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Distributed containment output-feedback control for a general class of stochastic nonlinear multi-agent systems

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ABSTRACT

This study considers a distributed containment output-feedback control approach for a general class of stochastic uncertain nonlinear multi-agent systems. At first, local linear state observers are designed to deal with the unmeasured states. Then, radial basis function (RBF) neural networks (NNs) and minimal learning parameter approach are employed to approximate unknown nonlinearities. On the basis of dynamic surface control (DSC), command filter technique, adaptive neural approximator and linear observers, a simplified systematic approach to design of the coordinated containment output-feedback controller for stochastic uncertain nonlinear multi-agent systems is offered. In the proposed distributed controller the problems of explosion of complexity and effect of DSC filter errors are eliminated, simultaneously. Via Lyapunov theory, it is shown that the proposed controller can guarantee that all the signals in the closed-loop network system are cooperatively semi-globally uniformly ultimately bounded (CSGUUB) in the sense of mean square; meanwhile all followers' outputs converge to the dynamic convex envelope spanned by the dynamic leaders. Finally, simulation results are shown to confirm efficiency of the proposed method.

1. Introduction

In recent years, multi-agent systems (MASs) have been widely developed because of their various features such as reliability, robustness, redundancy, etc. As a result, the problem of multi-agent systems control has received much attention. Multi-agent systems control can be investigated in diverse lookout such as distributed consensus [1,2], formation control [3], rendezvous [4], flocking [5] and so forth. The essential problem in the coordinated control of MASs is to ensure that the states of all agents to reach an agreement based on neighbors' information which is the so-called consensus. A consensus-like issue with multiple leaders is named containment control. For the containment case, the distributed tracking problem is defined as the problem to drive all followers into the convex hull spanned by the multiple leaders. Containment control has many potential applications in real-world. For example, in a network of robots, where part of them that possess the capability of detecting obstacles are called leaders and the others that only possess the capability of transporting are called followers, perform the mission of commodity diversion. By detecting the obstacles followers can form a safety area.

Numerous control approaches have been widely studied in the literature to attain consensus (or containment) for linear and nonlinear multi-agent systems. For linear case, [6] investigated the problem of containment for general linear MASs. Further results have been extended in [7,8] on containment control of first- and second-order nonlinear MASs. Then, containment controller design for network of Lagrangian systems was proposed in [9]. It should be noted that dynamics of controlled MASs in [6–9] are completely known. Clearly, in many real applications it is impossible to model agents with high accuracy, since they are often subject to uncertain factors. Therefore, the designed consensus (or containment) controllers should be equipped to adaptive algorithms to deal with uncertainties. Among these algorithms, adaptive backstepping technique as a recursive control approach has received considerable attention for coordinated control of multiple uncertain strict-feedback nonlinear systems. In summary, resorting to backstepping adaptive approaches, many results have been obtained for uncertain strict-feedback MASs, e.g. [10–12]. However, the consensus control methods in [10–12] require the system functions either known or parameterized, that is, the unknown parameters appear linearly with respect to the unknown nonlinear functions. If such prior knowledge of the agents is unavailable, these consensus methods become invalid. To eliminate this restriction, neural networks and fuzzy logic systems because of good approximation capability have been combined

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with distributed adaptive backstepping controller for nonlinear strict-feedback MASs with arbitrary uncertainties. As a first result, this developed approach has been applied for synchronized first-order multi-agent systems under undirected graph in [13], successfully. Then, much effort from the side of scholars has been directed to the design of distributed adaptive neural (or fuzzy) backstepping control for multi-agent systems, e.g., second-order strict-feedback multi-agent systems [14], high-order strict-feedback multi-agent systems [15] and so forth.

As we know, these control approaches essentially suffer from the main problem as explosion of complexity. To remove this drawback, Swaroop et al. proposed dynamic surface control strategy in [16]. By using DSC approach, in [17], a coordinated tracking adaptive neural control was designed for strict-feedback MASs, which greatly simplifies design procedure. In the sequel, a distributed adaptive containment DSC was extended for strict-feedback MASs in [18]. Besides, in [19] on the basis of DSC technique, an adaptive containment control was developed for pure-feedback MASs. Recently, in [20], via observer methodology, a coordinated adaptive fuzzy DSC was proposed for strict-feedback MASs in presence of input saturation. From the practical view point, a distributed adaptive DSC was also employed for different types of practical systems such as containment control of mobile robots [21], formation control of autonomous underwater vehicles [22] and so on. However, authors in [16–22] were ignored to compensate effect of the DSC filter errors, which caused stability analysis of the mentioned controllers to become more complicated. Recently, to eliminate this problem, in [23] a command filter backstepping was proposed for individual nonlinear systems, and it was developed to adaptive case for strict-feedback systems in [24].

