Coordination and Control of Complex Network Systems With Switching Topologies: A Survey

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***Abstract*—A great deal of attention from various scientific communities has been recently drawn to complex network systems (CNSs), with many profound results established in this active research field. This article provides a state-of-the-art survey on coordination and control of CNSs with switching network topologies, with emphasis on relationships between the switchings among different topology candidates and the network controllability, and between the switchings among different topology candidates and the emergence of coordination behaviors (including synchronization, consensus, and containment) of such CNSs. First, some fundamental properties of CNSs and the essentials of analytical methodologies for the stability of the fixed point of switched dynamical systems are briefly reviewed. Then, network controllability and the emergence of coordination behaviors of CNSs with switching topologies and the corresponding analytical approaches are discussed in detail, where some of the existing results along these topics are presented in a tutorial-like fashion. This article ends by presenting some interesting future research topics on the coordination and control of CNSs with switching topologies.**

***Index Terms*—Controllability, distributed coordination, fast switching, slow switching, switching topology.**

I. Introduction

FAR FROM being separate entities, many social and engineering systems can be considered as complex network systems (CNSs) associated with tight interactions among neighboring entities within them [1]–[4]. Prototypical examples include scientific collaboration networks, the Internet, power grids, multiple unmanned aerial systems, and various biological networks, to name just a few.

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Roughly speaking, a CNS refers to a networking system that is made up of lots of interactional individuals and could exhibit fascinating collective behaviors that cannot be anticipated from the inherent properties of the individuals themselves. Conceptually, the CNSs discussed in this article include complex dynamical networks (CDNs) and multiagent systems (MASs) as special cases. A lot of new research challenges have been raised about understanding the emergence mechanisms responsible for various coordination behaviors as well as global statistical properties of CNSs [5], [6]. Network science, as a strong interdisciplinary research field, has been established at the first ten years of 21st century [5]–[12]. It is increasingly recognized that a detailed study on controllability and coordination of CNSs would not only help researchers understand the evolution mechanism for macroscopical coordination behaviors, such as flocking and synchronization but also prompt researchers to utilize theoretical results in network science to solve various engineering problems, e.g., design of distributed sensor networks [13], formation control of multiple robots [14], distributed localization [15], and load assignment of multiple energy storage units in modern power grid [16].

Critical issues arising in coordination and control of CNSs include network controllability analysis [9]–[11], synchronization control of CDNs [12], [17]–[21], distributed consensus [22]–[26], and containment control [27], [28] of MASs. Specifically, network controllability describes our ability to drive the states of each individual within the networking systems from any initial states to any given final states infinite time, with suitable selections of driving nodes and appropriate control inputs [11]. Synchronization of CDNs exhibits the coordination behavior that the states of all entities within these networks achieve an agreement on some quantities of interest. Compared with stability analysis of an isolated control plant, analyzing the emergence of synchronization behavior for CNSs is much more challenging as the synchronization process is determined by the evolution of network topology as well as the inherent dynamics of individual units within these network systems [17]–[22]. As a closely related topic to synchronization of CDNs, consensus of MASs has recently gained much attention from various research fields, especially the systems science, control science and engineering, and electrical engineering communities [22]–[26]. The containment control problem arises generally in the coordination of multiple-leader multiple-follower MASs of which the coordination objective is to regulate the states or outputs of followers to evolve, respectively, onto some static or dynamic regions formed by those of the leaders, which has also received compelling research attention in the last decade [27]–[29].

Within the context of CNSs, a number of practical factors may lead to switching phenomena in underlying network topology, such as the addition or deletion of several links in evolving networks, external interferences on communication channels and limited sensing radius for some complex engineering networks. For example, many modern large-scale infrastructures can be modeled as CNSs with switching topologies, such as power grids, which are subject to transmission line switching [30] or communication line switching [31] during operations. As the effect of switchings on the evolution of CNSs with switching topologies should be fully considered, the methodologies that can be utilized to efficiently analyze and control such network systems are often completely different with those developed for CNSs with fixed topology [26], [32]–[34]. For example, synchronization-region-based analysis approaches [17], [35] are powerful tools for analyzing synchronization of coupling dynamical systems with fixed topology, such approaches are however invalid to synchronization of CNSs with switching topologies as there generally does not exist a common similarity transformation to simultaneously convert the Laplacian matrices of all possible interaction graphs (communication topologies) to their corresponding Jordan canonical forms. Moreover, though a number of methodologies for analysis and control of switched dynamical systems have been established in the past few decades [36]–[40], most of these methodologies can not be directly applied to CNSs with switching topologies as they do not scale well with the dimensions of the state space for the switched systems.

The motivations for writing this survey are manifold. A number of new methods have been developed in the literature during the last decade to analyze the network controllability and explore the emergence mechanisms for various coordination behaviors of CNSs with switching topologies, which are not covered in existing surveys [41]–[44] and tutorials [12], [32], [45]. It has been increasingly obvious that the related fields are mature enough to deserve a survey classifying the existing analytical approaches, the models used and the results for CNSs with switching topologies from systems and control perspective. In this survey paper, we offer our views of present challenges and survey recent advances on network controllability and coordination behaviors of CNSs under switching topologies, with emphasis on surveying the quantitative results and important analysis approaches for such CNSs. For the purpose of providing a clear and well-structured survey paper, we carefully classify the existing analysis methods for coordination and control CNSs with switching topologies based on some concepts in the field of analysis and control of switched dynamical systems.

