Method of Visual Formation Control for Large Group of AUV in Environment with Obstacles

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Abstract. The paper proposes a modification of the method for formation control of the group of autonomous uninhabited underwater vehicles (AUVs) in the unknown environment containing obstacles for large group of AUV. AUVs move in the "leader-follower" mode in the given formation. The AUV-leader has information about the mission, moves to the target and defines the motion trajectory to safely avoid the detected obstacles. AUV-followers follow the leader, in accordance with the place given to them in the formation. For this movement, information about the current position of the AUV-leader is used. In the basic proposed method, the followers receive this information via hydroacoustic communication channels. Obstacles and the distance to them are determined via onboard rangefinders. The low bandwidth of hydroacoustic channels and large delays in data transmission do not provide safe and accurate movement of group members when they are close to an obstacle or to another AUV. To solve this problem, using onboard video cameras of AUV-followers and technical vision to determine the position of the leader, on which a special light beacons are installed, is proposed. This approach makes possible eliminating delays in the receiving of information by the followers and ensure the safe movement of the AUV group when using high-precision control systems. The main difficulty of using visual information in underwater environment is the limited visibility distance. To consider this limitation, some AUV-followers can act as leaders for other followers. This will allow to form groups from a large number of AUV. At the same time, a control system with a predictive model is used to ensure high accuracy of controlling the movement of the AUV inside the formation when bypassing obstacles. The effectiveness of the proposed method is confirmed by the results of mathematical simulation.

Keywords: Formation control · Underwater vehicle · Path planning · Obstacle avoidance · Computer vision

1 Introduction

Currently, using autonomous underwater vehicles (AUVs) is one of the most promising approach for the studying and development of the World Ocean. AUVs are capable of performing a wide range of tasks related to survey and prospecting and geological exploration, oceanographic research.

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A certain disadvantage of using AUVs is the limited operation time during the mission, which is conditioned by a limited energy reserve of onboard batteries. This disadvantage complicates the performance of operations for the survey of sufficiently large areas. To eliminate this shortcoming, many researchers suggest using groups of AUVs cooperatively performing the mission [1].

One of the main strategies for using groups of AUVs is the "leader-follower" mode, in which one of the AUVs is appointed as a leader who has complete information about the given mission and defines the movement trajectory of the group, and other AUVs are considered as followers, receiving information from the leader about its current position and correcting their movement, taking into account their prescribed position in the formation.

An important condition for the implementation of this strategy is the availability of communication channels between all AUVs of the group, which allows exchanging information about the current position of the AUV-leader and each member of the group. This is especially important when a group of AUVs performs a joint mission in an environment containing obstacles. When avoiding obstacles, the trajectories of the leader and followers can change unpredictably. In this case, AUVs must move in such a way as to avoid these obstacles at a safe distance, while excluding the possibility of collision with other members of the group.

One of the approaches to ensure the safe movement of robots is using of a special schedule in which the robot collision is not allowed [2, 3]. But using of such a method is permissible only in cases where the working environment is known. At the same time, an additional problem for AUVs is large errors in determining their coordinates in the absolute system, which requires using of additional mechanisms for matching the indications of their navigation systems and thereby leads to a significant complication of the implementation of AUV group control systems [4–6].

Methods for controlling a group of robots based on algorithms that are intended for a swarm of robots are described in the works [7, 8]. These algorithms are hardly applicable for controlling a group of AUVs, because swarm control implies a frequent exchange of information between group members, which can be difficult in the underwater environment. Also, the control of a group of robots in an unknown environment is considered in [9], where collisions with obstacles are prevented by changing the type of a given formation or the speed of movement of a group of robots so the group avoids the obstacle at the safe distance.

In all the considered examples implementation of the correction of the robots group trajectories occurs due to the constant exchange of information with each other, containing data on the current position of group members, which makes possible to coordinate the trajectories of the robots. However, this approach is not always applicable to AUVs, because the possible data transmission via hydroacoustic channels is carried out with large delays and has low bandwidth. The method without the necessity for a large exchange of information between the group members is presented in [10]. The disadvantage of the proposed approach is using of hydroacoustic communication channels, which do not ensure the safe and accurate movement of a group of AUVs, when they are located at a small distance from each other.

