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Research article

Leader-follower formation control of underactuated surface vehicles based on sliding mode control and parameter estimation

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ABSTRACT

This paper studies the leader-follower formation control of underactuated surface vehicles with model uncertainties and environmental disturbances. A parameter estimation and upper bound estimation based sliding mode control scheme is proposed to solve the problem of the unknown plant parameters and environmental disturbances. For each of these leader-follower formation systems, the dynamic equations of position and attitude are analyzed using coordinate transformation with the aid of the backstepping technique. All the variables are guaranteed to be uniformly ultimately bounded stable in the closed-loop system, which is proven by the distribution design Lyapunov function synthesis. The main advantages of this approach are that: first, parameter estimation based sliding mode control can enhance the robustness of the closed-loop system in presence of model uncertainties and environmental disturbances; second, a continuous function is developed to replace the signum function in the design of sliding mode scheme, which devotes to reduce the chattering of the control system. Finally, numerical simulations are given to demonstrate the effectiveness of the proposed method.

1. Introduction

During the last two decades, the formation control problem of multi-vehicle system has drawn much attention in the marine control community [1,2]. This is partially due to the increasing practical potential in military and civilian applications [3], especially with the lack of land resources, the ocean has become the focus of attention of each country. In the field of ocean exploration, automatic ocean exploration is an effective way, compared to single ship exploration, formation control will greatly improve the efficiency of exploration. In the field of ocean environment inspection, formation control can inspect more sea areas in a limited time. Due to the deep water and the extreme marine conditions, it is difficult for us to carry out ocean rescue, such as the task to search for Malaysia Airlines MH370, which disappeared in south China sea on March 8, 2014, however, formation control can be a good way to improve our search efficiency, greatly extend the search areas. Moreover, formation control also can be better used for geological sampling. The actual needs of these marine activities can adequately explain the importance of formation control. However, with the development of marine engineering, theoretical challenges arise in such research area. Recent challenges may be related to designing a controller to make a group of underactuated surface vehicles follow the desired positions and orientations in presence of model uncertainties and environmental disturbances. These features of the underactuated surface vehicles are partially different with those of fully-actuated vehicles, since no actuator is used for the control of sway motion directly [4–8]. This restriction can meet the purpose of energy saving, but it also increases the difficulty of the controller design, especially in the formation control of underactuated surface vehicles. The second type of the challenges involves the solution of unknown plant parameters and unknown environmental disturbances. To achieve above challenges, several methods have been proposed in a class of formation control of underactuated surface vehicles and consensus of multi-agent systems control, such as behvioral-based method [9], virtual structure approach [10], leader -follower method [11–13], graph theory approach [2,14,15], neural network and dynamic surface control technique [1,16]. For above methods, [11] and [12] consider the leader-follower method as a widely adopted method to the design formation control for underactuated surface vehicles, the reasons for this design, to the best of our knowledge, simplicity and reliability.

During recent years, according to the available existing works, attractive results on this area have been proposed in

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[1,11–13,17–19], which are developed by employing the neural network to solve the problem of model uncertainties and environmental disturbances, and particular attention has been given to use the dynamic surface control technique to design the control law, but it is difficult to achieve in practical engineering. Although the above-aforementioned formation strategies are useful for the leader-follower formation control of underactuated surface vehicles, many aspects are still worthy of mentioning, especially in the practical engineering. Combined with the problems in ship motion control, the kinematic and dynamic of an underactuated surface vessel are highly nonlinear and strong coupling [1,20], moreover, the environmental disturbances also let the model of such nonlinear systems uncertain, which should be taken into account in the design of the controller. In addition, since sliding mode control is effective in solving the model uncertainties and environmental disturbances in ship motion control, recent reviews for the ship motion control may be found in [21,22], however, *signum* function is applied in the design of sliding manifold, and for the feature of its discontinuousness, it brings the chattering of the closed-loop control system, which is considered in this paper.

Motivated by the above-mentioned observations, a sliding mode control for leader-follower formation control of underactuated surface vehicles via parameter estimation is proposed. To apply this method in the formation control, the main contributions of this paper are twofold.

1). A parameter estimation and upper bound estimation is developed to solve the problem of unknown plant parameters and the environment disturbances in the leader-follower formation control of underactuated surface vehicles.

2). To enhance the robustness of the control system, a continuous *PI* sliding mode term is constructed to eliminate the chattering of the closed-loop system. Comparing to [1], a continuous PI sliding mode term is not only an effective method to solve the constraints, e.g. model uncertainties, environmental disturbances, but it is easy to implement in practical engineering. Unlike [23], the proposed algorithm can consider the constraints of propeller and also enhance the system robustness.

The remainder of this paper is generally organized by four parts: In Section 2, the kinematics and kinetics of the underactuated surface vessel are derived, and the objective of leader-follower formation control is presented. In Section 3, a sliding mode control for leader-follower formation control of underactuated surface vehicles via parameter estimation is proposed. And then in Section 4, simulation results are presented to illustrate the effectiveness of the proposed algorithm. Finally, a brief conclusion is given in Section 5 Table 1.

