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Consensus of mobile multiple agent systems with disturbance-observer-based control

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Abstract: Consensus problem of mobile multiple agents with nonlinear coupled function and exogenous disturbances is studied. A pinning control, which has poor disturbance compensation ability, is presented to bring the consensus of multi-agent to an expectation value without disturbances. By applying the disturbance-observer-based control(DOBC), all the agents in the network can asymptotically reach consensus when disturbances are generated by a linear exogenous system. By analyzing the mobile multi-agent systems with fixed and switching topologies, the convergence conditions are obtained for multi-agent dynamical systems with exogenous disturbances from the disturbance-observer-based control. Finally, numerical examples support the analytical results.

Key words: nonlinear coupled; multi-agent systems; consensus; pinning control; disturbance-observer-based control

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采用干扰–观测器控制的移动智能体系统之一致性

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摘要: 本文研究了具有非线性耦合与外部干扰的移动多智能体系统的一致性问题. 假设系统不存在外部干扰的情况, 设计了一个牵引控制使得移动智能体系统达到一个期望值. 假设系统存在一个外部干扰, 应用干扰–观测器控制, 使得系统中的所有智能体可以渐近达到一致. 通过分析具有固定拓扑和时变拓扑的移动多智能体动态系统, 得到了许多基于抗干扰观测器的系统收敛性条件. 最后应用仿真实例说明了结论的有效性.

关键词: 非线性耦合; 多智能体系统; 一致; 牵引控制; 干扰–观测器控制

1 Introduction

Developments in sensing, communicating, and computing have made it possible to manage teams of autonomous systems, e.g., unmanned air vehicles, which gives rise to an active area of research, known as multi-agent systems. Especially, recent years there have been increasing interest in a problem in distributed coordinated control of multi-agents. The problem is usually called the consensus problem. The basic idea of consensus is that each agent updates its state based on the states of its local neighbors in such a way that the final states of all agents converge to a common value.

Consensus problems have a long history in the field of computer science, particularly in automata theory and distributed computation[1]. In recent years, numerous results have been obtained for consensus problems from various perspectives[2∼6]. Vicsek et al.[2] proposed a simple model for phase transition of a group of self-driven particles and numerically demonstrated complex dynamics of the model. Moore and Lucarelli[3] extended the results for single consensus variables to include the ideas of forced consensus and multiple consensus variables separated by hard constraints. A similar problem was considered using the idea of a leader-node by Tanner[4], where a single node is chosen that ignores all other nodes, but continued to broadcast, and the controllability properties of the resulting graph were exploited. The result was extended to the case when

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one or more vehicles in the team are chosen to be controlled by Jin and Murray[5]. The consensus problem with a time-varying reference state has been studied for example by Ren[6]. However, virtually all physical systems are nonlinear in nature. Chen[7] proposed and analyzed consensus algorithms with nonlinear coupling so that each agent in the team reached consensus on a prescribed value. Lin[8] investigated consensus problems of the multi-agent systems on directed graphs with external disturbances and model uncertainty in absence and presence of time-delay.

Pinning control is an effective control scheme for controlling high-dimensional systems with numerous applications to turbulence, instabilities in plasma, multi-mode lasers, and reaction-diffusion systems, where the method could work in any region of parameter space and requires a significantly smaller number of controllers (Grigoriev, Cross, and Schuster[9]). Moreover, for a large complex network, it is usually difficult to control it by adding controllers to all nodes. In order to reduce the number of controller, a natural approach is to control the network by pinning parts of nodes[10,11]. Additionally, unmodeled dynamics and parametric variations as well as external disturbance widely exist in multi-agent systems. Analysis and synthesis of nonlinear dynamic systems with disturbances has been one of the most active research. A disturbance observer based control is designed to deduce external disturbances and then to compensate for the influence of the disturbances using proper feedback. Muller and Ackermann[12] and Nakao et al.[13] pioneered the development of disturbance-observer-based control(DOBC). After that, DOBC had been applied in many mechatronic systems including disk drivers, machining centers, dc/ac motors, manipulators, robots[14∼16]. Chen[17] developed a nonlinear disturbance observer for unknown constant using Lyapunov theory and applied it to a two-link manipulator.

