Neurocomputing 154 (2015) 33–40

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Distributed formation control of 6-DOF autonomous underwater vehicles networked by sampled-data information under directed topology

Chao Ma*, Qingshuang Zeng

Space Control and Inertial Technology Research Center, School of Astronautics, Harbin Institute of Technology, Harbin 150080, China

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form
6 November 2014
Accepted 2 December 2014
Communicated by Xudong Zhao
Available online 19 December 2014

Keywords:
6-DOF autonomous underwater vehicles
Formation control
Input-to-state stability
Sampled-data information

ABSTRACT

In this paper, a sampled-data networking strategy is investigated for the formation problem of multiple 6-DOF autonomous underwater vehicles (AUVs) in the presence of external disturbances. Unlike the common condition in most literatures associated with multiple vehicles, where the information is assumed to be exchanged continuously, in our proposed strategy, the position and orientation information of the multiple AUVs is exchanged according to a discrete-time sequence, which is more applicable to current technologies for underwater communications. More precisely, this strategy can be modeled by a sample-and-hold mechanism and is capable of both uniform and non-uniform sampling cases. In particular, it has a potential advantage from an energy perspective, since communication reduction always leads to less energy consumption. By model transformation, distributed controllers are designed based on input-to-state stability (ISS) property to ensure that both configuration formation and rendezvous-type formation can be achieved. An optimization procedure is also presented to calculate the maximum allowable sampling period. Finally, a numerical example is provided to illustrate the effectiveness and applicability of the theoretical results.

1. Introduction

With the worldwide trend of developing intelligent and unmanned systems, autonomous underwater vehicles (AUVs) have attracted a great deal of attention over the past decade, due to their broad applications in both military and civil fields, such as mine countermeasure, sea inspection and patrol, oceanographic mapping and so on [1–3]. However, as the underwater tasks are becoming increasingly complex, including reducing energy cost, increasing system efficiency and demanding redundancy against individual failure, it is almost practically impossible for a single AUV to complete such missions [4–6]. In order to meet these requirements, considerable interest in cooperative control of multiple AUVs has been fueled in recent years [7–9]. As an important problem in multiple AUVs cooperation, formation control has been extensively studied and encouraging results with various control methods have been reported in the literature [10–15] and references therein.

From the results of these researches, it can be found that there are two key factors determining the formation performance. One is the dynamic model of an AUV, which can be described as a double integrator system [15] or an Euler–Lagrange system [1,16]. Especially, the Euler–Lagrange equation has been widely adopted since it can well exhibit the intrinsic nonlinearity and coupling of the AUV. The other is the communication among the multiple AUVs. It is worth mentioning that as many researches are typically focused on different types of topologies such as fixed topology and switching topologies [17–19], little concern has been paid to the special ways of information exchanges in the underwater environment. Note that most studies are based on the assumption that each AUV can communicate with each other continuously and the information exchanges are considered as continuous-time processes. However, an important fact is that underwater communications mainly depend on underwater acoustic and optical devices, which have serious constraints including low bit rates and transmission loss [20–22], such that the aforementioned assumption for multiple AUVs is not realistic in practical applications. Unfortunately, to the best of the authors' knowledge, cooperative problems for multiple AUVs with consideration of the restrictions on underwater communications still have not yet been adequately studied and remain open.

Motivated by the above discussion, a novel distributed formation control strategy for multiple 6-DOF AUVs is introduced, where the information exchanges are modeled by a sampled-and-hold mechanism under directed topology. More precisely, each AUV

* Corresponding author.
E-mail addresses: cma@hit.edu.cn (C. Ma), zqshuang@hit.edu.cn (Q. Zeng).

http://dx.doi.org/10.1016/j.neucom.2014.12.022
0925-2312/

samples and transmits its own position and orientation information to the local neighbors while it receives the sampled-data information sent by others according to the sampling sequence, which distinguishes this strategy from the existing results. In this scenario, the relative position and orientation errors in the distributed controllers are kept constant during the sampling intervals and then updated until the next sampling time comes. Moreover, the proposed strategy is suitable for the case of non-uniform sampling which is more general in sample-data control systems [23–26]. The dynamic model of the 6-DOF AUV is described by Euler–Lagrange equation in the presence of underwater environmental disturbance which may be time-varying but bounded. By model transformation and input-to-state stability (ISS) analysis, sufficient conditions are derived to guarantee that the desired formation can be achieved. Based on the obtained results, an optimization procedure is further provided to calculate the maximum allowable sampling period. It is worth mentioning that the proposed control strategy can be adopted directly to solve the consensus or formation problems of other fully actuated Euler–Lagrange systems in which continuous-time information exchanges are not available or too expensive.

