Collaborative Control of Unmanned Underwater Vehicles

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Abstract. This paper targets at urgent issues, which are the search for complex underwater environments and the effective control of underwater seas. Firstly, studies the collaborative control of task-oriented UUV. Secondly, designs reasonable controllers and prove the rendezvous of UUV. At last, based on Matlab software and numerical simulation, verifies the effectiveness of controllers.

1. Introduction

Unmannedness is an important scientific and technological revolution after informatization, it will certainly have a profound impact on war. Therefore, unmanned naval warfare must also be a new maritime combat style that navy needs to face. It should be able to effectively control our waters and scare off acts intended to interfere and destroy our waters in order to ensure the strategic actions of the Community of Marine Destiny. UUV, as a "multiplier" for underwater power, is an important part of the unmanned equipment of navy, and it is also a research hotspot for science and technology workers. Lagrange system[2] is a special kind of dynamic system, which has the characteristics of high nonlinearity, coupling and uncertainty. Compared with the traditional first-order or second-order integration system, the Lagrange system can better describe UUV, Unmanned Aerial Vehicle (UAV), and Mobile Robots[3]. How to design a suitable controller and achieve some state consistency of multiple UUVs is a current research hotspot. According to the UUV main system, UUV collaboration can be roughly divided into three categories: (1) collaboration without a leader; (2) collaboration with a single leader; (3) collaboration with multiple leaders. In the UUV collaboration without a leader, all UUVs are equal, which is especially suitable for practical applications where the cooperative target value is not important, such as the rendezvous, flocking of UUVs. The rendezvous[4] of UUV means that the positions of all the navigating bodies tend to be the same and the speed tends to zero. At present, some literatures[5] have researched the rendezvous problem of UUV.

This paper focuses on the task-oriented UUV cooperative control, and designs a controller to achieve the rendezvous of UUV. The effectiveness of the controller is proved by simulation experiments.

2. Task-oriented UUV collaborative control

With reference to the "UUV Master Plan" issued by the US Navy, UUVs are mainly used in future battlefields for anti-submarine warfare, inspection and identification in underwater counter-terrorism, marine investigations, and information operations. UUV can configure different loads to supplement and expand the capabilities of traditional manned platforms according to different tasks. For example,
in shallow waters or seas that cannot be accessed by other conventional platforms, surveillance and UUVs with various sensors can be deployed to collect hydrological, meteorological, and target information. At the same time, for the complexity of the mission and the unknown of the target sea area, multiple UUVs can be deployed to form a UUV cluster, which expands the detection capability of a single UUV, significantly enhances the scope of detection and surveillance, and improves the accuracy, continuity and intelligence of intelligence Timeliness. However, the existing UUV mostly presents a single-platform working mode, mainly because the cooperative control technology of the UUV cluster is still not very mature. It is necessary to focus on the collaborative control rules, collision avoidance rules, and information interaction rules of the UUV cluster.

(1) Cooperative control rules for UUV clusters
First, sort out the cooperative control methods under different cooperative modes; second, establish a mathematical model combining physics knowledge and domain knowledge, analyze the platform's placeholder criteria, formation control criteria, and platform application state / attitude control criteria, etc., implement the collaborative control regularization of UUV cluster.

(2) Collision avoidance rules for UUV clusters
Based on the platform's state parameters and collision avoidance strategies, a collision avoidance model is established, which can achieve collision avoidance measures with different orientations and different mission requirements through depth adjustment, amplitude adjustment and speed change, and finally form a collision avoidance rule base for the UUV cluster.

(3) Information interaction rules of UUV cluster
Due to the special nature of the underwater environment, the communication distance is relatively limited, and the UUV cluster can only perform information interaction within a small range. UUVs can use their own communication equipment to obtain the navigation information of nearby navigating bodies, environmental information within the sensor's sensing range, etc. Using their designated communication protocols, form information interaction rules. Enabling multiple UUVs, exchange information, coordinate with each other and complete operations in a task.

