsymbol{P}_3| \leq P_{BT}^{max}$. Nonlinear constraints (1) determine the relationship between the controls that provide the necessary total forces P_x, P_y and moment M_z of the redundant structure to perform operations of dynamic positioning or given movement. Required total forces P_x, P_y and moment M_z, included in the system of nonlinear constraints (1), are determined by the deviation of the measured values of the vessel's movement parameters from their set values, using the PID controller

$$\begin{cases} P_x = k_1(X_g - X_g^*) + k_2(V_x - V_x^*) + k_3 \int (X_g - X_g^*)dt \\ P_y = k_4(Y_g - Y_g^*) + k_5(V_y - V_y^*) + k_6 \int (Y_g - Y_g^*)dt \\ M_z = k_7(\varphi - \varphi^*) + k_8(\omega_z - \omega_z^*) + k_9 \int (\varphi - \varphi^*)dt \end{cases}, \tag{4}$$

where $X_g - X_g^*$, $Y_g - Y_g^*$, $\varphi - \varphi^*$ is respectively the longitudinal, lateral and angular deviation of the measured parameters of the vessel's movement from their program values, $V_x - V_x^*$, $V_y - V_y^*$, $\omega_z - \omega_z^*$ are respectively the deviation of the measured values longitudinal, lateral speed and angular rate (in the yaw channel) from their program values, $k_1 - k_9$ are the gain coefficients of the PID controller.

As the aim function (2) can be used, for example, the aim function of minimum power consumption $Q_1(P_1, P_2, P_3) = P_1^2 + P_2^2 + P_3^2 \to min$, functions that maximize the control forces and moments in the lateral $Q_2(P_y) = |P_y| \to max$, longitudinal $Q_3(P_x) = |P_x| \to max$ and yaw $Q_4(M_z) = |M_z| \to max$ channels. The results of mathematical modeling, using some optimization functions (2), are given in section 4 Experiment.

3.2. Adjustment the redundant structure to the aim function during the functional task performance

The presence of redundant control allows, against the background of performing a non-optimization task, to adjust the redundant structure to the required aim function. For example, after carrying out dynamic positioning, it is planned to leave the platform with a lag, in the presence of a strong downwind. In this case, even during dynamic positioning, it is advisable to adjust the redundant structure to create the maximum lateral control force to overcome the downwind. We will adjust the structure using the gradient method. Let the aim function to which the redundant structure needs to be tuned is $Q(P_1, \alpha_1, P_2, \alpha_2, P_3)$. The derivative of a function $Q(P_1, \alpha_1, P_2, \alpha_2, P_3)$ in time is

$$\frac{\partial Q}{\partial t} = \frac{\partial Q}{\partial P_1}\dot{P}_1 + \frac{\partial Q}{\partial \alpha_1}\dot{\alpha}_1 + \frac{\partial Q}{\partial P_2}\dot{P}_2 + \frac{\partial Q}{\partial \alpha_2}\dot{\alpha}_2 + \frac{\partial Q}{\partial P_3}\dot{P}_3 = \langle \boldsymbol{grad}Q, \dot{\boldsymbol{u}} \rangle, \tag{5}$$

where $\boldsymbol{grad}Q = \left(\frac{\partial Q}{\partial P_1}, \frac{\partial Q}{\partial \alpha_1}, \frac{\partial Q}{\partial P_2}, \frac{\partial Q}{\partial \alpha_2}, \frac{\partial Q}{\partial P_3}\right)$ is the gradient of the aim function, $\dot{\boldsymbol{u}} = (\dot{P}_1, \dot{\alpha}_1, \dot{P}_2, \dot{\alpha}_2, \dot{P}_3)$ is the change speed vector of the redundant structure control parameters.