The main objective of this paper is to apply the method of DOBC with disturbance observer and pinning control to stabilize the states of mobile multiple agent systems with nonlinear coupling function. There are two parts of the main differences between this paper and Ref.[16]. First difference is the consensus algorithm; this paper studies the consensus protocol with a nonlinear coupling function, and Ref.[16] studies the consensus algorithm with a first-order linear coupling function. Second difference is the disturbance observers (DO's); this paper presents a linear DO's that is different from the nonlinear DO's in Ref.[16]. The problem of this paper is more generalized than that of Ref.[16], but the method presented in this paper is simpler than that in Ref.[16]. In section 2, some preliminaries are briefly outlined. The main results are obtained in Sections 3, which present a pinning control for multi-agent systems without disturbances and propose a design procedure of disturbance observer based control for multi-agent systems. In Section 4, we discuss the variable topology. The performances of DOBC is shown by computer simulation in Section 5. Finally, Conclusions are drawn in Section 5.

2 Problem statement

Let $G = (V, E)$ be a directed graph of order $n(n \geqslant 2)$ with a nonempty finite set V of elements called nodes and finite set $E \subseteq V \times V$ of ordered pairs of nodes called arcs. Consider a node i in the graph $G = (V, E)$, its neighboring set N_i is defined to be the set $\{j | j \in V, (i, j) \in E\}$.

In this paper, the relationships among agents are described by a directed graph G. In G, the ith agent and an arc from agent i to agent j denoted as (i, j) represents an unidirectional information exchange link from agent j to agent i, that is, agent i receives or obtains information from agent j.

Suppose that a system consists of n coupled nodes, with each node being of m dimensions. The state equations of the multi-agent systems with disturbance are given by

$$\dot{x}_i = \sum_{j \in N_i} h_{ij}(x_j - x_i) + u_i + d_i, \tag{1}$$

where $i = 1, 2, \cdots, n$, $x_i \in \mathbb{R}^m$, $u_i \in \mathbb{R}$ and $d_i \in \mathbb{R}$ are the state vector, input and external disturbance, respectively. N_i denotes the neighboring set of node i and it can be the time variant. The function $h_{ij}(x_j - x_i) = 0$, when $x_j - x_i = 0$. It is noted that $h_{ij}(\cdot)$ may be nonlinear. Moreover, $h_{ij}(\cdot)$ is valid only when $j \in N_i$.

3 Disturbance-observer-based control of multi-agent systems

In this section, firstly, the controller is designed under the assumption that there is no disturbance or the disturbance is measurable. Then, a disturbance observer is projected to estimate the disturbance. Based on the disturbance observer, a disturbance-observer-based control is synthesized to bring the agents with disturbances to the consensus.

3.1 Pinning control of system without disturbances

If there is no disturbance or the disturbance is measurable, the controller can be chosen as pinning controller, which can bring the consensus of multi-agent to an expected value. Here, the pinning strategy is applied on a small fraction $\delta (0 < \delta \ll 1)$ of the nodes. Suppose that nodes $i_1, i_2, \cdots, i_l$ are selected, where $l = \lfloor \delta N \rfloor$ stands for the smaller but nearest integer to the real number δN. Hence, the controlled system can be expressed as

$$\dot{x}_i = \sum_{j \in N_i} h_{ij}(x_j - x_i) + u_i, \tag{2}$$

where $i = 1, 2, \cdots, n$.

Suppose that one wants to stabilize network (1) onto a homogeneous stationary state $\bar{x}$ defined by

$$x_1 = x_2 = \cdots = x_n = \bar{x}. \tag{3}$$

If Eq.(2) is achieves, it is said that a consensus is reached about $\bar{x}$. Let pinning control

$$u_i = -k_i(x_i - \bar{x}), \tag{4}$$

where the control gain matrix $k_i > 0$ for $i \in \{i_1, i_2, \cdots, i_l\}$, otherwise $k_i = 0$ indicating there is no control over agent i. Define the error vector

$$e_i = x_i - \bar{x}. \tag{5}$$

So system (2) can be rewritten as

$$\dot{e}_i = \sum_{j \in N_i} h_{ij}(e_j - e_i) - u_i, i = 1, 2, \cdots, n. \tag{6}$$