At the same time, a method for generating the trajectories of a group of AUVs during their movement in the "leader-followers" mode in an unknown environment with obstacles that does not require the additional data transmission between the AUVs of the group to coordinate their trajectories when avoiding obstacles was proposed in [11]. This method assumes that all AUVs of the group must know their coordinates in the absolute coordinate system quite accurately, which requires expensive hydroacoustic navigation systems, as well as the use of methods for coordinating their readings.

A method for solving the problem of the necessity of using hydroacoustic systems on AUV-followers, for the coordinated movement of the AUVs group based on visual information about the position and orientation of the leader, obtained from the on-board cameras of the followers was proposed in [12]. When using this method for implementing the movement of the AUVs group in an environment with obstacles, a problem arises that, when avoiding an obstacle, AUV-followers can cover the AUV-leader from other AUVs moving behind them, which can lead to incorrect and unsafe movement of these AUVs relative to other AUVs of the group.

This article solves the problem of developing such a method of group movement that would allow the formation of the AUVs group in which the followers do not need expensive sonar systems to follow the leader and use high-speed communication channels to coordinate the trajectories of these AUVs in the avoiding obstacles process. At the same time, the approach described in [12] will be used as the basic method that implements the "leader-follower" strategy for the AUV group, and the method [11] will be used to implement the method for generating safe obstacle avoidance trajectories in the group, which will be modified taking into account the features of the method [13].

2 Problem Formulation

A group of AUVs, consisting of AUV-leader, AUV-followers and AUV which are followers for other AUV-followers considers in this article. The AUV-leader has all the information about the mission and forms its trajectory in such a way as to ensure the accomplishment of this mission. Several light beacons are installed on AUV-leader board, which can be observed by AUV-followers through their onboard video cameras. Using this video information, they form data about the position and orientation of the AUV-leader relatively to the follower. This information AUV-followers use to follow the leader and keep given them place in the formation (Fig. 1). At the same time, AUV-followers are leaders for other AUV-followers.

AUV-followers do not have information about their current position in the absolute coordinate frame (ACF). In this case, the position of the AUV-follower in the CF relative the AUV-leader will be determined by the following expression:

$$X_F^L = -(R_L^F)^T X_L^F, \tag{1}$$

where X_F^L is the coordinate vector of the AUV-follower position in the CF of the AUV-leader; X_L^F is the coordinate vector of the AUV-leader position in the CF of the AUV-follower; R_L^F is the is the orientation matrix of the AUV-leader in the CF of the AUV-follower.

The desired position of the AUV-follower in the formation is calculated in the CF relative to the AUV-leader, which makes possible to form the desired formation of the AUV group, regardless of their position and orientation in the ACF during the mission.

To determine the position and orientation of the AUV-leader relative to the followers, these followers are equipped with video cameras that observe light beacons on the video image, the location on the leader's body and the position of which is known relative to the leader's center of mass. The position of the beacons in the CF of the AUV-leader is known and is set by the coordinates $B = (B_1, B_2, \ldots, B_k)$, where $B_i = (x_{bi}, y_{bi}, z_{bi})^T$ is the coordinates of the i-th beacon in the CF of the AUV-leader; k is the number of beacons on the leader AUV. The beacons have such characteristics that they can be identified in the image received from the video camera.

The main difficulty of using visual information in underwater environment is the limited visibility distance. To consider this limitation, some AUV-followers can act as leaders for other followers. This will allow to form groups from a large number of AUV.

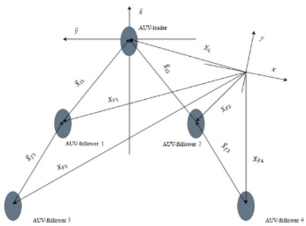

Fig. 1. AUV group formation

From the image received from the video camera of the follower, the vector $P = (P_1, P_2, \ldots, P_k)$ is formed, where $P_i = (p_{xi}, p_{yi})$ are the pixel coordinates of the i-th beacon.

The expressions binding the pixel coordinates of the beacons and the position and orientation of the leader in the camera CF:

$$\begin{aligned} &P_i = F_{B2P}\left(U, B_i, X_L^C, A_L^C\right), \\ &X_{Bi}^C(P_i) = R_L^C\left(A_L^C\right)B_i + X_L^C, \; i = \left(\overline{1, k}\right), \end{aligned} \tag{2}$$

where $X_{Bi}^C \in R^3$ is the coordinate vector of the i-th beacon in the CF of the AUV-follower; $X_L^C \in R^3$ is the coordinate vector AUV-leader in follower's camera CF; R_L^C is the transformation matrix AUV-leader relatively to CF of follower's camera; $A_L^C \in R^3$ is the vector of orientation angles of the AUV-leader relatively to the axes of the camera's CF.