For the fastest descent (ascent) along the gradient, the condition (5) must be met

$$\frac{\partial Q}{\partial t} = \langle \boldsymbol{grad}Q, \dot{\boldsymbol{u}} \rangle \to extr \tag{6}$$

In order for the automatic system to also perform control functions during the reconfiguration of the structure, it is necessary to take into account the nonlinear constraints (1), which will be written in the form

$$
\begin{cases}
P_x(n) = P_1(n)cos\alpha_1(n) + P_2(n)cos\alpha_2(n) \\
P_y(n) = P_1(n)sin\alpha_1(n) + P_2(n)sin\alpha_2(n) + P_3(n) \\
M_z(n) = P_1(n)bcos\alpha_1(n) - P_2(n)bcos\alpha_2(n) - P_1(n)asin\alpha_1(n) - P_2(n)asin\alpha_2(n) + P_3(n)c \\
P_1(n) = P_1(n-1) + \dot{P}_1(n)\Delta t \\
\alpha_1(n) = \alpha_1(n-1) + \dot{\alpha}_1(n)\Delta \\
P_2(n) = P_2(n-1) + \dot{P}_2(n)\Delta t \\
\alpha_2(n) = \alpha_2(n-1) + \dot{\alpha}_2(n)\Delta t \\
P_3(n) = P_3(n-1) + \dot{P}_3(n)\Delta t,
\end{cases} \tag{7}
$$

where $P_x(n)$, $P_y(n)$, $M_z(n)$ are necessary for controlling the forces and moment on the n cycle of the calculation, $P_1(n)$, $\alpha_1(n)$, $P_2(n)$, $\alpha_2(n)$, $P_3(n)$ are the thrust forces and angles of rotation ACD1, ACD2 and thrust force BT on n calculation cycles, $P_1(n-1)$, $\alpha_1(n-1)$, $P_2(n-1)$, $\alpha_2(n-1)$, $P_3(n-1)$ are the thrust forces and angles of rotation ACD1, ACD2 and thrust force BT on $(n-1)$ calculation cycles, $\dot{P}_1(n)$, $\dot{\alpha}_1(n)$, $\dot{P}_2(n)$, $\dot{\alpha}_2(n)$, $\dot{P}_3(n)$ are the optimization parameters (the control parameters derivatives), Δt is the calculation step.

In addition, it is necessary to take into account the limitations on control parameters and the speed of control parameters change

$$
\begin{cases}
|P_1| \le P_{ACD}^{max}, |\alpha_1| \le \pi, |P_2| \le P_{ACD}^{max}, |\alpha_2| \le \pi, |P_3| \le P_{BT}^{max} \\
|\dot{P}_1| \le \dot{P}_{ACD}^{max}, |\dot{\alpha}_1| \le \dot{\alpha}_{1ACD}^{max}, |\dot{P}_2| \le \dot{P}_{ACD}^{max}, |\dot{\alpha}_2| \le \dot{\alpha}_{2ACD}^{max}, |\dot{P}_3| \le \dot{P}_{BT}^{max}
\end{cases} \tag{8}
$$

To determine optimization parameters that satisfy condition (6), nonlinear constraints (7) and linear constraints (8), we use the optimization procedure (9) at each step of the on-board controller

$$
fmincon(@fun, \boldsymbol{x}0, \boldsymbol{A}, \boldsymbol{b}, \boldsymbol{A}eq, \boldsymbol{b}eq, \boldsymbol{l}b, \boldsymbol{u}b, @nonlcon), \tag{9}
$$

where $@fun$ is the reference to the function (6) being optimized, $@nonlcon$ is the reference to the system of nonlinear constraints (7).

The result of the optimization procedure (9) with the aim function (6), nonlinear constraints (7) and linear constraints (8) will be the optimal rates of the control parameters change, which ensure the adjustment of the redundant structure by the gradient method to the aim function against the background of solving the current functional problem.

4. Experiment

The experiment was carried out in the closed circuit "Automatic control system – Control object" created in the MATLAB environment. The mathematical model of the ESNAAD-224 vessel was used as the control object, the main characteristics of which are given in Table 1.

