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Modeling the management of a service underwater vehicle while maneuvering in an environment with obstacles

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Abstract. Difficulty in the development of the Arctic and the Far North are associated not only with the harsh natural conditions, but also with extreme professional risk. High-risk underwater operations at industrial facilities requires for underwater robots. Many works (inspection, docking with manifolds, etc.) are associated with operations in an environment with obstacles. The use of robotic systems is a natural choice in these conditions, especially at offshore facilities. The most difficult and dangerous are underwater operations on offshore production platforms and transporting offshore pipelines. For high-risk underwater operations at industrial facilities, service autonomous underwater vehicles (PA) are required. Many works (inspection, operations on manifolds docked with collectors, etc.) are associated with operations in an environment with obstacles; therefore the kinematic scheme of the underwater vehicle should provide increased maneuverability and ease of use when working in an environment with obstacles. When developing the appropriate control mode for the underwater vehicle (UV), it is important to consider the dynamic parameters of the UV when solving the problem of its positioning (the positioning problem itself can be solved by means of a technical vision system - TVS). The article discusses two generalized models of UV for work on man-made objects and the results of computational experiments that simulate the reduction of UV to a target point, the coordinates of which are determined using the TVS.

1. Introduction

Difficulties in the development of the Arctic Region are associated not only with the harsh natural conditions. Virtually all types of human activity in these regions fall into the category of increased or extreme professional risk. To date, the development of Arctic technology occurs mainly through the improvement of life support systems for vehicle crews or personnel of industrial enterprises. This entails an increase in non-productive costs, increases environmental risks, reduces the efficiency of human activity in the region. New solutions are needed to reduce the proportion of direct human presence in polar and arctic objects. The use of robotic systems is a natural choice in these conditions, especially at offshore facilities. The most difficult and dangerous are underwater operations on offshore production platforms and transporting offshore pipelines. For high-risk underwater operations at industrial facilities, autonomous underwater vehicle (UV) is required. Many works under water are associated with operations in limited and cramped conditions. Such operations include: inspection of underwater structures, work with executive bodies of manifolds, etc. There are a number of solutions to the problem of positioning an autonomous robot with respect to obstacles, when technical vision systems (TVS) based on different physical principles are used as the main sensor [1-5]. The main sensor of technical vision are television cameras that distinguish markers at a distance of 20-25 meters. The most difficult to implement are those tasks where TVS data are used directly in the control loop when moving in an environment with obstacles. Under these conditions, it is necessary to synthesize the control of the underwater vehicle

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taking into account the safety of its maneuvering. In the security and maneuvering algorithms, on the one hand, accounting for the dynamic parameters of the control object, on the other hand, its positioning accuracy relative to other objects, is decisive.

Successful UV maneuvering in a medium with obstacles of complex spatial configuration can be achieved by increasing the dimension of the observation and control vectors, for example, using an excessive number of propulsive devices (we will call this type of redundancy cybernetic). Another way to improve the maneuverability of a UV is in the redundancy of its kinematic scheme and the creation of a multi-link design. The multi-link design reduces the size requirements when working in narrow areas, since it can take the form of free space in longitudinal section. [6]

It is obvious that it is necessary to start the development of the UV control system in the positioning mode relative to underwater objects of complex spatial configuration with mathematical and computer simulation. This article discusses two types of mathematical models of highly mobile UV.

2 Modeling PA with excess dimension of the control vector

A simplified computer model of highly maneuverable UV, similar to the apparatus, been described in [8], was developed for the experiments. A specific feature of such UVs is the absence of rudders, which were replaced with thrusters. Figure 1 shows the forces applied to such a device: thrust force, inertia force, resistance force, buoyancy force and gravity.

