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Brief paper

Fault tolerant finite-time leader–follower formation control for autonomous surface vessels with LOS range and angle constraints[☆]

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ABSTRACT

In this work, we present a novel fault tolerant leader–follower formation control scheme for a group of underactuated autonomous surface vessels with partially known control input gain functions, where the line-of-sight (LOS) range and angle tracking errors are required to be constrained. Both parametric system uncertainties with time-varying unknown functions and nonparametric system uncertainties satisfying norm-bounded conditions are discussed. To address LOS range and angle constraints and finite time convergence, time-varying *tan*-type barrier Lyapunov functions (BLFs) are incorporated with the control scheme. For the formation control, only measurements of LOS range and angle are used for control implementation, no other information about the leader is required. We show that under the proposed control method, despite the presence of actuator faults and system uncertainties, the formation tracking errors can converge into arbitrarily small neighborhoods around zero in finite time, while the constraint requirements on the LOS range and angle will not be violated. All closed loop signals are bounded. Simulation results further demonstrate the effectiveness of the proposed method.

1. Introduction

During the past two decades, the formation control problem of multiagent systems has attracted great attention in the marine industry, where multiple surface vessels can be used for tasks like surveillance of territorial waters, rescue missions, exploration of natural resources, environmental monitoring and so on. Such tasks usually cannot be performed by a single vessel even with sophisticated equipment, since it not only has limited coverage that inevitably leads to an increase in the time to accomplish the whole mission, but also makes the performance vulnerable to any system faults. Among the various control methods proposed to achieve the desired formation, the leader–follower strategy is preferred in many applications due to its simplicity and scalability (Consolini, Morbidi, Pattrichizzo, & Tosques, 2008). Many works within this frame can be seen in the literature for maritime applications (Breivik, Hovstein, & Fossen, 2008; Cui, Ge, How, & Choo, 2010; Skjetne, Moi, & Fossen, 2002).

Currently, there are several challenging issues associated with the leader–follower formation control problems of autonomous surface vessels, two of which will be addressed in this work. The first challenging issue is about the system constraints. For all practical engineering systems, we always need the system output to remain in some compact sets due to system specifications or safety requirement. Any violation of such requirements may lead to unsatisfactory transient performance, or result in system failure and safety hazard. In the context of leader–follower formation control for autonomous surface vessels, we have applications in which the line-of-sight (LOS) range and angle between the leader and the follower have to be constrained within a certain range. If the LOS range is too small compared with the desired formation requirement, it may result in collision between the leader and the follower. On the other hand, if the LOS range is too large, the follower may lose contact with the leader, as the commonly used measurement and communication devices can only work effectively within a certain range. In search and rescue missions, for example, undesired LOS range and angle between the leader and the follower may result in leaving some critical areas unsearched. It is worth noticing that this problem about LOS range and angle constraints is different from the collision avoidance problem, as we not only wish to prevent the leader and the follower from getting too close to each other, but also from separating too far away, and the LOS angle constraints should not be violated. Despite the practical importance, this problem has

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not yet been considered in the formation control of autonomous surface vehicles. Similar yet different problems, sometimes framed as constrained formation, have been discussed in works on other types of systems. In Zhang and Hu (2007), the authors study the constrained formation problem where two agents forming an edge in the network should keep the distance at a prescribed value. In Bacconi, Mosca, and Casavola (2007), formation of the micro-satellite system is considered, with the formation accuracy error required to be bounded in a certain region. Angle constraints are not considered in these works. In Zhao, Lin, Peng, Chen, and Lee (2013), a distributed control law that stabilizes angle-constrained target formations with only local bearing measurements has been proposed, where circular formation is considered, and each agent has exactly two neighbors. In Egerstedt and Hu (2001), a formation constraint function has been introduced, so that the formation is given by the kernel of the formation constraint function. However, these results are not directly applicable to the leader–follower formation problem with LOS range and angle constraints for underactuated surface vessel systems.

The second challenge relates to the convergence speed of the formation tracking control system. In the literature, most of the formation control schemes for underactuated autonomous surface vessels, including those discussed in Fahimi (2007), Ghommam and Mnif (2009), Peng, Wang, and Hu (2011), Peng, Wang, Chen, Hu, and Lan (2013), and Yang and Gu (2007), can only guarantee asymptotical convergence of the formation tracking error. The convergence speed is at best exponential, which implies that the tracking errors will converge to the origin with infinite settling time (Huang, Wen, Wang, & Song, 2015). In reality, we often need the desired formation to be achieved in finite time. As a result, the problem of finite time convergence has received huge attention from the research community. In Cao, Ren, and Meng (2010), the problem of finite-time decentralized formation tracking of multiple autonomous vehicles has been studied with the introduction of decentralized sliding mode estimators. Du, Li, and Lin (2013) discusses finite-time formation control of multiple second-order agents via dynamic output feedback. Finite-time formation control problem for a group of nonholonomic mobile robots has been addressed in Ou, Du, and Li (2014). Xiao, Wang, Chen, and Gao (2009) introduces a finite-time formation control framework for multi-agent systems with a large population of members. However, besides the facts that these works do not consider constraint requirements in the formation, the control schemes presented in these works cannot be directly applied to underactuated autonomous surface vessels. How to develop an effective control scheme for the formation control problem of underactuated autonomous surface vessels, such that the constraint requirements in the formation are not violated during operation, and the desired formation can be achieved in finite time, is a challenging research topic that has not yet been properly addressed in the literature.