Table 1
Main characteristics of the ESNAAD-224 vessel

Parameter	Value
Main Propulsion	Tow (2) SCHOTTEL Azimuth Thrusters electrically driven , Type: SRP 1012 R/R, In put Power: 1250 Kw, 360 degree rotation
Propeller	Fixed pitch propeller, 2100 mm Ø, No of blades: 4
Steering system	SCHOTTEL Steering System, Type SST 612, Power: 45 kW
Transverse thrusters	Three (3) SCHOTTEL Tunnel thrusters electrically driven, Type: STT 002, Power: 600 Kw, Speed: 1770 rpm, Fixed pitch propeller, 1540 mm Ø
Max. Displacement	4020 t.
Max. Speed	13 kn.
Fuel Consumtion	16 t/d @ max. speed 13 Kts
Maximum Draught	4.85 m

Figure 2 shows a fragment of the main program code (program manager). As can be seen from the given fragment, the following were taken into account when conducting the experiment: a mathematical model of external meteo influences, a mathematical model of sensor meters, a control system model Rsysctr12, a numerical integration method of Runge–Kutty Rrunge12. The mathematical model of external influences meteo forms the magnitude and direction of wind and current in time. The mathematical model of the sensor meters forms the signals of the sensors measuring the linear and angular movement of the vessel, taking into account constant and fluctuating errors. The Rsysctr12 control system model forms the signals necessary for control by deviating the current parameters of the state vector from their program values (PID controller), splitting the generated signals by executive devices of the redundant structure, or calculating optimal controls, depending on the target function.

```
while t<=tmax
   [wd,sm]=meteo(t);
   xm=sensor(xn,wd,sm,t);
   [u,intDx,intDy,intDpsi,dcl]=Rsysctr12(xn,u,intDx,intDy,intDpsi,cc);
   xt=Rrunge12(xn,u,wd,sm,cc,dt);
   xn=xn+xt*dt;
   En=En+(u(1)^2+u(3)^2+u(5)^2)*dt;
   if t>=tp
   xp(1:12,jp)=xn(1:12);
   xp(13,jp)=u(1);
   xp(14,jp)=u(2);
   xp(15,jp)=u(3);
   xp(16,jp)=u(4);
   xp(17,jp)=u(5);
   xp(18,jp)=En;
   jp=jp+1;
   tp=jp*dp;
   end
   nt=nt+1;
   t=nt*dt;
end
```

Figure 2: Fragment of the main program code (program manager)

5. Result

When conducting experiments in the closed circuit "Control system – Control object", the results of modeling the optimal control of the redundant structure of executive devices with the target functions of minimum energy consumption, maximum control force of the structure in the channel of longitudinal movement, and also maximum control force of the structure in the channel of lateral movement were obtained.

5.1. Mathematical modeling of dynamic positioning processes with the minimizing energy consumption aim function

Aim function

$$Q(P_1, P_2, P_3) = P_1^2 + P_2^2 + P_3^2 \rightarrow min \qquad (10)$$

it is advisable to use to minimize energy consumption, for example, during dynamic positioning. For the objective function (10), a system of nonlinear constraints (1) and a PID controller (4) are used.

The system of non-linear constraints (1) on control provides the creation of found optimal controls of the forces and moment necessary to support a given movement or position. The forces and moment necessary to maintain a given movement or position are determined by the deviation of the current movement parameters from their programmed values using the PID controller (4).

