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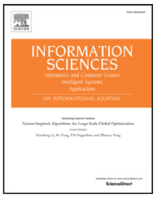

Incremental predictive control-based output consensus of networked unmanned surface vehicle formation systems

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ABSTRACT

This paper is concerned with the output consensus problem of networked unmanned surface vehicle (USV) formation systems under a leader-follower structure. First, a 3-degrees-of-freedom motion model is established for USV systems subject to disturbances induced by wind and waves. Second, based on the motion model, both an incremental state observer and an incremental predictive controller are constructed to investigate the effects of network-induced delays and packet dropouts on the systems under study. Third, a novel incremental predictive control scheme is developed to ensure that the outputs of all USVs in the formation reach consensus asymptotically. Finally, an illustrative example is given to verify the effectiveness of the proposed incremental predictive control scheme for networked USV formation systems.

1. Introduction

During the past two decades, formation control of multi-vehicle systems has attracted growing attention [11] due to that it aims at achieving and maintaining a desired geometric structure or pattern of multiple vehicles [18,21,46]. As a special case of formation control, consensus control can enable vehicles' states or outputs to approach consistency. Thus, consensus control has founded more and more applications in areas such as smart grid, sensor networks, and distributed parameter estimation.

It is true that unmanned surface vehicles (USVs) play a crucial role in a wide range of offshore activities [43], such as environmental monitoring, exploration, marine survey operations, and so on. Up until now, a number of notable results on USVs have been reported in the literature. For example, the navigation and trajectory tracking for a USV is studied in [19]; An autopilot design method for a USV is proposed in [26]; The path following control for a USV is considered in [28,29]; Both problems of rudder oscillation reduction and heading control are dealt with for a USV [32], where a stabilization criterion is derived to reduce the oscillation of the rudder angle and ensure the heading angle tracking performance. A common feature of the results aforementioned is that only a single USV system is involved. However, when executing several tasks, such as surveillance and information sharing, water surface multi-objective capturing and transportation, the mutual cooperation of a group of USVs is a prerequisite. This indicates that the states or outputs of USVs are required to be disseminated among USVs so as to reach consensus on a common value of interest. The consensus control problem has

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attracted intensive attention for various forms of multi-agent systems, such as general linear dynamics [9,10], autonomous underwater vehicles (AUVs) [4,16], unmanned aerial vehicles (UAVs) [1,17,27], and robots [3,15,20]. Nevertheless, to the best of the authors' knowledge, *there are few results available in the literature concerning consensus of USV formation systems, which gives rise to the first motivation of the current work.*

With the rapid development of communication technologies, network-based multi-agent systems have been attractive, in which agents communicate with each other through a communication network [38,40,41]. The introduction of communication networks into multi-agent systems does bring many advantages [42,43], such as reduced volume of wiring, low cost of installation and maintenance, increased system flexibility and easy reconfigurability [12,39,45]. However, it may also incur some network-induced constraints, such as packet disordering [31,33,34], network-induced delays [2,13,24,30,37], packet dropouts [6,35], quantization [5], random network topologies [10,36], event-triggering [23,25], and finite bandwidth and limited computation resources [14,22,44]. Thus, recent attention has been paid to consensus control of networked multi-agent systems under various network-induced constraints. To mention a few, the distributed observer-based consensus scheme is proposed in [2]. A new communication framework is introduced [5], in which a quantization scheme and an event-triggering strategy are considered simultaneously. A class of general second-order multi-agent systems subject to network-induced delays are considered in [13]. By coupling intra-subgroup and extra-subgroup information, a distributed event-driven controller is designed [14] to reduce frequent occupancy of limited bandwidth. In directed networks, the average consensus problem is addressed for multi-agent systems with uncertain time-varying delays [30]. Dynamic interaction edges are concerned with for a class of linear multi-agent network systems [36]. The consensus of second-order multi-agent systems with Markovian characterisation is studied in [37]. Global bounded consensus is investigated for network-based nonlinear systems with nonidentical node dynamics and network-induced delays [45]. The l_1-gain performance analysis and positive filter design for a positive discrete-time Markov jump linear system is discussed in [47]. However, for USV formation systems in ocean environments, it is significant to establish a dynamic model by taking network-induced delays and packet dropouts into consideration so that an effective controller design scheme can be developed. To the best of our knowledge, little investigation has been made on this issue, which is the second motivation of the current work.

In this paper, the problem of network-based output consensus is addressed for USV formation systems. The main contributions are twofold:

- With a leader-follower structure, *a unified discrete-time network-based formation model is established for USV systems by taking external disturbance, network-induced delays and packet dropouts into account*. Based on this model, consensus control is studied for the related USV systems. It is shown that the proposed consensus control scheme is applicable even if some of the followers or only one follower can receive information from the leader; and
- *An improved incremental predictive control scheme is presented to compensate the negative influences of network-induced delays and packet dropouts. As a result, the USV formation systems can reach output consensus asymptotically*.

The remainder of this paper is organized as follows. Some preliminaries are given in Section 2; A discrete-time motion model is established in Section 3, where a novel incremental predictive control scheme is introduced; Section 4 presents the error system construction and stability results; Simulation is made in Section 5, and conclusions are drawn in Section 6.

Notations: The symbol $\mathbb{R}^{m\times n}$ denotes the set of all $m\times n$ real matrices; I and 0 denote the identity matrix and zero matrix, respectively. Matrices, if not clearly stated, are assumed to have appropriate dimensions. For matrices $Z=(z_{op})\in\mathbb{R}^{o\times p}$ and $H=(h_{qr})\in\mathbb{R}^{q\times r}$, the Kronecker product $\otimes$ of matrices Z and H is defined as

$$Z\otimes H=\begin{bmatrix} z_{11}H & \cdots & z_{1p}H\\ \vdots & \ddots & \vdots\\ z_{o1}H & \cdots & z_{op}H\end{bmatrix}$$

2. Preliminaries

2.1. The individual USV motion model

The dynamics of a USV in 6 degrees of freedom (DOF) include surge, sway, yaw, roll, heave, and pitch. In this paper, we focus on the motions in surge, sway, and yaw. The 3-DOF (surge-sway-yaw) motion model [7,8] takes the following form

$$M\dot{\nu}+D\nu+G\eta=\tau+\omega \tag{1}$$

where $\nu=[u,\ v,\ r]^T$ and $\eta=[\bar{x},\ y,\ \psi]^T$ represent states of the USV with u, v, r, $\bar{x}$, y, and ψ denoting the surge velocity, the sway velocity, the yaw velocity, the position in X axis, the position in Y axis, and the heading angle, respectively (see Fig. 1, where x_b, y_b, and z_b denote the body-fixed reference frame; X, Y, and Z denote the North–East–Down coordinate system); τ denotes the control vector; ω denotes the external disturbance; M, D, and G are described as

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