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Short communication

Finite-time extended state observer-based distributed formation control for marine surface vehicles with input saturation and disturbances

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ABSTRACT

This paper investigates the finite-time extended state observer-based distributed formation control for marine surface vehicles with input saturation and external disturbances. Initially, a novel finite-time extended state observer is proposed to estimate the unavailable velocity measurements and external disturbances simultaneously. No longer regarding the time derivative of external disturbances as zero, the proposed finite-time extended state observer is designed by transforming the disturbances as an extended state of the system to be estimated. Then, based on the estimated values, a distributed finite-time formation controller is designed for a group of marine surface vehicles to track a time-varying virtual leader. The position state of virtual leader only can be accessed by a subset of the group members. Furthermore, a saturation function is incorporated into the controller to solve the input saturation problem. Finally, a rigorous Proof demonstrates that the finite-time stability of the proposed extended state observer and formation controller can be guaranteed by using homogeneous method and Lyapunov theory. Numerical simulations illustrate the effectiveness of the proposed formation control scheme.

1. Introduction

In recent years, with the rapid development of ocean engineering, the motion control of marine surface vehicle (MSV) has attracted significant attention (Skjetne et al., 2002; Dong and Farrell, 2008; Do, 2010; Yi et al., 2016; Du et al., 2016), especially the formation control of multiple MSVs. This is because of the fact that a group of networked vehicles can perform many complicated tasks more effectively than a single vehicle, such as sea investigation, exploration, maritime rescue, and surveillance (Børhaug et al., 2011). Among the various control strategies proposed to achieve the desired formation in the literature (Balch and Arkin, 1998; Edwards et al., 2004; Fua et al., 2007; Ren and Sorensen, 2008), the leader-follower scheme is preferred for formation control of MSVs because of its reliability and simplicity (Breivik et al., 2008; Cui et al., 2010). Based on this, some nonlinear control techniques by full state-feedback for MSVs have been proposed to obtain desirable performance and stability, e.g., just to name a few, backstepping control (Ghommam and Mnif, 2009), sliding-mode control (Fahimi, 2007), passivity control (Wang et al., 2012), adaptive dynamic surface control (Peng et al., 2013).

Note that the measurements of velocity cannot always be obtained in practice, sometimes in order to reduce weight and cost, or even because of sensor failures. Therefore, the full state-feedback formation control schemes cannot be directly applied to the MSVs without velocity measurements. In addition, most of the existing formation control schemes assume that the actuator of each vehicle is able to generate arbitrary level of control signals. In practice, because of the actuators' physical limitations, the generated control signals may compel the actuators exceeding their capabilities. This, in turn, may lead to deterioration of control performance, especially in the transient response, or even system instability. Meanwhile, another fact cannot be ignored, that is, the dynamics of MSV in 3-degree of freedom (DOF) (surge, sway, and yaw) are strongly coupled and the motion of MSV inevitably suffers from environmental disturbances induced by winds, waves, and ocean currents.

Recently, these problems mentioned above have been discussed separately for distributed control of MSVs (Wang et al., 2014a; Zheng and Sun, 2016; Wang et al., 2014b; Liu et al., 2015; Peng et al., 2016). In Wang et al. (2014a) and Zheng and Sun (2016), the cooperative path following problem for multiple MSVs subject to input saturation and disturbances has been considered, where the velocity measurements of the vehicles are assumed to be available. Wang et al. (2014b) has proposed a high-gain observer-based formation control scheme for MSVs

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without measuring the velocity of each vehicle. In Liu et al. (2015), the cooperative dynamic positioning of MSVs with dynamical uncertainty and disturbances has been considered. Then, in Peng et al. (2016), a modular design approach-based cooperative control scheme has been presented for the dynamic positioning of multiple offshore vessels with ocean disturbances, and has been extended to the output feedback case. However, in Wang et al. (2014b), Liu et al. (2015) and Peng et al. (2016), the input saturation problem is not considered. In Shojaei (2015) and Shojaei (2016), the observer-based neural adaptive formation control has been addressed respectively for under-actuated and fully actuated MSVs with limited torque under environmental disturbances.