The system of Eqs. (2) contains 6 unknown variables, at least 3 beacons are required for their definite determination. Equations (2) are significantly non-linear and cannot be solved analytically, the determination of the values A_L^C and X_L^C is possible using numerical optimization methods [14].

The coordinate vector of the AUV-leader in CF of follower can be determined by equation:

$$X_L^F = R_C^F X_L^C + X_C^F, \tag{3}$$

where $X_C^F \in R^3$ is the camera's position coordinate vector of i-th follower in CF of follower, $R_C^F \in R^{3\times 3}$ is the orientation matrix of onboard camera in CF of follower.

To provide the ability of the AUVs to determine surrounding obstacles, they are equipped with rangefinders (sonars), which form information about the distance to the obstacle in the direction of these rangefinders. During the operation of rangefinders and the movement of the AUV, a vector $D = (d_1, d_2, \ldots, d_n)$ is formed, where d_i is the distance to the obstacle determined by the i-th rangefinder. This vector is used for calculating the AUV target point.

The problem of forming such trajectories of AUV-followers moving behind the AUV-leader as part of a group in an environment containing obstacles is solving in this paper. These trajectories must satisfy the following requirements:

- The formation of the trajectories of the AUVs of group should occur independently of each other and do not require data exchange between the AUVs of group via hydroacoustic communication channels. At the same time, AUV-followers form their trajectories using information about the position of the AUV-leader received from their onboard video cameras and readings from onboard rangefinders.
- The trajectories of the AUVs of group pass at a safe distance from the detected obstacles.
- During movement and avoiding obstacles, the possibility of collision between members of the group should be excluded.
- In the process of avoiding obstacles, keeping a given formation is not required.
- Due to limited visibility, another AUV-follower can act as a leader.

3 Trajectories Formation Method

Due to the lack of communication channels between the AUV-followers, the problem of coordinating the trajectories of the group members movement in the process of avoiding obstacles arises. In this case, the desired position of the AUV-followers is determined relatively to the position of the AUV-leader, and all followers can determine the position of the leader relatively to themselves. This fact can be used to guarantee the safe movement of followers when avoiding obstacles without directly coordinating their trajectories.

The method described in [13] will be used as a base method, which will be modified for the case when the position determination of the leader is based on video information, and the followers do not have information about their coordinates in the ACF.

This method is illustrated in Fig. 2. This figure shows the AUV-followers moving in a given formation behind the AUV-leader and being at their prescribed positions in the formation.

The black dots on Fig. 2 indicate the desired positions of the AUV-followers in the formation, and the dotted lines indicate the trajectories of the adjusted displacement of the AUV-followers within the formation when avoiding the detected obstacles.

When the onboard rangefinders detect obstacles located at a distance less than safe, the desired position of the AUV-follower inside the formation begins to shift along the dotted lines towards the trajectory along which the AUV-leader passed. Since the AUV-leader has already found a safe trajectory, shifting to this trajectory, the AUV-followers will also provide themselves with a safe passage. At the same time, the trajectories of AUV-followers movement within the formation are chosen to ensure their safe movement relatively to each other.

Setting the trajectories of AUV-followers movement inside the formation is as follows. The indicated motion trajectories are segments of straight lines in the CF of the AUV-leader. The starting point of the i-th AUV-followers trajectory corresponds to its desired position in the formation with coordinates $\tilde{X}_{Fi} = (\tilde{x}_{fi}, \tilde{y}_{fi})$, and the end point lies on the axis $\tilde{x}$ in CF of AUV-leader and has coordinates $\tilde{X}^0_{Fi} = (\tilde{x}_{fi} \pm D_a/2,\ 0)$. The value D_a is chosen so that when different AUVs move along these given trajectories inside the formation, the distances between them would always be no less than the safe distance $D_{\min}$. The choice of sign when determining the point $\tilde{X}^0_{Fi}$ depends on the location of the AUV-follower relatively to the axis $\tilde{x}$ (sign "+" indicates that the AUV is located to the left of the $\tilde{x}$, sign "−" indicates that the AUV is located to the right of the $\tilde{x}$). Value $D_a > D_{\min}$ depends on the number of columns, on the features of the formation and the number of AUV-followers.