The remainder of this survey paper is structured as follows. We present some preliminaries on graph theory, switched dynamical systems and CNSs in Section II. We introduce the major kinds of models for CNSs with switching topologies, and then review the corresponding analytical approaches on controllability, synchronization, consensus, and containment control of these CNSs in Section III. At last, we conclude the work and provide some future research directions in Section IV.

II. Preliminaries

This section recalls some preliminaries on graph theory, fundamentals on stability analysis of the fixed point of switched dynamical systems and some fundamentals on controllability and coordination of CNSs.

A. Preliminaries on Fixed and Switching Interaction Graphs

The interaction topology of a CNS can be conveniently described by a graph where the vertices represent the units within the considered CNS and the links are used to mimic the interactions among the units. Denote by $\mathcal{G}(\mathcal{V},\mathcal{E},\mathcal{A})$ the digraph associated with the set of vertices $\mathcal{V}=\{v_1,v_2,\ldots,v_N\}$, a set of links $\mathcal{E}\subseteq\mathcal{V}\times\mathcal{V}$, and an adjacency matrix $\mathcal{A}=[a_{jk}]_{N\times N}$ with non-negative elements. Suppose that $a_{jk}>0$, one may denote by $e_{jk}=(v_k,v_j)\in\mathcal{E}$ a link in $\mathcal{G}(\mathcal{V},\mathcal{E},\mathcal{A})$ where v_k and v_j are, respectively, called the parent and child vertices, and vertex v_k is a neighbor of vertex v_j. In the context of CNS, vertex v_k is a neighbor of vertex v_j implies that v_j can get access to the information of v_k. $\mathcal{G}(\mathcal{V},\mathcal{E},\mathcal{A})$ is called an undirected graph if $\mathcal{A}$ is symmetric. For the sake of simplicity, denote $\mathcal{G}(\mathcal{V},\mathcal{E},\mathcal{A})$ by $\mathcal{G}(\mathcal{A})$ if no confusion will arise. The Laplacian matrix $\mathcal{L}=[l_{jk}]_{N\times N}$ associated with $\mathcal{G}(\mathcal{A})$ is defined as $l_{jk}=-a_{jk}$, $j\neq k$, and $l_{jj}=\sum_{m=1,\,m\neq j}^{N}a_{jm}$, for $j=1,2,\ldots,N$.

To facilitate modeling of CNSs under switching topologies, we introduce a piecewise-constant function (switching signal) $\sigma(t):[0,+\infty)\mapsto\mathcal{S}$ to describe the switching actions among different topology (graph) candidates where $\mathcal{S}=\{1,2,\ldots,s_0\}$ indicates the index set of all the possible topology candidates. For convenience, denote the set of natural numbers by $\mathbb{N}$. Assume that $[t_i,t_{i+1})$, $i\in\mathbb{N}$, is an infinite sequence of nonoverlapping and uniformly bounded time intervals with $t_0=0$, $t_{i+1}-t_i\geq\tau_0>0$, at which the underlying interaction topology is fixed. The time sequence $t_0,t_1,\ldots$ is called the switching sequence, over which the underlying topology changes. Here, the positive scalar τ_0 is usually called the dwell time (DT) for switching signal $\sigma(t)$. For notational brevity, let $\mathcal{G}(\mathcal{A}^{\sigma(t)})$ be the interaction graph of the considered CNS with N individual systems at time t. The Laplacian matrix of $\mathcal{G}(\mathcal{A}^{\sigma(t)})$ is represented by $\mathcal{L}^{\sigma(t)}=[l_{jk}^{\sigma(t)}]_{N\times N}$.

B. Preliminaries on Switched Systems

As a special kind of hybrid dynamical systems, switched systems have been studied for quite some time by researchers from applied mathematics, systems and control fields [36]. Roughly speaking, a switched system is a dynamical system that consists of a number of subsystems and a switching rule that determines switchings among these subsystems [40]. Before moving forward, the notion of average DT (ADT) for a given switching signal $\sigma(t)$ is given as follows.

Definition 1 [46]: Use $N_\sigma(t,T)$ to denote the number of switchings of $\sigma(t)$ during the time interval (t,T) for any given $T>t\geq 0$. The scalars $\tau_a>0$ and $N_0\geq 0$ are, respectively, called the ADT and chatter bound of $\sigma(t)$ if the following inequality holds:

$$N_\sigma(t, T) \leq N_0 + (T - t)/\tau_a. \tag{1}$$

Remark 1: The essence of the ADT condition given in (1) is that there may exist some consecutive switchings separated by the time intervals with length less than τ_a, but the length of the average time interval between consecutive switchings should not be less than τ_a. More precisely, inequality (1) implies that, for $N_0 > 0$, the average length of time intervals between consecutive switchings should not be less than τ_a by discarding the first $\lceil N_0 \rceil$ switchings, where $\lceil N_0 \rceil$ represents the smallest integer larger than N_0 [37], [46]. Note also that $N_0 = 0$ means that there is no switching over any given time interval.

