SCIENCE CHINA
Information Sciences

• REVIEW •
Special Focus on Distributed Cooperative Analysis, Control and Optimization in Networks

November 2017, Vol. 60 110202:1–110202:14
doi: 10.1007/s11432-017-9141-x

Distributed cooperative anti-disturbance control of multi-agent systems: an overview

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Received April 6, 2017; accepted June 16, 2017; published online September 21, 2017

Abstract This paper reviews some main results and recent progress in distributed cooperative anti-disturbance control (DCADC) of multi-agent systems. Compared with anti-disturbance control in single systems, DCADC is more challenging because of the existence of coupling in multi-agent systems and the aim is to design distributed cooperative control based on the local information of each agent. This paper is concerned with some kinds of DCADC methods, such as distributed cooperative variable structure control, distributed cooperative sliding mode control, distributed cooperative disturbance-observer-based control, and distributed cooperative output regulation control approaches. Some future research topics regarding DCADC methods are also pointed out.

Keywords distributed cooperative control, anti-disturbance control, multi-agent system, variable structure control, sliding mode control, disturbance-observer-based control, output regulation

Citation Yu W W, Wang H, Hong H F, et al. Distributed cooperative anti-disturbance control of multi-agent systems: an overview. Sci China Inf Sci, 2017, 60(11): 110202, doi: 10.1007/s11432-017-9141-x

1 Introduction

In real control systems, disturbance is very common because of environment interference, measurement noise, friction, and load variation of mechanical and electrical systems. Thus, disturbance exists in almost all practical processes, which could have a negative effect on system performance. In addition, with the rapid development of modern engineering systems, high-precision control has become a priority, which makes disturbance processing much more important in industrial applications as well as academic research. Anti-disturbance control is the topic of how to design a proper controller to eliminate the effects caused by disturbances.

In the past few decades, distributed cooperation in multi-agent systems has received much attention because of its applications in industrial manufacturing and even dangerous missions, such as unmanned aerial vehicles (UAVs) [1, 2], distributed sensor networks [3], space exploitation [4], and marine exploration [5]. In particular, distributed cooperative control aims to design distributed controllers for each agent to make them achieve a global goal with only local information. In general, advantages such as low cost, easy maintenance, and high efficiency can be yielded by employing distributed controllers.

Concerning the distributed cooperative control of multi-agent systems in the presence of disturbances in each agent, one natural thought is to implement the anti-disturbance control for each agent separately

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based on local neighboring information and fulfill the global goal cooperatively. There are many studies on distributed cooperative control of multi-agent systems without disturbances [6–13] and anti-disturbance control for single systems [14–22]. The anti-disturbance control methods for single disturbed systems can be divided into two types. One type is a kind of feedback control, including H_∞ control, robust adaptive control, and variable structure control (VSC). These methods improve the control performance of closed-loop systems by suppressing disturbances, which has lagged effects and cannot attenuate disturbances in time. The other type is a kind of feedforward control, such as disturbance-observer-based control (DOBC), and active disturbance rejection control (ADRC). These methods try to estimate the disturbances and then compensate them in a timely manner. Each kind of anti-disturbance control has its own merits and shortcomings. DOBC [14] is easy to implement because the disturbance observer and control design can be carried out separately. However, this method depends on the exact modeling of disturbances and system dynamics. Sliding-mode control [15] does not require knowledge of the system dynamics and is very efficient in dealing with bounded disturbances. However, sliding-mode control may cause chattering phenomena that can damage the system in real implementations. Multi-agent systems in reality could have all kinds of disturbances. Thus, choosing appropriate anti-disturbance control methods is very important in practice.

Although the idea that each agent handles its own disturbances is feasible, the design is complicated and even unnecessary. Sometimes there may exist proper distributed cooperative control design strategies to fulfill the cooperation goal and disturbance rejection missions together, which could be more efficient. Furthermore, as mentioned previously, external interference can also be treated as a disturbance. If all the agents are affected by the same kind of disturbance, there is no need for each agent to reject the disturbance completely, which is actually a waste of energy. The better choice is to eliminate the difference caused by the disturbances, which could prevent the distributed cooperative control goals from being achieved. For example, distributed cooperative output regulation control (DCORC) [23–25] based on an internal model can achieve output tracking consensus without rejecting the disturbances totally.

