Development of AUV path planner based on unstable mode

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Abstract. In this article, development of an autonomous underwater vehicle (AUV) path planner based on unstable mode is considered. The path planner is based on the bionic approach and does not require pre-mapping, it reduces requirements for the sensor subsystem of AUV. In the path planner, we use a method for obstacle avoidance in which an unstable mode is realized in a separate dynamic link. The output of the dynamic link corrects the desired angles of the AUV orientation. It allows setting the unstable mode only at the planning level, and at the regulatory level, a control system works in a stable mode. In addition, this approach allows planning the direction of obstacle avoidance. Detailed description of the proposed path planner and results of the study in Matlab are provided.

1. Introduction

Many studies are devoted to the development and research of control systems for autonomous underwater vehicles [1-8]. One research task in the development of such systems is the development of path planners using intelligent technologies [9], because AUVs should be able to operate autonomously in an environment with obstacles, the location of which is not indicated on the map. There are a lot of intelligent methods for obstacles avoidance, among which we can note the method are based on unstable mode [10]. This method is based on the bionic approach and does not require pre-mapping, it reduces requirements for the sensor subsystem of AUV. The main idea of the method is as follows: a bifurcation parameter $\beta$ is introduced into the regulator structure. The value of the bifurcation parameter $\beta$ depends on the distance to an obstacle. If the distance from the AUV to an obstacle is greater than the allowable distance $R^*$, the bifurcation parameter $\beta = 0$ and desired AUV trajectory is stable. If this distance is less than the allowable distance $R^*$, then $\beta \neq 0$ and the desired trajectory of the AUV becomes unstable, it leads to a change in the real trajectory of the AUV movement.

It is important to note that, on the one hand, the introduction of the bifurcation parameter directly to the controller provide an instantaneous reaction of an AUV to an obstacle that appears on the path. On the other hand, unstable trajectories of motion can lead to the exit of the AUV coordinates to technologically acceptable boundaries, to loss of controllability, to abrupt switching of control signals on actuators. In addition, as shown in [10], in this case, a direction of obstacle avoidance is not controlled. In this research, we propose a method for obstacle avoidance in which an unstable mode is realized in a separate dynamic link. The output of the separate dynamic link corrects the desired angles of the AUV orientation. It allows setting the unstable mode only at the planning level, and at the regulatory level, the control system functions in a stable mode. In addition, this approach allows planning the direction of obstacle avoidance.
2. Control system with the path planner developing

To represent the mathematical model of the AUV, we use two rectangular coordinate systems, movable and fixed, shown in Figure 1.

![Coordinate system K0 (OX 0 Y 0 Z 0) and K (OX YZ)](image)

Let mathematical model of an AUV is based on well-known solid-state equations. We define a mathematical model of an AUV as a system of nonlinear differential equations and present it in the following vector-matrix form [11]:

\[
\dot{Y} = \begin{bmatrix} R_v & 0_{3x3} \\ 0_{3x3} & R_\omega \end{bmatrix} X, \\
M \ddot{X} = F_u(X, Y, \delta, l, t) + F_d(P, V, W) + F_\nu(G, A, R),
\]

(1)

(2)

where \( T_{actuator} \) is the diagonal (m×m)-matrix of actuators time constants; \( \Psi_{actuator}(U, \delta) \) is the m-vector of nonlinear functions of right parts of the actuator equations; \( \delta \) is the m-vector controlled coordinates (engine angles and trusts); \( U \) is the control m-vector generated by AUV control system depending on the arrangement of the actuators; \( X = \begin{bmatrix} R_v \\ R_\omega \end{bmatrix} \) is the m-vector of internal coordinates (coordinates state); \( M \) is the (m×m) matrix of weight and inertia parameters whose elements are the mass, moments of inertia, added masses; \( F_u(X, Y, \delta, l, t) \) is the m-vector of control forces and moments, here \( l \) is the vector of design parameters; \( F_d(P, V, W) \) is the m-vector of nonlinear elements AUV dynamics; \( F_\nu(G, A, R) \) is the m-vector of measured and unmeasured external disturbances; \( Y = \begin{bmatrix} P \\ \theta \end{bmatrix} \) is the n-vector of an AUV position and orientation in the coordinate frame \( K(OXYZ) \) relative to the base coordinate frame \( K^0(OX'Y'Z') \). Procedure for the conversion of the vector \( F_u(X, Y, \delta, l, t) \) into vector \( U \) was described in detail and can be found in [11, 12].