The main contributions of this paper can be summarized as follows.

(i) Since it is almost practically impossible to achieve continuous-time underwater communications, our proposed sampled-data networking strategy is more practical and reliable for the multiple AUVs cooperation. Moreover, this strategy does not require the velocity information of each AUV to be exchanged, such that the communication network loads can be effectively reduced.
(ii) Note that it is of great importance to consider the energy consumption problem of the multiple AUVs in the real world applications. As discrete-time information exchanges can consume less communication energy, our proposed strategy has a significant advantage to save communication energy and increase the working time of the multiple AUVs.

The rest of this paper is organized as follows. Section 2 introduces some preliminaries on the AUV dynamics and graph theory, and formulates the problem to be investigated. In Section 3, main results on the formation problem are given. Section 4 provides a numerical example to illustrate the effectiveness of the theoretical results and the paper is concluded in Section 5.

Notation: The notation used in this paper is standard. $\mathbb{R}^n$ denotes the n dimensional Euclidean space, $\mathbb{R}^{m\times n}$ represents the set of all $m\times n$ real matrices. I and 0 represent identity matrix and zero matrix with appropriate dimensions, respectively. For any function $f:\mathbb{R}_{\geq 0}\to\mathbb{R}^n$, the $\mathbb{L}_2$-norm is defined as $\|f\|_2^2=\int_0^\infty |f(t)|^2dt$ with the $\mathbb{L}_2$ space defined as the set $\{f:\mathbb{R}_{\geq 0}\to\mathbb{R}^n \,|\, \|f\|_2<\infty\}$, while the $\mathbb{L}_\infty$-norm is defined as $\|f\|_\infty=\sup_{t\geq 0}|f(t)|$ with the $\mathbb{L}_\infty$ space defined as the set $\{f:\mathbb{R}_{\geq 0}\to\mathbb{R}^n \,|\, \|f\|_\infty<\infty\}$. $\mathbb{L}_2([-r,0];\mathbb{R}^n)$ represents the space of all square integrable functions $\phi:[-r,0]\to\mathbb{R}^n$ which are absolutely continuous on $[-r,0]$ and have square integrable first-order derivatives denoted by W with the norm $\|\phi\|_W=\max_{\theta\in[-r,0]}|\phi(\theta)|+(\int_{-r}^0|\dot{\phi}(\varphi)|^2\,d\varphi)^{1/2}$. A continuous function $\alpha:[0,a]\to[0,\infty)$ is said to be of class $\mathcal{K}$ if it is strictly increasing and $\alpha(0)=0$. The function is said to be of class $\mathcal{K}_\infty$ if $a=\infty$ and $\alpha(r)=\infty$ when $r\to\infty$. A function $\beta:[0,\infty)^2\to[0,\infty)$ is said to be of class $\mathcal{KL}$ if, for each fixed t, the mapping $\beta(s,t)$ is of class $\mathcal{K}$ and, for each fixed s, it is decreasing and $\beta(s,t)\to 0$ as $t\to\infty$.

$A\otimes B$ denotes the Kronecker product of the matrices A and B. $1_N\in\mathbb{R}^N$ is the column vector with all entries being 1. Re() and Im() denote the real and imaginary part of a complex number, respectively. The notation $P>0$ means P is real symmetric and positive definite, and the superscript "T"denotes matrix transposition. $\lambda_{\min}(P)$ and $\lambda_{\max}(P)$ denote the largest and the smallest eigenvalues of the symmetric matrix P, respectively. In addition, in symmetric block matrices, $*$ is used as an ellipsis for the terms that are introduced by symmetry and diag$\{\cdots\}$ denotes a block-diagonal matrix. Finally, if not explicitly stated, all variables and functions are written in a simplified form, e.g., $f(t)$ is written as f and all matrices are assumed to have compatible dimensions.

2. Preliminaries and problem formulation

2.1. 6-DOF autonomous underwater vehicle (AUV) dynamics

Consider a group of N networked AUVs indexed by the set $\mathcal{I}=\{1,2,\ldots,N\}$, where each AUV is equipped with a communication device and a sensing device. For the motion description of the AUV, a body-fixed frame $\{B\}$ and an Earth-fixed frame $\{E\}$ are defined. In the body-fixed frame $\{B\}$, the dynamics of an AUV can be described as [27]

$$\begin{cases}\dot{p}_i=R_i(p_i)q_i,\\ M_i\dot{q}_i=-C_i(q_i)q_i-D_i(q_i)q_i-g_i(p_i)+\tau_i+\tau_{di}, i\in\mathcal{I}.\end{cases}$$

