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Three-dimensional formation control based on nonlinear small gain method for multiple underactuated underwater vehicles

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ABSTRACT

This paper proposes a distributed formation tracking controller for multiple underactuated underwater vehicles (UUVs) which move in three dimensional space. The formation controller designing process is divided into two parts. In the first part, the condition which the formation controller must be satisfied is given. And the controllers are designed to ensure the condition mentioned before. In the second part, decentralized formation controller are proposed, and the stability analysis based on small gain theorem is introduced. Simulation results illustrate that the designed controller can track three-dimensional formation trajectory accurately.

1. Introduction

Considerable effort has focused on coordination control of underactuated underwater vehicles (UUVs). For the coordination control problem, multiple UUVs are required to fulfill the formation requirements. Numerous approaches to the formation control of multiple UUVs have been reported in the literature, such as behavior-based control (Takahashi et al., 2004; Balch & Arkin, 1999), the virtual structure approach (Anthnoy Lewis & Tan, 1997; Beard et al., 2001), leader following strategy (Chen et al., 2009; Consolini et al., 2008; Das et al., 2002), decentralized coordinated control (Yamaguchi, 2003; Dong & Farrell, 2008; Dong & Jay, 2009; Sun et al., 2009), graph theory-based methods (Fax & Murray, 2004; Jadbabaie et al., 2004), artificial potential mechanism (Leonard & Fiorelli, 2001), and so on.

The aim of coordination control of multiple UUVs is to drive each UUV to converge and keep relative distance from its neighbors. Distributed formation control of multiple UUVs using available relative position measurements has attracted considerable attention. In (Liu & Jiang, 2013), a class of distributed nonlinear controllers for leader-following formation of unicycle robots without global position measurements are proposed. The distributed controller is robust to position measurement errors and the linear velocities of the robots can be restricted to specific bounded ranges. In (Liu & Jiang, 2014), the coexistence of constraints on information exchange and complex nonlinear dynamics in distributed control systems is analyzed. The cyclic small gain methods are introduced to design the distributed nonlinear controllers. In (Ghabcheloo et al., 2009), the coordinated path following problem is divided into two steps. First, a path following control law is designed to drive each vehicle to its assigned path. Second, the coordinated states are adjusted to their nominal values so as to achieve coordination. In (Peng et al., 2011), using NN- based dynamic surface control approach, a decentralized cooperative controller for underactuated autonomous surface vehicles is proposed. The proposed controller can make a group of underactuated autonomous surface vehicles converge to a trajectory which is relative to a time-varying reference signal. Since the proposed algorithm only depends on the local information from its neighbors, it works in a distributed manner.

Based on the above presented discussion, distributed controllers for leader following formation control of multiple UUVs are proposed. The local relative position measurements are used to design the control algorithm. Firstly, the formation control system is transformed into a state agreement problem. Then, the distributed control laws are developed. When the linear velocity of the UUV is zero, there is a singularity problem for distributed control laws. This singularity problem must be taken into consideration when we design distributed coordination control laws. To avoid the singularity problem, the linear velocity of the UUV must satisfy a condition. The closed-loop distributed system is transformed into a network of input-to-output stable (IOS) systems. And the recently

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developed nonlinear network small gain theorems are employed to guarantee state agreement. This paper has made the following contributions.

First, we propose a new distributed coordination algorithm to drive multiple UUVs to the specified spatial paths in advance with desired formation.

Second, the control algorithm designed in this paper using only local relative location information, which has more practical application value for underwater vehicles.

Third, the condition which the linear velocities of multiple UUVs must satisfy is developed. Based on the condition, the actual speed of the i-th UUV is less than the expected speed.

This paper is organized as follows: Section 2 presents the mathematical and dynamic models of a UUV in three dimensional space. The formation error systems are deduced in this part. The objective of this paper is introduced. In Section 3, spatial formation controller is derived. And the stability analysis based on small-gain method is presented in this part. Simulation studies are discussed in Section 4, and Section 5 summarizes the paper.

