Ocean Engineering 167 (2018) 36–44

Contents lists available at ScienceDirect

Ocean Engineering

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

Short communication

Adaptive cooperative formation control of autonomous surface vessels with uncertain dynamics and external disturbances

Yu Lu[a], Guoqing Zhang[a,b], Zhijian Sun[a], Weidong Zhang[a,*]

[a] Department of Automation, Shanghai Jiao Tong University, Shanghai, 200240, P.R. China
[b] Navigation College, Dalian Maritime University, Liaoning, 116026, P.R. China

ARTICLE INFO

Keywords:
Formation
Surface vessels
Adaptive
Dynamic surface control
Minimal learning parameter

ABSTRACT

This paper investigates the leader-follower cooperative formation control problem of autonomous surface vessels (ASVs) with uncertain dynamics and external disturbances. Especially, ASVs can communicate with each other under a directed interaction topology. Based on directed graph theories, backstepping and the minimal learning parameter (MLP) algorithm, a novel distributed robust formation controller with two different adaptive laws is developed for each ASV. Dynamic surface control (DSC) is utilized to eliminate repeated derivative of virtual control laws, which is important to generate real-time control signals. Neural networks (NNs) approximation combined with an MLP-based adaptive law is incorporated into the proposed controller to enhance the robustness against model uncertainties. Then only one learning parameter instead of the enormous weights matrix is estimated for each ASV. An auxiliary adaptive law is designed to obtain a continuous controller when compensating approximation errors and disturbances. It is shown that desired formation shapes can be achieved with the proposed controller if the interaction topology has a directed spanning tree, and formation errors are guaranteed to be semi-global uniformly ultimately bounded (SGUUB). Simulations and comparison results are provided to illustrate the effectiveness of theoretical results.

1. Introduction

Nowadays, the formation of autonomous surface vessels (ASVs) plays an increasingly important role in marine missions (Xiao et al., 2017). For instance, in marine search and rescue operations, the formation of ASVs can provide adequate coverage to accomplish the whole mission with less time (Liu et al., 2016). Other applications can be found in oceanic mineral exploration (Yu et al., 2017), surveillance of territorial waters (Liu et al., 2017a) and so on.

In the past two decades, numerous studies focus on the formation control problem (Oh et al., 2015), which aim to make a group of ASVs maintain or track desired positions and orientations with predefined geometrical shapes. Various formation approaches have been proposed to address such problem, e.g., behavior-based (Balch and Arkin, 1998), virtual structure (Beard et al., 2001) and leader-follower (Breivik et al., 2008; Xiang et al., 2010). Among these approaches, the leader-follower approach is widely adopted due to its simplicity and reliability. Since in the leader-follower formation, formation shapes associated with followers are set with respect to leaders or virtual leaders. Many attractive results on leader-follower formation control have been presented in the field of ocean engineering. In (Cui et al., 2010), the authors propose a virtual vessel scheme, where a position tracking controller is utilized to follow the virtual trajectory of each follower. Unlike (Cui et al., 2010), the line-of-sight (LOS) range and angle are used in (Peng et al., 2013a), where a robust adaptive formation controller is developed by NNs and DSC. Under LOS range and angle constraints, Jin further presents a novel fault tolerant finite-time leader-follower formation control scheme (Jin, 2016). Although the aforementioned schemes are effective in the leader-follower formation control, they have a common limitation: the information of the leader is assumed to be known by all followers, which inevitably suffers from the single-point failure problem of the leader, i.e. if the leader is under attack or out of work, the whole formation would no longer be maintained.

In order to reduce the dependence on the leader, the interaction topology is introduced. Then the idea of cooperative control can be utilized to the leader-follower formation control of ASVs (Ge et al., 2017; Xi et al., 2018). In this scenario, the information of the leader is only available to a few followers but the formation can still be achieved (Ding et al., 2013; Xi et al., 2016). The related research has been conducted in (Thorvaldsen and Skjetne, 2011; Peng et al., 2013b; Liu et al., 2017b). Using group agreement protocols and maneuvering control theories, a novel coordinated formation scheme is presented in

* Corresponding author.
E-mail address: wdzhang@sjtu.edu.cn (W. Zhang).

https://doi.org/10.1016/j.oceaneng.2018.08.020
Received 19 May 2017; Received in revised form 18 July 2018; Accepted 9 August 2018

(Thorvaldsen and Skjetne, 2011). By integrating NNs and the graph theory, a robust cooperative formation controller is developed in (Peng et al., 2013b). To realize cooperative path maneuvering of ASVs, a modular adaptive control method is proposed in (Liu et al., 2017b). Although these works can eliminate the single-point failure problem, the interaction graph is undirected, which implies that only bidirectional communication is allowed. In practical applications, unidirectional communication is inevitable due to limited communication range and possible equipment malfunction. Therefore, the formation of ASVs under the directed interaction topology should be further investigated. It is worth mentioning that controllers in (Peng et al., 2013b; Liu et al., 2017b) are designed based on the backstepping technique (Li et al., 2017; Tong et al., 2016a, 2016b). A major drawback in the backstepping design is the explosion of complexity problem, which is caused by repeated differentiations of virtual control laws and needs to be taken into account in the cooperative formation of ASVs.