To develop control algorithms of AUV, the method [13] is used, which allows solving positional and trajectory problems uniformly. To do this, we define trajectory and velocity vector forms:

\[
\Psi_v = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix}, \quad \Psi_{\vartheta r} = \begin{bmatrix} \vartheta \\ \delta \\ y \end{bmatrix}, \quad \nu = \begin{bmatrix} -V_k \\ 0 \\ 0 \end{bmatrix} = 0,
\]

(4)

where \( V_k \) is the desired speed of the AUV, \( \delta^* = \tan^{-1}[(y_k - y_0)/(x_k - x_0)] \), \( \vartheta^* = \tan^{-1}[(z_k - z_0)/(x_k - x_0)] - \tan^{-1}(V_z/V_x) \).

Then, we define the desired behavior of a closed-loop system as follows:

\[
\Psi_v + T_\nu \Psi_v = 0,
\]

(5)
where \( T_1, T_2, T_3 \) are positive definite diagonal matrices.

To avoid obstacles, we introduce into the position-trajectory controller the bifurcation parameter in the following form [10]:

\[
\beta = |R - R^*| - (R - R^*),
\]

where \( R \) is the distance to obstacles measured by the sensor; \( R^* \) is an allowable distance to obstacles, i.e., the distance on which you want to start the process of obstacle avoidance, \( | \cdot | \) - the module number, it is an absolute value. It is easy to show that if \( R \geq R^* \), then \( \beta = 0 \). If the distance from the AUV to an obstacle is less than allowable, \( R < R^* \) then \( \beta = -2(R - R^*) \). Given the fact that \( (R - R^*) < 0 \), \( \beta > 0 \).

Than we introduce into the structure of the regulator an additional dynamical link of the following form:

\[
\dot{z}_i = -(T_{zi} - \beta)\dot{z} + \beta,
\]

where \( z \) is an additional variable of the \( i \) control channel, \( T_{zi} \) is a setting parameter for the \( i \) control channel.

We introduce the parameter \( z \) into the trajectory vector form in the following way:

\[
\Psi_{tr} = \begin{bmatrix} \varphi \\ \delta \\ \gamma \end{bmatrix} + \begin{bmatrix} -\varphi^* \\ -\delta^* \\ 0 \end{bmatrix} + A Z = 0,
\]

where \( A = \begin{bmatrix} \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & 0 & \alpha_3 \end{bmatrix} \), \( \alpha_i \) - can take the values +1 or -1, thus defining the direction of the obstacle avoidance, \( Z = [z_1 \ z_2 \ z_3]^T \) is the state vector of additionally dynamical link (9). The direction of the obstacle avoidance can be chosen, for example, from the angle between the direction vectors to the target and to the obstacle or using other intellectual planning methods [9].

3. Closed-loop control system research

To research of the developed controller, we use the following parameters of the AUV [11] in the mathematical model (1), (2):

- AUV mass \( m_{\text{AUV}} = 272.1985 \) kg;
- Matrix of moments of inertia: \( jm = \begin{bmatrix} 3.3482822 & -0.1472487 & 0 \\ -0.1472487 & 231.9484349 & 0 \\ 0 & 0 & 231.9922593 \end{bmatrix} \),
- Added mass: \( \lambda(1,1) = k_{11} \times m_{\text{AUV}}; \lambda(2,2) = k_{22} \times m_{\text{AUV}}; \lambda(3,3) = k_{33} \times m_{\text{AUV}}; \lambda(4,4) = k_{44} \times jm(1,1); \lambda(5,5) = k_{55} \times jm(2,2); \lambda(6,6) = k_{66} \times jm(3,3) \), where the remaining elements of the matrix are zero,
- \( k_{11} = 0.02; k_{22} = 1.2; k_{33} = 1; k_{4} = 0; k_{55} = 1.05; k_{66} = 1.1 \);
- AUV volume \( V = 0.26183 \) m³;
- AUV length \( L = 3.7 \) m;
- AUV area \( S = 0.07162 \) m²;
- Center Masses position \( x_t = (0, -0.1, 0) \).

The AUV propulsion and steering system consists of a propulsion engine that generates the thrust \( P_1 \), horizontal thruster \( P_2 \) and vertical thruster \( P_3 \), in accordance with Figure 2.
Figure 2. Propulsion system of the AUV

Projection of thrust, created by the main propulsion engine - \( P_{1x}, P_{1y}, P_{1z} \). Forces are created by thrusters: horizontal - \( P_2 \), vertically - \( P_3 \).