Table 1
Notations.

$|\cdot|$ denote the norm of a scalar
$\|\cdot\|$ denote the norm of a vector
$\|\cdot\|^2 = \Sigma_{i,j}(\cdot)^2_{i,j}\cdot(\cdot)_{i,j}$ denote the element of $(\cdot)$ in row i and column j
$\tilde{(\cdot)} = (\cdot) - \hat{(\cdot)}$; $\hat{(\cdot)}$ is the estimate of $(\cdot)$; $\tilde{(\cdot)}$ is the estimation error

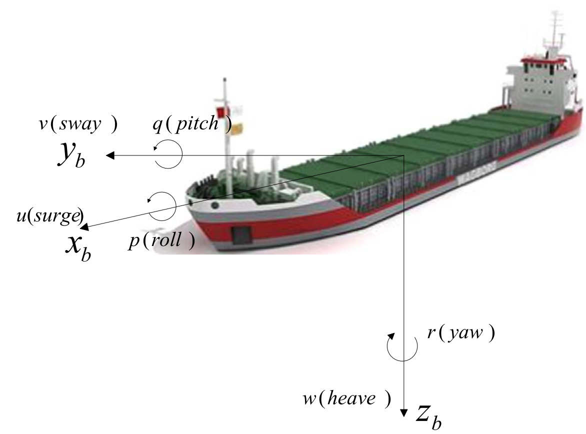

Fig. 1. Reference frames of an underactuated surface ship.

2. Problem formulation

2.1. Underactuated surface vehicle dynamics

Following the references [20,23,24], the system model (1) is employed to describe the underactuated surface vessel, including the kinematic and dynamical equations. It has with two control inputs: the force in surge degree and the control torque in the yaw [25]. The kinematic and dynamic of an underactuated surface vessel model can be written as Eq. (1) under the following Assumptions 1 – 4.

$$\begin{cases} \dot{x}_i = \cos(\psi_i)u_i - \sin(\psi_i)v_i \\ \dot{y}_i = \sin(\psi_i)u_i + \cos(\psi_i)v_i \\ \dot{\psi}_i = r_i \\ \dot{u}_i = \Theta_{i\mathbf{1}}^T f_{u_i}(\dot{\eta}_i, \eta_i) + \zeta_{i1}\tau_{ui} + \tau_{w_{i1}} \\ \dot{v}_i = \Theta_{i\mathbf{2}}^T f_{v_i}(\dot{\eta}_i, \eta_i) + \tau_{w_{i2}} \\ \dot{r}_i = \Theta_{i\mathbf{3}}^T f_{r_i}(\dot{\eta}_i, \eta_i) + \zeta_{i3}\tau_{ri} + \tau_{w_{i3}} \end{cases} \tag{1}$$

where x_i and y_i denote the surge and sway displacement coordinates of the follower underactuated surface vessel model in the earth-fixed frame and ψ_i is the yaw angle in the earth-fixed coordinate frame. (u_i, v_i, r_i) is the velocities vector in surge, sway and yaw directions, respectively. The surge force τ_{ui} and the yaw moment τ_{ri} are considered as control inputs. The known nonzero constant control coefficients can be in the form of ζ_{i1} and ζ_{i3}. $\Theta_{i\mathbf{1}} \in \Re^{n_{u_i}}$, $\Theta_{i2} \in \Re^{n_{v_i}}$ and $\Theta_{i3} \in \Re^{n_{r_i}}$ are unknown constant vectors with known dimensions n_{u_i}, n_{v_i} and n_{r_i}. $f_{u_i}(\dot{\eta}_i, \eta_i) \in \Re^{n_u}$, $f_v(\dot{\eta}, \eta) \in \Re^{n_v}$ and $f_{r_i}(\dot{\eta}_i, \eta_i) \in \Re^{n_r}$ are all known smooth vector fields, which can be defined as $f_u(\dot{\eta}, \eta) = [v_i r_i; u_i]^T$, $f_{v_i}(\dot{\eta}_i, \eta_i) = [u_i r_i; v_i]^T$ and $f_r(\dot{\eta}, \eta) = [u_i v_i; r_i]^T$. $\tau_{w_{i1}}$, $\tau_{w_{i2}}$ and $\tau_{w_{i3}}$ are the unknown environmental disturbances acting on the surge, sway and yaw axes, respectively Fig. 1.

Assumption 1. The inertia, added mass and damping matrices are diagonal.

Assumption 2. The environmental disturbances are bounded, satisfying $|\tau_{w_{i1}}| \le \tau_{w_{i1max}}$, $|\tau_{w_{i2}}| \le \tau_{w_{i2max}}$, $|\tau_{w_{i3}}| \le \tau_{w_{i3max}}$ [1,11,13,26].

Assumption 3. The desired output vector of formation $[\xi_{ijd}, \dot{\xi}_{ijd}]^T$ are all bounded.

Assumption 4. The velocity of sway motion is passive-bounded.

2.2. Leader-follower formation

In order to facilitate the statements of the formation controller,