Due to imprecise measurements and external disturbances, accurate model parameters cannot be obtained. To deal with uncertain dynamics, some literature utilizes adaptive control to estimate unknown upper bound of uncertainties (Jin, 2016; He and Meng, 2018). Combined with adaptive control, the NNs technique is found effective to approximate systems with uncertainties (Ge and Wang, 2004), and many good results have been achieved for different types of nonlinear systems (He et al., 2016, 2017a; Xu and Sun, 2018; Xu and Shou, 2018). In the field of ship motion control, adaptive NN controllers have also been widely adopted (Du et al., 2015; He et al., 2017b; Xiang et al., 2017; Zhang et al., 2017). However, these adaptive NN controllers suffer from the computational effort caused by updating of the enormous weights matrix, especially when the number of NNs nodes increases. In (Li et al., 2010a), the MLP algorithm is incorporated to reduce learning parameters for NNs. This algorithm has been successfully applied in path-following of ships (Zhang and Zhang, 2017) and control of PMSMs (Yu et al., 2015), but is still not employed in the cooperative formation of ASVs, where states of ASVs are coupled under the interaction topology. Considering the robustness against disturbances induced by wind, waves and current, disturbance observation schemes in (Fu et al., 2015; Du et al., 2016) perform well. But the assumption that there exists the first-order derivative of disturbances is too strict. Meanwhile, discontinuous control laws are sometimes adopted to compensate disturbances (Li and Zhang, 2010; Bessa et al., 2010; Li et al., 2010b; Xu et al., 2015), which may cause undesired chattering effects and the inferior performance of the formation system. Therefore, it is necessary to explore new cooperative formation controllers for ASVs such that the robustness against model uncertainties and external disturbances can be enhanced, especially in terms of reducing the computational effort and relaxing assumptions on the formation system.

Motivated by aforementioned discussions, we further investigate the leader-follower cooperative formation problem of ASVs with model uncertainties and external disturbances, where ASVs can communicate with each other under a directed interaction topology. A novel distributed neural formation controller with two adaptive laws is proposed for each ASV. First, virtual control laws are developed based on static consensus protocols and directed graph theories. Then dynamic surface control is utilized to derive the formation controller. By the NNs technique, the nominal control law is designed to deal with uncertain dynamics with an MLP-based adaptive law. The auxiliary control law and corresponding adaptive law are added to obtain a continuous controller when compensating approximation errors and external disturbances. Finally, Lyapunov-based stability analysis is provided to show the closed-loop performance. Main contributions of this paper are summarized as follows:

(1) Considered ASVs are nonlinear and strongly coupled agents and they are connected in a directed topology. A new neural adaptive cooperative formation control scheme is presented for ASVs such that the formation can be achieved under a directed interaction topology.
(2) The proposed formation controller is based on the DSC technique and the MLP algorithm. Then repeated derivative of virtual control laws is avoided and only one learning parameter instead of the enormous weights matrix requires to update for each vessel, which can reduce the computational effort.
(3) Two different adaptive laws are designed associated with the formation controller to enhance the robustness against model uncertainties and disturbances. Thus, a continuous rather than discontinuous controller is guaranteed and the assumption on the first-derivative of disturbances is relaxed.

The rest of the paper is organized as follows. In section 2, interaction graph and function approximation based on RBF NNs are introduced. Then the cooperative formation control problem is formulated in section 3. Main results are presented in section 4. Simulations and comparison results are given in section 5. Section 6 concludes this paper.