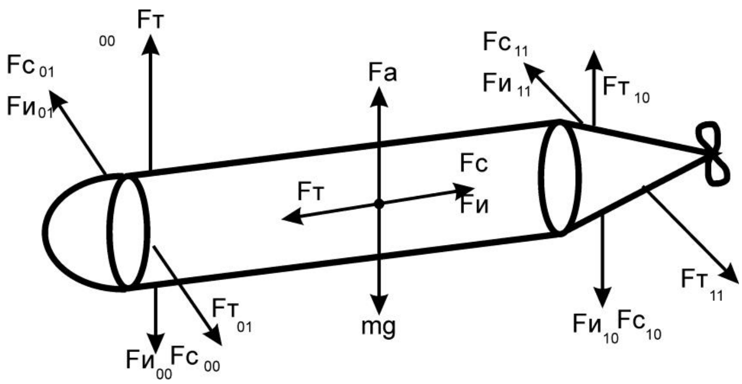

Fig. 1. Forces applied to the UV

Buoyant force is denoted Fa, the force of gravity - mg, the thrust force - Ft, the resistance force - Fr, the force of inertia - Fi. Meaning of indices: 00 - vertical forces of the bow thruster, 01-horizontal forces of the bow thruster, 10-vertical forces of the stern thruster and 11 – horizontal forces of the stern thruster . Using theoretical mechanics methods let's find the total force and the total moment of forces, applied to the UV (see figure 2). In order not to clutter up the picture, the thrust force of the main marching propulsion is not shown.

Therefore, we can write the sum of forces and moments in vector form:

$$\vec{F}_{\Sigma} = \vec{F}_{\mathrm{t00}} + \vec{F}_{\mathrm{t01}} + \vec{F}_{\mathrm{T10}} + \vec{F}_{\mathrm{t11}} + \vec{F}_{\mathrm{t}} + \vec{F}_{\mathrm{A}}$$

$$\vec{M}_{\Sigma} = \vec{a} \times \vec{F}_{\mathrm{t00}} + \vec{a} \times \vec{F}_{\mathrm{t01}} + \vec{b} \times \vec{F}_{\mathrm{t10}} + \vec{b} \times \vec{F}_{\mathrm{t11}}$$

From here we obtain projections of forces and moments:

$$F_{\Sigma\mathrm{x}} = F_{t01} + F_{t11}$$

$$F_{\Sigma\mathrm{y}} = F_{T}$$

$$F_{\Sigma\mathrm{z}} = F_{t00} + F_{t10}$$

$$M_{\Sigma\mathrm{x}} = a\, F_{t00} - b\, F_{t01}$$

$$M_{\Sigma\mathrm{y}} = 0$$

$$M_{\Sigma\mathrm{z}} = a\, F_{t01} - b\, F_{t11}$$

The found forces and moments are required for substitution in the equation of body hydrodynamics forces:

$$A\,\dot{y} = U - C\,y^2, \quad y(t0) = y0$$

where
A - analogue of the inertial coefficient (mass and inertia moment);
y - analogue of linear and angular velocities, hereinafter referred to as the generalized velocity;
U - control action (force and torque);
C - analogue of the hydrodynamic resistance coefficient (for forward and rotational movements).

3 The generalized model of kinematically excess UV

Consider a PA model consisting of spherical modules connected by hinges of the 4th class (i.e., having two degrees of mobility - at the rate and at the trim). The simplified model contains four such modules (by analogy with known reconfigurable UVs)

Let for each spherical module coincide geometrically: the center of mass (CM), the center of magnitude (ie, the center of buoyancy - CB), the geometric center (GC), and let the axis of the thrust force of the propulsor pass through the geometric center of the module.

Consider all the forces applied to the apparatus: the forces of inertia, forces of resistance, Archimedean force and gravity. Let the device also have zero buoyancy, that is, the force of gravity and the Archimedean force can be ignored. Consider Figure 2.

