# STUDY OF A MINIMALLY EXCESSIVE COMPLANARY CONTROL STRUCTURE WITH TWO AZIMUT CONTROL DEVICES

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**Introduction.** Large number of vessels such as Oil and Gas Platform Supply / Support Vessels (PSV), Offshore Supply / Support Vessels (OSV), Diving Support Vessels (DSV), Remote Controlled Vessels (RSV), Rigging Vessels, Storage Vessels, Cable Layers and cable repair vessels, pipelayers, dredgers, floating cranes, semi-submersible heavy-lift vessels, mobile offshore drilling rigs, shuttle tankers, floating production, storage and unloading units, passenger and naval ships are equipped with redundant control structures, including several azimuth control devices (ACDs), bow and stern thrusters. Control redundancy is traditionally used to improve the reliability and maneuverability of the vessel. At the same time, the presence of redundancy also makes it possible to organize control in such a way as to minimize the selected control quality functional. This article examines the control structure with two stern ACDs, without bow and stern thrusters [1]. This structure is minimally redundant, since four controls $P_1, P_2, \alpha_1, \alpha_2$ (two screw thrust forces and two ACDs rotation angles) provide control over three degrees of freedom (longitudinal movement, lateral movement and rotational movement in the yaw channel). A minimally redundant coplanar structure with two stern ACDs is standard for many vessels, in addition, structures with additionally installed thrusters can be reduced to it after the latter fails. The minimally redundant coplanar structure of the two stern ACDs is also interesting because this is the last frontier when three-dimensional controllability of the vessel is ensured. The issues of redundant control were previously considered, for example, in works [2] - [4] and others.

**The relevance of research.** Taking into account the above, the development of an automatic control system for the movement of a vessel with a minimally redundant coplanar structure of 2 stern ACDs is an urgent scientific and technical task.

**Formulation of the problem.** For vessels with a minimally redundant coplanar structure of 2 stern ACDs, it is required to develop structure control algorithms that ensure three-dimensional control of the vessel, subject to minimization of energy costs for control.

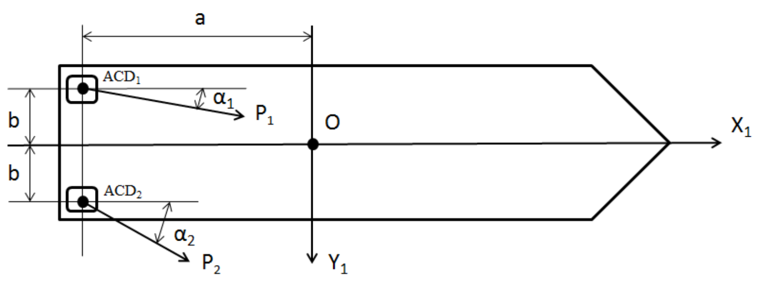


Figure 1. Control scheme for the mini mum redundant structure of 2 stern ACDs

**Research results**. Fig. 1 shows the control scheme for the minimum redundant structure of 2 stern ACDs.

The equations of forces and moment in projections on the axis of the associated coordinate system $X_1Y_1Z_1$, created by the structure under consideration, are given below.

$$P_x = P_1 \cos\alpha_1 + P_2 \cos\alpha_2, \quad (1)$$

$$P_y = P_1 \sin\alpha_1 + P_2 \sin\alpha_2, \quad (2)$$

$$M_z = P_1 b\cos\alpha_1 - P_2 b\cos\alpha_2 - P_1 a\sin\alpha_1 - P_2 a\sin\alpha_2. \quad (3)$$