Switched systems can be categorized into different categories from different perspectives. For example, switched systems can be categorized into switched nonlinear and switched linear systems according to the inherent dynamics of their subsystems. Furthermore, according to whether there is an explicit constraint for lower bound of the DT or ADT for switching signals, switched systems can be divided into slow switched systems and fast switched systems. Yet, switched systems can be generally classified into switched systems with time-dependent switchings and those with state-dependent switching signals according to whether the switching signals depend on the internal states of the systems under consideration. Generally, continuous- and discrete-time switched nonlinear systems can be, respectively, described by

$$\dot{z}(t) = f_{\widetilde{\sigma}(t)}(z(t), u(t)) \tag{2}$$

and

$$z[k+1] = f_{\widetilde{\sigma}[k]}(z[k], u[k]) \tag{3}$$

of which $t \in [0, +\infty)$, $k \in \mathbb{N}$, $\widetilde{\sigma}(t)$ and $\widetilde{\sigma}[k]$ are the switching signals such that $\widetilde{\sigma}(t), \widetilde{\sigma}[k] \in \mathcal{Q}$ with $\mathcal{Q} = \{1, 2, \ldots, q_0\}$ being the index set of subsystems, q_0 is a given positive integer, $z(t) \in \mathbb{R}^n$ and $z[k] \in \mathbb{R}^n$ are, respectively, the state vectors of the switched systems (2) and (3) with $\mathbb{R}^n$ being the set of n-dimensional real column vectors, $u(t)$ and $u[k]$ are the control inputs. Particularly, continuous- and discrete-time switched nonlinear autonomous systems can be, respectively, described as

$$\dot{z}(t) = f_{\widetilde{\sigma}(t)}(z(t)) \tag{4}$$

and

$$z[k+1] = f_{\widetilde{\sigma}[k]}(z[k]). \tag{5}$$

Let $\mathbf{0}_n$ be the n-dimensional column vector with each element being 0. Assume that $z_{eq} = \mathbf{0}_n$ is a fixed point for switched systems (4) and (5). Stability of the zero fixed point for switched systems (4) and (5) has been extensively studied by using common Lyapunov function (CLF)- and multiple Lyapunov functions (MLFs)-based approaches. Note that the stability of the zero fixed point for switched systems (4) and (5) depends not only on the inherent properties of subsystems but also upon the switchings determined by the switching signals. It is also worth noting that various CNSs can be modeled as such switched systems, e.g., the CDNs studied in [47] and [48]. Suppose that each subsystem in switched systems (4) and (5) is a linear and autonomous system, one may then get the continuous- and discrete-time switched linear autonomous systems as follows:

$$\dot{z}(t) = A_{\widetilde{\sigma}(t)} z(t) \tag{6}$$

and

$$z[k+1] = A_{\widetilde{\sigma}[k]} z[k] \tag{7}$$

where $A_i \in \mathbb{R}^{n \times n}$ for each $i \in \mathcal{Q}$. Noticeably, $\mathbf{0}_n$ is a fixed point for switched systems (6) and (7). Analytical techniques for stability of the zero equilibrium for switched system (6) include the CLF- and MLFs-based approaches while the corresponding analytical techniques for (7) include the CLF-based approach and the analytical method based on Schur stability test for products of system matrices [37], [38], [40]. Specifically, under the condition that A_i is Hurwitz stable for each $i \in \mathcal{Q}$, it was shown in [36] that the zero fixed point of switched linear systems (6) is globally asymptotically stable for any given time-dependent switching signal $\widetilde{\sigma}(t)$ with a sufficiently large DT $\widetilde{\tau}_0$ such that $\widetilde{\tau}_0 > \sup_{i \in \mathcal{Q}}\{a_i/\lambda_i\}$, $a_i \geq 0$ and $\lambda_i > 0$ satisfying $\|e^{A_i t}\| \leq e^{a_i - \lambda_i t}$ for all $t \geq 0$. For switched linear systems (6) with both Hurwitz stable and unstable linear time-invariant subsystems, some ADT-based criteria were provided in [49] to ensure the globally asymptotical stability of the zero fixed point of such switched dynamical systems under time-driven switching laws.

Concerning the stability of zero fixed point for fast switched systems, existing research works are mainly focused on continuous-time switched systems with time-dependent fast switchings, see [50]–[52] where some efficient averaging-based approaches have been proposed. It is noteworthy that the solutions of switched systems with time-dependent switchings can be defined in the sense of *Carathéodory* [37].

C. Fundamentals on CNSs

Today, the study of CNSs pervades all scientific communities, ranging from statistical physics to applied mathematics and electronic engineering, and even to neurobiology. Roughly speaking, a CNS contains a large number of individuals interconnected by various links among them. Individuals in different CNSs generally represent different practical or virtual entities and the links among neighboring individuals may also have quite different meanings under different scenarios. The complexities of such systems are mainly reflected in the following two aspects. First, most of practical CNSs contain a huge number of coupled individuals where the traditional analysis methods fail to deal with the high-dimensional networking dynamics. Second, various collective dynamics can be emerged from these systems which cannot be predicted from the intrinsic properties of individuals. Substantial research topics within the context of CNSs include how the underlying topology and the inherent dynamics of individuals influence the emergence of collective behaviors and how to efficiently control the collective behaviors of these CNSs.