This paper reviews some main results and recent progress in the distributed cooperative anti-disturbance control (DCADC) of multi-agent systems. For distributed cooperative control of nominal multi-agent systems and anti-disturbance control of single systems, one can refer to [26, 27], respectively. The rest of this paper is arranged as follows. In Section 2, some basic concepts of graph theory and multi-agent systems are introduced. In Sections 3–6, the distributed cooperative variable structure control (DCVSC), distributed cooperative sliding mode control (DCSMC), distributed cooperative disturbance-observer-based control (DCDOBC), and DCORC methods are reviewed, respectively. In Section 7, some other DCADC methods are further reviewed. An extension of DCADC is discussed in Section 8. The conclusion is given in Section 9.

2 Preliminary

In this section, some concepts regarding graph theory and multi-agent systems are presented.

For a networked system of N agents, the network topology can be modeled as a directed graph denoted by $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$, where $\mathcal{V} = (v_1, v_2, \ldots, v_N)$ is the set of agents, $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$ is the set of edges, and $\mathcal{A} = (a_{ij}) \in \mathbb{R}^{N\times N}$ is the adjacency matrix, with $a_{ii} = 0$ and $a_{ij} \geqslant 0$ for all $i \neq j$. Here $a_{ij} > 0$ if and only if there is an edge from node j to node i. The Laplacian matrix $\mathcal{L} = (l_{ij}) \in \mathbb{R}^{N\times N}$ is defined by $l_{ij} = -a_{ij}$, $i \neq j$, $l_{ii} = \sum_{j=1,j\neq i}^{N} a_{ij}$. A path from node i to node j means that there is a sequence of distinct edges in the form $(v_i, v_{k_1}), (v_{k_1}, v_{k_2}), \ldots, (v_{k_l}, v_j)$. A digraph has a directed spanning tree if there exists a node called the root such that there exist directed paths from this node to every other node. A digraph is strongly connected if there exists a directed path from every node to every other node.

A graph with the property that $(v_i, v_j) \in \mathcal{E}$ implies $(v_j, v_i) \in \mathcal{E}$ is said to be bidirected. If $a_{ij} = a_{ji}$, the network is undirected. The set of neighbors of node v_i is denoted by $\mathcal{N}_i = \{v_j \in \mathcal{V} : (v_j, v_i) \in \mathcal{E}\}$.

Definition 1 ([9]). Consider a multi-agent system with N agents and let x_i represent the state of agent i. If $\lim_{t\to\infty} \|x_i(t) - x_j(t)\| = 0$, for all $i, j = 1, 2, \ldots, N$, it is said that the multi-agent system can reach consensus. Furthermore, if there exists a leader whose state is $x_0(t)$, then $\lim_{t\to\infty} \|x_i(t) - x_0(t)\| = 0$, for all $i = 1, 2, \ldots, N$, means the tracking consensus is achieved.

3 Distributed cooperative variable structure control

VSC is an efficient anti-disturbance control method [28], composed of a pair of systems called variable structure systems (VSSs) and a switching law [29–32]. The switching law defines the switching rules for the systems of how to switch among VSSs so as to present stable system performance, where any single system alone in a VSS may be unstable. Recently, the development of VSC in multi-agent system shows a strong vitality of VSC. With VSC, the multi-agent systems could achieve the distributed cooperative control goal faster (finite-time convergence) [33–37], and thus it has better robust performance against disturbances.

Consider a group of N agents driven by the following dynamics:

$$\dot{x}_i(t) = u_i(t) + d_i(t), \tag{1}$$

where $x_i(t)$, $u_i(t)$, and $d_i(t)$ are the state, control input, and disturbance of agent i. Assume that $\|d_i(t)\|_\infty \leqslant \delta_i$, with $\delta_i > 0$. Consider the following two kinds of control protocols [34, 35]:

$$u_i = -k_i \mathrm{sign}\left(\sum\nolimits_{j\in\mathcal{N}_i} a_{ij}(x_i - x_j)\right), \tag{2}$$

$$u_i = -k_i' \sum\nolimits_{j\in\mathcal{N}_i} a_{ij}\mathrm{sign}(x_i - x_j), \tag{3}$$

where k_i and k_i' are the control gains. One may note that, with control protocol (2), each agent i could switch among two kinds of structures (i.e., $u_i = \pm k_i$). If one takes the multi-agent system with N agents as a whole system, it could have 2^{N-1} kinds of structures. When considering control protocol (3), more structures for each agent in the whole multi-agent system could appear. Fortunately, in [34] it was shown that the robust finite-time consensus of multi-agent system (1) under general directed communication topologies could be achieved with (2) with a properly chosen k_i by constructing a special Lyapunov function. In addition, through analyzing a specially designed Lyapunov function, it was shown in [35] that the multi-agent system (1) without disturbance d_i could achieve finite-time consensus. In fact, the robust finite-time consensus could also be achieved with (3) by choosing some proper control gain k_i'.