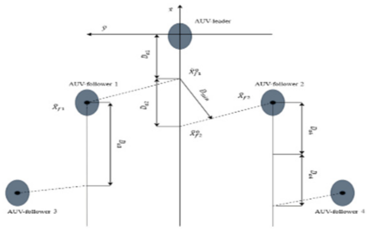

Fig. 2. AUV-followers movement trajectories when avoiding obstacles

The equation of the displacement trajectory of the i-th AUV-follower inside the formation, passing through the points $\tilde{X}_{Fi}$ and $\tilde{X}^0_{Fi}$ in CF of AUV-leader in horizontal plane [15]:

$$\pm\frac{D_a}{2}(\tilde{y} - \tilde{y}_{Fi}) + \tilde{y}_{Fi}(\tilde{x} - \tilde{x}_{Fi}) = 0, \tag{4}$$

As information about the position of the AUV-leader is obtained by AUV-follower using video information from the onboard video camera that observes the leader's light beacons, it becomes possible that during the process of displacement, AUV-follower will cover the visibility area of the beacons for other group members.

To eliminate this situation, it is proposed to carry out an additional displacement in the vertical plane along the axis (Fig. 3). The trajectory of such displacement passes through points $\tilde{X}^z_{Fi} = (0, \tilde{y}_{fi})$ and $\tilde{X}^{z0}_{Fi} = (\pm D_b,\ 0)$, where $\tilde{X}^z_{Fi}$ – is the initial position of the i-th AUV-follower in the absence of obstacles, $\tilde{X}^{z0}_{Fi}$– is the point located on the axis $\tilde{z}$, that determines the position of the i-th follower when moving behind the AUV-leader in the plane $\tilde{x}\tilde{z}$ of the CF of the AUV-leader. The choice of the sign when determining the point $\tilde{X}_{Fi}^{z0}$ depends on the desired displacement of the AUV-follower relative to the axis $\tilde{z}$ when avoiding the detected obstacle.

The formation of the displacement trajectory along the axis $\tilde{z}$ occurs similarly to Eq. (4):

$$\pm\frac{D_b}{2}(\tilde{y} - \tilde{y}_{Fi}) + \tilde{y}_{Fi}\tilde{z} = 0, \tag{5}$$

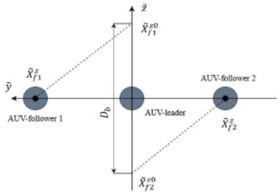

Fig. 3. Changing the depth of AUV-followers during displacement

The value D_b depends on the characteristics of the video cameras installed on the AUV-followers, the characteristics of the beacons of the AUV-leader and the type of formation. D_b is chosen for each follower in such a way that any displacement along the given trajectories within the formation does not cover the beacon's visibility area for other members of the group.

In the process of moving behind the leader, the followers determine the presence and proximity of obstacles to the trajectories using onboard rangefinders. If this distance is less than a safe distance $D_{\min}$, the program point of this follower, which set its position in the formation, is shifted along the trajectory described by Eqs. (4), (5). When several rangefinders are triggered at once, the distance to all obstacles is estimated and the nearest one is selected. If the distance to obstacles is more than safe, then AUV-followers continue to move in the place, gave them in the formation.

To determine the required shift of the AUV-follower program point, it is necessary to determine the obstacle point closest to the follower, which must be avoided. As the shift of the AUV-follower is set in the AUV-leader's CF, the coordinates of the extreme point of the obstacle are respectively translated into the leader's CF. This calculation is carried out as follows:

$$X_{dj} = X_F^L + R_L R_F^T \begin{bmatrix} d_j \cos(\alpha_j) \\ d_j \sin(\alpha_j) \end{bmatrix}, j = \left(\overline{1, n}\right), \tag{6}$$

where X_{dj} are the coordinates of detected point of obstacle in ACF, fixed by j-th rangefinder of AUV-follower; ψ_f is the follower heading angle; α_j is the angle of orientation of j-th rangefinder relatively to longitudinal axis of the AUV-follower; d_j is the distance to the obstacle point, determined by the j-th range finder.

Next, it is necessary to determine where the program point, which sets the position of the AUV-follower in the formation, should move to ensure its safe avoidance of the detected obstacle.

