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On decentralized adaptive full-order sliding mode control of multiple UAVs

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ABSTRACT

In this study, a novel decentralized adaptive full-order sliding mode control framework is proposed for the robust synchronized formation motion of multiple unmanned aerial vehicles (UAVs) subject to system uncertainty. First, a full-order sliding mode surface in a decentralized manner is designed to incorporate both the individual position tracking error and the synchronized formation error while the UAV group is engaged in building a certain desired geometric pattern in three dimensional space. Second, a decentralized virtual plant controller is constructed which allows the embedded low-pass filter to attain the chattering free property of the sliding mode controller. In addition, robust adaptive technique is integrated in the decentralized chattering free sliding control design in order to handle unknown bounded uncertainties, without requirements for assuming a priori knowledge of bounds on the system uncertainties as stated in conventional chattering free control methods. Subsequently, system robustness as well as stability of the decentralized full-order sliding mode control of multiple UAVs is synthesized. Numerical simulation results illustrate the effectiveness of the proposed control framework to achieve robust 3D formation flight of the multi-UAV system.

1. Introduction

Sliding mode control (SMC) has attracted significant amount of attention in control engineering fields for many years [1–4]. This is due to the fact that sliding mode control has appealing advantages of insensitivity to model uncertainties and high robustness to external disturbances, together with the simple structure for technical implementations. Thanks to these advantages, SMC has broad applications in a variety of engineering areas, from sole-control systems including underwater vehicles [5,6], robotic manipulators [7,8], spacecraft [9,10], unmanned aerial vehicles [11,12], and underactuated surface vessels [13,14], to multi-agent control systems including finite-time position consensus or containment for multiple autonomous underwater vehicles [15,16], synchronization of multiple robotic manipulators [17], attitude containment of multiple spacecraft [18], formation pattern control of underactuated surface vessels [19], and close formation flying of multiple unmanned aerial vehicles [20,21], to name just a few.

Along with sliding mode controllers, other classic control methods including fuzzy logic [5,22,23] and neural network [16,24,25], just to name a few, have been widely adopted for UAV systems with uncertainties. Neural network method requires off-line learning in advance or on-line learning to achieve weight adjustments. The main challenge in this process is to calculate the optimal weight changes for the system input and output as well as the reference trajectory for the system. Fuzzy logic requires complex fuzzy approximation or fuzzy inference based on a large number of fuzzy rules in each cycle to deal with the system uncertainties. Hence, it will cost substantial computational power for technical implementations. Compared with neural network and fuzzy logic algorithms, SMC has main advantages of insensitivity to system uncertainties, as well as easy implementations. However, classic sliding mode control suffers from a major problem in practical applications for real physical systems, that is the phenomenon of chattering [26,27]. In fact, chattering is the high-frequency oscillations in the controller resulted by the high-speed switching necessary for the attainability of a sliding manifold, yet chattering is highly undesirable since it might excite unmodeled high-frequency plant dynamics and even cause unforeseen instabilities [28]. A number of methods for attenuating or eliminating the chattering phenomenon have been proposed, such as boundary layer method [29,30], second-order or higher-order sliding modes [31,32], observer-based sliding mode control [26,33], and full-order sliding mode control [34,35]. In [29,30], a boundary layer technique is proposed which uses the saturation function instead of the signum function to introduce a boundary layer around the sliding surface,

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such that the discontinuous control caused by the signum function is approximated by the continuous control function. However, it can only guarantee the existence condition of the sliding mode outside a small boundary layer around the sliding mode manifold, such that the boundary layer function reduces the control chattering with a compromise in reduced robustness and increased steady-state error [28]. Another method to address the chattering problem is based on the second-order or higher-order sliding modes, in which integrators are added at the input side and the time derivative of the control input is taken as the new control variable [31,32]. If the discontinuous signal coincides with the highest derivative of the actual plant control, the subsequent results are continuous with a smoothness degree depending on the considered derivative order. In this way, chattering reduction is obtained by hiding the discontinuity of control in its higher derivatives, but additional information is needed where the knowledge of the derivative of the sliding variable is required and the original higher order sliding mode approach is only applicable to single-input nonlinear systems [28]. The observer-based sliding mode control is well detailed in [26,33], which utilizes asymptotic observers to construct a high-frequency bypass loop. The controller is discontinuous only with respect to the observer variables, and chattering is localized inside a high-frequency loop which bypasses the control plant. However, this approach assumes an asymptotic observer can indeed be designed to guarantee the observation error converging to zero asymptotically. In [34,35], full-order sliding mode control is proposed to eliminate the chattering. A desirable full-order dynamics rather than a reduced-order dynamics during the ideal sliding mode motion is constructed, such that a dedicated first-order low pass filter can be embedded in the full-order dynamics to smooth the control signal. In [36], the first-order low pass filter is originally adopted in the sliding mode design without stability analysis. In [34], the concept of a virtual plant/controller is proposed to build a function-augmented sliding surface through the combination of the low pass filter and the actual plant, and the stability of the resulted full-order dynamic system is well synthesized. In [35], the full-order sliding mode control is used to address the singularity and chattering problem in the terminal sliding mode control.