As one can see, DCVSC could equip multi-agent system with the ability of achieving distributed cooperative control goal in finite time, as well as excellent robust system performance. While the analysis usually depends on constructing a special Lyapunov function [38–43], and thus could be complicated in designing and analyzing. Furthermore, DCVSC can be improved to solve robust fixed-time consensus problems [44], which has a faster convergence performance comparing with finite-time consensus and the settling time can be independent of the initial conditions. In both [44, 45], several distributed control protocols containing DCVSC were proposed to achieve the robust fixed-time consensus of first-order multi-agent systems with nonlinearity and bounded disturbances.

4 Distributed cooperative sliding mode control

Sliding mode control (SMC) is a special control method derived from VSS. The key to SMC involves a proper design of a special function, called the sliding mode variable. A sliding mode variable equal to zero defines the sliding surface. The main idea of SMC is to drive a system state to the suitably designed sliding surface, and then remain on this surface thereafter. The sliding surface is usually independent of disturbances, and thus is insensitive to disturbances matched with control input. Usually, SMC can be applied to fulfill finite-time control goals [15, 46, 47].

4.1 Dynamics-based design

SMC has the merit that the sliding surface can be reached in finite time, therefore SMC is especially suitable for a class of multi-agent systems driven by chained integrator dynamics with matched disturbances with respect to control. Typically, consider N agents with the nth integrator described by

$$x_i^{(n)} = f_i(X_i, t) + b_i(X_i, t)u_i^\star(t) + d_i(t), \quad i = 1, \ldots, N, \tag{4}$$

where $X_i = [x_i, x_i^{(1)}, \ldots, x_i^{(n)}]^{\mathrm{T}}$, $f_i(X_i, t) : R^{n+1} \times R \to R$ and $b_i(X_i, t) : R^{n+1} \times R \to R$ are two known nonlinear functions representing the dynamics of agent i. Here $x_i(t) \in R$, $u_i^\star(t) \in R$, and $d_i(t) \in R$ are the state, control input, and the external disturbance of agent i, respectively. In addition, $b_i(X_i, t) \neq 0$. Here f_i, b_i, x_i, $u_i^\star$, and d_i are utilized for simplicity thereafter. One can always take $u_i^\star = b_i^{-1}(u_i - f_i)$, and then Eq. (4) becomes

$$x_i^{(n)} = u_i(t) + d_i(t), \quad i = 1, \ldots, N. \tag{5}$$

Usually the disturbance d_i satisfies the following assumptions.

Assumption 1. For each agent i, $i = 1, \ldots, N$, there exists a constant $\delta_i > 0$ such that

$$\|d_i(t)\|_\infty \leqslant \delta_i. \tag{6}$$

Assumption 2. For each agent i, $i = 1, \ldots, N$, there exists a constant $\bar{\delta}_i > 0$ such that

$$\|\dot{d}_i(t)\|_\infty \leqslant \bar{\delta}_i. \tag{7}$$

In some cases, the boundedness of higher-order derivatives of d_i is required, but omitted here.

Suppose that there exists some proper control protocol $\bar{u}_i$ for agent i, such that the distributed cooperative control goal (consensus, tracking consensus, consensus formation) can be achieved for the following nominal multi-agent system:

$$x_i^{(n)} = \bar{u}_i(t), \quad i = 1, \ldots, N. \tag{8}$$

Then, the idea of DCSMC is to design the sliding variable such that the sliding surface or its derivative is just equivalent to the nominal system (8), i.e.,

$$s_i = x_i^{(n)} - \bar{u}_i(t), \tag{9}$$

$$\text{or } s_i = x_i^{(n-1)} - \int_0^t \bar{u}_i(s)\mathrm{d}s. \tag{10}$$

For the sake of uniformity, $x_i^{(0)}$ is used to represent x_i. As long as the sliding surface $s_i = 0$ is reached in finite time, the distributed cooperative control goal is finally solved. Specifically, the control protocol is composed of two parts:

$$u_i = \bar{u}_i + \hat{u}_i, \tag{11}$$

where $\bar{u}_i$ ensures that the distributed cooperative control goal is achieved, while $\hat{u}_i$ steers the disturbed system (5) to the nominal dynamics (8). One can observe from the sliding variable design (9) and (10) that the states of agents are coupled on the sliding surface (designing $\bar{u}_i$ to achieve the distributed cooperative control goal) and the sliding variables are decoupled out of this surface ($s_i = \hat{u}_i + d_i$ with (9), and $\dot{s}_i = \hat{u}_i + d_i$ with (10)), which makes the design of SMC independent.

