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Neural network based adaptive dynamic surface control for cooperative path following of marine surface vehicles via state and output feedback ☆

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ABSTRACT

This paper addresses the problem of steering a group of marine surface vehicles along given spatial paths, while holding a desired formation pattern subject to dynamical uncertainty and ocean disturbances induced by unknown wind, waves and ocean currents. The control design is categorized into two envelopes. One is to steer individual marine surface vehicle to track a given spatial path. The other is to synchronize the speed of each vehicle along its path and path variables under the constraints of an underlying communication network in order to holding a desired formation pattern. The key features of the developed controllers are that, first, the neural network adaptive technique allows one to handle the dynamical uncertainty and ocean disturbances, without the need for explicit knowledge of the model; second, the proposed dynamic surface control technique simplifies the controller design by introducing the first-order filters and avoids the calculation of derivatives of virtual control signals. Further, this result is extended to the output feedback case, where a high-gain observer based cooperative path following controller is developed without measuring the velocity of each vehicle. Under the proposed controllers, all signals in the closed-loop system are guaranteed to be uniformly ultimately bounded for both state and output feedback cases. Simulation results validate the performance and robustness improvement of the proposed strategy.

1. Introduction

During the past few years, there has been a growing interest in the development of multiple vehicles for a number of scientific and commercial mission scenarios. Successful applications can be found in diverse areas, which include the use of unmanned aerial vehicles for fire detection in forests, autonomous underwater vehicles for seabed surveying and environmental monitoring, marine surface vehicles for data acquisition at sea or to serve as mobile baseline systems for target positioning, and so on [1–5]. In order to achieve cooperative control of multiple vehicles, several methods have been proposed, ranging from cooperative target tracking [6], cooperative trajectory tracking [7,8], to cooperative path following [9–11]. In particular, the objective of *cooperative path following* is to steer a group of vehicles along predefined paths while keeping a desired spatial formation.

Recently, there has been much research activity focusing on the cooperative path following problem of marine surface vehicles. Different approaches to this problem have been reported in the literature. For instance, in [9], a passivity based approach for cooperative path following is developed. A major advantage of this approach is that it allows for a designer to construct filters that preserve the passivity properties of the closed-loop system and this additional flexibility is capable of improving the system performance and robustness. In [12], the problem of path following and formation control for a group of marine surface vessels in the presence of unknown ocean currents is solved based on an adaptive control technique. The controller derived implicitly compensates for the effect of the ocean currents without the need for direct measurements of its velocity. In [13], a cascade system based method for cooperative path following is developed. The problem of temporary communication losses is solved by putting together the path following and coordination strategies as a cascade system form. In [14], a curve extension method is developed to stabilize multiple fully actuated surface vessels moving around convex loops in a relative attitude pattern. To avoid the assumption of nonzero speed, a potential function is introduced to

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avoid collisions between vehicles. In spite of a significant progress in the area, however, much work remains to be done to develop strategies capable of yielding robust performance of a fleet of vehicles in the presence of uncertain nonlinear dynamics and environment disturbance for the problem of cooperative path following. Since neural network (NN) has an inherent ability of learning nonlinear dynamics, it is attractive to apply them to the controller design [15–23,34,35]. In the literature, neural network based cooperative control of multi-agent/robot systems can be found in [24–29]. However, such a technique has not been explored for cooperative path following problem of marine surface vehicles.

It is worthwhile to mention that the cooperative path following controllers developed in [2,9,11,13,14,20] are designed based on a backstepping technique [30–33,36–39]. A major drawback in the traditional backstepping design is the problem of computational complexity, which is caused by the repeated differentiations of virtual controls. In [40], a dynamic surface control (DSC) technique is proposed to eliminate this problem by introducing a first-order filtering of the synthetic input. In [16], the neural network based DSC approach is proposed for adaptive tracking control of strict-feedback systems with arbitrary uncertain nonlinearities. In [24], the DSC technique is employed to solve the leader–follower formation control problem of autonomous surface vehicles with uncertain local dynamics and uncertain leader dynamics, which leads to a much simpler controller than the backstepping based design. In [26], a distributed DSC approach is proposed for consensus tracking of multi-agent systems with unknown nonlinearities under a directed graph topology, the simple local controllers can be designed despite the order of the followers and the complexity of communication links increase. In [41], a DSC based robust formation controller for electrically driven non-holonomic mobile robots is presented to achieve desired formation tracking and collision avoidance with static and moving obstacles. Although the DSC technique has been explored for many kinds of cooperative control of multi-agent/robot systems [24–26,41,42], it is still not employed for the problem of cooperative path following of marine surface vehicles.

On the other hand, most of the cooperative path following algorithms are based on the full state measurement [4,10,12–14,20,21]. For full state feedback control, the measurements of position and velocity are required. However, some state variables may not be available in practice due to technical reasons or saving of implementing cost. In order to eliminate the need for measurement of state variables but maintain high control accuracy, one option is to use an observer [43–46]. In [47], the proposed observer features the estimation of both the low-frequency position and the velocity from noisy position measurements, and the number of tuning parameters is reduced to a minimum by using passivity theory. In [48], the proposed controllers are designed by backstepping and cascade system theory. The sway and yaw velocities are estimated by a nonlinear passive observer. In [49], an observer–controller scheme is proposed to track a trajectory in real-time using the position measurements of the ship. Furthermore, a gain tuning procedure for the observer–controller scheme is developed. Despite these efforts, there are still no results on output feedback based cooperative path following of marine surface vehicles, especially with the case the vehicle dynamics are totally unknown.