The vector $p_i=[x_i,y_i,z_i,\phi_i,\theta_i,\varphi_i]^T$ denotes the generalized location and orientation in the Earth-fixed frame $\{E\}$. $R(p_i)$ is the kinematic transformation matrix from the body-fixed frame $\{B\}$ to $\{E\}$. The vector $q_i=[u_i,v_i,r_i,\delta_i,\zeta_i,\rho_i]^T$ represents the translational velocity vector in the body-fixed frame $\{B\}$. M_i is the inertia matrix, $C_i(q_i)$ groups the Coriolis and centripetal forces, $D_i(q_i)$ represents the damping matrix, $g_i(p_i)$ is the restoring force vector, $\tau_i\in\mathbb{R}^6$ is the control input of the AUV and $\tau_{di}\in\mathbb{R}^6$ represents time-varying but bounded disturbance. For an angle $\alpha\in\mathbb{R}$, denote $s_\alpha=\sin\alpha$, $c_\alpha=\cos\alpha$ and $t_\alpha=\tan\alpha$ for simplicity. In detail:

$$R_i(p_i)=\text{diag}\{R_{1i}(p_i),R_{2i}(p_i)\},$$

$$R_{1i}(p_i)=\begin{bmatrix}c_{\varphi_i}c_{\theta_i} & -s_{\varphi_i}c_{\phi_i}+c_{\varphi_i}s_{\theta_i}s_{\phi_i} & s_{\varphi_i}s_{\phi_i}+c_{\varphi_i}c_{\phi_i}s_{\theta_i}\\ s_{\varphi_i}c_{\theta_i} & c_{\varphi_i}c_{\phi_i}+s_{\phi_i}s_{\theta_i}s_{\varphi_i} & -c_{\varphi_i}s_{\phi_i}+s_{\theta_i}s_{\varphi_i}c_{\phi_i}\\ -s_{\theta_i} & c_{\theta_i}s_{\phi_i} & c_{\theta_i}c_{\phi_i}\end{bmatrix},$$

$$R_{2i}(p_i)=\begin{bmatrix}1 & s_{\phi_i}t_{\theta_i} & c_{\phi_i}t_{\theta_i}\\ 0 & c_{\phi_i} & -s_{\phi_i}\\ 0 & s_{\phi_i}/c_{\theta_i} & c_{\phi_i}/c_{\theta_i}\end{bmatrix},$$

$$M_i=\text{diag}\{m_{i1},m_{i2},\ldots,m_{i6}\},$$

$$C_i(q_i)=\begin{bmatrix}0 & C_{1i}(q_i)\\ C_{1i}(q_i) & C_{2i}(q_i)\end{bmatrix},$$

$$C_{1i}(q_i)=\begin{bmatrix}0 & m_{i3}r_i & -m_{i2}v_i\\ -m_{i3}r_i & 0 & m_{i1}u_i\\ m_{i2}v_i & -m_{i1}u_i & 0\end{bmatrix},$$

$$C_{2i}(q_i)=\begin{bmatrix}0 & m_{i6}\rho_i & -m_{i5}\zeta_i\\ -m_{i6}\rho_i & 0 & m_{i4}\delta_i\\ m_{i5}\zeta_i & -m_{i4}\delta_i & 0\end{bmatrix},$$

$$D_i(q_i)=\text{diag}\{d_{L_{i1}}+d_{Q_{i1}}|u_i|,d_{L_{i2}}+d_{Q_{i2}}|v_i|,d_{L_{i3}}+d_{Q_{i3}}|r_i|d_{L_{i4}}+d_{Q_{i4}}|\delta_i|,d_{L_{i5}}+d_{Q_{i5}}|\zeta_i|,d_{L_{i6}}+d_{Q_{i6}}|\rho_i|\},$$

where $m_{ij},d_{L_{ij}},d_{Q_{ij}}>0,i\in\mathcal{I},j=1,2,3$. Note that $R_i(p_i)R_i^T(p_i)=I_6$, $M_i=M_i^T>0$, $\dot{M}_i=0$, $C_i(q_i)=C_i^T(q_i)$ and $D_i(q_i)>0$.

Consequently, by applying the kinematic transformations (assuming that $R_i(p_i)$ is non-singular), the dynamics of the multiple AUVs in the Earth-fixed frame $\{E\}$ can be obtained as

$$M_{p_i}(p_i)\ddot{p}_i+C_{p_i}(q_i,p_i)\dot{p}_i+D_{p_i}(q_i,p_i)\dot{p}_i+g_{p_i}(p_i)=\tau_{p_i}(p_i)+\tau_{dp_i}(p_i), i\in\mathcal{I}, \quad (1)$$

where

$$M_{p_i}(p_i)=R_i^{-T}(p_i)M_iR_i^{-1}(p_i),$$