In this work, we present a novel adaptive fault tolerant leader–follower formation control scheme for a group of underactuated autonomous surface vessels with LOS range and angle constraints. Both parametric system uncertainties with time-varying unknown functions and nonparametric system uncertainties satisfying norm-bounded conditions are discussed. In particular, the control input gain functions are assumed to be only partially known. To address LOS range and angle constraints, time-varying *tan*-type barrier Lyapunov functions (BLFs) are incorporated in the control scheme. Command filters and auxiliary systems (Chen, Ge, & How, 2010; Chen, Ge, & Ren, 2011) are integrated with the control law so that to avoid "explosion of complexity" in calculating the stabilizing function in the backstepping process. For the formation control, only measurements of LOS range and angle are used for control implementation, no other information about the leader, such as the velocity of the leader, is required. We show that under the proposed control method, the formation tracking errors can converge into an arbitrarily small neighborhood around zero in finite time, while the constraint requirements on the LOS range and angle will not be violated. All closed loop signals are bounded. The main contributions of this work can be summarized as follows: (1) both time-varying multiplicative and additive actuator faults for autonomous surface vessels are addressed; (2) *tan*-type BLFs have been incorporated with the control scheme to meet the constraint requirements on the LOS range and angle; (3) finite-time convergence for the leader–follower formation control of underactuated autonomous surface vessels has been studied; (4) control input gain functions that are partially known are analyzed.

2. Problem formulation

A: *Vehicle dynamics*

Consider the follower vessel with the following form of mathematical model:

$$\begin{bmatrix}\dot{x}(t)\\ \dot{y}(t)\\ \dot{\psi}(t)\end{bmatrix} = \begin{bmatrix}\cos\psi(t) & -\sin\psi(t) & 0\\ \sin\psi(t) & \cos\psi(t) & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}u(t)\\ v(t)\\ r(t)\end{bmatrix},$$

$$\begin{bmatrix}\dot{u}(t)\\ \dot{v}(t)\\ \dot{r}(t)\end{bmatrix} = \begin{bmatrix}\theta_u^T(t)F_u(\eta(t)) + d_u(\eta(t),t)\\ \theta_v^T(t)F_v(\eta(t)) + d_v(\eta(t),t)\\ \theta_r^T(t)F_r(\eta(t)) + d_r(\eta(t),t)\end{bmatrix} + \begin{bmatrix}g_u(\eta(t),t) & 0\\ 0 & 0\\ 0 & g_r(\eta(t),t)\end{bmatrix}\begin{bmatrix}\tau_u^F(t)\\ \tau_r^F(t)\end{bmatrix}, \tag{1}$$

where $(x(t), y(t))$ is the coordinate of the ship, $\psi(t)$ is the yaw angle in the earth-fixed frame, $\eta(t) = [u(t), v(t), r(t)]^T$ with $u(t), v(t), r(t)$ denote the velocities in the surge, sway and yaw directions, respectively, $\theta_u(t) \in \mathscr{R}^{n_u}$, $\theta_v(t) \in \mathscr{R}^{n_v}$, $\theta_r(t) \in \mathscr{R}^{n_r}$ are unknown time-varying functions, $F_u(\cdot) \in \mathscr{R}^{n_u}$, $F_v(\cdot) \in \mathscr{R}^{n_v}$, $F_r(\cdot) \in \mathscr{R}^{n_r}$ are known smooth functions. $g_u(\cdot) \in \mathscr{R}$ and $g_r(\cdot) \in \mathscr{R}$ are control input gain functions which are not totally known, and $d_u(\cdot) \in \mathscr{R}$, $d_v(\cdot) \in \mathscr{R}$, $d_r(\cdot) \in \mathscr{R}$ are unstructured nonparametric uncertainties such as exogenous disturbances, measurement noise, etc. $\tau_u^F(t)$, $\tau_r^F(t)$ represent the surge force and the yaw moment, respectively, which are subject to actuator faults. In particular, we are considering time-varying multiplicative and additive actuator faults in this work, which can be formulated as

$$\tau_u^F(t) = \mu_u(t)\tau_u(t) + \phi_u(t), \tag{2}$$

$$\tau_r^F(t) = \mu_r(t)\tau_r(t) + \phi_r(t), \tag{3}$$

where $\tau_u(t)$, $\tau_r(t)$ are the control signals to be designed, $\mu_u(t), \mu_r(t)$ represent the multiplicative actuator faults, and $\phi_u(t), \phi_r(t)$ represent the additive actuator fault. If $\mu_u(t) = \mu_r(t) = 1$ and $\phi_u(t) = \phi_r(t) = 0$, we say that the follower ship is free from actuator faults.

Remark 1. In terms of the formulation of the vessel model, (1) can be viewed as an extension from the formulation presented in Li, Lee, Jun, and Lim (2008). The formulation of the ship kinematics presented in the works such as Do and Pan (2006), Ghommam and Mnif (2009), Peng et al. (2013, 2011) can also be converted into the form of (1). The formulation (1) improves the model discussed in Li et al. (2008) in three ways. First, both time-varying multiplicative and additive actuator faults are considered in (1). Second, as pointed out in Shi and Shen (2015), it is important to consider the control input gain functions $g_u(\cdot)$ and $g_r(\cdot)$ that are not totally known, whereas in Li et al. (2008) the control input gain functions are assumed to be fully known and constant. Third, instead of considering only constant unknown vectors $\theta_u, \theta_v, \theta_r$, we discuss time-varying unknown functions in this work.