Two typical researches under this framework are [48, 49]. Both of these researches investigated a class of second-order multi-agent systems. They considered the finite-time tracking consensus and leaderless consensus problems with bounded disturbances, respectively. The sliding variable designed in [48] is of type (10), and $\bar{u}_i$ there is designed as a kind of homogeneous tracking consensus protocol [50] for each follower. The sliding variable designed in [49] has the form of (9), and $\bar{u}_i$ there is designed as a kind of homogeneous leaderless consensus protocol [51] for each agent. The techniques of super-twisting control and a low-pass filter were utilized for designing continuous control protocol $\hat{u}_i$ to weaken the chattering phenomenon in [48, 49], respectively.

4.2 Relative-state-based design

Another consideration is using the relative state to construct the sliding variable. Typically, for first-order multi-agent systems ($n = 1$ in (4)), one can choose the sliding variable as

$$s_i = \sum\nolimits_{j\in\mathcal{N}_i} a_{ij}(x_i - x_j). \tag{12}$$

When all the s_i reach 0, all the states reach an agreement.

As for the second-order multi-agent systems ($n = 2$ in (4)), one can choose the sliding variable as

$$s_i = \sum\nolimits_{j\in\mathcal{N}_i} a_{ij}(x_i - x_j) + \left(\sum\nolimits_{j\in\mathcal{N}_i} a_{ij}(\dot{x}_i - \dot{x}_j)\right)^{[\alpha]}, \tag{13}$$

where $\alpha \geqslant 1$, and $x^{[\alpha]} = \mathrm{sign}(x)|x|^{\alpha}$. Here $\alpha = 1$ results in asymptotical stability of relative states on the sliding surface while $\alpha > 1$ is a first-order terminal sliding variable, and thus the relative states reach the origin in finite time on the sliding surface. In this kind of method, the sliding variables are coupled through states, and the main difficulty lies in designing the control protocol.

In [52] the finite-time tracking problem for the first-order multi-agent systems with unknown dynamics and matched disturbances was considered. In this work, an equation of the type of (12) was constructed for both one leader and multiple leaders situations. In [53] a sliding variable of the type of (13) was utilized with $\alpha > 1$ to solve the finite-time tracking consensus problem for second-order multi-agent systems without unknown dynamics but bounded disturbances, and applied the results to the finite-time tracking problem of multi-robot systems. Owing to the coupling of sliding variables, neighbors' inputs were employed to eliminate the coupling effects in [53]. A sliding variable of the type of (13) was introduced in [54] with $\alpha = 1$ to solve the asymptotic tracking consensus problem of second-order multi-agent systems with unknown dynamics and disturbances, where the boundedness of the first two derivatives of disturbances was required. Furthermore, the results in [53] were extended in [55] to the finite-time tracking problem of higher-order multi-agent systems with bounded disturbances. There, multi-surface sliding control was utilized to introduce sliding surfaces for each order of derivatives of the states in a recursive way.

Under the above discussion, one can find that the coupling among agents and the complicated dynamics causes difficulty in designing DCSMC for multi-agent systems. In [56,57] the tracking problem of second-order multi-agent systems with general unknown nonlinearity and bounded disturbances was considered. Both works use neural networks to handle unknown nonlinearity. In [56] the directed communication topology was considered and sliding variables of form (13) were introduced to deal with bounded disturbances, while Ref. [57] considered the undirected communication topology with a type of fast terminal sliding variable modified from (12).

One can find that the framework introduced in the former subsection relies heavily on the knowledge of the system dynamics, and is invalid especially when there exist unknown nonlinear dynamics, such as f_i is unknown in (4). In the method proposed in this subsection, the sliding variable design is only related to relative states, and thus it is possible to handle unknown dynamics. The combination of DCSMC and other kinds of control methods is a possible scheme for solving the distributed cooperative control of multi-agent systems with more complicated dynamics and more general communication topologies.

5 Distributed cooperative disturbance-observer-based control

The disturbances discussed in the previous two sections are assumed bounded, and non-smooth feedback-type control protocols are required to eliminate the effects caused by disturbances, which may have lower response speed to disturbances and could sacrifice part of system performance (chattering phenomenon). Another idea for dealing with disturbances is to estimate and compensate for the disturbances so that the systems can have faster response speed to disturbances and can have better system performance. One typical method is the DOBC.

DOBC is composed of two parts [14, 27, 58]. One part is used to stabilize the nominal system and achieve ideal performance. The other is used to compensate for the disturbance. The two parts follow the separation principle, which makes DOBC applicable for handling exogenous disturbances in multi-agent systems. Specifically, DCDOBC in multi-agent systems has two goals: one is to achieve the distributed cooperative control goal for multi-agent systems with nominal dynamics; the other is that each agent attenuates their own disturbances separately.