It is easy to verify that $e_1 = e_2 = \cdots = e_n = 0$ is an equilibrium point of system (6). The objective of u_i is to guide the agents to reach a consensus about $\bar{x}$, namely

$$\lim_{t \to \infty} \|e_i\| = 0, \ i = 1, 2, \cdots, n. \tag{7}$$

Definition 1 Let B be a $m \times n$ matrix and D be an $p \times q$ matrix. Then the Kronecher product of B and D is the $mp \times nq$ matrix

$$B \otimes D = (b_{ij}D). \tag{8}$$

The error system (6) is rewritten in matrix form as

$$\dot{e} = h(e) - (K \otimes I_n)e, \tag{9}$$

where

$$\begin{aligned} & e = [e_1^{\mathrm{T}} \ \cdots \ e_n^{\mathrm{T}}]^{\mathrm{T}}, \\ & h(e) = [\sum_{j \in N_1} h_{1j}^{\mathrm{T}}(e_j - e_1) \ \sum_{j \in N_2} h_{2j}^{\mathrm{T}}(e_j - e_2) \ \cdots \\ & \qquad \sum_{j \in N_n} h_{nj}^{\mathrm{T}}(e_j - e_n)]^{\mathrm{T}}, \\ & K = \mathrm{diag}\{k_1, k_2, \cdots, k_n\}. \end{aligned}$$

Lemma 1 For system (2) with $h_{ij}(\cdot)$ continuously differentiable, if the matrix

$$F = \frac{1}{2}(\frac{\partial h^{\mathrm{T}}}{\partial e} + \frac{\partial h}{\partial e} - 2(K \otimes I_m)) \tag{10}$$

is negative definite, then system (2) reaches a consensus about $\bar{x}$ asymptotically with the pinning control (4). Here $\frac{\partial h}{\partial e}$ is defined as:

$$\frac{\partial h}{\partial e} = \begin{pmatrix} \frac{\partial h_1}{\partial e_1} \cdots \frac{\partial h_1}{\partial e_n} \\ \vdots \qquad \vdots \\ \frac{\partial h_n}{\partial e_1} \cdots \frac{\partial h_n}{\partial e_n} \end{pmatrix}, \tag{11}$$

with $h_i = \sum_{j \in N_i} h_{ij}(e_j - e_i)$.

Proof Let Lyapunov candidate as follows: $V = \sum_{i=1}^{n} e_i^{\mathrm{T}} e_i$. Thus, one has

$$\dot{V} = 2\mathrm{e}^{\mathrm{T}} F e.$$

From the condition of the Lemma, the result is straightforward.

3.2 Disturbance-observer-based control of multi-agent systems

The unknown external disturbance is supposed to be generated by an exogenous system described by

$$\begin{cases} \dot{\xi}_i(t) = A\xi_i(t), \\ d_i(t) = C\xi_i(t). \end{cases} \tag{12}$$

where $\xi_i \in \mathbb{R}^l$ is the internal state variables of the exogenous system and $d_i \in \mathbb{R}$ is the output of the exogenous system, namely the disturbance of system (1), A and C are system matrix with appropriate dimensions.

A disturbance observer of system (1) to estimate the disturbance d_i is given as

$$\begin{cases} \dot{z}_i = (A - WC)(z_i + Wx_i) - \\ \qquad W(\sum_{j \in N_i} h_{ij}(x_j - x_i) + u_i), \\ \hat{\xi}_i = z_i + Wx_i, \\ \hat{d}_i = C\hat{\xi}_i. \end{cases} \tag{13}$$

where $z_i \in \mathbb{R}^l$ is the internal state variables of the observer, $\hat{\xi}_i \in \mathbb{R}^l$ and $\hat{d}_i \in \mathbb{R}$ are the estimates of ξ_i and d_i, respectively. W is control gain. Define the error vector