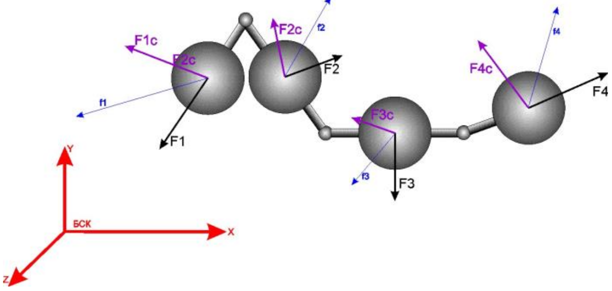

Figure 2 - Forces applied to the apparatus

In Figure 4, black arrows indicate thrust forces from thrusters: F1 and F4 are directed along lines passing through the centers of the extreme spherical modules and the centers of the hinges. That is, these forces, relatively speaking, are pulling the apparatus either "forward" or "backward"; F2 - relatively speaking, right-left, and F3 - also conditionally, up and down. The purple arrows F1c-F4c designate the forces of hydrodynamic resistance, which, as is well known, are opposite to the direction of the linear velocities of the modules. The blue arrows f1-f4 indicate the resultant forces between the thrust (propulsion) forces and the resistance forces. Orange shows the basic coordinate system (BCS).

Given the fixed angles in the hinges, using the methods of theoretical mechanics we find the total force and the total moment of forces acting on the device.

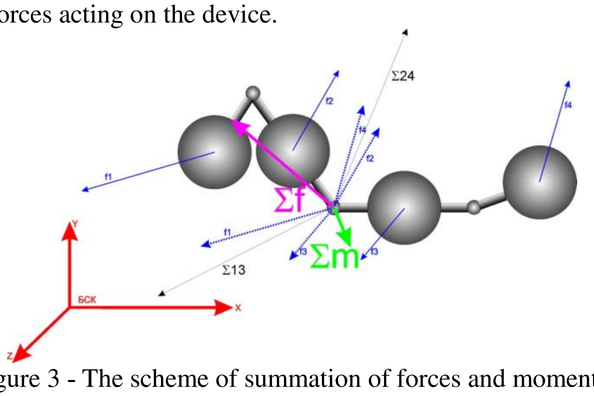

Figure 3 - The scheme of summation of forces and moments

Based on this, the PA, as a multi-tier system, can be presented according to the rules for the representation of manipulation robots. First you need to set the coordinate system and parameters, guided by the Denavit-Hartenberg formalism. Consider Figure 4, which shows a kinematic chain similar to the kinematics of a UV.

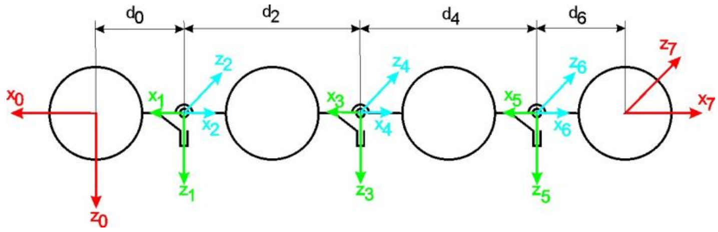

Figure 4 – UV coordinates

For successful control of the apparatus, it is necessary to solve two inverse kinematic problems: the first must give the necessary resultant force and moment vectors from the drives, and the second, the kinematic configuration of the apparatus.

The first task is to decompose the required thrust force (remembering that this force is opposite in the direction of the target speed) along the drives for the stationary vehicle, since the resistance forces are not known to us a priori. They occur when the robot moves and change as functions of speeds:

The equation of total force:

$$\overrightarrow{\Sigma \mathrm{f}} = \overrightarrow{\mathrm{F}_1} + \overrightarrow{\mathrm{F}_2} + \overrightarrow{\mathrm{F}_3} + \overrightarrow{\mathrm{F}_4}$$

Projection on coordinate axes:

$$\Sigma f_{\mathrm{x}} = \mathrm{F}_{1\mathrm{x}} + \mathrm{F}_{2\mathrm{x}} + \mathrm{F}_{3\mathrm{x}} + \mathrm{F}_{4\mathrm{x}}$$
$$\Sigma f_{\mathrm{y}} = \mathrm{F}_{1\mathrm{y}} + \mathrm{F}_{2\mathrm{y}} + \mathrm{F}_{3\mathrm{y}} + \mathrm{F}_{4\mathrm{y}}$$
$$\Sigma f_{\mathrm{z}} = \mathrm{F}_{1\mathrm{z}} + \mathrm{F}_{2\mathrm{z}} + \mathrm{F}_{3\mathrm{z}} + \mathrm{F}_{4\mathrm{z}}$$