2. Model description for UUV in three dimensional space

In this part, the dynamic model of the i-th UUV in three dimensional space is introduced. $i = 0, 1, 2, \cdots, n-1$. The UUV with index 0 is the leader, and the UUVs with indexes $1, \cdots, n-1$ are followers. In a general case, the shape of the UUV considered in this paper is shown in Fig. 1. If the influence of roll is ignored, a group of n UUVs whose mathematical models are described as follows:

$$\begin{aligned} &\dot{x}_i = u_i \cos\psi_i \cos\theta_i - v_i \sin\psi_i + w_i \cos\psi_i \sin\theta_i \\ &\dot{y}_i = u_i \sin\psi_i \cos\theta_i + v_i \cos\psi_i + w_i \sin\psi_i \sin\theta_i \\ &\dot{z}_i = -u_i \sin\theta_i + w_i \cos\theta_i \\ &\dot{\theta}_i = q_i \\ &\dot{\psi}_i = \frac{r_i}{\cos\theta_i} \end{aligned} \tag{1}$$

When discussing the kinematics of the UUV, we first need to determine an inertial reference frame. Let $\{E\}$be the earth-fixed frame of all UUVs. The earth-fixed frame is used as an inertial reference frame and is also called static coordinate system. The origin O of the earth-fixed frame can be taken from the sea surface or at any point in the sea. According to the rules, the axis OZ is directed toward the center of the earth, and the other two axes can be selected arbitrarily. In this paper, the axis OX points north, and the axis OY points to the east. In order to facilitate the discussion of the problem, the body-fixed frame $\{B_i\}$ is adopted for the i-th UUV. The body-fixed frame is attached to the body of the UUV. In principle, the origin of the body-fixed frame and the directions of the coordinate axes can be selected arbitrarily. For convenience, the axis OU_i can be aligned with the main axis of the UUV, while the axis OV_i is in alignment with the auxiliary axis of the UUV. Let Q_i be the center of gravity of the i-th UUV. Q_i is chosen to coincide with the origin of $\{B_i\}$. $[x_i, y_i, z_i]^{\mathrm{T}}$ denotes the position of the point Q_i in $\{E\}$. $[\theta_i, \psi_i]^{\mathrm{T}}$ denotes the orientation of the point Q_i in $\{E\}$. $[u_i, v_i, w_i]^{\mathrm{T}}$ is the velocities of the i-th UUV in $\{B_i\}$. $[q_i, r_i]^{\mathrm{T}}$ is the angular velocities of the i-th UUV in $\{B_i\}$.

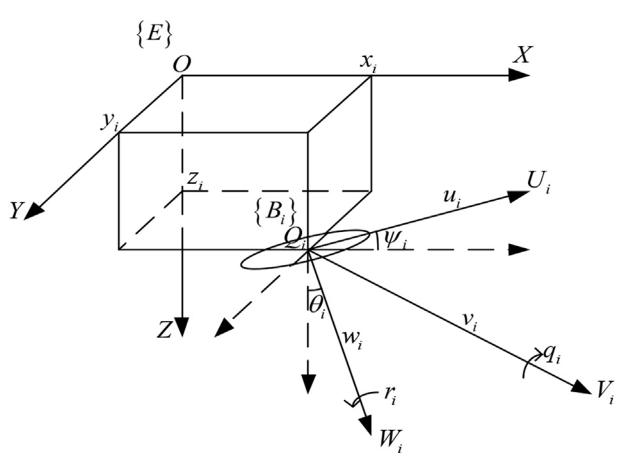

Fig. 1. Earth-fixed and body-fixed coordinate systems of the i-th UUV.

