The Method for Estimating the Maximum Velocity of the AUV Motion with Trajectories Re-Planning According to their Dynamic Properties

D A Yukhimets¹, S V Karmanova²

¹Laboratory of Robotic Systems, Institute of Automation and Control Processes FEB RAS, 5 Radio St., Vladivostok, 690041, Russia
²Laboratory of Intelligent Control Systems, Institute of Marine Technology Problems FEB RAS, 5 A Sukhanov St., Vladivostok, 690091, Russia

E-mail: karmanova.svia@dvfu.ru

Abstract. The paper considers the problem of adjusting the value of a predetermined velocity required for horizontal motion of autonomous underwater vehicles (AUVs) in an environment containing obstacles, when trajectories change in order to avoid obstacles. Therewith, the velocity estimation generated during the re-planning of the AUVs motion trajectories is the maximum possible and is carried out on the basis of the AUVs dynamics model, considering their dynamic limitations and changes in the parameters of the motion trajectories. The topicality of the task is determined by the need to improve the efficiency of underwater missions in various areas of human activity (environmental monitoring, laying and maintenance of underwater communications, etc.). It depends on the mode of the AUVs motion: their velocity and parameters of the trajectories. The simulation results confirm the efficiency of the proposed method for estimating the maximum possible velocity of the AUVs motion.

1. Introduction
Underwater robots are required to perform various operations under water in an uncertain environment: data collection [1], inspection of underwater structures [2], monitoring of pipelines [3], detection of chemical leaks [4]. To successfully complete such missions, it is necessary to ensure the accurate motion of the robots along the given trajectories. At present, many scientific papers are devoted to solving this issue, for instance [5]-[9]. During the motion, these trajectories are re-planned to avoid obstacles. However, often in existing approaches (for example, [10]-[12]), this process does not consider the dynamics of the AUVs. In addition, the motion velocity does not change, which often leads to the fact that program signals generated can exceed the power limits of the AUVs propulsion system, as a result the AUVs leave their motion trajectories.

Thus, it is also necessary to adjust the motion velocity of the underwater vehicles. In existing works, this is implemented, as a rule, in an indirect way by introducing additional control loops [13] or using analytical expressions to calculate the correct value of the program velocity of the AUVs motion [14, 15], which does not always allow to get the desired results due to the slow response of the methods to changes in the value of the program signals generated. Therefore, the paper addresses the problem of adjusting set in advance value of the velocity of the AUVs motion in the uncertain
environment in accordance with the parameters of the given trajectories, the dynamic properties of the AUVs and the power limits of their thrusters.

2. The object description and problem statement
The paper considers the AUVs described by the system [2]:

\[
\begin{align*}
\tau_x &= (m_a - \lambda_{11})\dot{u}_x + (-m_a\dot{v}_y + \alpha_2)\omega_x + (d_{1x} + d_{2x}\alpha_2)v_x, \\
\tau_y &= (m_a - \lambda_{22})\dot{v}_y + (m_a\dot{u}_y + \alpha_1)\omega_y + (d_{1y} + d_{2y}\alpha_2)v_y, \\
M_z &= (J_{zz} - \lambda_{66})\dot{\omega}_z + (m_a\dot{u}_y + \alpha_2)v_x + (-m_a\dot{v}_y - \alpha_1)v_y + \\
&\quad + (d'_{1z} + d'_{2z}\alpha_2)v_z.
\end{align*}
\]  
(1)

where \( \alpha_1 = \lambda_{11}\dot{u}_x + \lambda_{12}\dot{v}_y + \lambda_{16}\omega_x; \alpha_2 = \lambda_{12}\dot{u}_x + \lambda_{22}\dot{v}_y + \lambda_{26}\omega_x; \tau = [\tau_x, \tau_y, M_z]^T eR^3 \) – a vector of propulsion forces and moments in the AUV body-fixed coordinate frame (CF); \( v = [\dot{u}_x, \dot{v}_y, \dot{\omega}_z]^T eR^3 \) – a vector of linear and angular velocities in the AUV body-fixed CF; \( m_a \) – the AUV mass; \( \lambda_{ij} \) – elements corresponding to the added mass and liquid inertia moments (\( i, j = 1,6 \)); \( J_{zz} \) – the AUV inertia relative to its main inertia axis \( Z \); \( d_{ij}, d'_{ij} \) – coefficients of viscous friction corresponding to the linear and quadratic dependences of hydrodynamic forces (moments) on the velocities of the AUV along its specific degrees of freedom (DOFs).

The forces developed by the AUVs thrusters are determined by the kinematics of their propulsion complexes (PC) and the values of the desired forces and moments for each degree of freedom:

\[
F_{ti} = f(\tau) = a\tau_x + b\tau_y + cM_z, \quad |F_{ti}| \leq F_{t\text{max}}
\]  
(2)

where \( F_{ti} \) – the force of each AUV thruster, \( a, b, c \) – coefficients corresponding to the PC configuration, \( F_{t\text{max}} \) – the maximum possible force of each thruster of the AUV.

The trajectories are set in parametric form in the horizontal plane, and their curvature changes smoothly along these trajectories.

The paper states the problem of preliminary estimation of the constant and maximum possible value of the program velocity of the AUVs motion along the smooth trajectories, taking into account their dynamic properties (1) and the power limits of their PC (2).