Consider a group of N agents with the following dynamics:

$$\dot{x}_i = h_i(x, u_i + d_i), \tag{14}$$

$$\begin{cases} \dot{\xi}_i = a_i(\xi_i), \\ d_i = c_i(\xi_i), \quad i = 1, \ldots, N, \end{cases} \tag{15}$$

where $x_i \in \mathbb{R}^m$ is the state of agent i, ξ_i and d_i are the state and output of matched exogenous disturbance dynamics with appropriate dimensions, respectively. In addition, h_i is the system dynamics, and $x = [x_1^{\mathrm{T}}, \ldots, x_N^{\mathrm{T}}]^{\mathrm{T}}$ in h_i represents the coupling among neighbors. In some related literature on DOBC, the exogenous disturbance system is assumed to be a linear system, described as

$$\begin{cases} \dot{\xi}_i = A\xi_i, \\ d_i = C\xi_i, \end{cases} \tag{16}$$

where $(A,\ C)$ is assumed to be observable.

In general, u_i is designed as

$$u_i = u_i^{co} - \hat{d}_i, \tag{17}$$

where u_i^{co} is the control protocol to achieve the distributed cooperative control goal considering the nominal multi-agent system:

$$\dot{x}_i = h_i(x, u_i^{co}), \quad i = 1, \ldots, N. \tag{18}$$

In addition, $\hat{d}_i$ is the estimation of d_i, which is obtained by constructing an observer for (15).

In [59], Yang et al. considered the consensus problem of a class of first-order multi-agent systems with nonlinear couplings and disturbances generated by a linear exogenous system. Both fixed and switching communication topologies were discussed there. In [60], a tracking consensus problem for first-order multi-agent systems was considered, where each follower is affected by disturbances generated by a linear exogenous system. Based on [59], Yang et al. further investigated the consensus problem of first-order multi-agent systems with more complicated dynamics in [61, 62]. Yang et al. [62] considered that in the exogenous system, the generated disturbances has modeling uncertainty. There, the exogenous disturbance cannot be estimated exactly, and thus the distributed robust H_∞ controller was introduced for each agent to achieve consensus. In [61], the dynamics of each agent was assumed to be affected by time delay. In addition, all the agents were affected by disturbances generated by a linear exogenous system, as well as unknown bounded disturbances. Yang et al. [63] and Zhang and Liu [64] discussed the consensus problem of second-order multi-agent systems. The exogenous disturbances in [63] are generated by linear systems, while in [64] disturbances can be generated by a nonlinear exosystem, which is more general.

Ding [65] provided another aspect to treat exogenous disturbances. If the disturbances existing in each agent are generated by the same system, then there is no need to reject the disturbances completely. One only needs to eliminate the difference among disturbances, which could affect common trajectories from being achieved. In addition, only the relative state information is used for difference elimination. There, the consensus problem of a linear multi-agent system was considered. A state observer was designed since only relative state information is available, and a consensus disturbance observer was designed to eliminate the difference among the disturbances in each agent.

6 Distributed cooperative output regulation control

As one can see, most DCVSC, DCSMC, and DCDOBC take disturbances as negative influences on the systems. Similar to [65] mentioned above, another way to treat disturbances is to consider them as part of a system, and then there is no need to eliminate the influence caused by disturbances completely. Output regulation control is one such idea.

DCORC means that designing a distributed control protocol to make multi-agent systems achieve asymptotic tracking of a common reference input and/or maintain asymptotic rejection of disturbances. Usually, the distributed cooperative output regulation problem of multi-agent systems can be viewed as a generalization of the leader-following output consensus problem with a leader generated by an exosystem that lumps the reference input and disturbances together, because it will not only address the issue of asymptotic tracking, but also address such issues as disturbance rejection, robustness with respect to parameter uncertainties. In the last few years, the distributed cooperative output regulation problem has been extensively investigated by many researchers [23–25, 66–79].

Roughly, designing a distributed control protocol to solve the distributed cooperative output regulation problem can be concluded as three steps: (i) solving the regulator equations corresponding to the multi-agent systems; (ii) designing a dynamic compensator to estimate the states of the leader (or the exosystem), which is also called an internal model or a distributed observer; (iii) using the solution of the regulation equation and the internal model to design a distributed controller. By embedding the internal models into the controller, the distributed cooperative output regulation problem can be converted into a stabilization problem for an augmented multi-agent system.