For this, first need to determine which point on the obstacle is closest to the AUV-follower trajectory. As the AUV-follower does not know in advance the trajectory of its movement, because it is determined by the movement of the AUV-leader, will assume that the predicted trajectory of the AUV-follower is a straight line parallel to the axis $\tilde{x}$. Therefore, the proximity of the detected points X_{dj} to the specified trajectory can be calculated by the formula:

$$\begin{gathered}\delta_j = S\left(\tilde{y}_{dj}\right)\left(\tilde{y}_{dj} - \tilde{y}_F\right), j = \left(\overline{1, m}\right), \\ S\left(\tilde{y}_{dj}\right) = \begin{cases} 1, \ if \ \tilde{y}_{dj} \geq 0, \\ -1, \ if \ \tilde{y}_{dj} < 0 \end{cases}\end{gathered} \tag{7}$$

The multiplier $S(\tilde{y}_{dj})$ is necessary to take into account on which side of the slave an obstacle is detected.

The closest point to the trajectory of movement X_{dc} is considered to be the point X_{dj} for which the value will have a minimum value.

The new program position of the point in the CF of the AUV-leader for the AUV-follower can be calculated by the expression:

$$\begin{aligned}\tilde{y}_F^* &= \begin{cases} y_{dc} - sign(y_{dc}) \cdot D_{\min}, \ if \ \min(\delta_j) < D_{\min}, \ j = (\overline{1, m}) \\ \tilde{y}_F, \ if \ \min(\delta_j) \geq D_{\min}, \ j = (\overline{1, m}) \end{cases}, \\ \tilde{x}_F^* &= \tilde{x}_F \pm \frac{D_a(\tilde{y}_F - \tilde{y}_F^*)}{2\tilde{y}_F}, \\ \tilde{z}_F^* &= \pm \frac{D_b(\tilde{y}_F^* - \tilde{y}_F)}{2\tilde{y}_F},\end{aligned} \tag{8}$$

where $\tilde{x}_F^*, \tilde{y}_F^*, \tilde{z}_F^*$ – coordinates of the new position of the target point $\tilde{X}_F^*$ AUV-follower during obstacle avoidance in formation.

If obstacles are detected or there is a lot of noise in the data generated by the sonar, the position of the target point may suddenly change, which will lead to the generation of incorrect control signals. To eliminate this situation, it is possible to use a low-pass filter [16] to smooth the trajectories:

$$\hat{X}_F^*(k) = \hat{X}_F^*(k-1) + \beta(\tilde{X}_F^*(k) - \hat{X}_F^*(k-1)), \tag{9}$$

where $\tilde{X}_F^*$ is the desired position of the AUV-follower at the current step of the system operation. $0 \leq \beta \leq 1$ is the smoothing coefficient.

Thus, the proposed method for generating AUV trajectories during their movement in a group makes it possible to dispense with the use of acoustic communication channels to coordinate the AUV trajectories when avoiding detected obstacles.

4 AUV Control System

AUV is a complex object described by a system of nonlinear equations. At the same time, in the process of moving in a group and bypassing obstacles, the ability to move along complex spatial trajectories is required. Thus, it is necessary to obtain a control system that ensures the movement of the AUV in space with sufficient accuracy.

4.1 Mathematical Model of AUV

Mathematical model of spatial movement of AUV has following view [14]:

$$
\begin{aligned}
&M\dot{\upsilon} + (C(\upsilon) + D(\upsilon))\upsilon + g(\eta) = \tau, \\
&\dot{\eta} = J(\eta)\upsilon,
\end{aligned} \tag{10}
$$

where $M = M_R + M_A \in R^{6x6}$; $M_R \in R^{6x6}$ is an AUV inertia matrix; $M_A \in R^{6x6}$ is a matrix of added mass and moment inertia; $C(M, \upsilon) \in R^{6\times 6}$ is a matrix of Coriolis and centripetal forces and torques; $\mathrm{D}(d_1, d_2, \upsilon) \in R^{6x6}$ is a matrix of hydrodynamic forces and moments; $g(\eta) \in R^6$ is a vector of hydrostatic forces and torques; $\eta = [x_a, y_a, z_a, \varphi_a, \theta_a, \psi_a]^T \in R^6$ is a vector of the AUV position and orientation in an ACF; $J(\eta)$ is a transition matrix from body-fixed CF (BCF) to ACF; $\tau = [\tau_x, \tau_y, \tau_z, M_x, M_y, M_z]^T \in R^6$ is a vector of propulsion forces and moments in the AUV BCF; $\upsilon = [\upsilon_x, \upsilon_y, \upsilon_z, \omega_x, \omega_y, \omega_z]^T \in R^6$ is a vector of linear and angular velocities in the AUV BCF.