1) Controllability of CNSs: One basic issue within the context of control of CNSs is controllability. The controllability of a CNS describes our ability to control the states of individuals in the network system from any initial states to any given final states infinite time. To begin with, we briefly review some fundamentals on structural controllability and state controllability of linear time-invariant system. Consider the following linear time-invariant system:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{8}$$

of which $A \in \mathbb{R}^{n\times n}$ and $B \in \mathbb{R}^{n\times r}$ are, respectively, the system matrix and control input matrix, $x(t) \in \mathbb{R}^n$ denotes the state vector of (8) and $u(t) \in \mathbb{R}^r$ is the control input vector, $t \in [0, +\infty)$. The linear time-invariant system (8) is state controllable if, for any given initial condition $x(0) = x_0 \in \mathbb{R}^n$ and any final state $x_f \in \mathbb{R}^n$, there exist a control input $u(t)$ and a finite time instant t_f such that $x(t_f) = x_f$. The concept of structural controllability for linear time-invariant system (8) was first introduced in [53] where the entries of system matrix and control input matrix are set as either zero or free parameters. Such a system with parameterized system matrix A and control input matrix B is called structurally controllable if there is a set of nonzero parameter values of A and B such that system (8) is state controllable. Recently, many efficient criteria on structural controllability and state controllability of CNSs have been established, including various controllability conditions based on the rank analysis for controllability matrix and different kinds of graphical property-based controllability criteria [54], [55].

2) Synchronization of CDNs: Achieving synchronization in CNSs is critical for controlling these CNSs and thus helpful in dealing with various distributed control problems for practical network systems. For instance, reaching synchronization of velocities for all individual agents is a precondition in achieving flocking in various second-order MASs [56]. In another instance, the frequency synchronization of multiple generator units within a power system is one of the most critical issues in the normal operation of power systems [57]. In addition, clock synchronization among sensors within wireless sensor networks is highly desirable in their applications [58]. It is also worth noting that synchronization problems for CDNs could be classified as local synchronization problem [8], [18] or global synchronization problem [19]–[21]. Specifically, the global synchronization means that the state agreement for all individuals in the networks under consideration can be ensured for any given initial state conditions, while the local synchronization requires that the initial states of individuals be selected within the attractive region of the specific synchronization trajectory under consideration.

Generally, a continuous-time CDN of N coupled nodes with time-dependent switching topologies can be described as [47]

$$\dot{x}_i(t) = f(x_i(t), t) + c\sum_{j=1}^{N} a_{ij}^{\sigma(t)}\Gamma(x_j(t) - x_i(t)) \tag{9}$$

where the nonlinear function $f : \mathbb{R}^n \times [0, +\infty) \mapsto \mathbb{R}^n$ describes the inherent (uncoupling) nonlinear dynamics of node i, $\mathcal{A}^{\sigma(t)} = [a_{ij}^{\sigma(t)}]_{N\times N}$ is the adjacency matrix of network topology at time t with $a_{ii}^{\sigma(t)} = 0$ for all $i = 1, 2, \ldots, N$, $c > 0$ is the coupling strength, $\Gamma \in \mathbb{R}^{n\times n}$ is the inner linking matrix. CDN (9) associated with some given switching signal $\sigma(t)$ is said to achieve global synchronization, if

$$\lim_{t\to+\infty}\|x_i(t) - x_j(t)\| = 0 \quad \forall\, i, j = 1, 2, \ldots, N \tag{10}$$

with $\|\cdot\|$ being the Euclidean norm, for any given initial conditions $x_i(0) \in \mathbb{R}^n\ \forall\, i = 1, 2, \ldots, N$. The definition of synchronization for network (9) given by (10) does not concern about the final synchronization states. However, it is sometimes important to make the states of all individuals in the considered network to finally converge to some predesigned trajectory, especially from the viewpoint of controlling various complex engineering networks. To ensure the states of all individuals in network (9) synchronize to some desired states, a target system is introduced to the network (9) as

$$\dot{s}(t) = f(s(t), t) \tag{11}$$

for some given $s(0) \in \mathbb{R}^n$. The pinning-controlled network (9) with a target system (11) can be generally described as

$$\begin{aligned}\dot{x}_i(t) = f(x_i(t), t) &+ c\sum_{j=1}^{N} a_{ij}^{\sigma(t)}\Gamma\big(x_j(t) - x_i(t)\big)\\ &- cd_i^{\widehat{\sigma}(t)}\Gamma(x_i(t) - s(t))\end{aligned} \tag{12}$$

where $d_i^{\widehat{\sigma}(t)}$ is the pinning gain such that $d_i^{\widehat{\sigma}(t)} > 0$ when node i is selected and pinned at time t and $d_i^{\widehat{\sigma}(t)} = 0$ otherwise. CDN (12) associated with some given switching signals $\sigma(t)$, $\widehat{\sigma}(t)$, and a target system (11) is said to achieve global pinning synchronization, if

$$\lim_{t\to+\infty}\|x_i(t) - s(t)\| = 0 \quad \forall\, i = 1, 2, \ldots, N. \tag{13}$$

Here, both $\sigma(t)$ and $\widehat{\sigma}(t)$ are time-dependent switching signals. Under the condition that the nonlinear function f is continuous over t and globally Lipschitz in $x_i(t)$ uniformly in t, the solutions of systems (9) and (12) exist over the time interval $[0, +\infty)$ in the sense of *Carathéodory* [37].