Figure 3 shows the program code of the automatic control module with the aim function (10).

```
function [u,intDx,intDy,intDpsi,dcl] = Rsysctr12( xn,u,intDx,intDy,intDpsi,cc)
global Px Py Mz
Vnxg=xn(1)*cos(xn(9))-xn(2)*sin(xn(9));
Vnyg=xn(1)*sin(xn(9))+xn(2)*cos(xn(9));
k(1)=50.0;  k(2)=1.0;  k(3)=0.0;  k(4)=50.0;  k(5)=1.0;  k(6)=0.0;  k(7)=50;  k(8)=1;  k(9)=0.0;
Dx=xn(10)-xz(10);
intDx=intDx+Dx;
Dy=xn(11)-xz(11);
intDy=intDy+Dy;
Dpsi=xn(9)-xz(9);
intDpsi=intDpsi+Dpsi;
sig1=k(1)*Vnxg+k(2)*Dx+k(3)*intDx;
sig2=k(4)*Vnyg+k(5)*Dy+k(6)*intDy;
sig3=k(7)*xn(6)+k(8)*Dpsi+k(9)*intDpsi;
Px=-3000*sig1; Py=-3000*sig2;  Mz=-5000000*sig3;
…………
if flag==6              P1^2+P2^2+P3^2=min
A = [];
b = [];
Aeq = [];
beq = [];
lb = [-Pmax,-pi,-Pmax,-pi,-0.25*Pmax];
ub = [Pmax,pi,Pmax,pi,0.25*Pmax];
fun = @(u) u(1)^2+u(3)^2+u(5)^2;
u = fmincon(fun,u,A,b,Aeq,beq,lb,ub,@nonlcon6);
end
end
```

Figure 3: Program code fragment with the aim function $Q(P_1, P_2, P_3) = P_1^2 + P_2^2 + P_3^2 \to min$

Figure 4 shows the program code of the non-linear constraints (1)

```
function [c,ceq] = nonlcon6(u)
global L B Px Py Mz;
ceq=[u(1)*cos(u(2))+u(3)*cos(u(4))-Px;
   u(1)*sin(u(2))+u(3)*sin(u(4))+u(5)-Py;
   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/4-Mz];
c=[];
end
```

Figure 4: Program code of the non-linear constraints

Figure 5 shows the graphs of changes in state vector parameters over time with optimal control (blue lines), equal-vector control (green lines) and equal-module control with orthogonal vectors (red lines). The graph shows longitudinal velocity Vx[m/s], longitudinal displacement Xg[m], lateral velocity Vy[m/s], lateral displacement Yg[m/s], angular velocity Wz[dg/s], course Psi[dg], propeller thrust force P1 and the angle of rotation alfa1 ACD1, propeller thrust force P2 and angle of rotation alfa2 ACD2, thrust force P3 BT and integral value of aim function $Q(P_1, P_2, P_3) = P_1^2 + P_2^2 + P_3^2 \to min$ "Energy" proportional to energy consumption. As can be seen from the above graphs, the vessel first moves to the position of dynamic positioning $X_g^* = 100m, Y_g^* = 50m, \varphi^* = 30dg$ and then maintains this position. As can be seen from the given "Energy(t)" graphs, the integral value of the aim function $Q_1(P_1, P_2, P_3) = P_1^2 + P_2^2 + P_3^2 \to min$ for optimal control is $\int_0^t Q_1\, dt = 1{,}1e^{12}[N^2 s]$, the integral value of the aim function for equal vector control is $\int_0^t Q_1\, dt = 1{,}7e^{12}[N^2 s]$, and the integral value of the aim function for equal modular (with orthogonal vectors) control is $\int_0^t Q_1\, dt = 2{,}2e^{12}[N^2 s]$.

