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Coordinated path following of multiple underacutated marine surface vehicles along one curve

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ABSTRACT

This paper investigates the coordinated path following problem for a fleet of underactuated marine surface vehicles (MSVs) along one curve. The dedicated control design is divided into two tasks. One is to steer individual underactuated MSV to track the given spatial path, and the other is to force the vehicles dispersed on a parameterized path subject to the constraints of a communication network. Specifically, a robust individual path following controller is developed based on a line-of-sight (LOS) guidance law and a reduced-order extended state observer (ESO). The vehicle sideslip angle due to environmental disturbances can be exactly identified. Then, the vehicle coordination is achieved by a path variable containment approach, under which the path variables are evenly dispersed between two virtual leaders. Another reduced-order ESO is developed to identify the composite disturbance related to the speed of virtual leaders and neighboring vehicles. The proposed coordination design is distributed since the reference speed does not need to be known by all vehicles as *a priori*. The input-to-state stability of the closed-loop network system is established via cascade theory. Simulation results demonstrate the effectiveness of the proposed design method.

1. Introduction

During the past few years, coordinated control of multi-vehicle systems has received significant attention from various research communities [1–3]. This is partially due to its wide applications in diverse fields, such as aircraft and spacecraft formation flying [1], coordinated control of mobile robots [2,3], and formation control of multiple surface and underwater vehicles [4–6]. Topics related to this line of research include coordinated target tracking [7,8], coordinated trajectory tracking [9,10], and coordinated path following [11,12]. In particular, the objective of *coordinated path following* is to steer a group of vehicles to follow pre-specified spatial paths while keeping a desired formation pattern.

Coordinated path following of marine vehicles has been studied by many researchers. In [11], a consensus-based coordination method is proposed for a group of fully actuated surface vessels to follow a set of convex and closed orbits with a time-invariant reference orbital velocity. In [12], a neural adaptive path following controller is proposed to steer a group of MSVs with dynamical uncertainty and ocean disturbances. In [13], a path following controller is developed to force a group of underactuated MSVs to follow a set of paths where the path variables are synchronized. In [14], a nonlinear path following controller is designed to drive two underactuated autonomous underwater vehicles (AUVs) along parallel paths in three-dimensional space, where one vehicle acts as a leader and the other as a follower. In [15], a synchronized path following control method for multiple homogenous underactuated AUVs is proposed where a helmsman behavior is injected into the individual path following control. In [16], a straight line path following problem of underactuated MSVs under influence of constant ocean currents is considered. In [17], a combination of Lyapunov direct method, backstepping, and concepts from graph theory is employed to develop the coordinated path following controller under time-varying communication delays. Other representative works on coordinated path following of autonomous vehicles can be found in [1–3]. It is worthwhile to mention that the aforementioned studies [1–3,11–17] focus on the coordinated path following of multiple vehicles on multiple paths, i.e., each vehicle should be assigned one parameterized path to follow. However, in some practical applications, multiple vehicles have to track the same path to avoid obstacles and dangerous areas, or to reduce the workload of planning multiple paths. Moreover, as observed in nature, birds would align one line to save energy. These motivate us to study a different formation scenario to steer a fleet of MSVs along one spatial path, which has not been reported before.

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Coordinated path following of multiple MSVs poses significant theoretical challenges. This is partially due to the fact that, on one hand, most marine vehicles do not have actuators in their sway direction, and are underactuated. This is by far the most common configurations. Coordinated path following of underactuated marine vehicles has been reported in [11–17]. One limitation of these studies is that the sideslip angle, which represents the angle between vehicle's moving orientation and the vehicle's heading, is ignored or assumed to be known. However, the value of sideslip angle is usually not available due to technical reasons or saving the implementing cost [18,19]. Although the sideslip angle is small, it may degrade the path following performance at large. On the other hand, owing to the limited sensing ability of sensors and communication constraints of the network, coordinated control of multiple vehicles with minimized communication is of special interest in practical implementations. Decentralized coordinated control for multiple marine vehicles has been studies in [11–17], and the reference speed of path variables is assumed to be known by each vehicle as a priori. Obviously, it will increase the communication burden to convey the reference speed to each vehicle, especially when a large number of vehicles are involved.

Unlike the coordinative path following design over multiple parameterized paths [1–3,11–17], this paper considers coordinated path following of multiple underacutated MSVs along one parameterized curve. The solution to this problem contains two basic subproblems. The first one is to make each underactuated vehicle follow a desired path in the presence of environmental disturbances induced by wind, waves, and ocean currents. The second one is to coordinate the motion of these vehicles such that the path variables can be evenly dispersed between two virtual leaders. An individual path following controller is designed by integrating an LOS guidance method and a reduced-order ESO. The vehicle sideslip angle due to environmental disturbances can be exactly identified. Next, a path variable containment design approach is developed at the coordination stage. An reduced-order ESO is further developed to allow each MSV to learn the speed information of virtual leaders and neighboring vehicles. The proposed coordinated path following controller is fully dynamics-independent, which can be used by various vehicles with different dynamics. The stability of the closed-loop system is established via input-to-state stability and cascade theory. Simulation results are given to verify the effectiveness of the new coordination method.