Distance along the axes to the point of application of forces:

\[
\begin{align*}
\text{OX:} & \quad x_{md} = -1.9; & \quad y_{md} = 0; & \quad z_{md} = 0; \\
\text{OY:} & \quad x_{hr} = 1.28; & \quad y_{hr} = 0; & \quad z_{hr} = 0; \\
\text{OZ:} & \quad x_{vr} = 1.18; & \quad y_{vr} = 0; & \quad z_{vr} = 0;
\end{align*}
\]

Equations of forces and moments acting on the AUV:

\[
\begin{align*}
F_{ux} &= P_{1x} \\
F_{uy} &= P_{1y} + P_3 \\
F_{uz} &= P_{1z} + P_2 \\
N_{ux} &= 0 \\
N_{uy} &= -P_{1x}x_{md} + P_2x_{hr} \\
N_{uz} &= -P_{1y}x_{md} + P_3x_{vr}
\end{align*}
\]  
(10)

The system (10) is a direct transformation of the forces and moments acting on the apparatus. We write the inverse transformation:

\[
\begin{align*}
P_{1x} &= \frac{x_{md}}{x_{vr} + x_{md}} F_{ux} - \frac{1}{x_{md} + x_{vr}} N_{uz} \\
P_{1y} &= \frac{x_{vr}}{x_{md} + x_{hr}} F_{uy} - \frac{1}{x_{hr} + x_{md}} N_{uy} \\
P_{1z} &= \frac{x_{hr}}{x_{md} + x_{hr}} F_{uz} - \frac{1}{x_{hr} + x_{md}} N_{uy} \\
P_2 &= \frac{x_{md}}{x_{md} + x_{hr}} F_{uz} + \frac{1}{x_{hr} + x_{md}} N_{uy} \\
P_3 &= \frac{x_{md}}{x_{md} + x_{vr}} F_{uy} + \frac{1}{x_{md} + x_{vr}} N_{uz}
\end{align*}
\]

The sensor for detecting obstacles is a forward-looking sonar. Sensor model is given as a ray that comes from the nose of AUV. If there is an obstacle in the path of the AUV, i.e. ray intersects the obstacle; sensor model calculates the distance to the obstacle \( R \). If the distance \( R \) is less than the radius of sensor action \( R_s = 50 \) meters, then the sensor model returns the distance to the control system. We simulated the closed-loop control system of the AUV. During the simulation, the underwater vehicle should move from the point \( (0; 0; 0) \) to the point \( (200; 100; 200) \) at a speed of \( 5 \) m/s. On the AUV path there are two obstacles with a radius of \( 15 \) m. Obstacle №1 has coordinates \( (50, 35, 50) \), obstacle №2 - \( (120, 70, 120) \). Modeling results with the motion trajectory of the AUV in the environment with two obstacles are shown in Figures 3 and 4.
Figure 3. Trajectory of the AUV movement in three-dimensional space in the environment with two obstacles.

Figure 4. Trajectory of the AUV movement - top view (left) and side view (right).

The additional dynamic system was used only in the course control channel; the value of the parameter $\alpha_1$ is one. Figure 5 shows how the parameter $z_1$ changes.

Figure 5. Parameter $z_1$ in the course control channel.

Changing of AUV velocity and control forces are shown in Figure 6.
4. Conclusion
In this paper, we propose a hybrid method of path planning of AUV which based on an unstable mode. Description of the method and way of using in AUV control system are given. This method is based on the bionic approach and does not require pre-mapping, it reduces requirements for the sensor subsystem of AUV. We proposed a method for obstacle avoidance in which an unstable mode is realized in a separate dynamic link. The output of the separate dynamic link corrects the desired angles of the AUV orientation. It allows setting the unstable mode only at the planning level, and at the
regulatory level, the control system functions in a stable mode. In addition, this approach allows planning the direction of obstacle avoidance. The method proposed in this article can be compared with the method of artificial potential fields [14,15]. As we known, in the method of potential fields, attractive and repulsive forces are functions of the coordinates

\[ F_{\text{attr}} = F_{\text{attr}}(y), F_{\text{rep}} = F_{\text{rep}}(y), \]  

(11)

where \( F_{\text{attr}}(y) \) is the resultant of attractive forces; \( F_{\text{rep}}(y) \) is the resultant of repulsive forces. In the method proposed in this article, attractive and repulsive forces are functions of the coordinates, velocities and accelerations of the mobile object and the bifurcation parameter \( \beta \). They are formed as a solution of a differential equation of the form

\[ F_{ar}(y, \dot{y}, \ddot{y}, \beta) = 0, \]  

(12)

where \( F_{ar}(y, \dot{y}, \ddot{y}, \beta) \) is a function, depending on the value of the parameter \( \beta \), which is attractive or repulsive. Obviously, the using of Eq. (12) gives more opportunities to take into account the velocities and accelerations of the mobile object to avoid obstacles. Also, due to the sensitivity of the unstable solutions of equation (12) to the initial conditions, the using of unstable trajectories of motion gives a greater variability of trajectories to avoid obstacles, increases the probability of passing of environment with moving obstacles.

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