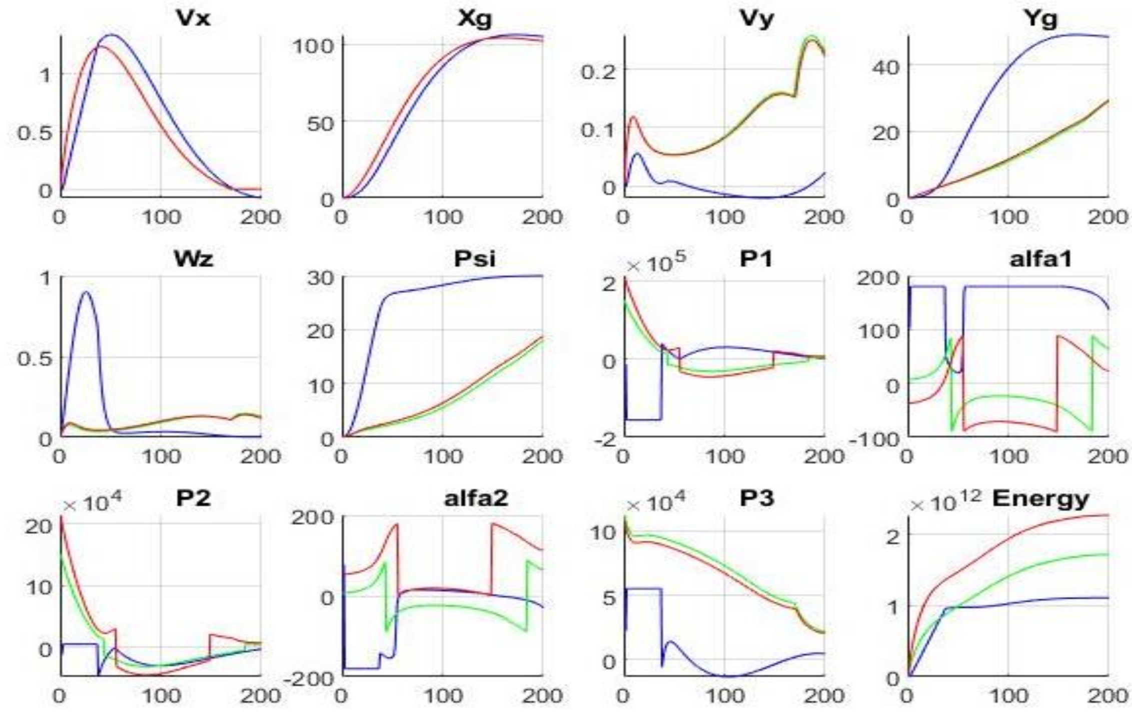

Figure 5: Graphs of changes in state vector parameters over time

The results of the conducted experiment show that the use of an intelligent system of optimal control with the aim function of minimum energy consumption allows reducing the energy consumption of the structure by (35–50) %, compared to controls that are not optimized for energy consumption.

5.2. Mathematical modeling of lateral movement of the vessel with the maximizing lateral force aim function

Aim function

$$Q_2(P_y) = |P_y| \to max \quad (11)$$

it is expedient to use, for example, when the vessel departs with a lag from the platform, when there is a downwind, or when a quick lateral movement is necessary. For the objective function (11), the system of nonlinear constraints (1) will have the form

$$\begin{cases} P_x = P_1 cos\alpha_1 + P_2 cos\alpha_2 \\ M_z = P_1 bcos\alpha_1 - P_2 bcos\alpha_2 - P_1 asin\alpha_1 - P_2 asin\alpha_2 + P_3 c \end{cases} \quad (12)$$

The physical meaning of system (12) is that during the optimization of function (11) (creating the maximum lateral control force), the control system must simultaneously support control in the channels of longitudinal and angular movement. The parameters P_x, M_z, included in the system of nonlinear constraints (12) are from the system of PID controller equations (13)

$$\begin{cases} P_x = k_1(X_g - X_g^*) + k_2(V_x - V_x^*) + k_3 \int (X_g - X_g^*)dt \\ M_z = k_7(\varphi - \varphi^*) + k_8(\omega_z - \omega_z^*) + k_9 \int (\varphi - \varphi^*)dt \end{cases} \quad (13)$$

The results of mathematical modeling with aim function $Q_2(P_y) = |P_y| \to max$ (11) are shown in Figure 6.