In spite of these developments for the coordinated control of MASs with DSC technique, all of the mentioned control approaches are only valuable for a class of deterministic MASs, which severely restricts the applicability in practice. It is well known that stochastic disturbances are frequently encountered in many real-world systems and are a source of instability. Hence, studies on the distributed control design for stochastic MASs have become a worthwhile and challenging topic. More recently, a coordinated tracking backstepping control was studied for stochastic MASs in [25]. Nevertheless, this approach offers a solution to the coordinated tracking problem for MASs in the presence of stochastic disturbances, it has some main limitations, namely, (i) the proposed approach is obtained under state-feedback framework. However, state variables are usually unknown or partially unknown in many practical situations; therefore, this control strategy cannot be implemented in practice. (ii) It is a primary study which focuses on consensus performance for a network of agents with one dynamic leader in the presence of stochastic disturbances. Therefore, it cannot be applied for coordinated control of stochastic MASs with multiple leaders, i.e., it is not valuable for solving containment problem for stochastic MASs. (iii) This distributed control approach is not suitable for completely unknown stochastic MASs because it requires some prior information about drift and diffusion terms, such as their upper bounds and satisfying Lipschitz condition. (iv) For the ease of the distributed controller design, the diffusion terms are assumed to be the function of the previous state variables. Clearly, if the diffusion terms in the considered stochastic MASs are in a more general form, this control scheme becomes invalid.

Motivated by the previous discussion, in this paper we consider the problem of distributed adaptive NN containment control design for a general class of stochastic uncertain MASs based on the output-feedback design. To the best author's knowledge, until now, no effective containment output-feedback adaptive NN control for stochastic MASs has been reported in control community. In this paper, both the problems of explosion of complexity and output-feedback design are considered for stochastic uncertain MASs. Also, by employing minimal learning parameter approach and command filter technique, curse of dimension and effect of DSC filter errors are counteracted, respectively. On the basis of direct Lyapunov theory, it can be guaranteed that all the signals in the closed-loop network systems remain CSGUUB in probability and outputs of all follower agents converge to the convex envelope spanned by the multiple dynamic leaders. The main contributions of the proposed approach are as follows.

1) This paper studies the containment problem of more general nonlinear systems, i.e., the stochastic nonlinear systems. This is different from the existing works, where the random disturbance is ignored in [17–22]. On the other hand, unlike [25], this paper studies containment problem for high-order stochastic nonlinear multi-agent systems with completely unknown drift and diffusion functions. Furthermore, it avoids explosion of complexity in [25]. 2) It is the first trial to the design of containment adaptive NN output-feedback control for stochastic multi-agent systems, which is more applicable in practice. However, the proposed distributed output-feedback controller in [20] is only suitable for solving leader-follower synchronization problem for deterministic multi-agent systems. 3) It is the first result to design adaptive NN containment control for stochastic MASs based on the DSC incorporated with command filter technique. Therefore, compared with [17–22], the restrictive assumption on the bounds of the derivative of the intermediate control functions are removed. 4) Via Young's inequality fewer parameters need to be tuned which is more efficient in practice. Besides, the proposed approach is independent of prior knowledge of NNs. 5) In this paper a simplified systematic design procedure is presented for a class of stochastic nonlinear systems with a more general form of the diffusion term than [25].

2. Problem formulation

2.1. Preliminaries

2.1.1. Stochastic systems

Consider a network of multiple stochastic nonlinear systems. The dynamic of the i-th system is described as

$$dx_i(t) = f_i(t, x_i(t))dt + g_i^T(t, x_i(t))dw_i, \quad i = 1, ..., N, \tag{1}$$

where $x_i(t) \in \mathfrak{R}^n$ is the state vector, $f_i(t, x_i(t)) : \mathfrak{R}^+ \times \mathfrak{R}^n \to \mathfrak{R}^n$ is a drift vector and $g_i^T(t, x_i(t)) : \mathfrak{R}^+ \times \mathfrak{R}^n \to \mathfrak{R}^{n \times r}$ is a diffusion vector both of which are locally Lipschitz functions in $x(t)$ and satisfy $f_i(t, 0) = g_i(t, 0) = 0$. w_i is an independent r-dimensional standard Wiener process defined on the complete probability space $(\Omega, F, \{F_t\}_{t \ge 0}, P)$ with Ω as sample space, F as a σ-field, $\{F_t\}_{t \ge 0}$ as a filtration and P as the probability measure. For stability analysis of the multiple stochastic systems (1), the following definitions are necessary.

Definition 1. [27]. The differentiation operator L (Itô stochastic rule) is defined as follows:

$$LV_i(x_i(t), t) := \frac{\partial V_i}{\partial t} + \frac{\partial V_i}{\partial x_i^T} f_i(t, x_i(t)) + \frac{1}{2} Tr\left\{ \sigma_i^T g_i(t, x_i(t)) \frac{\partial^2 V_i}{\partial x_i \partial x_i^T} g_i^T(t, x_i(t)) \sigma_i \right\}, \tag{2}$$

where $V_i(x_i(t), t) \in C^{2,1}$ is a Lyapunov function associated to i-th agent of (1) and $Tr(A)$ denotes the trace of matrix A.

Definition 2. [29]. Let $p \ge 1$, the trajectory $\{x_i(t), t \ge 0\}$ of i-th stochastic nonlinear agent (1) with initial state $x_i(t_0) \in \Omega_{i0}$ (where Ω_{i0} is some compact set including the origin) under the graph communication are said to be p-moment CSGUUB in probability if