$$e_i = x_i - \bar{x}. \tag{14}$$

So system (1) can be rewritten as

$$\dot{e}_i = \sum_{j \in N_i} h_{ij}(e_j - e_i) - k_i e_i + d_i. \tag{15}$$

Defined

$$\varepsilon_i = \xi_i - \hat{\xi}_i, \tag{16}$$

we can have

$$\dot{\varepsilon}_i(t) = (A - WC)\varepsilon_i(t). \tag{17}$$

Theorem 1 Consider multi-agent systems (1) with the disturbance (12). The closed-loop multi-agent systems under the disturbance observer (13) can reach consensus asymptotically, if there exists an appropriate matrix $P > 0$, Q, such that

$$\Psi = \begin{pmatrix} \Lambda & \Theta \\ \Theta^{\mathrm{T}} & \Omega \end{pmatrix} < 0, \tag{18}$$

where

$$\Lambda = (\frac{\partial h}{\partial e} - (K \otimes I_m))^{\mathrm{T}} + (\frac{\partial h}{\partial e} - (K \otimes I_m)),$$
$$\Theta = I_n \otimes C,$$
$$\Omega = I_n \otimes (PA + A^{\mathrm{T}}P - (C^{\mathrm{T}}Q^{\mathrm{T}} + QC)).$$

Proof In order to asymptotically stabilize the system for any disturbance, a part of the control effort $u_i(x_i, \hat{d}_i)$ shall depend on the disturbance $\hat{d}_i$. Let

$$u_i = -k_i(x_i - \bar{x}) - \hat{d}_i, \tag{19}$$

where $\bar{x}$ is expected consensus value for multi-agents. Substituting (19) into system (15) obtains

$$\dot{e}_i = \sum_{j \in N_i} h_{ij}(e_j - e_i) - k_i e_i - \hat{d}_i + d_i = \sum_{j \in N_i} h_{ij}(e_j - e_i) - k_i e_i + C\varepsilon_i. \tag{20}$$

The error system is rewritten in matrix form as

$$\dot{e} = \frac{\partial h}{\partial e} e - (K \otimes I_m)e + (I_n \otimes C)\varepsilon, \tag{21}$$

where $e = [e_1^{\mathrm{T}} \ \cdots \ e_n^{\mathrm{T}}]^{\mathrm{T}}$, $\varepsilon = [\varepsilon_1^{\mathrm{T}} \ \cdots \ \varepsilon_n^{\mathrm{T}}]^{\mathrm{T}}$. Now, we discuss system (21) with the observer error dynamics (17), the closed-loop system under the composite controller can be described by

$$\begin{cases} \dot{e} = (\frac{\partial h}{\partial e} - (K \otimes I_m))e + (I_n \otimes C)\varepsilon, \\ \dot{\varepsilon}(t) = I_n \otimes (A - WC)\varepsilon(t). \end{cases} \tag{22}$$

Consider Lyapunov function

$$V(t) = \sum_{i=1}^{n} (e_i^{\mathrm{T}} e_i + \varepsilon_i^{\mathrm{T}} P \varepsilon_i),$$

where matrix $P > 0$. The derivative of $V(t)$ is

$$\dot{V}(t) = \sum_{i=1}^{n} (\dot{e}_i^{\mathrm{T}} e_i + e_i^{\mathrm{T}} \dot{e}_i + \dot{\varepsilon}_i^{\mathrm{T}} P \varepsilon_i + \varepsilon_i^{\mathrm{T}} P \dot{\varepsilon}_i) = e^{\mathrm{T}}(\frac{\partial h}{\partial e} - (K \otimes I_m))^{\mathrm{T}} e + e^{\mathrm{T}}(\frac{\partial h}{\partial e} - (K \otimes I_m))e + \sum_{i=1}^{n} (\varepsilon_i^{\mathrm{T}} C^{\mathrm{T}} e_i + e_i^{\mathrm{T}} C \varepsilon_i) + \sum_{i=1}^{n} (\dot{\varepsilon}_i^{\mathrm{T}} P \varepsilon_i + \varepsilon_i^{\mathrm{T}} P \dot{\varepsilon}_i). \tag{23}$$

Let the gain $W = P^{-1}Q$, we can obtain

$$\dot{V}(t) = (e \ \ \varepsilon)^{\mathrm{T}} \Psi (e \ \ \varepsilon). \tag{24}$$

Thus, we can obtain the consensus of the multi-agent systems under the condition (18).

