ISA Transactions xxx (2018) 1–19

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Neural network disturbance observer-based distributed finite-time formation tracking control for multiple unmanned helicopters

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A R T I C L E I N F O

Article history:
Received 22 April 2017
Revised 26 November 2017
Accepted 8 December 2017
Available online XXX
Handling Editor XXX

Keywords:
Unmanned helicopters
Distributed formation control
Finite-time multivariable neural network disturbance observer
Nonsingular fast terminal sliding mode
Integral filters

A B S T R A C T

The distributed finite-time formation tracking control problem for multiple unmanned helicopters is investigated in this paper. The control object is to maintain the positions of follower helicopters in formation with external interferences. The helicopter model is divided into a second order outer-loop subsystem and a second order inner-loop subsystem based on multiple-time scale features. Using radial basis function neural network (RBFNN) technique, we first propose a novel finite-time multivariable neural network disturbance observer (FMNNDO) to estimate the external disturbance and model uncertainty, where the neural network (NN) approximation errors can be dynamically compensated by adaptive law. Next, based on FMNNDO, a distributed finite-time formation tracking controller and a finite-time attitude tracking controller are designed using the nonsingular fast terminal sliding mode (NFTSM) method. In order to estimate the second derivative of the virtual desired attitude signal, a novel finite-time sliding mode integral filter is designed. Finally, Lyapunov analysis and multiple-time scale principle ensure the realization of control goal in finite-time. The effectiveness of the proposed FMNNDO and controllers are then verified by numerical simulations.

1. Introduction

As a special kind of unmanned aerial vehicle (UAV), the unmanned helicopter has attracted a great deal of attention in the past several years, due to its various applications such as surveillance, data acquisition, and rescue [1,2]. Some robust control methodologies such as PID [3], H_∞ [4], model prediction control (MPC) [5], adaptive backstepping [6], sliding mode control [7], feedback linearization [8] and adaptive RBFNN [2,9], to name a few, were developed for multiple unmanned helicopters subject to modeling uncertainties and disturbances. Compared with other methods, sliding mode control (SMC) technique is one of the most robust and effective tools to deal with matched and mismatched synthesis uncertainties [7,10] for its insensitivity to a family of uncertainty. The SMC can be classified as: traditional sliding mode control (1st order SMC), 2nd order SMC and higher order SMC (HOSMC). 1st order SMC is simple with largest chattering. HOSMC remove the chattering effect and retain the robustness of 1st order SMC and improve their accuracy. However, HOSMC requires every derivative of the sliding surface. The derivative information of 2nd order SMC has been demonstrated is not required for second-order SMC, such as super-twisting sliding control, for more details one can see Ref. [11]. In order to handing the second-order system and achieve higher accuracy, terminal sliding mode (TSM) and STW are combined [12].

The multiple unmanned helicopters formation tracking problem can be classified as either leaderless tracking problem or leader-following tracking problem [13]. In Ref. [14], the dynamic inversion control method was employed to achieve the leader-following formation control for UAV helicopters linear system, and the flight test about a quadrotor formation tracking a virtual leader at outdoor was given. In Ref. [15], Wang *et al.* proposed a nonlinear robust tracking controller using the H_∞ control technology and approximate feedback linearization method, and then leader-follower formation control problem for multiple unmanned helicopters was solved. He *et al.* [16] studied the decentralized formation flight of multiple unmanned helicopter systems using receding horizon optimization approach. Yu *et al.* [17] studied the decentralized tracking control for helicopters using signal compensation technique and backstepping method, the tracking error can reach equilibrium point as the expected convergence rate. It should be pointed that the aforementioned formation control is decentralized, where all fol-

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https://doi.org/10.1016/j.isatra.2017.12.011
0019-0578/

lower helicopters can receive the leader information. To the best of our knowledge, few works discussed the distributed formation tracking control problem for multiple unmanned helicopters system with six-degrees-of-freedom (6-DOF) kinematic equation. Taking into account wind and airflow between helicopters, Wu [7] investigated the finite-time trajectory tracking control for a helicopter with 6-DOF kinematics equation using multivariable super-twisting (MSTW) algorithm. The dynamics of the unmanned helicopter are not only nonlinear, but are also coupled with each other and underactuated, which make the control design challenging, especially distributed formation control.

The finite-time control method is superior to asymptotic control because the protocols designed by finite-time control have faster convergence rate [18]. Besides, system with finite-time controller have higher control accuracy better disturbance rejection and robustness against uncertainties. In Ref. [18], some observer-based control algorithms are designed to achieve finite-time consensus tracking control problem for second-order multi-agent systems. It is well known that NN and/or fuzzy logic systems (FLS) can approximate any smooth functions over a compact set to arbitrary accuracy [19,20]. Hou *et al.* designed a neural-network-based decentralized control protocol to solve the leaderless consensus control problem of multi-agent systems [21]. An adaptive neural controller was proposed for consensus tracking control of second-order multi-agent systems in the presence of unknown nonlinearities and disturbances [22]. Zou *et al.* studied the output feedback formation control problem for multi-agent systems using Chebyshev neural networks [23]. In Ref. [24], Zong *et al.* designed a robust adaptive dynamic surface controller based on RBFNN for flexible air-breathing hypersonic vehicle, where RBFNN was used to approximate the given function. However, all the above mentioned neural network-based results can only be asymptotically stable. The finite-time control may be more attractive for its higher convergence rate, higher accuracy and better disturbance rejection [25,26]. Zhang *et al.* [27] designed a neural network finite-time observer for the follower robot to estimate the states of leader robot. Liu and Zhang ([28,29]) proposed a novel neural network-based robust finite-time control strategy for the trajectory tracking of robotic manipulators with structured and unstructured uncertainties. Wu *et al.* [30] proposed a finite-time neural network adaptive controller to make the position tracking of joint rapidly. In Refs. [27–30], the sign function with fixed gain was used to eliminate the NN approximation error which may cause gain overestimation. Therefore, Cai *et al.* [31] developed an adaptive neural finite-time control design scheme based on the backstepping method and the adding-a-power-integrator technique for a class of switched nonlinear systems, and the bounds of neural network approximation errors were estimated online. However, problem of differentiating a composite reference trajectory (i.e., virtual input) at each step and problems of computational complexity and combination explosion are worth noting drawbacks associated with the backstepping procedure [32]. It is urgent need to find a simple method which can estimate the neural network error online in finite-time.