The results of the conducted experiment show that the use of an intelligent system of optimal control with aim function $Q_2(P_y) = |P_y| \to max$ provides fast lateral movement of the vessel with simultaneous maintenance of the longitudinal and angular position. The “clock loading(t)” graph shows the clock loading of the on board computer, caused by the operation of the optimization procedure (3), which is 25ms on average.

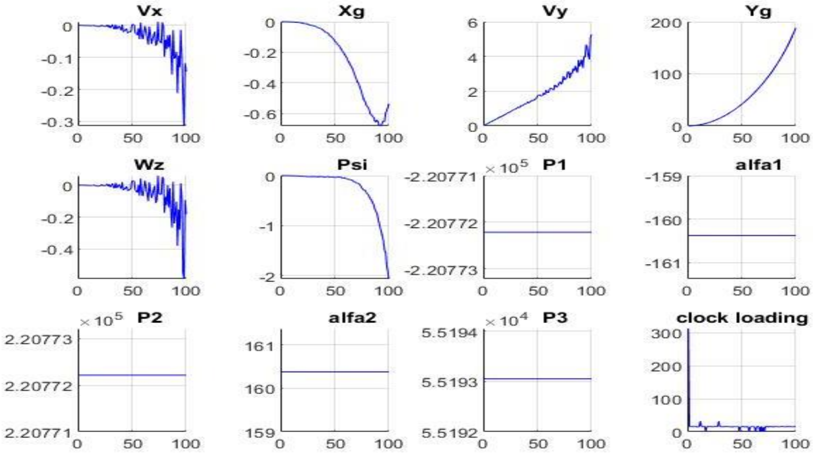

Figure 6: The results of mathematical modeling with aim function $Q_2(P_y) = |P_y| \to max$

5.3. Mathematical modeling of the vessel's longitudinal motion with the maximizing longitudinal force aim function

Aim function

$$Q_3(P_x) = |P_x| \to max \tag{14}$$

it is advisable to use when moving away from the platform forward or backward and when fast longitudinal movement is necessary. For the objective function (14), the system of nonlinear constraints (1) will have the form

$$\begin{cases} P_y = P_1 sin\alpha_1 + P_2 sin\alpha_2 + P_3 \\ M_z = P_1 bcos\alpha_1 - P_2 bcos\alpha_2 - P_1 asin\alpha_1 - P_2 asin\alpha_2 + P_3 c \end{cases} \tag{15}$$

The physical meaning of system (15) is that during the optimization of function (14) (creating the maximum longitudinal control force), the system must simultaneously support control in lateral and angular movement channels. The parameters P_y, M_z, included in the system of nonlinear constraints (15) are from the system of PID controller equations

$$\begin{cases} P_y = k_4(Y_g - Y_g^*) + k_5(V_y - V_y^*) + k_6 \int (Y_g - Y_g^*)dt \\ M_z = k_7(\varphi - \varphi^*) + k_8(\omega_z - \omega_z^*) + k_9 \int (\varphi - \varphi^*)dt \end{cases} \tag{16}$$

The results of mathematical modeling of OSV vessel motion processes, using the aim function (14), nonlinear constraints (15), PID controller (16), are shown in Figure 7.

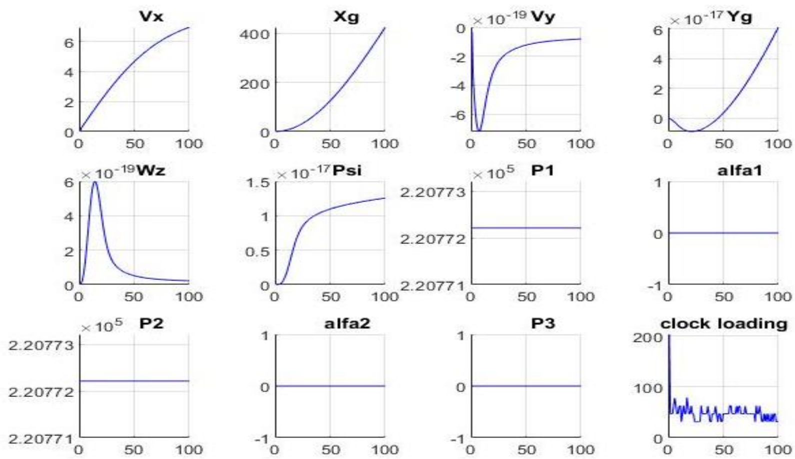

Figure 7: The results of mathematical modeling with aim function $Q_3(P_x) = |P_x| \to max$