To the best of the authors' knowledge, only few works apply the full-order sliding mode method to coordinated motion control of multi-agent system. In [17], position synchronization of multiple robotic manipulators is achieved through full-order sliding mode control in which information exchange is constrained by cross coupling links between every pair of neighboring manipulators within a ring-like communication topology. Moreover, in [17,34–36], all the developed full-order sliding mode methods assume a priori knowledge of bounds to the plant uncertainties. Motivated by those considerations, a novel decentralized adaptive chattering free sliding mode control framework is proposed in this paper, in order to address the problem of robust synchronized formation of multiple UAVs in 3D space subject to unknown bounded system uncertainty. Compared with the highly related existing results, the main contributions of this paper can be unfolded in the following three aspects.

(1) First, compared with neural network requiring sample learning and fuzzy logic algorithms requiring fuzzy approximation or inference [22–25], SMC has the simple structure for potential implementations as well as high robustness to the system uncertainties. Yet, in order to avoid chattering phenomenon of the classic sliding mode control, a novel decentralized adaptive full-order sliding mode controller embedded with a low-pass filter to attain the chattering free property is proposed for the formation control of multiple UAVs.

(2) Second, in order to address the synchronized formation motion of multiple UAVs, a new type of full-order sliding mode surface incorporating both the individual position tracking error and the synchronized formation error is designed in a decentralized manner. In addition, a more general information exchange topology is adopted in the decentralized UAV formation control design rather than the specific ring-like communication topology proposed in the existed references [17].

(3) Third, robust adaptive technique is elaborately integrated in the decentralized chattering free SMC design to handle unknown bounded uncertainties, by relaxing the restricted requirements for assuming a priori knowledge of bounds on the system uncertainty as stated in conventional chattering free control systems [17,34–36]. Furthermore, system robustness as well as stability of the whole closed-loop UAV system is formally synthesized by using Lyapunov function technique.

Finally, numerical simulations are carried out in order to illustrate the effectiveness and the performance of the decentralized adaptive full-order sliding mode controller for multiple UAVs under system uncertainties. Moreover, quantitatively comparison between the proposed chattering free SMC and the classic SMC is conducted, which illustrates that an embedded low-pass filter in the decentralized full-order SMC ensures chattering free control signals on the multiple UAV plants.

The rest of the paper is organized as follows. Problem statement is presented in the next section, including the kinematics and dynamics model of the UAV and the control objective of synchronized formation. In Section 3, a decentralized full-order sliding surface is designed for the multi-UAV system. Section 4 proposes an adaptive chattering free sliding mode controller and the stability of the whole system is synthesized. Numerical simulation results are given in Section 5 to illustrate the performance of the proposed controller. Conclusions are given in Section 6 that also warrant further research.

2. Problem statement

This section describes the kinematic and dynamic model of the unmanned aerial vehicle (UAV) in three-dimensional space, and formulates the synchronized formation problem of multi-UAV system.

2.1. UAV modelling

As shown in Fig. 1, an unmanned aerial vehicle in $\mathbb{R}^3$ is schematically depicted, where the lift force, thrust force, drag force, and the bank, flight path and heading angles rotating around the roll, pitch, yaw axes are illustrated, respectively. The position of the ith UAV is denoted as

$$\mathbf{p}_i(t) = \left[x_i(t)\ y_i(t)\ z_i(t) \right]^T \tag{1}$$

Considering a multi-vehicle system of n UAVs, the kinematics of the ith UAV is given as follows:

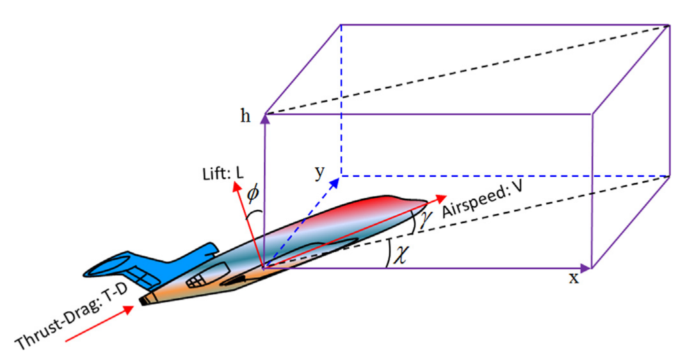

Fig. 1. UAV model in three-dimensional space.