4 Switching topology

In this section, the system with switching topology is described by

$$\dot{x}_i = \sum_{j \in N_i(t)} h_{ij}(x_j - x_i) + u_i + d_i, \tag{25}$$

where $i = 1, 2, \cdots, n$, u_i is defined by Eq.(4) and $N_i(t)$ is the time-varying neighboring set of agent i. Define the error vector

$$e_i = x_i - \bar{x}. \tag{26}$$

So system (25) can be rewritten as

$$\dot{e}_i = \sum_{j \in N_i(t)} h_{ij}(e_j - e_i) - k_i e_i + d_i, \quad i = 1, 2, \cdots, n. \tag{27}$$

Theorem 2 Consider multi-agent systems (25) with the disturbance subsystem (12). The closed-loop multi-agent systems with switching topologies under the disturbance observer (13) can reach consensus asymptotically, if there exist appropriate matrix $P > 0$, Q, such that

$$\begin{pmatrix} \Lambda & \Theta \\ \Theta^{\mathrm{T}} & \Omega \end{pmatrix} < 0, \tag{28}$$

where

$$\Lambda = (\frac{\partial \hat{h}}{\partial e} - (K \otimes I_m))^{\mathrm{T}} + (\frac{\partial \hat{h}}{\partial e} - (K \otimes I_m)),$$
$$\Theta = I_n \otimes C,$$
$$\Omega = I_n \otimes (PA + A^{\mathrm{T}}P - (C^{\mathrm{T}}Q^{\mathrm{T}} + QC)),$$
$$\hat{h}(e) = [\sum_{j \in N_1(t)} h_{1j}^{\mathrm{T}}(e_j - e_1) \ \sum_{j \in N_2(t)} h_{2j}^{\mathrm{T}}(e_j - e_2) \cdots \sum_{j \in N_n(t)} h_{nj}^{\mathrm{T}}(e_j - e_n)]^{\mathrm{T}}.$$

5 Examples and simulation results

The following four graphs (Fig.1) will be needed in the analysis of this section. The example includes the following coupling function:

$$h_{ij}(x_j - x_i) = \mathrm{e}^{x_j - x_i} - 1 + (x_j - x_i), \quad (29)$$

where $\mathrm{e}^{x_j - x_i}$ is nonlinear. In the simulations, the initial states are generated randomly in the range $[0, 5]$.

Example 1 The first example demonstrates the fixed topology G_{a}. Suppose that there is a periodic disturbance $d(t)$ acting on every agent, given by

$$A = \begin{pmatrix} 0 & 2 \\ -2 & 0 \end{pmatrix},$$
$$C = [1 \quad 0],$$
$$\xi(0) = \begin{pmatrix} 0.5\sin 1 \\ 0.5\cos 1 \end{pmatrix}.$$

Applying linear matrix inequality, we can get the positive definite matrix $P = \begin{pmatrix} 1/2 & -1/4 \\ -1/4 & 1/3 \end{pmatrix}$ and $W = [3.2 \ \ 2.4]^{\mathrm{T}}$. A disturbance observer is designed by (13). In Fig.2, it is observed that a consensus about $\bar{x} = 1$ is reached asymptotically with disturbance observer based on control. In Fig.3, the disturbance estimated by the disturbance observer (13) is shown, where the dot line is the exogenous disturbance. The observer exhibits excellent tracking performance.