The matrix of Coriolis and centripetal forces and moments described by expressions [17]:

$$
C(M, \upsilon) = C_{RB}(M_R, \upsilon) + C_A(M_A, \upsilon), \tag{11}
$$

where $C_{RB}(M_R, \upsilon) = \begin{bmatrix} 0_{3\times 3} & -S(M_{11}\upsilon_1 + M_{12}\upsilon_2) \\ -S(M_{11}\upsilon_1 + M_{12}\upsilon_2) & -S(M_{21}\upsilon_1 + M_{22}\upsilon_2) \end{bmatrix}$, $M_R = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$, $M_{ij} \in R^{3x3}, i, j = (\overline{1, 2})$; $C_A(M_A, \upsilon) = \begin{bmatrix} 0_{3\times 3} & -S(A_{11}\upsilon_1 + A_{12}\upsilon_2) \\ -S(A_{11}\upsilon_1 + A_{12}\upsilon_2) & -S(A_{21}\upsilon_1 + A_{22}\upsilon_2) \end{bmatrix}$, $M_A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$, $A_{ij} \in R^{3x3}, i, j = (\overline{1, 2})$; $\upsilon_1 = \begin{bmatrix} \upsilon_x & \upsilon_y & \upsilon_z \end{bmatrix}^T$; $\upsilon_2 = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T$, and operator S(.) described by expression: $S(\boldsymbol{\lambda}) = \begin{bmatrix} 0 & -\lambda_3 & \lambda_2 \\ \lambda_3 & 0 & -\lambda_1 \\ -\lambda_2 & \lambda_1 & 0 \end{bmatrix}$, $\boldsymbol{\lambda} = \begin{bmatrix} \lambda_1 & \lambda_2 & \lambda_3 \end{bmatrix}^T \in R^3$ is the parameter of operator S.

The elements of diagonal matrix $D\ (d_1, d_2, \upsilon)$ are described following expression:

$$
D_{ii} = d_{1i} + d_{2i}|\upsilon_i|, i = (\overline{1, 6}), \tag{12}
$$

where $d_{1i}, d_{2i}, i = (\overline{1, 6})$ are hydrodynamic coefficients respective linear and quadratic dependances of hydrodynamic forces and torques from AUV velocities along all degree of freedom.

The vector of hydrostatic forces and torques has the following form [14]:

$$
g(\eta) = \begin{bmatrix} (W - B)\sin\theta \\ -(W - B)\cos\theta\ \sin\varphi \\ -(W - B)\cos\theta\ \cos\varphi \\ -B_y\ \cos\theta\ \cos\varphi + B_z\ \cos\theta\ \sin\varphi \\ B_z\ \sin\theta + B_x\ \cos\theta\ \cos\varphi \\ -B_x\ \cos\theta\ \sin\varphi - B_y\ \sin\theta \end{bmatrix}, \tag{13}
$$

where W_a is the gravity force; B_a is the buoyancy force; $B_x = W_a x_G - B_a x_B$, $B_y = W_a y_G - B_a y_B$, $B_z = W_a z_G - B_a z_B$; x_G, y_G, z_G are coordinates of the center of gravity (CG) in the AUV BCF; x_B, y_B, z_B are coordinates of the center of buoyancy (CB) in the AUV BCF.

4.2 Model Predictive Control for AUV

The essence of the control approach with a predictive model is in the formation of current control actions based on the analysis of the predicted AUV response to various sequences of their changes. This makes it possible to improve the adaptive and robust properties of the developed control systems (CS). To build an CS with a predictive model, it is rational to use a discrete model of AUV dynamics [18]:

$$\begin{aligned} x_{i+1} &= f(x_i, u_i) + w_i, i = 0, 1, 2 \ldots \\ y_i &= Hx_i + v_i \end{aligned} \tag{14}$$

where the vectors $x_i \in E^n$, $u_i \in E^m$, $y_i \in E^r$ represent the current state of the object, the control actions and the observation vector, i is the current step of the system, f is a known nonlinear vector function, H is the matrix measurements. Such a model is random in nature, since it is impossible to determine in advance the values of external disturbances w_i and measurement errors v_i.