Based on the above discussions, it should be pointed out that all the aforementioned formation controllers can only obtain asymptotic convergence at best, which implies that exact convergence cannot be guaranteed in finite time. In contrast, finite-time controllers enable the system errors converge within finite time, and thus obtain faster convergence speed and better disturbance rejection properties (Zou, 2014; Hu et al., 2014; Hu and Zhang, 2015). In Li et al. (2015), the finite-time output feedback trajectory tracking control problem for autonomous underwater vehicle has been investigated. In Yan et al. (2015), the globally finite-time tracking control strategy for under-actuated unmanned underwater vehicles (UUVs) with model parameter perturbation has been addressed. In Wang et al. (2016), the finite-time tracking control scheme for a single MSV with unknown time-varying disturbances has been studied. Liu et al. (2017) have proposed the nonlinear disturbance observer-based finite-time control law for underwater vehicle with uncertainties and external disturbances. However, how to solve all the aforementioned problems, i.e., input saturation, unavailable velocity measurements, external disturbances simultaneously for MSVs to obtain the desired formation in finite time is still an open issue.

The main contribution of this paper is to propose the finite-time extended state observer-based distributed formation control scheme for fully actuated MSVs subject to input saturation and time-varying disturbances. More specifically, the extended state observer (ESO), which was first proposed in Han (1995), has the capability of state observation and can provide real-time estimation of system uncertainties and disturbances, does not dependent on accurate system model. Although a variety of ESO-based controllers have been developed and successfully verified by many applications (Talole et al., 2010; Yao et al., 2014; Cui et al., 2016), the ESO can only achieve asymptotic convergence. In contrast, the proposed finite-time extended state observer (FTESO) not only can estimate the velocity measurements and time-varying disturbances simultaneously, but also can achieve bounded estimated errors in finite time. In addition, the extension of the finite-time control algorithms from the single one to the multiple vehicles is nontrivial, especially that only a subset of followers can obtain the state information of the virtual leader. Under such a circumstance, a distributed finite-time formation controller (FTFC) is constructed based on the estimated values, and a saturation function is incorporated into the controller such that the actual control signals can be constrained. By using homogeneous method and Lyapunov function, all signals of the closed-loop system can be guaranteed to be bounded in finite time.

This paper is organized as follows. Several preliminaries and problem formulation are presented in section 2. Section 3 addresses the FTESO and distributed FTFC for MSVs with theoretical analysis on finite time convergence, and section 4 demonstrates the effectiveness of the proposed control scheme by presenting numerical simulation results. Conclusions are provided in section 5.

2. Preliminaries and problem formulation

2.1. Definitions and lemmas

Definition 1. (Nakamura et al., 2004). Given a vector $\boldsymbol{x} = [x_1, x_2, \ldots, x_n]^{\mathrm{T}} \in \mathbb{R}^n$, a continuous function $f(\boldsymbol{x}) : \mathbb{R}^n \to \mathbb{R}$ is homogeneous of degree k with respect to the dilation $(\lambda^{r_1}x_1, \lambda^{r_2}x_2, \ldots, \lambda^{r_n}x_n)$ if $f(\lambda^{r_1}x_1, \lambda^{r_2}x_2, \ldots, \lambda^{r_n}x_n) = \lambda^k f(\boldsymbol{x})$, $\forall \lambda > 0$, where $k > -\min\{r_i\}$, $i = 1, 2, \ldots, n$. A differential system $\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x})$ (or a vector field f), with continuous $\boldsymbol{f}(\boldsymbol{x}) : \mathbb{R}^n \to \mathbb{R}^n$, is homogeneous of degree k with respect to the dilation $(\lambda^{r_1}x_1, \lambda^{r_2}x_2, \ldots, \lambda^{r_n}x_n)$ if $\boldsymbol{f}(\lambda^{r_1}x_1, \lambda^{r_2}x_2, \ldots, \lambda^{r_n}x_n) = \lambda^{k+r_i}\boldsymbol{f}(\boldsymbol{x})$, $i = 1, 2, \ldots, n$, $\forall \lambda > 0$.