Figure 2 shows the surface $P_x = f_x(P_1^*, P_2^*, \alpha_1, \alpha_2)$

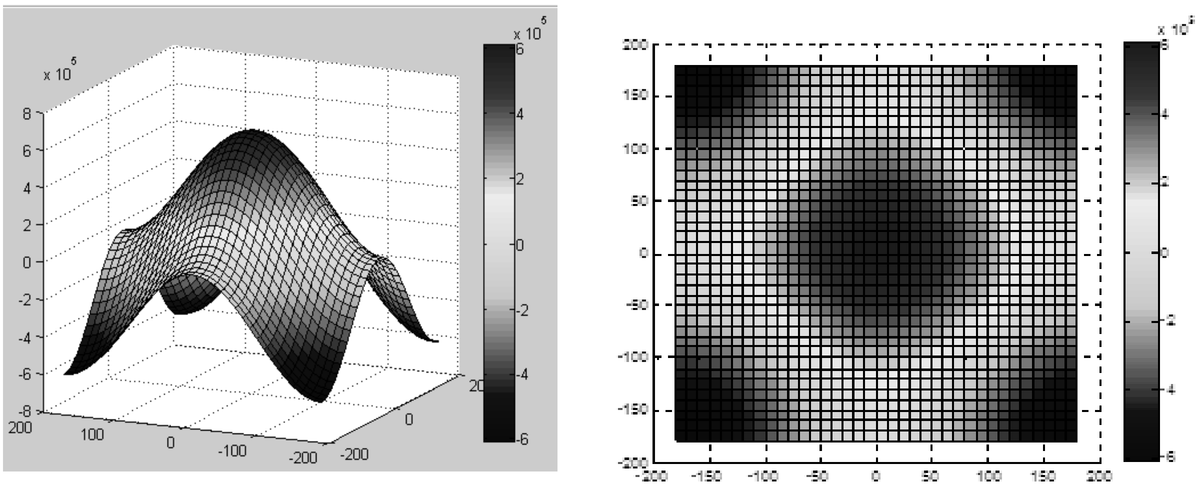


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Figure 2. Surface $P_x = f_x(P_1^*, P_2^*, \alpha_1, \alpha_2)$

Figure 3 shows the surface $P_y = f_y(P_1^*, P_2^*, \alpha_1, \alpha_2)$

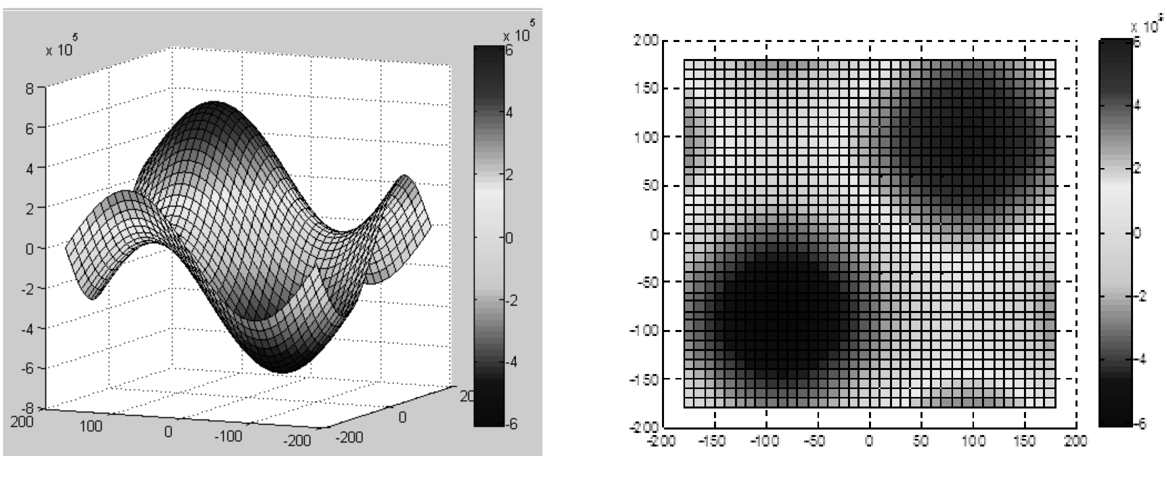


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Figure 3. Surface $P_y = f_y(P_1^*, P_2^*, \alpha_1, \alpha_2)$