Inspired by all the above analysis, the NFTSM control in Ref. [33], MSTW in Ref. [11] and the disturbance observer in Ref. [34], in this paper, full dynamics of unmanned helicopter system in Refs. [7,8] are considered in this paper. Differs from the previous works, the main contributions of this paper for multiple unmanned helicopters formation tracking control with comprehensive disturbances and uncertainties can be generalized in three aspects.

- Compared with the previous works [22–24] in which the finite-time neural network control algorithm is designed with fixed gains and the network errors are assumed to be bounded with a known constant; in this paper, a novel FMNNDO is designed to address the comprehensive uncertainty, which contains external disturbance and model uncertainty and the NN approximation errors can be simultaneously compensated online in finite-time. The proposed FMNNDO opens a door to handle the interferences of a family of four order system.
- Compared with the existing decentralized asymptotic formation control scheme for unmanned helicopter with linear/3-DOF dynamics, a novel integrated FMNNDO and finite-time formation control scheme can achieve distributed finite-time tracking and attitude tracking for unmanned helicopters with 6-DOF nonlinear dynamics using NFTSM method.
- Compared with the integral filters in Ref. [32] which were used to deal with the development of the derivation of virtual inputs asymptotically, a new integral filter in this paper is to facilitate the development of the second-order derivation of the virtual inputs in finite-time.

The organization of this paper is as follows: Section 2 preliminaries the graph theory, helicopter model, control object and mathematical preliminaries. Section 3 presents FMNNDO, FMNNDO-based distributed formation tracking controller, integral filters and FMNNDO-based attitude tracking controller. Section 4 gives numerical simulation results to illustrate the effectiveness and applicability of the theoretical results derived in this paper. Section 5 presents the conclusions.

1.1. Notations

For $x \in R$, define $\text{sign}^{\gamma}(x) = |x|^{\gamma} \cdot \text{sign}(x)$. For $X = [x, y, z] \in R^3$, $\text{sign}^{\gamma}(X) = \text{diag}(|X|^{\gamma}) \cdot \text{sign}(X) = [|x|^{\gamma}\text{sign}(x), |y|^{\gamma}\text{sign}(y), |z|^{\gamma}\text{sign}(z)]^T$, and $|x|$ is the absolute value of x. $\|X\|$ is the Euclidean norm of vector X. For a real symmetric positive semidefinite matrix A with only one eigenvalue equal to zero, denote $\lambda_{\max}(A)$ and $\lambda_{\min}(A)$, respectively, as the maximum eigenvalue and the minimum eigenvalue of A. The norm of matrix A is $\|A\| = \sqrt{\lambda_{\max}(A^TA)}$. The derivative of $\text{sign}^{\gamma}(X)$ is $\frac{d}{dt}sig^{\gamma}(X) = \gamma|X|^{\gamma-1}\dot{X}$. $\otimes$ is the Kronecker product of matrices.

A directed graph G is pair (V, ε), where $V = (\upsilon_1, \upsilon_2, \ldots, \upsilon_n)$ is a nonempty finite set of nodes and $\varepsilon \in V \times V$ is a set of edges, in which an edge is represented by an ordered pair of distinct nodes. For an edge (υ_i, υ_j), node υ_i is called the parent node, node υ_j the child node, and υ_i is a neighbor of υ_j. A directed graph contains a directed spanning tree if there exists a node called the root, which has no parent node, such that the node has directed paths to all other nodes in the graph. The adjacency matrix $A = [a_{ij}] \in R^{n\times n}$ associated with the directed graph G is defined by $a_{ij} = 1$ if $(\upsilon_i, \upsilon_j) \in \varepsilon$ and $a_{ij} = 0$ otherwise. The Laplacian matrix $L = [l_{ij}] \in R^{n\times n}$ is defined as $l_{ii} = \sum_{j\neq i} a_{ij}$ and $l_{ij} = -a_{ij}, i \neq j$. A directed graph $\widetilde{G}$ is pair $(\widetilde{V}, \widetilde{\varepsilon})$, where $\widetilde{V} = (\upsilon_0, \upsilon_1, \upsilon_2, \ldots, \upsilon_n)$ is a nonempty finite set of nodes and $\widetilde{\varepsilon} \in \widetilde{V} \times \widetilde{V}$ is a set of edges. a_{i0} respects the connection between agent i and the leader. If agent i is connected to the leader $a_{i0} = 1$, and otherwise $a_{i0} = 0$. Define $B = [a_{10}, \ldots, a_{n0}]^T$.

2. Preliminaries and model description

2.1. Helicopter dynamic model

Fig. 1 shows a basic model of the i–th unmanned helicopter in the body frame and the north-east-down (NED) inertial frame, and a leader-follower formation diagrammatic sketch. The motion of this helicopter is controlled by main rotor collective pitch, tail rotor collective pitch, longitudinal flapping angle and lateral cyclic pitch. A six-degrees-of-freedom rigid body model ([7,8]) with internal couplings, unmodelled dynamics and wind gusts is considered in this paper.