Eliminating unknown random components, a predictive model of the form is selected:

$$\begin{aligned} x_{i+1} &= f(x_i, u_i), i = 0, 1, 2 \ldots \\ y_i &= Hx_i \end{aligned} \tag{15}$$

Model (15) is initialized at the initial cycle by the current state of the control object and allows one to approximately predict its dynamics. The final sequence of vectors $x_{i+j}, j = 1, \ldots, P$ - calculated according to the system (15), is called the forecast of the movement of the object on the prediction horizon P.

To quantify the quality of control, the following functional should be specified [19]:

$$\begin{aligned} J &= J(\overline{x}, \overline{u}); \\ \overline{x} &= (x_{i+1}, x_{i+2} \ldots x_{i+P}) \in E^{nP}, \\ \overline{u} &= (u_i, u_{i+1} \ldots u_{i+P-1}) \in E^{mP}. \end{aligned} \tag{16}$$

The quality of AUV motion control depends on the method of forming control actions on the forecast horizon and the performance of the onboard computer system.

Consider the solution of the optimal control problem based on predictive model (15). The quality of the control process is determined by the functional (16). The behavior of system (15) on cycles $i = 1, 2, \ldots, P$, uniquely depends on the choice of the vector $\overline{u}$. Considering that there is a functional dependence $\overline{x} = f(\overline{u})$, we can assume that $J = J(\overline{x}, \overline{u}) = J(\overline{u})$. Thus, the constrained optimization problem is formulated as follows:

$$J = J(\overline{u}) \rightarrow \underset{u \in \Omega \subset E^{mP}}{min}, \tag{17}$$

where $\Omega = \{\overline{u} \in E^{mP} : u_{i+j-1} \in U, j = 1, 2, \ldots, P\}$ – admissible set of finite sequences of m- dimensional vectors. $J(\overline{u})$ is a function of mP arguments.

Thus, the control scheme for a specific optimization problem (17) takes the following form:

1. The state vector y_i is measured;
2. Optimization problem (17) is solved for predictive model (15) with initial conditions $\overline{x} = x_i$. The extremum of the functional $J(u_i, u_{i+1} \ldots u_{i+P-1})$ is calculated on the admissible set of values Ω.
3. From the generated optimal sequence $u_i^*, u_{i+1}^* \ldots u_{i+P-1}^*$ the first vector is used as a control action at the next cycle of the system.
4. For the next measure, operations 1–3 are repeated. When controlling the AUV movement based on a predictive model, the control quality functional (17) on the forecast horizon is chosen as:

$$J = \rho_1 \sum\nolimits_{j=1}^{P} e_{i+j}^2 + \rho_2 \sum\nolimits_{j=1}^{P} (u_{i+j} - u_{i+j-1})^2, \tag{18}$$

where e_{i+j} is the system output error, ρ_1 is the contribution of the cost of changing the error to the final functional J, ρ_2 is the contribution of the cost of changing the control signal to the final functional J. This form allows minimizing not only the system output error, but also abrupt changes in the control impact on the device.

The structure of the CS with a predictive model is shown in Fig. 4. The setting signal r_i and the current estimate y_i^* are fed to the input of the optimization block. This block generates sequences of control actions $\widetilde{u}_i$ applied to the predictive model of the control object, and receives a prediction of the object behavior $\widetilde{y}_i$ for P cycles ahead. The value of the functional $J(\overline{y}, \overline{u})$ is calculated for each sequence. The found optimal value u_i^* is the input of the control object, which is also affected by external disturbances w_i. The state of the object x_i changes, measurements of y_i are made with unknown noises v_i, and the state of the object is specified by the observer.

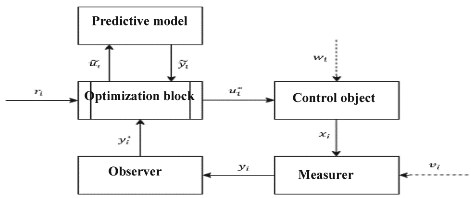

Fig. 4. AUV CS structure

5 Simulation Results

To test the effectiveness of the method, mathematical modeling of the movement of a group of underwater vehicles consisting of five robots (1 leader, 2 followers, 2 followers by followers) moving in a triangular formation was carried out. Each AUV-follower is equipped with a video camera with a resolution of 512 × 512 pixels, has 4 rangefinders on board, located in front of the AUV. Four beacons are installed at the stern of the leader AUV. The simulation was carried out in the CoppeliaSim environment (Fig. 5). The AUV-leader moves in a straight line, passing through a narrow passage between two obstacles, and the AUV-followers, being unable to pass the obstacles while keeping formation, move beyond the trajectory of the leader.