Motivated by the above observations, this paper considers the cooperative path following problem of multiple marine surface vehicles subject to dynamical uncertainty and ocean disturbances induced by unknown wind, waves and ocean currents. The control design to this problem unfolds into two basic aspects. First, in order to force each marine surface vehicle to follow a predefined path, an NN adaptive path following controller is designed based on the DSC technique. Second, with the analytic tool of graph theory, the along-path speed and path variables are synchronized to each vehicle owing to the proposed decentralized synchronization control law. Then, an extension to the output feedback case is further studied. A high-gain observer based cooperative path following scheme is developed without measuring the velocities of the vehicles. Based on the Lyapunov analysis, it is proved that with the developed algorithms, all signals in the closed-loop system are uniformly ultimately bounded (UUB). The contributions of this paper are summarized as follows. (i) Compared with [2,9,11,13,14,20], the NN based DSC technique is employed to solve the cooperative path following problem of marine surface vehicles with dynamical uncertainty and ocean disturbances induced by unknown wind, waves and ocean currents, which leads to a much simpler controller than the traditional backstepping based design. (ii) In contrast to the existing works of cooperative path following problem [4,10,12–14,20,21], the output feedback control with the NN based DSC technique is developed in this paper. Moreover, compared with our previous works of cooperative control for marine surface vehicles [19,24,25], the assumption of measurable velocities is relaxed by the observer based control.

This paper is organized as follows: Section 2 introduces some preliminaries and gives the problem formulation. Section 3 presents the state feedback controller design and stability analysis. Section 4 extends the state feedback case to the output feedback case. Section 5 provides the simulation results to illustrate the proposed controllers. Section 6 concludes this article.

2. Preliminaries and problem formulation

2.1. Notation

The notation used in this paper is quite standard. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space. $\lambda_{\min}(\cdot)$, $\lambda_2(\cdot)$ and $\lambda_{\max}(\cdot)$ denote the smallest, the second smallest, and the biggest eigenvalue of a matrix, respectively. $\|\cdot\|$, $\|\cdot\|_F$, and $\mathrm{tr}(\cdot)$ represent the Euclidean norm, the Frobenius norm, and the trace of a matrix, respectively. $\mathrm{diag}[b_1,\dots,b_n]$ represents a diagonal matrix with scalars $b_1,\dots,b_n$ on the diagonal. $\mathbf{1}_n \in \mathbb{R}^n$ denotes a column vector with all entries equal to one.

2.2. Graph theory

An undirected graph $\mathcal{G}=\mathcal{G}(\mathcal{V},\mathcal{E})$ consists of a finite set $\mathcal{V}=\{1,2,\dots,n\}$ of n vertices and a finite set $\mathcal{E}$ of m pairs of vertices $\{i,j\}\in\mathcal{E}$ named edges. If $\{i,j\}$ belongs to $\mathcal{E}$, then i and j are said to be adjacent. A *path* from i to j is a sequence of distinct vertices called adjacent. If there is a path between any two vertices, then the graph $\mathcal{G}$ is said to be *connected*. The adjacency matrix of the graph $\mathcal{G}$, denoted by $\mathcal{A}=[a_{ij}]\in\mathbb{R}^{n\times n}$, is a square matrix with rows and columns indexed by the vertices, such that a_{ij} equals one if $\{j,i\}\in\mathcal{E}$ and zero otherwise. The degree matrix $\mathcal{D}=[d_{ij}]\in\mathbb{R}^{n\times n}$ of the graph $\mathcal{G}$ is a diagonal matrix where d_{ij} equals to the number of adjacent vertices of vertex i. The Laplacian associated with the graph $\mathcal{G}$ is defined as $L=\mathcal{D}-\mathcal{A}$. If the graph $\mathcal{G}$ is connected, then zero is an eigenvalue of L and all nonzero eigenvalues are positive. This implies that for a connected undirected graph, there exists a matrix $G\in\mathbb{R}^{n\times(n-1)}$ such that $L=GG^T$, where rank $G=n-1$. If each vehicle can be represented by a vertex, then the communication relationship between any two vehicles can be described by an edge between the corresponding vertices.

Lemma 1. *If $\mathcal{G}$ is a connected undirected graph, then there exists a positive definite matrix P such that $\theta^T L\theta = s^T Ps$, where $\theta=[\theta_1,\dots,\theta_n]^T\in\mathbb{R}^n$, $s=[s_1,\dots,s_n]^T\in\mathbb{R}^n$, $s_i=\sum_{i=1}^n a_{ij}(\theta_i-\theta_j)$.*

Proof. The proof can be found in [27], and thus omitted here for brevity. □