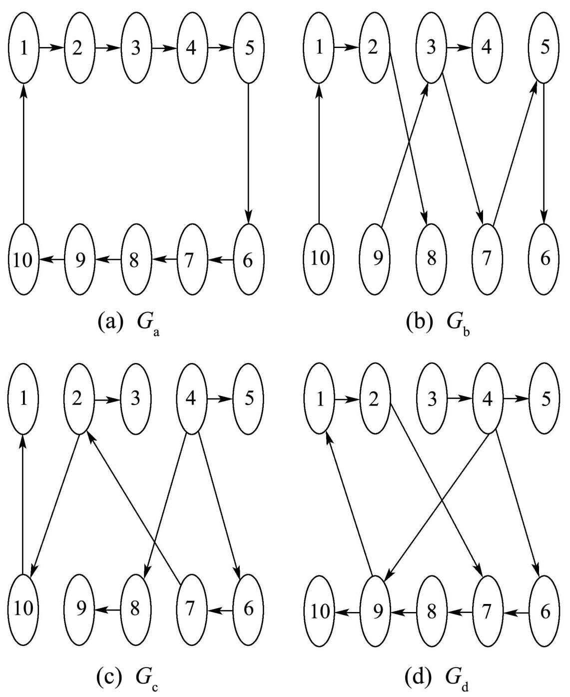

Fig. 1 Network graph consisting of 10 nodes

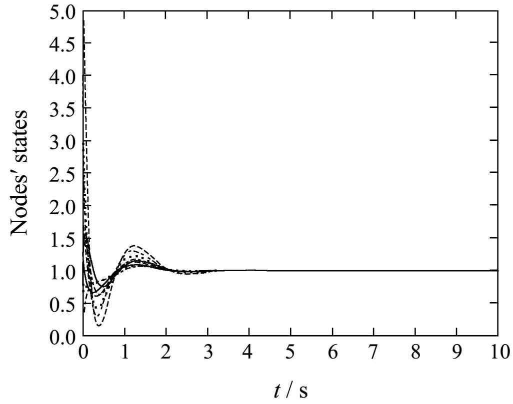

Fig. 2 Output of multi-agent systems with DOBC

Example 2 In the second example, the variable topology is considered. Four possible topologies, which are referred to as G_{a}, G_{b}, G_{c}, G_{d} respectively, are shown in Fig.1. In this case, some of the existing communication links fail and some of them are created due to the moving of the agents. In the simulation G_{a}, G_{b}, G_{c}, G_{d} switch among them randomly.

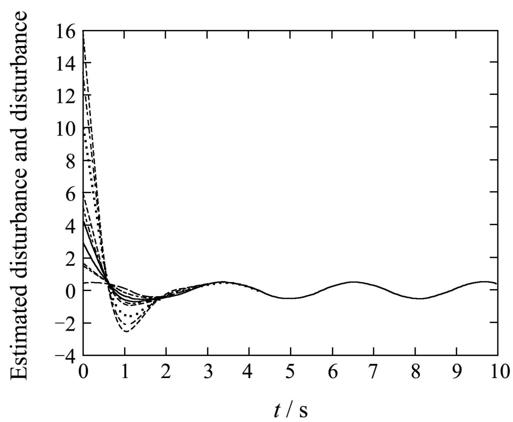

Fig. 3 Disturbance estimated by the disturbance observer

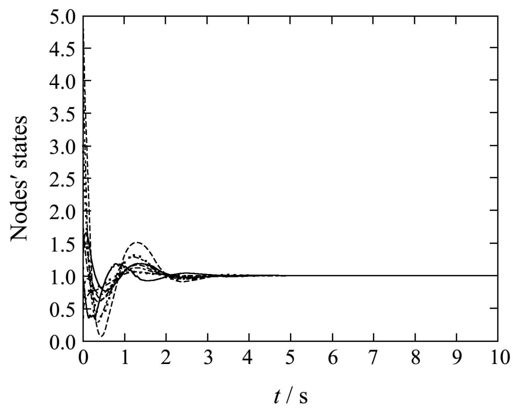

Fig. 4 Consensus of multi-agent systems reach asymptotically with DOBC

Use the disturbance observer designed, in Fig.4, the output of the multi-agent systems reach asymptotically with nonlinear disturbance observer based on control, namely, the consensus about $\bar{x} = 1$ reached. It can see that the observer exhibits excellent tracking performance.

6 Conclusions

This paper has considered the consensus problems with nonlinear coupling in networks of multi-agent systems based on disturbance observer. Two cases have been considered: fixed topology and switching topology. By introducing the disturbance-observer-based control, all the nodes in the network can reach consensus asymptotically. It is shown that this approach is quite flexible and can be integrated with the pinning control method which have poor disturbance attenuation ability. The effectiveness of the DOBC procedure is illustrated by the control problem of consensus in network of multi-agent systems subject to disturbances generated by a linear exogenous system. The simulation results have been presented to demonstrate the effective of the method.

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