AUV CS was performed in MATLAB Simulink. The AUV with following parameters is considered in this simulation:

$$m_a = 325kg, J_{xx} = 225kg \cdot m^2, J_{yy} = 175kg \cdot m^2, J_{zz} = 215kg \cdot m^2,$$

$$Y_c = 0.05m, \lambda_{ijmin} = 40kg(i, j = 1, 2, 3), \lambda_{ijmax} = 300kg(i, j = 1, 2, 3),$$

$$\lambda_{ijmin} = 20kg \cdot m^2(i, j = 4, 5, 6), \lambda_{ijmax} = 225kg \cdot m^2(i, j = 4, 5, 6),$$

$$d_{1min} = \text{Ns/m}, d_{1max} = 50\text{Ns/m}, d_{2min} = 75kg \cdot m^{-2}, d_{2max} = 125kg \cdot m^{-2}.$$

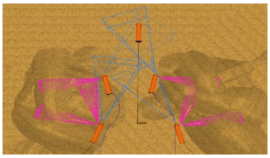

Fig. 5. The movement of the AUV group in an unknown environment

Figures 6 and 7 show the processes of changing the coordinates of the AUV group during their movement while avoiding obstacles. Figure 6 shows that in the process of movement, AUV-follower detect obstacles in their path and avoid them along the computed safe trajectories. At the same time, the AUV-followers trajectories follow the shape of obstacles, and the distances between the AUVs of the group are always greater than the specified safe distance (Figs. 9, 10, 11). Figure 8 shows that the distance between

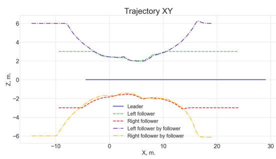

Fig. 6. Movement trajectories of the AUV group in the horizontal plane when avoiding obstacles

the AUV-followers and obstacles does not exceed 2 m. After passing the obstacles, the AUV-followers return to their prescribed position in the formation. At the same time, AUV-followers are also shifted in the vertical plane (Fig. 7), which provides them with continuous tracking of the leader AUV with the help of onboard video cameras, even when these AUVs line up one after another in the process of avoiding obstacles.

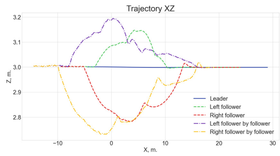

Fig. 7. Movement trajectories of the AUV group in the vertical plane when avoiding obstacles

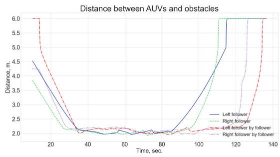

Fig. 8. Distances between AUV-followers and detectable obstacles

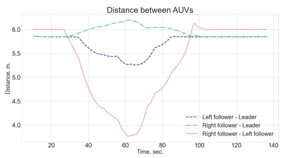

Fig. 9. Distances between AUVs while moving

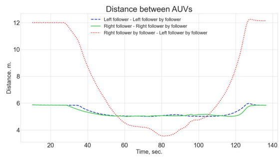

Fig. 10. Distances between AUVs while moving

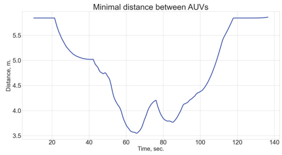

Fig. 11. Minimal distance between AUVs

6 Conclusions

The paper presents a method for formation control of the AUVs group in the "leader-follower" mode in an environment containing unknown obstacles. A feature of the proposed method is to ensure the safe movement of these AUVs in conditions when there is no data transmission between the AUVs of the group via hydroacoustic communication channels to coordinate their movement trajectories. This is achieved by using information from the onboard video cameras of the followers to determine the position and orientation of the leader AUV relatively to these followers, and by presetting the movement trajectories of each follower AUV within the formation. A feature of the proposed method is the setting of such a displacement of the followers within the formation, which excludes the loss of beacons of the AUV-leader in the visibility area of the cameras of the followers.

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