Specifically, taking a linear multi-agent system as an example, consider the following multi-agent system with N agents under a directed graph described by

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_i u_i + E_i \omega, \\ e_i &= C_i x_i + D_i u_i + F_i \omega, \quad i = 1, 2, \ldots, N, \end{aligned} \tag{19}$$

where $x_i \in \mathbb{R}^{n_i}$, $e_i \in \mathbb{R}^{p_i}$, and $u_i \in \mathbb{R}^{m_i}$ are the state, regulated output, and control input of the ith agent, $i = 1, 2, \ldots, N$. The exogenous signal $\omega \in \mathbb{R}^q$, which can be viewed as a leader, represents the reference input to be tracked or the disturbances to be rejected, and is assumed to be generated by a so-called exosystem whose dynamic is given by

$$\dot{\omega} = S\omega. \tag{20}$$

Assumption 3. At least one agent in system (19) can access the exogenous signal ω (the leader's information) and there exists a spanning tree with the leader being the root.

Assumption 4. We assume that S has no eigenvalue with negative real parts.

Remark 1. Assumption 4 is often given in linear systems for convenience because the models corresponding to those eigenvalues with negative real parts will decay to zero. In fact, in nonlinear systems, it is usually assumed that the exosystem is neutrally stable, i.e., all the eigenvalues of S are semi-simple with zero real parts.

Assumption 5. The pairs (A_i, B_i), $i = 1, 2, \ldots, N$, are stabilizable.

Assumption 6. The linear matrix equations, which are called the regulator equations of system (19),

$$\begin{aligned} X_i S &= A_i X_i + B_i U_i + E_i, \\ 0 &= C_i X_i + D_i U_i + F_i, \quad i = 1, 2, \ldots, N, \end{aligned} \tag{21}$$

have solution pairs $(\boldsymbol{X}_i, \boldsymbol{U}_i)$, respectively.

Designing a dynamic compensator with the state $\eta_i \in \mathbb{R}^q$ as follows:

$$\eta_i = S\eta_i + \mu \left(\sum_{j=1}^{N} a_{ij}(\eta_j - \eta_i) + a_{i0}(\omega - \eta_i) \right), \tag{22}$$

where μ is a positive constant, $a_{i0} > 0$ if agent i can access the information of the leader directly, otherwise $a_{i0} = 0$.

Then a distributed dynamic state feedback control law can be designed as

$$\begin{aligned} u_i &= K_{1i}x_i + K_{2i}\eta_i, \quad i = 1, 2, \ldots, N, \\ \eta_i &= S\eta_i + \mu\left(\sum_{j=1}^{N} a_{ij}(\eta_j - \eta_i) + a_{i0}(\omega - \eta_i)\right), \end{aligned} \tag{23}$$

where K_{1i} is a matrix such that $A_i + B_iK_{1i}$ is Hurwitz, and $K_{2i} = \boldsymbol{U}_i - K_{1i}\boldsymbol{X}_i$.

Remark 2. It is well known that there exists K_{1i} such that $A_i + B_iK_{1i}$ is Hurwitz under Assumption 5.

Definition 2 (Linear distributed cooperative output regulation problem [74])**.** Given the systems (19) and (20), and the digraph consisting the leader and followers, find a distributed law (23) such that:

(1) the origin of the closed-loop system is asymptotically stable when ω is set to zero;

(2) for any initial condition $x_i(0)$, $\eta_i(0)$, $i = 1, 2, \ldots, N$, and $\omega(0)$, the tracking error satisfies $\lim_{t\to\infty} e_i(t) = 0$, $i = 1, 2, \ldots, N$.

The distributed control law (23) can solve the distributed cooperative regulation problem by choosing a proper μ.

Recently, a number of results have been reported on the linear distributed cooperative output regulation problem [23–25, 66–76]. For example, Refs. [24, 72] studied the robust distributed cooperative output regulation for linear multi-agent systems with parameter uncertainties. Su and Huang [74] designed two types of control laws called distributed dynamic state feedback and distributed dynamic measurement output feedback under a switching communication topology. To overcome global information in the observer gain, Li et al. [75] designed an adaptive distributed observer for distributed cooperative linear output regulation of heterogeneous multi-agent systems with periodic switching topology. In the above results, the assumption that each follower knows the system matrix of the leader system is needed. To remove this assumption, Cai et al. [76] proposed an adaptive distributed observer to estimate both the system matrix and the state of the leader system, and an adaptive algorithm to calculate the solutions of the regulator equations online.