Figure 4 shows the surface $M_z = f_z(P_1^*, P_2^*, \alpha_1, \alpha_2)$

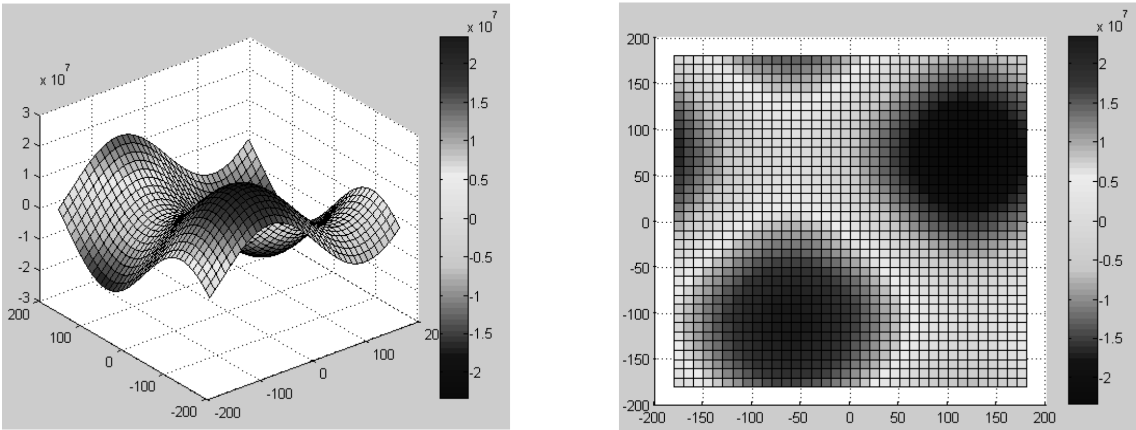


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Figure 4. Surface $M_z = f_z(P_1^*, P_2^*, \alpha_1, \alpha_2)$

As can be seen from Fig. 2 - Fig. 4, surfaces $P_x = f_x(P_1^*, P_2^*, \alpha_1, \alpha_2)$, $P_y = f_y(P_1^*, P_2^*, \alpha_1, \alpha_2)$ and $M_z = f_z(P_1^*, P_2^*, \alpha_1, \alpha_2)$ are smooth.

Finding optimal control. Let us introduce the criterion of control quality

$$F(P_1, P_2) = P_1^2 + P_2^2 \qquad (4)$$

and determine its smallest value under constraints (1) - (3). This will allow minimizing energy costs for control while solving the main functional problem. Control quality criterion (4) and constraints (1) - (3) are nonlinear functions of their variables. Considering also that functions (1) - (3) are smooth, in the MATLAB Optimization Tool we choose the fmincon - constrained nonlinear minimization solver and the interior point algorithm [5]. The results of the search for optimal controls for a set of external influences are presented in Table 1.

*Table 1.*

**Optimal controls for a set of external influences**

| External influence vector | $P_1$ | $P_2$ | $\alpha_1$ | $\alpha_2$ | $F = P_1^2 + P_2^2$ |
|---|---|---|---|---|---|
| [0,0,0] | 0 | 0 | 0,99 | 0,99 | 0 |
| [1,0,0] | 0,5 | 0,5 | 0 | 0 | 0,5 |
| [0,1,0] | 3,709 | -3,571 | 0,273 | 0 | 26,51 |
| [0,0,1] | 0,071 | -0,071 | 0,006 | 0,006 | 0,0102 |
| [1,1,0] | 4,192 | -3,071 | 0,241 | 0 | 27,01 |
| [0,1,1] | 3,778 | -3,643 | 0,268 | 0 | 27,54 |
| [1,0,1] | 0,571 | -0,429 | 0,001 | 3,141 | 0,51 |
| [1,1,1] | 4,262 | -3,143 | 0,237 | 0 | 28,04 |
| [-1,0,0] | -0,5 | 0,5 | 0,001 | 3,141 | 0,5 |
| [0,-1,0] | -3,709 | 3,571 | 0,273 | 0 | 26,51 |
| [0,0,-1] | -0,071 | 0,071 | 0,006 | 0,006 | 0,0102 |

Let us compare the obtained optimal controls with several particular redundancy resolution schemes. Redundancy resolution schemes are obtained by imposing additional restrictions on system (1) - (3).