It is noted that CDNs (9) and (12) can be utilized to model various practical network systems with switching topologies.

3) Consensus of MASs: As a topic closely related to the synchronization of CDNs, the consensus of MASs has aroused tremendous attention from systems and control field in the past decades [22], [24], [25], [59]. Generally, the first-order continuous-time MAS consisting of N agents with a time-dependent switching communication topology could be described as [25]

$$\dot{x}_i(t) = u_i(t) \tag{14}$$

with consensus protocol (controller) given as

$$u_i(t) = -\sum_{j\in\mathcal{N}_i(t)} a_{ij}^{\sigma(t)}[x_i(t) - x_j(t)] \tag{15}$$

of which $x_i(t) \in \mathbb{R}^n$ represents the state vector of agent i at time t, $\mathcal{A}^{\sigma(t)} = [a_{ij}^{\sigma(t)}]_{N\times N}$ is the adjacency matrix of the interaction topology at time t, $\mathcal{N}_i(t)$ is the set of neighbors of agent i (i.e., the set of agents whose information is available to agent i). Consensus in the first-order MAS (14) is achieved if for any given initial conditions, the following holds: $\lim_{t\to+\infty}\|x_i(t) - x_j(t)\| = 0\ \forall i, j = 1, 2, \ldots, N$. Correspondingly, the first-order discrete-time MAS consisting of N agents with a time-varying (switching) communication topology can be described as [25]:

$$x_i[k+1] = u_i[k] \tag{16}$$

with consensus protocol given by

$$u_i[k] = \sum_{j\in\mathcal{N}_i[k]\cup\{i\}} d_{ij}[k]x_j[k] \tag{17}$$

of which $x_i[k] \in \mathbb{R}^n$ represents the state vector of agent i at time point $k \in \mathbb{N}$, $\sum_{j\in\mathcal{N}_i[k]\cup\{i\}} d_{ij}[k] = 1$ and for each $j \in \mathcal{N}_i[k]\cup\{i\}$, $d_{ij}[k] > 0$. Similar to the case with continuous-time dynamics, consensus in MAS (16) is achieved if, for any given $x_i[0] \in \mathbb{R}^n$, the following holds: $\lim_{k\to+\infty}\|x_i[k] - x_j[k]\| = 0\ \forall i, j = 1, 2, \ldots, N$. More recently, consensus problems of MASs with inherent linear or nonlinear dynamics and switching topologies have been formulated and addressed in [60]–[64].

4) Containment Control of MASs: There may exist multiple leaders as well as multiple followers in some practical MASs where the multiple leaders could take the role of guiding all the followers to move onto some prespecified fixed or time-varying regions. To take this into account, containment control of multileader multifollower MASs has been investigated under various scenarios [27]–[29]. The first-order continuous-time multileader multifollower MAS consisting of N agents with a time-dependent switching communication topology and stationary leaders can be modeled as [28]

$$\dot{x}_i(t) = u_i(t), \quad i = 1, 2, \ldots, N \tag{18}$$

with

$$\begin{aligned} &u_i(t) = 0, \quad i \in \mathcal{R} \\ &u_i(t) = -\sum_{j\in\mathcal{F}\bigcup\mathcal{R}} a_{ij}(t)\big[x_i(t) - x_j(t)\big], \quad i \in \mathcal{F} \end{aligned} \tag{19}$$

of which $x_i(t) \in \mathbb{R}$ is the state of agent i, $\mathcal{A}(t) = [a_{ij}(t)]_{N\times N}$ is the adjacency matrix of the interaction topology at time t whose elements are piecewise-constants, symbols $\mathcal{R}$ and $\mathcal{F}$ represent, respectively, the sets of leaders and followers such that $\mathcal{F}\bigcup\mathcal{R} = \{1, 2, \ldots, N\}$. Containment in the first-order continuous-time multileader multifollower MAS (18) under (19) is guaranteed if for any given initial conditions $x_i(0) \in \mathbb{R}$, $i \in \mathcal{F}$, the states of all followers converge to the static region $\mathbf{Co}\{x_j(t), j \in \mathcal{R}\}$, i.e., the stationary convex hull spanned by the states of all leaders. Note that containment control of MAS (18) in the presence of multiple dynamic leaders, containment control of first-order discrete-time multileader multifollower MAS with stationary and dynamic leaders under switching interaction topologies were also addressed in [28]. Containment control problems of first-order continuous- and discrete-time multileader multifollower MAS with high dimensional dynamics were further investigated in [29].