another:

$$\Sigma f_{\mathrm{x}} = n_1\, i_1 + n_2 i_2 + n_3 i_3 + n_4 i_4$$
$$\Sigma f_{\mathrm{x}} = n_1\, j_1 + n_2 j_2 + n_3 j_3 + n_4 j_4$$
$$\Sigma f_{\mathrm{x}} = n_1\, k_1 + n_2 k_2 + n_3 k_3 + n_4 k_4$$

where $(i_l, j_l, k_l),\ l \in [1{,}4]$ - projections onto the axes of the coordinate system of unit vectors aligned with the stop vectors;

n_l - scale factors.

As a result, we have a system of three equations with four variables, which can be solved (i.e., find one of many solutions):

Let

$$\mathcal{E} = \begin{pmatrix} \Sigma f_{\mathrm{x}} \\ \Sigma f_y \\ \Sigma f_{\mathrm{z}} \end{pmatrix}, N = \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{pmatrix} \text{ and } I = \begin{pmatrix} i_1 & i_2 & i_3 & i_4 \\ j_1 & j_2 & j_3 & j_4 \\ k_1 & k_2 & k_3 & k_4 \end{pmatrix},$$

Then the equation reduces to a matrix one:

$$\mathcal{E} = I \cdot N$$

The solution:

$$N = I^T (I \cdot I^T)^{-1} \mathcal{E}$$

To solve the second kinematic problem: there is a need to have certain directions of forces:

$$\Phi_l = \begin{pmatrix} \phi_{00l} & \phi_{01l} & \phi_{02l} & \xi_1 \\ \phi_{10l} & \phi_{11l} & \phi_{12l} & \xi_2 \\ \phi_{20l} & \phi_{21l} & \phi_{22l} & \xi_3 \\ 0 & 0 & 0 & 1 \end{pmatrix}, l \in [1{,}4]$$

where ϕ_{ijl} - cosine guides for each drive.

IOP Conf. Series: Earth and Environmental Science **302** (2019) 012058 doi:10.1088/1755-1315/302/1/012058

Here, the values of "displacements" ξ_i for us do not matter, since it is only necessary to find directions, i.e., angles in the hinges. In the formula these symbols are included only in order to exclude from the resulting equations those where they will be, as insignificant for the required solution.

It does not make sense to give here the whole solution process, since the intermediate formulas are extremely cumbersome. We only say that the solutions were obtained by parametrizing the target position by Euler angles. We present only the solutions themselves:

$$t_3 = \frac{2+2t_1^2 \pm \sqrt{(2+2t_1^2)^2 - 4(C_\psi S_\vartheta + 2S_\vartheta S_\psi t_1 - C_\psi S_\vartheta t_1^2)}}{2(C_\psi S_\vartheta + 2S_\vartheta S_\psi t_1 - C_\psi S_\vartheta t_1^2)}$$

$$t_1 = \frac{-p1 + S_\vartheta S_\psi d_6 \pm \sqrt{p1^2 + p2^2 - (d_2+d_3)^2 + S_\vartheta d_6(2p2C_\psi - 2p1S_\psi + S_\vartheta d_6)}}{p2 + d_2 + d_3 + C_\psi S_\vartheta d_6}$$

$$t_2 = \frac{8f_2a_2^2 \pm \sqrt{8(1+4f_2^2+f_3^2)a_2^2a_3^2 - 4a_3^4 - 4(4f_2^2+f_3^2-1)^2}}{2(4f_2^2+(1+f_3)^2)a_2^2 - 2a_3^2};$$

4. Conclusion

The considered architecture of the VS software provides all the necessary operations to solve functional problems of UVVS. The developed software prototype was tested on a computer model of UV and confirmed its applicability to solve the problem of UV positioning when working on man-made offshore facilities, where constant maneuvering is required. The simulation results confirmed the possibility of successful solution of this problem with acceptable speed (about 8 fps) and the required accuracy.

In the future, the proposed architecture and the developed software prototype can be used to solve other problems of underwater vehicles FTZ due to their flexibility and extensibility.

5. Acknowledgments

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