The main features of the proposed coordinated path following design are summarized as follows.

- This paper is the first trial to address the coordinated path following problem of multiple underactuated MSVs along one curve. In contrast to the existing works [1–3,11–17] where a reference path should be assigned to each vehicle, the proposed coordination method aims to force the vehicles to follow the same parameterized path. Therefore, the presented coordinated controller is suitable to accomplish some special tasks, for example, steering a group of vehicles along a spatial path to avoid obstacles and dangerous areas. At the same time, only one parameterized path is used here, and thus reduce the workload of path planning.
- Compared with the existing coordinated path following controllers developed in [13–17] where the sideslip is ignored or assumed to be known, the proposed controller is able to identify the sideslip angle timely and exactly. Although the integral LOS guidance method has been proposed to compensate the effect of the sideslip angle [18,19], they can only deal with constant sideslip angle. By contrast, the time-varying sideslip angle can be compensated by using the proposed reduced-order ESO.
- For the first time, a path variable containment design approach is proposed to fulfill the vehicle coordination, and thus the path variables are evenly dispersed between two virtual leaders. The amount of information exchanged between the vehicles is minimized to one single path variable. Furthermore, in the existing path following design [11–17], the reference speed of the path variable is assumed to be known by each vehicle. By contrast, the proposed coordination method is distributed lies in the fact the reference speed does not require to be known by all vehicles. Each MSV is able to learn the speed information of virtual leaders and neighboring vehicles by the reduced-order ESO.

This paper is organized as follows. Section 2 presents some preliminaries. Section 3 gives the problem formulation. Section 4 offers the solution to the individual path following problem. Section 5 presents the coordination design for multiple vehicles. Section 6 provides simulation results for illustrations. Section 7 concludes this paper.

2. Preliminaries

2.1. Notation

Throughout this paper, $(\cdot)^T$ and $(\cdot)^{-1}$ denote the transpose and inverse of a matrix $(\cdot)$, respectively. $\mathbb{R}^n$ denotes the n-dimensional Euclidean Space. $||\cdot||$ represents the Euclidean norm. diag{ $\Lambda_1,\dots,\Lambda_N\}$ represents a block-diagonal matrix with matrixes $\Lambda_i, i=1,\dots,N$, on its diagonal. $f_2 \circ f_1$ is the composition of the functions f_1 and f_2.

2.2. Graph theory

Some graph concepts are introduced as below. A graph $\mathcal{G}=\{\mathcal{V},\mathcal{E}\}$ consists of a node set $\mathcal{V}=\{n_1,\dots,n_N\}$ and an edge set $\mathcal{E}=\{(n_i,n_j)\in\mathcal{E}\times\mathcal{E}\}$. The element (n_i,n_j) describes the communication from node i to node j. The adjacency matrix $\mathcal{A}=[a_{ij}]\in\mathbb{R}^{N\times N}$ associated with the graph $\mathcal{G}$ is defined as $a_{ij}=1$, if $(n_j,n_i)\in\mathcal{E}$; and $a_{ij}=0$, otherwise. In addition, self connections are not allowed, i.e., $a_{ii}=0$. The Laplacian matrix $\mathcal{L}$ associated with the graph $\mathcal{G}$ is defined as $\mathcal{L}=\mathcal{D}-\mathcal{A}$ where $\mathcal{D}=\text{diag}\{d_1,\dots,d_N\}$ with $d_i=\sum_{j=1}^N a_{ij}, i=1,\dots,N$.

2.3. Input-to-state stability and cascade stability

Some definitions and lemmas are used in the coordinated path following design and analysis.

Definition 1 (*Sontag and Wang [20]*). The system

$$\dot{x}=f(t,x,u), \tag{1}$$

where $f:\mathbb{R}\times\mathbb{R}^n\times\mathbb{R}^m\to\mathbb{R}^n$ is continuously differentiable, is said to be input-to-state stable (ISS), if there exist class $\mathcal{KL}$ function σ and class $\mathcal{K}$ function $\overline{\kappa}$, such that for any bounded input u and any initial condition $x(0)$, it holds that

$$\|x(t)\|\le\sigma(\|x(0)\|,t)+\overline{\kappa}(\|u\|), \tag{2}$$

for all $t\ge 0$.

The following lemma establishes a connection between the existence of a Lyapunov-like function and input-to-state stability.

Lemma 1 (*Sontag and Wang [20], Krstić et al. [21]*). *Suppose that for the system (1), there exists a smooth function $V:\mathbb{R}^n\to\mathbb{R}^+$ such that for all $x\in\mathbb{R}^n$ and $u\in\mathbb{R}^m$,*

$$\kappa_1(\|x\|)\le V(t,x)\le\kappa_2(\|x\|), \tag{3}$$