Remark 2: The mathematical definitions for synchronization of CDNs and consensus in MASs are exactly similar. However, some differences between these two topics are briefly summarized as follows from our own viewpoint.

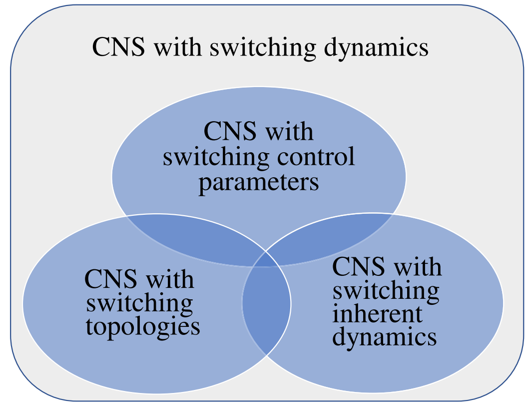

Fig. 1. Simple illustration for the relationships among CNS with switching dynamics, CNS with switching topologies, CNS with switching control parameters, and CNS with switching inherent dynamics.

1) A CDN typically contains a great number of individual nodes (e.g., the protein interaction networks and the Internet) while the scale of an MAS may be relatively quite small (e.g., a team of several robots and a group of unmanned aerial vehicles).
2) The objective of synchronization control is to make the states of a large-scale network achieve state agreement under some given inner linking matrices by selecting only the coupling strength, while the objective of consensus is to make the states of agents achieve state agreement by designing the gain matrices as well as the coupling strength.
3) Significant attention has been paid to revealing the relationship between the qualitative values (e.g., the clustering coefficient, the betweenness of vertices, the degree distribution, and the symmetry) of statistical properties of network topology and the synchronizability of CDNs within the context of synchronization in CDNs, while in the context of consensus of MASs, much attention has been focused on addressing the relationship between the algebraic properties (e.g., the algebraic connectivity for undirected interaction topology and the general algebraic connectivity for directed interaction topology) of interaction topology and the consensusability.

Note also that this article only focuses on surveying some recent results on the coordination and controllability of CNS with switching topologies. Actually, a more broad research field is CNS with switching dynamics that contains CNS with switching topologies, CNS with switching control parameters and CNS with switching inherent dynamics (as shown in Fig. 1).

III. Coordination and Control of CNSs With Switching Topologies

A. Controllability

It is noted that research on the controllability of CNSs with inherent switching dynamics is still at its infancy stage, though quite a few results on the controllability of CNSs with switching topologies have been reported in the literature. From the viewpoint of controlling CNSs with switching topologies, one is particularly interested in the effect of switching actions as well as the connectivity properties of topology candidates on the controllability of such network systems.

By taking the single leader as an external input to some informed following agents, state controllability for a class of discrete-time first-order MASs with switching topologies was addressed in [65] by using tools from the reachability analysis of the switched linear systems. Then, state controllability for discrete-time first- and second-order MASs with multiple leaders and switching topologies were studied in [66]. In [67], some sufficient criteria for state controllability of discrete-time first-order MASs with switching topologies and communication delays were provided. Concerning the MASs with continuous-time dynamics, state controllability of first-order MASs with delayed communication and switching topologies was studied in [68].

Some graph-theoretic characterisations for structural controllability of discrete-time first-order MASs under switching topologies with a single leader or multiple leaders were, respectively, provided in [69]. Two frameworks were suggested in [70] to analyze the structural controllability of switching networks. Based on state controllability analysis of piecewise linear time-varying systems, structural controllability and strong structural controllability for the temporally switching networks were studied in [71] where it was shown that the n temporally independent walks are essential to the structural controllability as well as the strong structural controllability. In [72], a kind of switching controllers with an appropriately selected location at some specific time points were introduced to enhance the structural controllability of a temporally switching network. Structural controllability for MASs with continuous-time second-order, high-order dynamics, and general linear node dynamics were, respectively, studied in [73] where it was shown that the structure of union communication topology plays an important role in structural controllability of the considered MASs. Controllability of continuous-time first-order MASs with periodical switching topologies and switching leaders was analyzed in [74]. More recently, the controllability of first-order MASs with inherent switching dynamics composed of continuous- and discrete-time subsystems have been addressed in [75].

B. Synchronization

Within the field of synchronization in CDNs with switching topologies, a wide range of research has been recently focused on dealing with issues related to the switchings and their effects on synchronization.

There has been an increasing recognition that the properties of each topology candidate and the switching strategy for topological switching play important roles in achieving synchronization for CDNs with switching topologies. The analytical approaches for synchronization of continuous- and discrete-time CDNs with switching topologies are generally different. Mathematically, the continuous-time CDN with switching topologies is a special kind of those with time-varying topology. However, it is preliminarily assumed in some existing works on synchronization of continuous-time network systems with time-varying topology that the connection links evolve continuously over time with a known bound for the changing rate [76] or with a time-varying Laplacian matrix being simultaneously diagonalizable [77]. Thus, the techniques developed in these works to solve the synchronization problem of CDNs with special time-varying topologies are generally hard to apply to that with switching topologies, especially to the case with directed switching topologies.