Redundancy Resolution Scheme $\alpha_1 = -\alpha_2$. Substituting the constraint $\alpha_1 = -\alpha_2$ into system (1) - (3), we obtain analytical expressions for determining controls.

$$\alpha_1 = arctg(\frac{P_y b}{M_z + P_y a}), \quad (5)$$

$$\alpha_2 = -\alpha_1, \quad (6)$$

$$P_1 = \frac{1}{2}(\frac{P_x}{\cos\alpha_1} + \frac{P_y}{\sin\alpha_1}), \quad (7)$$

$$P_2 = \frac{1}{2}(\frac{P_x}{\cos\alpha_1} - \frac{P_y}{\sin\alpha_1}). \quad (8)$$

The controls for the redundancy resolution scheme $\alpha_1 = -\alpha_2$ are presented in Table 2.

*Table 2.*

**Controls for the redundancy resolution scheme $\alpha_1 = -\alpha_2$**

| External influence vector | $P_1$ | $P_2$ | $\alpha_1$ | $\alpha_2$ | $F = P_1^2 + P_2^2$ |
|---|---|---|---|---|---|
| [0,0,0] | 0,211 | -0,210 | 0,136 | -0,136 | 0,088 |
| [1,0,0] | 0,508 | 0,501 | 0,136 | -0,136 | 0,509 |
| [0,1,0] | 3,607 | -3,606 | 0,139 | -0,139 | 26,011 |
| [0,0,1] | 0,076 | -0,075 | 0,007 | -0,007 | 0,011 |
| [1,1,0] | 4,111 | -3,101 | 0,139 | -0,139 | 26,521 |
| [0,1,1] | 3,678 | -3,677 | 0,136 | -0,136 | 27,041 |
| [1,0,1] | 0,575 | 0,425 | 0,007 | -0,007 | 0,511 |
| [1,1,1] | 4,182 | -3,172 | 0,136 | -0,136 | 27,55 |
| [-1,0,0] | -0,501 | -0,508 | 0,136 | -0,136 | 0,509 |
| [0,-1,0] | -3,606 | 3,607 | 0,139 | -0,139 | 26,009 |
| [0,0,-1] | -0,067 | 0,068 | -0,007 | 0,007 | 0,009 |

*Redundancy Resolution Scheme* $\alpha_1 = \alpha_2$. Substituting the constraint $\alpha_1 = \alpha_2$ into system (1) - (3), we obtain analytical expressions for determining controls.

$$\alpha_1 = arctg(\frac{P_y}{P_x}), \quad (9)$$

$$\alpha_2 = \alpha_1, \quad (10)$$

$$P_1 = \frac{P_x b + P_y a + M_z}{2b\cos\alpha_1}, \quad (11)$$

$$P_2 = \frac{P_x b - P_y a - M_z}{2b\cos\alpha_1}. \quad (12)$$

The controls for the redundancy resolution scheme $\alpha_1 = \alpha_2$ are presented in Table 3.

*Table 3.*

**Controls for the redundancy resolution scheme $\alpha_1 = \alpha_2$**

| External influence vector | $P_1$ | $P_2$ | $\alpha_1$ | $\alpha_2$ | $F = P_1^2 + P_2^2$ |
|---|---|---|---|---|---|
| [0,0,0] | 0,006 | -0,004 | 0,785 | 0,785 | 0 |
| [1,0,0] | 0,504 | 0,496 | 0,001 | 0,001 | 0,5 |
| [0,1,0] | 3572,002 | -3571,002 | 1,57 | 1,57 | 25511250,511 |
| [0,0,1] | 0,107 | -0,105 | 0,785 | 0,785 | 0,023 |
| [1,1,0] | 5,758 | -4,344 | 0,785 | 0,785 | 52,022 |
| [0,1,1] | 3643,359 | -3643,359 | 1,57 | 1,57 | 26540843,367 |
| [1,0,1] | 0,575 | 0,425 | 0,001 | 0,001 | 0,511 |
| [1,1,1] | 5,859 | -4,445 | 0,785 | 0,785 | 54,082 |
| [-1,0,0] | -0,496 | -0,504 | -0,001 | -0,001 | 0,5 |
| [0,-1,0] | -3570,859 | 3571,859 | -1,57 | -1,57 | 25509209,693 |
| [0,0,-1] | -0,095 | 0,097 | 0,785 | 0,785 | 0,018 |

*Redundancy Resolution Scheme* $\alpha_1 = 0$. Substituting the constraint $\alpha_1 = 0$ into system (1) - (3), we obtain analytical expressions for determining controls.

$$P_1 = \frac{P_x b + P_y a + M_z}{2b}, \tag{13}$$

$$\alpha_1 = 0, \tag{14}$$

$$\alpha_2 = arctg\left(\frac{P_y}{P_x - P_1}\right), \tag{15}$$

$$P_2 = \frac{P_y}{\sin\alpha_2}, \tag{16}$$

The controls for the redundancy resolution scheme $\alpha_1 = 0$ are presented in Table 4.