3. The method for adjusting the program velocity of the AUVs motion
The proposed algorithm consists in the fact that when the new trajectory is generated during the motion of the AUV, the maximum value \( C_{\text{max}} \) of its curvature is calculated. Then, using \( C_{\text{max}} \), estimations of the maximum possible resulting forces and moments that can be developed by the PC, based on equations (1), the limiting evaluations of the velocity \( u_{\text{max}}^* = f(\tau_{\text{max}}, C_{\text{max}}) \) for each degree of freedom are calculated. The smallest value among the obtained ones is considered to be the desired value \( u^* \). Then, it is checked whether the PC is able to develop the required forces and moments for all degrees of freedom when the AUV moves at the velocity of \( u^* \) along the trajectory within the power limits of the AUV thrusters (2). If any thruster is not able to develop the required force, then the velocity \( u^* \) is reduced by a certain set value and the check is performed again.

Expressions for calculating the limiting evaluations of \( u_{\text{max}}^* \) can be obtained from the model (1), taking into account that the velocity of motion along the trajectory is assumed to be constant, rotation around the \( Z \) axis is carried out at the velocity of \( \omega_z = u^* C \), and the vector \( v \) when performing accurate motion has the form: \( v = [u^* \quad 0 \quad u^* C] \). So, the maximum possible values \( u_{\text{max}}^{*,}\max, u_{\text{r},\max}, u_{\text{m},\max}^{*,}\max \) of the linear velocity for motion along the longitudinal and transverse axes and rotation around the vertical axis have the following form:
where \( a \) is a first derivative of the \( C_{\text{max}} \) with respect to parameter, \( D = (d_{1x} - \lambda_{16} C'_{\text{max}})^2 + 4\tau_{x_{\text{max}}} (d_{2x} - C_{\text{max}} (\lambda_{12} + \lambda_{26} C_{\text{max}})), \)
\( \lambda_{26} C'_{\text{max}} \pm \sqrt{(-\lambda_{26} C'_{\text{max}})^2 + 4\tau_{x_{\text{max}}} C_{\text{max}} (m_a + \lambda_{11} + \lambda_{12} C_{\text{max}})} \),
\( \lambda_{12} + \lambda_{26} C_{\text{max}} + d_{2x} C_{\text{max}} || C_{\text{max}} | \).

4. The simulation results

The mathematical simulation was carried out via the CoppeliaSim for investigation of proposed method. During the simulation, the AUV with the following parameters was considered: \( m_a = 300 \text{ kg}, \ J_{xx} = 30 \text{ kg} \cdot \text{m}^2, \ J_{11} = 80 \text{ kg}_r, \ J_{22} = 140 \text{ kg}_r, \ J_{66} = 30 \text{ kg} \cdot \text{m}^2, \ J_{ij} = 0 \ (i \neq j, i, j = 1,6), \)
\( d_{1x} = 30 \text{ kg} \cdot \text{s}^{-1}, d_{2x} = 10 \text{ kg} \cdot \text{m}^{-1}, d_{1y} = 60 \text{ kg} \cdot \text{s}^{-1}, d_{2y} = 30 \text{ kg} \cdot \text{m}^{-1}, d_{1z} = 40 \text{ Nms}, \)
\( d_{2z} = 20 \text{ Nms}^2. \) Configuration of the PC is shown in Figure 1. The maximum possible force \( F_{\text{max}} \) of each thruster of the AUV was 200 \( N \) and \( L_{\psi} = 0.5 \text{ m}. \)

![Figure 1. The considered configuration of the PC.](image)

According to Figure 1, the restrictions imposed on the values of the elements of the vector \( \tau \) were given in the form:
\[
\frac{\tau_x}{2} + \frac{|M_z|}{2 L_{\psi}} < F_{\text{max}},
\]
where \( \tau_x = F_{pk} + F_{tk}, M_z = L_{\psi}(F_{pk} - F_{tk}) \).

The simulation was performed for two cases: the motion of the AUV considered at constant and at variable velocity generated by means of the proposed method respectively. During motion at constant velocity (see Figure 2) the \( C_{\text{max}} \) varies between \([-0.7206; 0.6250]\) \( m^{-1} \) and between \([-0.6095; 0.4903]\) \( m^{-1} \) if the velocity changes (see Figure 3). So, it should be noted that the shape of resulting trajectory that is re-planned for obstacle avoidance, differs in these two cases and variable velocity case is more desirable due to the lower values of the curvature. The comparison of the Figure 4 and Figure 6 illustrates that if the AUV moves at constant velocity, the value of \( M_z \) changes more dramatically and the rate of change of this variable is wider then one in the case of the variable velocity. Therefore, the AUV is required to turn rapidly and sharply, so the accuracy and safety of the motion suffer. Figures 5 and 7 confirm the previous conclusions: limitation (4) is not satisfied in the case of constant velocity and otherwise when the AUV moves at the variable velocity.
Figure 2. Changing of the maximal curvature when re-planning the trajectory and moving at constant velocity.

Figure 3. Changing of the maximal curvature when re-planning the trajectory and moving at variable velocity.

Figure 4. The resulting force and moment of the thrusters for constant velocity case.

Figure 5. The compliance of the results with the power limits of the thrusters for constant velocity case.

Figure 6. The resulting force and moment of the thrusters for variable velocity case.

Figure 7. The compliance of the results with the power limits of the thrusters for variable velocity case.
5. Conclusions
The proposed method allows to estimate the program velocity of the AUVs in the process of motion, taking into account their dynamic properties and changing parameters of the trajectories. The adjustable value is the maximum possible. However, the velocity changes dramatically, which can also lead to decrease in the accuracy of motion. As for future work, it is planned to develop a method that will allow to generate and re-plan the trajectories of the AUVs considering their dynamics, and adjust the velocity of motion in such a way that there are no sharp changes in its value.

6. References
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