Specifically, averaging-based approaches were developed to analyze synchronization of continuous-time CDNs with fast switching topologies [78], [79] while MLFs-based approaches were developed to analyze synchronization of continuous-time CDNs with slow switching topologies (especially for the case with directed switching topologies) [47]. Furthermore, common Lyapunov functional (CLFL)- and multiple Lyapunov functionals (MLFLs)-based approaches were usually employed to analyze synchronization of continuous-time CDNs with switching topologies under delayed or sampled-data coupling [80]–[82]. CLFL-based approaches are applicable only to some special continuous-time CDNs with switching topologies, such as each possible topology candidate is undirected [81], [83], [84]. Particularly, the analytic methods for synchronization of continuous-time CDNs with switching topologies can be summarized as follows.

1) *Averaging-Based Approaches:* In [78], synchronization of small-world networks with fast on-off switching links was studied where it was shown that the probability p of switchings for shortcut in blinking CDN model plays a critical role in guaranteeing synchronization. In [79], local synchronization of a kind of complex networks with fast switching undirected topologies was addressed where it was shown that the time-average graph Laplacian is a synchronizability indicator.
2) *CLF- and CLFL-Based Approaches:* In [83], adaptive synchronization of continuous-time CDNs with undirected switching topologies and a target node was studied by using CLF-based approach. Synchronization of CDNs with simultaneously diagonalizable Laplacian matrices and delayed coupling was studied in [80] by constructing CLFL. Some efficient CLF-based criteria for local synchronization of CDNs with undirected switching topologies were provided in [84]. A CLFL was constructed and utilized in [81] to investigate the synchronization problem of a general Kuramoto-type CDN with undirected switching and regular connection graphs. Then, the CLFL-based approach was adopted in [82] to study the pinning synchronization of CDNs with sampled-data coupling. Both local and global synchronization of CDNs with undirected switching topologies were studied in [85] via constructing CLF. It was shown in [85] that the time average of the second smallest eigenvalues of Laplacian matrices associated with topology candidates plays a key role in achieving synchronization. Globally almost sure synchronization of a class of CDNs with stochastically switching topologies was addressed in [86] by constructing CLF and utilizing tools from stochastic stability theory. A general class of CLF was constructed in [87] to analyze

synchronization of CDNs with node dynamics satisfying a global Lipschitz condition under directed switching topologies. By showing that the maximum values of Euclidean norm of relative errors between neighboring nodes have contraction property, synchronization of CDNs with sequentially connected topology was studied in [88]. By transforming the agents' dynamics into unit vectors' dynamics on a sphere of suitable dimension, a kind of CLF was developed in [89] to investigate the attitude synchronization problem of a group of agents in $\mathbb{SO}(3)$ under switching strongly connected directed graphs.

3) *MLFs- and MLFLs-Based Approaches:* In [90], MLFLs-based methods were developed to solve the local and global exponential synchronization of CDNs with undirected switching topologies and delayed coupling where some ADT-based criteria were derived and discussed. By utilizing tools from nonsingular M-matrix theory, a class of multiple quadratic-form Lyapunov functions was proposed in [47] to study the pinning synchronization problem of CDNs with directed switching topologies. The stochastic MLFs-based approach was adopted in [91] to solve the local synchronization problem of CDNs with randomly fast switching topologies.

For discrete-time CDNs with switching topologies, global synchronization for nonautonomous linear CDNs with randomly switching topologies was studied in [92] by developing a kind of approaches from ergodicity theory for nonhomogeneous Markovian chains. A method based on the Hajnal diameter of infinite coupling matrices was proposed in [48] to analyze the local synchronizability of a class of discrete-time CDNs with directed switching topologies. Synchronization of discrete-time CDNs with undirected switching topologies and impulsive controller was studied in [93] by constructing MLFs. Globally almost sure synchronization for discrete-time CDNs with switching topologies was investigated in [94] by using super-martingale convergence theorem.

C. Consensus

Consensus of MASs has recently attracted increasing attention from different scientific fields [2]. Many research works on consensus of MASs under switching topologies are motivated by result of heading consensus on Vicsek's model [95]. The Vicsek's model is an efficient discrete-time model for analyzing the emergence of heading consensus in a group of autonomous particles(agents) moving in the plane with the common velocity $v > 0$ but different headings $\theta_i(k)$ where the dynamic evolution of agent i is described by

$$\begin{aligned} x_i[k+1] &= x_i[k] + v(\cos(\theta_i[k]), \sin(\theta_i[k]))^T \\ \theta_i[k+1] &= \langle\theta_i[k]\rangle_r + \Delta\theta_i[k] \end{aligned} \tag{20}$$

where $x_i[k] \in \mathbb{R}^2$ denotes the position vector of agent i at time point k, $\langle\theta_i[k]\rangle_r$ represents the average headings of the velocities of agent i and its neighbors defined as

$$\langle\theta_i[k+1]\rangle_r = \arctan\left(\frac{\sum_{j\in\mathcal{N}_i(k)} \sin(\theta_j[k])}{\sum_{j\in\mathcal{N}_i(k)} \cos(\theta_j[k])}\right)$$

with $\mathcal{N}_i(k) = \{j : \|x_i[k] - x_j[k]\| < r\}$ for some given $r > 0$, and $\Delta\theta_i[k]$ being a noise variable. Numerical simulations show that headings consensus can be emerged in network systems (20) with a relatively high agent density and small noise [95]. Unfortunately, it is still an open issue how to theoretically explain the emergence of headings consensus in network systems (20) due to the state-dependent topology switching and the inherent nonlinear dynamics of (20). By assuming that the switching mode of underlying topology is time-controlled switching, some rigorous analysis on heading consensus of the linearized Vicsek's model in the absence of noise was provided in [22] and [23]. Since then, the consensus of MASs with switching topologies has attracted increasing attention from a wide range of scientific interests.