Definition 2. (Hong et al., 2006a). Consider the following system:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}(t)), \boldsymbol{f}(0) = 0, \boldsymbol{x} \in U \subset \mathbb{R}^n \tag{1}$$

where $f : U \to \mathbb{R}^n$ is continuous on an open neighborhood U of the origin $\boldsymbol{x} = 0$. The zero solution of (1) is (locally) finite-time stable if it is Lyapunov stable and finite-time convergent in a neighborhood $U_0 \subseteq U$ of the origin. The ¡°finite-time convergence¡± means: for any initial condition $\boldsymbol{x}(t_0) = \boldsymbol{x}_0 \in U_0$ at any given initial time t_0, if there is a settling time $T > t_0$, such that every solution $\boldsymbol{x}(t, \boldsymbol{x}_0)$ of system (1) satisfies $\boldsymbol{x}(t, \boldsymbol{x}_0) \in U_0 \backslash \{0\}$ for $t \in [t_0, T)$, $\lim_{t \to T} \boldsymbol{x}(t, \boldsymbol{x}_0) = 0$, and $\boldsymbol{x}(t, \boldsymbol{x}_0) = 0, \forall t > T$. When $U = U_0 = \mathbb{R}^n$, then the zero solution is said to be globally finite-time stable.

Lemma 1. (Yu et al., 2005) Suppose that there is a positive definite continuous Lyapunov function $V(\boldsymbol{x})$ defined on U_1, where $U_1 \subseteq U \in \mathbb{R}^n$ is a neighborhood of the origin, and

$$\dot{V}(\boldsymbol{x}) \leq -c_1 V^{\alpha}(\boldsymbol{x}) - c_2 V^{\beta}(\boldsymbol{x}), \forall \boldsymbol{x} \in U_1 \backslash \{0\} \tag{2}$$

where $c_1 > 0$, $c_2 > 0$ and $0 < \alpha < 1$, $\beta \geq 1$. Then the origin of system (1) is locally finite-time stable. The settling time satisfies

$$T \leq \frac{V^{1-\alpha}(\boldsymbol{x}(t_0))}{c_1(1-\alpha)} \overline{F}\left(1.\frac{1-\alpha}{\beta-\alpha}.1 + \frac{1-\alpha}{\beta-\alpha}. - \frac{c_2}{c_1} V^{\beta-\alpha}(\boldsymbol{x}(t_0))\right)$$

for a given initial condition $\boldsymbol{x}(t_0) \in U_1$, where $\overline{F}(\cdot)$ denotes the Gaussian hypergeometric function. For more details on the Gaussian hypergeometric function, one can refer to Abramowitz and Stegun (1965).

Lemma 2. (Zhu et al., 2011). Suppose that there exists a positive definite continuous Lyapunov function $V(\boldsymbol{x})$, scalars $\lambda > 0$, $0 < \alpha < 1$ and $0 < \vartheta < \infty$ such that

$$\dot{V}(\boldsymbol{x}) \leq -\lambda V^{\alpha}(\boldsymbol{x}) + \vartheta \tag{3}$$

Then, the solution of the system is practical finite-time stable (PFTS). The settling time satisfies $T \leq \frac{V^{1-\alpha}(\boldsymbol{x}(t_0))}{\lambda \rho_0 (1-\alpha)}$, $0 < \rho_0 < 1$.

Lemma 3. (Hardy et al., 1952). For $\forall x_i \in \mathbb{R}, i = 1, \ldots, n$, and $0 < p \leq 1$, then

$$\left(\sum_{i=1}^{n} \left|x_i\right|\right)^p \leq \sum_{i=1}^{n} \left|x_i\right|^p \leq n^{1-p}\left(\sum_{i=1}^{n} \left|x_i\right|\right)^p$$

Lemma 4. (Zou et al., 2016). For any $x_i \in \mathbb{R}$, $i = 1, 2, \ldots, n$, and a real number $p > 1$,

$$\sum_{i=1}^{n} \left|x_i\right|^p \leq \left(\sum_{i=1}^{n} \left|x_i\right|\right)^p \leq n^{p-1} \sum_{i=1}^{n} \left|x_i\right|^p$$

2.2. Graph theory

Define an undirected connected weighted graph $\mathscr{G} = \mathscr{G}(\nu, \varepsilon, \mathscr{A})$, where $\nu = \{1, 2, \ldots, n\}$ represents the set of vehicles, $\varepsilon \subseteq \nu \times \nu$ is the set of edges, $\mathscr{A} = [a_{ij}] \in \mathbb{R}^{n \times n}$ is the weighted adjacency matrix, $a_{ij} > 0$, $a_{ij} = a_{ji}$ and $a_{ii} = 0$. That is, the weighted adjacency matrix $\mathscr{A} = [a_{ij}] \in \mathbb{R}^{n \times n}$ is a