The dynamic of the i-th UUV is written in the actuated directions as follows:

$$\begin{aligned} &m_{11i}\dot{u}_i = m_{22i}v_i r_i - m_{33i}w_i q_i - d_{11i}u_i + F_{1i} \\ &m_{22i}\dot{v}_i = -m_{11i}u_i r_i - d_{22i}v_i \\ &m_{33i}\dot{w}_i = m_{11i}u_i q_i - d_{33i}w_i \\ &m_{55i}\dot{q}_i = (m_{33i} - m_{11i})u_i w_i - d_{55i}q_i - \rho g \nabla \overline{GM_{L_i}} \sin\theta_i + F_{2i} \\ &m_{66i}\dot{r}_i = (m_{11i} - m_{22i})u_i v_i - d_{66i}r_i + F_{3i} \end{aligned} \tag{2}$$

where, $m_{11i} = m_i - X_{\dot{u}i}$, $m_{22i} = m_i - Y_{\dot{v}i}$, $m_{33i} = m_i - Z_{\dot{w}i}$, $m_{55i} = I_{Yi} - M_{\dot{q}i}$, $m_{66i} = I_{zi} - N_{\dot{r}i}$, $d_{11i} = -X_{ui}$, $d_{22i} = -Y_{vi}$, $d_{33i} = -Z_{wi}$, $d_{55i} = -M_{qi}$, $d_{66i} = -N_{ri}$. m_i and $m_{(\cdot)}$ are the mass and associated mass of the i-th UUV. F_{1i}, F_{2i} and F_{3i} are the force and torque signals which are provided by the actuators. $X_{(\cdot)}$,$Y_{(\cdot)}$,$Z_{(\cdot)}$, $M_{(\cdot)}$ and $N_{(\cdot)}$ are the hydrodynamic coefficients. $I_{(\cdot)}$ is the moment of inertia. ρ is the density of water. g is the acceleration of gravity. ∇ is the volume of water. $\overline{GM_{L_i}}$ is the longitudinal metacentric height.

Remark 1. In practice, the response of the actuators and thrusters is much faster than that of the UUV. Therefore, the dynamics of the actuators and thrusters is reasonably neglected in this paper.

To facilitate the derivation of the controller, the new variables are defined as follows:

$$v_{xi} = u_i \cos\psi_i \cos\theta_i - v_i \sin\psi_i + w_i \cos\psi_i \sin\theta_i \tag{3}$$

$$v_{yi} = u_i \sin\psi_i \cos\theta_i + v_i \cos\psi_i + w_i \sin\psi_i \sin\theta_i \tag{4}$$

$$v_{zi} = -u_i \sin\theta_i + w_i \cos\theta_i \tag{5}$$

then the dynamics $\dot{x}_i = v_{xi}$, $\dot{y}_i = v_{yi}$, and $\dot{z}_i = v_{zi}$ are deduced. By combining (2) with (3)–(5), the derivatives for v_{xi}, v_{yi}, and v_{zi} can be calculated. To simplify the problem, we present dynamic systems as follows:

$$\dot{v}_{xi} = u_{xi} \tag{6}$$

$$\dot{v}_{yi} = u_{yi} \tag{7}$$

$$\dot{v}_{zi} = u_{zi} \tag{8}$$

where u_{xi}, u_{yi}, and u_{zi} are seemed to be new inputs to simplify the structure of the dynamics (6), (7), and (8). In this way, we can get the simplified dynamic system of the i-th UUV as follows:

$$\dot{x}_i = v_{xi}, \quad \dot{v}_{xi} = u_{xi} \tag{9}$$

$$\dot{y}_i = v_{yi}, \quad \dot{v}_{yi} = u_{yi} \tag{10}$$

$$\dot{z}_i = v_{zi}, \quad \dot{v}_{zi} = u_{zi} \tag{11}$$

In fact, for multiple UUVs, the relative position information is easier to be obtained than the absolute position information. So we use the relative position information to realize the formation control objective. In order to show the relative position information more clearly and concretely, we first introduce the concept of the information exchange topology map. Let G be the directed graph induced by the multiple UUVs' communication network. There are n nodes (each corresponding to a UUV) in G. If the i-th UUV can get a relative position $(x_i - x_j)$ from the j-th UUV, there is a directed connection from node j to node i in G. And the

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