*Table 4.*

**Controls for the redundancy resolution scheme $\alpha_1 = 0$**

| External influence vector | $P_1$ | $P_2$ | $\alpha_1$ | $\alpha_2$ | $F = P_1^2 + P_2^2$ |
|---|---|---|---|---|---|
| [0,0,0] | 0,004 | -0,003 | 0 | -0,308 | 0 |
| [1,0,0] | 0,504 | 0,496 | 0 | 0,002 | 0,5 |
| [0,1,0] | 3,572 | -3,708 | 0 | -0,273 | 26,511 |
| [0,0,1] | 0,076 | -0,075 | 0 | -0,013 | 0,011 |
| [1,1,0] | 4,072 | -3,23 | 0 | -0,315 | 27,011 |
| [0,1,1] | 3,643 | -3,777 | 0 | -0,268 | 27,541 |
| [1,0,1] | 0,575 | 0,425 | 0 | 0,002 | 0,511 |
| [1,1,1] | 4,143 | -3,298 | 0 | -0,308 | 28,041 |
| [-1,0,0] | -0,496 | -0,504 | 0 | -0,002 | 0,5 |
| [0,-1,0] | -3,571 | 3,709 | 0 | -0,273 | 26,509 |
| [0,0,-1] | -0,067 | 0,068 | 0 | 0,015 | 0,009 |

As follows from the results obtained, the redundancy resolution scheme $\alpha_1 = \alpha_2$ is not suitable for control in the presence of the lateral component of the disturbance, and also strongly differs from the optimal one in the presence of a disturbing moment in the yaw channel. The redundancy resolution scheme $\alpha_1 = -\alpha_2$ differs by no more than 2% from the optimal one for all considered disturbances, except for the case of pure disturbance in the yaw channel, where the maximum deviation is up to 10%. The redundancy resolution scheme `$\alpha_1 = 0$ differs by no more than 0.23% from the optimal one for all considered disturbances, except for the case of pure disturbance in the yaw channel, where the maximum deviation is up to 11.6%.

**Conclusions.** The work has solved the following tasks:

– control surfaces are constructed $P_x = f_x(P_1^*, P_2^*, \alpha_1, \alpha_2)$, $P_y = f_y(P_1^*, P_2^*, \alpha_1, \alpha_2)$, $M_z = f_z(P_1^*, P_2^*, \alpha_1, \alpha_2)$, it was concluded that these surfaces are smooth;

– using the fmincon – constrained nonlinear minimization solver and the interior point algorithm of MATLAB Optimization Tool, optimal controls are obtained for the minimally redundant ACD structure that minimizes the power consumption for control;

– the considered criterion of minimum power consumption and the algorithms obtained on its basis can also be used to adjust the redundant structure that best counteracts external disturbances, which can be used to reduce the dynamic component of the positioning error;

– considered redundancy resolution schemes $\alpha_1 = -\alpha_2$, $\alpha_1 = \alpha_2$, $\alpha_1 = 0$, allowing to obtain analytical expressions for splitting controls;

– it is shown that the redundancy resolution scheme $\alpha_1 = \alpha_2$ is not suitable for control in the presence of the lateral component of the disturbance, and also strongly differs from the optimal one in the presence of a disturbing moment in the yaw channel;

– the redundancy resolution scheme $\alpha_1 = -\alpha_2$ differs by no more than 2% from the optimal one for all considered disturbances, except for the case of pure disturbance in the yaw channel, where the maximum deviation is up to 10%;

– the redundancy resolution scheme $\alpha_1 = 0$ best matches the optimal control scheme, differs from it by no more than 0.23% for all considered disturbances, except for the case of pure disturbance in the yaw channel, where the maximum deviation is up to 11.6%.

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