Notations: $\mathbb{R}^n$ denotes the n dimensional real space. Given a vector $\boldsymbol{x} = [x_1, \cdots, x_N]^T$, $\|\boldsymbol{x}\|_1 = \sum_{i=1}^{N} |x_i|$ denotes the ℓ_1 -norm of $\boldsymbol{x}$, $\|\boldsymbol{x}\|_2 = \sqrt{\boldsymbol{x}^T\boldsymbol{x}}$ denotes the ℓ_2 -norm of $\boldsymbol{x}$, and $\|\boldsymbol{x}\|_\infty = \max_{i=1,\cdots,N}\{|x_i|\}$ denotes the ℓ_∞ -norm of $\boldsymbol{x}$. Given the hyperbolic tangent function $\tanh(\cdot)$ and the sign function $\mathrm{sgn}(\cdot)$, define $\mathbf{tanh}(\boldsymbol{x}) = [\tanh(x_1), \cdots, \tanh(x_N)]^T$, and $\mathrm{sgn}(\boldsymbol{x}) = [\mathrm{sgn}(x_1), \cdots, \mathrm{sgn}(x_N)]^T$. For a vector $\boldsymbol{h} = [\boldsymbol{h}_1^T, \cdots, \boldsymbol{h}_N^T]^T$, where $\boldsymbol{h}_i$, $i = 1, \cdots, N$ is also a vector, we define $\boldsymbol{h} \circ \boldsymbol{h} = [\boldsymbol{h}_1^T\boldsymbol{h}_1, \cdots, \boldsymbol{h}_N^T\boldsymbol{h}_N]^T$. $\boldsymbol{I}$ is the identity matrix of appropriate dimensions. $\boldsymbol{I}$ is the column vector with all entries equal to 1. We write $\boldsymbol{A}^T$ for the transpose of matrix $\boldsymbol{A}$ and $\lambda(\boldsymbol{A})$ for the eigenvalue of square matrix $\boldsymbol{A}$. $\boldsymbol{A} = \mathrm{diag}\{\boldsymbol{A}_{11}, \cdots, \boldsymbol{A}_{NN}\}$ is utilized to represent a diagonal matrix $\boldsymbol{A}$ with leading diagonal elements $\boldsymbol{A}_{11}, \cdots, \boldsymbol{A}_{NN}$. $\boldsymbol{A} \otimes \boldsymbol{B}$ represents the Kronecker product of two matrices $\boldsymbol{A}$, $\boldsymbol{B}$.

2. Preliminaries

In this section, we introduce some basic theories of interaction graph and function approximation based on RBF NNs. The interaction graph is utilized to represent the communication topology of multiple ASVs. Function approximation based on RBF NNs is powerful when addressing model uncertainties of ASVs.

2.1. Interaction graph

A weighted digraph $\mathscr{G}$ is employed to model communication topology of a network consisting of multiple ASVs. The set of vessels can be viewed as the set of nodes and the set of directed communication links can be viewed as the set of edges. Let $\mathscr{V} = \{\mathscr{V}_i | i \in \mathcal{I}\}$ represents a set of N vessels, where $\mathcal{I} = \{1, 2, \cdots, N\}$. A directed edge from $\mathscr{V}_i$ to $\mathscr{V}_j$ denoted as $(\mathscr{V}_i, \mathscr{V}_j) \in \mathscr{E}$ represents a directed communication link from vessel $\mathscr{V}_i$ to vessel $\mathscr{V}_j$, that is, vessel $\mathscr{V}_j$ can receive information from vessel $\mathscr{V}_i$, where $\mathscr{E}$ is the set of edges. The adjacency matrix of graph $\mathscr{G}$ is denoted as $\mathscr{A} = (a_{ij})_{N\times N}$, where a_{ij} is the element at the i-th row and the j-th column of $\mathscr{A}$. If $(\mathscr{V}_j, \mathscr{V}_i) \in \mathscr{E}$, $a_{ij} = 1$, otherwise, $a_{ij} = 0$. Moreover, we assume that $a_{ii} = 0$ for all $i \in \mathcal{I}$. The set of neighbors of node $\mathscr{V}_i$ is denoted by $\mathscr{N}_i = \{\mathscr{V}_j \in \mathscr{V} | (\mathscr{V}_j, \mathscr{V}_i) \in \mathscr{E}\}$.

The Laplacian matrix $\mathcal{L} = (l_{ij})_{N\times N}$ associated with graph $\mathscr{G}$ is defined as $l_{ij} = -a_{ij}$, $i \neq j$ and $l_{ii} = \sum_{k=1}^{N} a_{ik}$. A directed path from node $\mathscr{V}_{i_1}$ to node $\mathscr{V}_{i_s}$ is a sequence of different nodes $\{\mathscr{V}_{i_1}, \cdots, \mathscr{V}_{i_s}\}$ where $(\mathscr{V}_{i_j}, \mathscr{V}_{i_{j+1}}) \in \mathscr{E}$, $j = 1, \cdots, s-1$. A digraph has a directed spanning tree if there exists at least one node, called the root, having a directed path to all of the other nodes. The following lemma presents a basic property of a graph with directed spanning trees, which is related to its Laplacian matrix.

Lemma 1. (Li and Wang, 2013) *If the interaction graph $\mathscr{G}$ contains at least one directed spanning tree, then its corresponding Laplacian matrix $\mathcal{L}$ is positive definite.*