More recently, the distributed cooperative output regulation problem has been further studied for various nonlinear multi-agent systems [77–85]. In particular, a local result for multi-agent systems composed of general nonlinear dynamics was presented in [77] and a global result for a class of nonlinear multi-agent systems was given in [80] under a static communication graph. Furthermore, Liu and Huang [81] extended this problem to the case where the communication graph is switched with an appropriate average dwell time. Liu [82] proposed an adaptive control law to solve the nonlinear distributed cooperative output problem when control direction is unknown by using the Nassbaum gain technique. Su and Huang [83] investigated the distributed cooperative global output regulation problem for a class of heterogeneous second-order nonlinear uncertain multi-agent systems. Ding [84] studied this problem for a class of multi-agent systems where each agent has a nonlinear system in the output feedback form with relative degree one.

Observing the above research, one can find that the DCORC can efficiently solve the consensus problem for a class of heterogenous multi-agent systems with each agent having different dynamics, which is very challenging in consensus control. Furthermore, it can handle the consensus problem for multi-agent systems with parameter uncertainties. However, it is very complicated to design a distributed control protocol by using the internal model-based method, especially for nonlinear systems, since it requires some standard assumptions such as the existence of solutions for regulator equations and the stabilizable condition. Owing to the complexity of the design procedure, it is hard to extend asymptotic consensus to finite-time consensus to achieve a higher convergence rate.

7 Further discussion on distributed cooperative anti-disturbance control

As mentioned in the previous sections, the DCADC is the organic bond of multi-agent systems and anti-disturbance control methods for single systems, and thus the evolution of DCADC methods is based on the research on anti-disturbance control methods for single systems. Owing to the length limit and of course the limitation of the authors' knowledge, it is impossible to cover all the anti-disturbance methods in detail. In this section, in addition to the methods mentioned above, some other anti-disturbance control methods are reviewed briefly to make this overview self-contained.

In fact, there are lots of classical anti-disturbance control methods for single systems. For example, H_∞ control [19], backstepping control [20], robust adaptive control [21], and active-disturbance-rejection control (ADRC) [22].

When it comes to distributed robust H_∞ consensus in multi-agent systems, agents with external disturbances and model uncertainties are usually considered, and the final consensus should satisfy the H_∞ performance index. Suppose each agent has the following dynamics:

$$\dot{x}_i(t) = u_i(t) + d_i(t), \quad i = 1, \ldots, N, \tag{24}$$

with $x_i(t_-) = x_i(0)$, $t_- \in (-\infty, 0]$, where $u_i(t)$ is the control input, $d_i(t) \in \mathcal{L}_2[0,\infty)$ is the external disturbance. Design the control input as

$$u_i = \sum\nolimits_{j\in\mathcal{N}_i} (a_{ij} + \Delta a_{ij})[x_j(t) - x_i(t)], \tag{25}$$

where Δa_{ij} denotes the uncertainty of a_{ij}, which reflects the modeling uncertainty. Define the relative state by

$$z_i = x_i - \frac{1}{N}\sum_{j=1}^{N} x_j, \quad i = 1, \ldots, N. \tag{26}$$

Let $z = [z_1^{\mathrm{T}}, \ldots, z_N^{\mathrm{T}}]^{\mathrm{T}}$ and $d = [d_1^{\mathrm{T}}, \ldots, d_N^{\mathrm{T}}]^{\mathrm{T}}$. Then define the H_∞ performance index with level γ for the multi-agent system (24),

$$J(d) = \int_0^\infty [z(t)^{\mathrm{T}} z(t) - \gamma^2 d(t)^{\mathrm{T}} d(t)]\,\mathrm{d}t. \tag{27}$$

Definition 3. The robust H_∞ consensus of multi-agent system (24) is said to be achieved if $J(d) < 0$ with level γ.

Lin et al. [86] considered the robust H_∞ consensus problem of multi-agent system (24). Some sufficient conditions for achieving this goal were investigated. Control input with time delay was also discussed in [86]. Lin and Jia [87] further considered the robust H_∞ consensus problem for second-order multi-agent systems. The robust H_∞ consensus problem for general linear multi-agent systems has also been investigated in [88–90].

As for distributed cooperative ADRC of multi-agent systems, since ADRC focuses more on single real systems, there are few researches about this topic. As the foundation of ADRC, the extended state observer (ESO) is practical in observing inner and outer disturbances of uncertain systems [16–18, 91]. Thus, ESO can be used in other kinds of DCADC methods to deal with disturbances in multi-agent systems. In [92], the tracking consensus problem of general linear multi-agent systems with matched unknown external disturbances was considered. A distributed ESO based on relative output information was proposed to estimate the disturbance for each agent. Then, the disturbances were compensated for by the estimation.