The results of the conducted experiment show that the use of an intelligent system of optimal control with aim function provides fast longitudinal acceleration of the vessel and simultaneous support of the lateral and angular position. The “clock loading(t)” graph shows the clock loading of the on-board computer, caused by the operation of the optimization procedure (3), which is 50ms on average.

6. Discussion

Summing up and taking into account the results of the experiment, it can be noted that the proposed method, the algorithmic and software developed on its basis allow automating and optimizing the processes of controlling a vessel with redundant structures of executive devices.

The obtained result is explained by the presence of redundant control and the use of an on-board computer. At each step of the on-board computer, an optimization problem is solved with a selected nonlinear aim function, linear and nonlinear control constraints. The total forces and moments included in the system of nonlinear constraints are determined from the PID controller, based on the deviation of the measured parameters of the vessel's movement from their program values.

The optimization problem of minimal energy consumption during dynamic positioning operations, the optimization problem of creating maximum control in the channels of longitudinal and lateral movement, for safe departure from the platform after completion of dynamic positioning, and the optimization problem of reconfiguring the redundant structure from one aim function to another by the gradient method are considered. Unlike known solutions, the proposed method allows using redundant structures of executive devices not only to increase the reliability of the control system, but also to optimize control processes.

The developed method can be used on vessels, provided it is integrated into the existing automated system of an on-board computer with an open architecture, to increase the capabilities of automatic motion control, in this case, the possibility of automatic optimal control of the redundant structure of executive devices.

The theoretical significance of the obtained result lies in the development of automatic optimal control methods of the vessel's executive devices redundant structures.

The practical significance of the obtained result lies in the possibility of using modules of automatic optimal control of redundant structures in automated vessel control systems, which allows to reduce by (35–50) % energy consumption when maintaining a position, increase control forces and moments and, due to this, reduce the risks of piling on platform, when moving away from the platform in the presence of a downwind.

The limitations of the developed method include the impossibility of its application for manual control.

7. Conclusion

An analysis of literary sources was carried out, in which the authors considered the issue of automatic optimal control of redundant structures of executive devices. It was found that the closest technical solutions for automatic control of redundant vessel structures are implemented in dynamic positioning systems of manufacturers Navis, Marine Technologies, Rolls Royce, Transas, Consberg, etc. However, these solutions do not solve the problem of optimal control of redundant structures of executive devices of vessels with a aim function.

The relevance of the research and the purpose of the research are formulated.

The methods, algorithmic and software of the modules for the optimal control of the redundant structure of the offshore vessel with two ACDs and a bow thruster have been developed, which provide optimal control of the redundant structures using three target functions: a) aim function of minimum energy consumption for performing operations. This function can be used for long-term dynamic positioning. The simulation results showed that the use of this aim function provides a reduction in energy consumption by (35–50) %; b) the aim function, which provides the maximum longitudinal force. This aim function can be used when moving away from the platform by the bow or stern, in the presence of a downwind, or for longitudinal movement of the vessel at maximum speed; c) the aim function, which provides the maximum lateral force. This function can be used for lagging away from the platform, in the presence of downwind, or for lateral movement at maximum speed.

The issue of adjusting the redundant structure to the target function of the next stage of maneuvering is also considered. This makes it possible to ensure a smooth transition between the aim functions of the current and next stage, reduce the risk of temporary loss of controllability and piling onto the platform.

Further research is planned for other redundant structures and aim functions.

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