3. Collaborative control

Assuming \( n \) three degrees of freedom, the motion model in a fixed coordinate system is described by the Lagrange equation as:

\[
M(q)\ddot{q} + (C(q, \dot{q}) + D(q, \dot{q}))\dot{q} + \delta = \tau
\]

In the formula: \( M(q) = \text{diag}\{M_1(q_1), M_2(q_2), \ldots, M_n(q_n)\} \in \mathbb{R}^{3n \times 3n} \) is the inertial matrix, \( C(q, \dot{q}) = \text{diag}\{C_1(q_1, \dot{q}_1), C_2(q_2, \dot{q}_2), \ldots, C_n(q_n, \dot{q}_n)\} \in \mathbb{R}^{3n \times 3n} \) is the Coriolis and centripetal force matrix, \( D(q, \dot{q}) = \text{diag}\{D_1(q_1, \dot{q}_1), D_2(q_2, \dot{q}_2), \ldots, D_n(q_n, \dot{q}_n)\} \in \mathbb{R}^{3n \times 3n} \) is the hydrodynamic damping matrix, \( \delta = [\delta_1^T, \delta_2^T, \ldots, \delta_n^T]^T \in \mathbb{R}^{3n} \) is the environmental disturbance dynamic vector, \( \tau = [\tau_1^T, \tau_2^T, \ldots, \tau_n^T]^T \in \mathbb{R}^{3n} \) is the control input vector, \( q = [q_1^T, q_2^T, \ldots, q_n^T]^T \in \mathbb{R}^{3n} \) is the position vector, \( \dot{q} = [\dot{q}_1^T, \dot{q}_2^T, \ldots, \dot{q}_n^T]^T \in \mathbb{R}^{3n} \) is the speed vector, \( \ddot{q} = [\ddot{q}_1^T, \ddot{q}_2^T, \ldots, \ddot{q}_n^T]^T \in \mathbb{R}^{3n} \) is acceleration.

At the same time, Lagrange's equation is antisymmetric, we can know \( M(q) - 2C(q, \dot{q}) = 0 \). Define auxiliary variables \( s = \dot{q} + \alpha(I_d \otimes I_3)q \), then \( \dot{s} = \ddot{q} + \alpha(I_d \otimes I_3)\dot{q} \). Equation (1) is rewritten as:

\[
M(q)(\dddot{s} - \alpha(I_d \otimes I_3)\ddot{q}) + (C(q, \dot{q}) + D(q, \dot{q}))(s - \alpha(I_d \otimes I_3)q) + \delta = \tau
\]

Theorem: For any initial state of UUV, design the following controller:
\( \tau = -\alpha [M(q)(L_d \otimes I_3)q + (C(q, \dot{q}) + D(q, \dot{q}))(L_d \otimes I_3)q] - ks + D(q, \dot{q})s + \delta \), among them, \( k > 0 \).

Then, UUV can achieve assembly.

Proof: Select the following Lyapunov function:
\[
V = \frac{1}{2} s^T M(q)s
\]  
(3)

Equation (3) derives time \( t \) along the error system, we get:
\[
\dot{V} = \frac{1}{2} (\dot{s}^T M(q)s + s^T M(q)\dot{s} + s^T \dot{M}(q)s) \\
= \frac{1}{2} s^T \dot{M}(q)s - s^T C(q, \dot{q})s - ks^T s = -ks^T s < 0
\]  
(4)

Therefore, it is easy to know that with \( t \to \infty, \ q_i \to q_j, \dot{q}_i \to 0 \), that is to say, UUV has achieved rendezvous.

4. Numerical simulation

In order to verify the correctness of the theoretical results, Matlab software was used for numerical simulation experiments. Select six UUVs, the initial value of the position vector is \( q_i = (10i, 10i, i)^T \), the initial value of the speed vector is \( \dot{q}_i = (i+1, i, i+1)^T \), \( i = 1, 2, \cdots, 6 \). The mass is \( m = 125 \), the hydrodynamic coefficient is \( X_u = -48, Y_v = -48, N_r = -80, X_u = -62, Y_v = -62, N_r = -30 \).

Using the linear matrix inequality toolbox, the position error trajectories of the six UUV bodies in Figure 1-3 and the speed trajectories of the six UUV bodies in Figure 4-6 are obtained. It can be seen that at time \( t = 35s \), the yaw angle of the six UUVs is \( 0.257^\circ \), the corresponding yaw angular velocity is also small; at that time \( t = 40s \), the yaw angle difference and the yaw angular velocity are both zero; at that time \( t = 250s \), the vertical and lateral position differences and velocities of the six UUVs were all zero. Therefore, it can be seen that at that time \( t = 250s \), six UUVs are flocking to the target area and the speed is zero, that is, the rendezvous control is realized.

![Figure 1. The vertical position error trajectories of the six UUV bodies.](image1)

![Figure 2. The lateral position error trajectories of the six UUV bodies.](image2)
This paper focuses on the task-oriented UUV cooperative control, and designs a controller to make the UUV achieve rendezvous. Numerical simulation experiments with Matlab prove the effectiveness of the controller. In the next work, we can focus on the rendezvous or tracking control of UUV under communication constraints.

6. References

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