Similar to ESO, a sliding-mode differentiator is another type of disturbance observer generated from sliding-mode control, which can estimate a class of differentiable disturbances in finite time. In [93], the drive-response problem was investigated, where the responder was a class of nonlinear systems in the block controllable form [94] affected by matched and mismatched disturbances. A high-order sliding-modes differentiator was applied to estimate those disturbances in finite time, and the backstepping control was employed to make the responder track the driver asymptotically.

Another two methods, backstepping control and robust adaptive control, are usually combined with other anti-disturbance control methods. Backstepping approach provides a recursive method for stabilizing the origin of a system in strict-feedback form. Thus, the backstepping method can be used in higher-order multi-agent systems with other anti-disturbance control methods to reject disturbances completely. Robust adaptive control can adjust the control gain online, so it can be applied in multi-agent systems with other anti-disturbance control methods to provide new types of fully distributed anti-disturbance control methods. The work mentioned in [55] shows the combination of backstepping control and sliding-mode control to solve the consensus problem of higher-order disturbed multi-agent systems. In [75, 76] methods were given to combine adaptive control and output regulation for solving consensus problems.

As one can see, the combination of two or more DCADC methods can unite the advantages of these methods to deal with the effect of composite and complicated disturbances on multi-agent systems.

8 Distributed cooperative anti-disturbance control: a revisit

DCADC in multi-agent systems is not just suitable for handling disturbances, it can also be employed to deal with other problems.

Consider the tracking consensus problem of the following multi-agent system with linear dynamics:

$$\dot{x}_i = Ax_i + Bu_i, \quad i = 0, 1, \ldots, N, \tag{28}$$

where the agent labeled with 0 is assumed to be the leader, and the others are followers.

Assumption 7. Assume that the leader's control input u_0 is continuous and bounded, i.e., $\|u_0\|_\infty \leqslant \gamma$, with $\gamma > 0$.

When analyzing the dynamics of $e_i = x_i - x_0$:

$$\dot{e}_i = Ae_i + B(u_i - u_0), \quad i = 1, \ldots, N, \tag{29}$$

the input u_0 of the leader can be treated as a bounded disturbance. Then, the DCADC method can be applied to solve such kinds of tracking consensus problems. Li et al. [95] proposed a discontinuous control protocol to achieve the tracking consensus goal and reject the equivalent disturbance (i.e. the leader's bounded input) at the same time. Since the spectrum information of the communication topology and the bound of the leader's input are impossible to be known to all the followers, Li et al. also proposed an adaptive law to update the coupling gain in u_i to abandon the use of these two kinds of global information. In addition, the communication among followers is undirected and connected. Li and Liu [96] further considered the tracking consensus problem for a linear multi-agent system when only relative output information can be obtained. Based on the former two works, Lü et al. expanded these results to the situation that communication topology is generally directed in [97, 98]. Unlike the aforementioned researches, in [95–98] consensus tracking and disturbance rejection were achieved at the same time. Notice that the communication topology is an important factor for rejecting disturbances. Thus, the difficulty of [97, 98] compared with [95, 96] lies in the directed communication topology, which makes the DCADC more complicated. Furthermore, with such kind of idea, Fu and Wang [99] solved the fixed-time tracking consensus problem of a class of second-order multi-agent systems by constructing a fixed-time observer for the leader with bounded input. In [100], the fixed-time tracking consensus problem was discovered with the leader having a bounded velocity. In addition, Hong et al. [101] considered the fixed-time distributed average tracking problem with the time-varying reference signals having bounded derivatives.

As one can see, the idea of DCADC can also be powerful when dealing with other kinds of distributed cooperative control problems. The investigation of DCADC is far from being complete.

9 Conclusion

The development of DCADC methods in multi-agent systems partly depends on the development of disturbance control for single systems and partly depends on the development of the distributed cooperative control of multi-agent systems with nominal dynamics. However, because the disturbances could be composite and even very complicated, the DCADC in multi-agent systems has its own characteristics compared with the anti-disturbance control in single systems. This literature review has provided a brief overview of DCADC methods in multi-agent systems. The DCSMC, DCDOBC, and DCORC have been reviewed and some other methods have been discussed briefly. DCADC is a very realistic research topic and has many applications in real-world systems. The theoretical research and practical application of cooperative anti-disturbance control have just started. More effort should be devoted to this research area.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 61673107, 61673104), National Ten Thousand Talent Program for Young Top-notch Talents, Cheung Kong Scholars Programme of China for Young Scholars, and Fundamental Research Funds for the Central Universities of China (Grant No. 2242016K41058).

Conflict of interest The authors declare that they have no conflict of interest.

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