1) Consensus of First-Order MASs With Switching Topologies: In the year of 2004, the consensus problem of continuous-time first-order (integrator-type) MASs [defined by (14)] with directed switching and balanced topology was formulated and studied in [24]. Due to the balanced property of each possible topology candidate, a CLF was constructed in [24] for analyzing the convergence behaviors of disagreement vector. Consensus of continuous- and discrete-time first-order MASs with directed switching topologies were further studied in [25] where each possible topology candidate is not required to be balanced. Note that in [25], the consensus problem of discrete-time first-order MASs was studied by using the convergence property of infinite products of stochastic matrices [96] while the consensus problem of continuous-time first-order MASs was studied by transforming such a problem to that of a corresponding discrete-time first-order MASs and then solved by using the tools for consensus of discrete-time first-order MASs. Some interesting issues on consensus of a class of first-order MASs with switching topologies were further addressed in [97] and [98] by using graphical approaches.

In [99], the following protocol was proposed for system (14):

$$u_i(t) = -\sum_{j\in\mathcal{N}_i(t)} a_{ij}(t)[x_i(t-\tau(t)) - x_j(t-\tau(t))] \tag{21}$$

where $\mathcal{N}_i(t)$ is the set of neighbors of agent i at time t, $\tau(t) \geq 0$ is the time-varying delay. By employing a CLFL-based approach, it was proven in [99] that average consensus in system (14) with protocol (21) can be achieved if each topology candidate is strongly connected and balanced, and some linear matrix inequalities hold. The fact that there does not exist a common quadratic Lyapunov function for analyzing consensus of some discrete-time first-order MASs with switching topologies was pointed out in [100]. Note that most of the aforementioned results are mainly concerned with the consensus of first-order MASs with deterministically switching topologies. However, considering the underlying topology may randomly switch among a set of topology candidates in some practical applications, there have been a number of results focusing on the consensus of first-order MASs with randomly switching topologies [101]–[104]. Specifically, without assuming that adapted sequences describing the switching actions are stationary or ergodic, almost sure consensus of first-order discrete-time MASs with stochastic switching topologies and time delays was studied in [104].

2) Consensus of Second-Order MASs With Switching Topologies: Continuous- and discrete-time second-order MASs can be respectively described as

$$\begin{aligned}\dot{x}_i(t) &= v_i(t)\\ \dot{v}_i(t) &= u_i(t)\end{aligned} \tag{22}$$

and

$$\begin{aligned}x_i[k+1] &= x_i[k] + Tv_i[k]\\ v_i[k+1] &= v_i[k] + Tu_i[k]\end{aligned} \tag{23}$$

where $x_i(t)$ (resp. $x_i[k]$) and $v_i(t)$ (resp. $v_i[k]$) are, respectively, the position and velocity states of agent i at time point t (resp. k), $u_i(t)$ and $u_i[k]$ are, respectively, the consensus protocols of systems (22) and (23), $T > 0$ represents the sampling period.

In [105], the following consensus protocol is proposed for (22):

$$u_i(t) = -\sum_{j=1}^{N} g_{ij}k_{ij}[(x_i(t) - x_j(t)) + \gamma(v_i(t) - v_j(t))] \tag{24}$$

of which k_{ij} and γ are positive scalars, $G = [g_{ij}]_{N\times N}$ is a (0, 1)-matrix with zeros on its diagonal and $g_{ij} = 1$ if there is a directed link from j to i. Based on the stability results for switched systems (6) provided in [36], some DT-based criteria for consensus of (22) under directed switching topologies were established in [105] where it was revealed that consensus in (22) with directed switching topologies can be achieved if each topology candidate contains a directed spanning tree and the DT for switchings among different topology candidates is larger than a threshold value. In [106], the following consensus controller was designed for MAS (22):

$$\begin{aligned}u_i(t) = &-\kappa v_i(t) - b_i(t)(x_i(t) - x_0(t))\\ &- \sum_{j\in\mathcal{N}_i(t)} a_{ij}(t)(x_i(t) - x_j(t))\end{aligned} \tag{25}$$

where $x_0(t)$ represents the state vector of the single leader, $b_i(t) > 0$ if the state information of the leader is available to agent i at time t and $b_i(t) = 0$ otherwise, notation $\mathcal{N}_i(t)$ represents the set of agents whose information is available to agent i at time t. With the condition that the graph describing the interaction relationships among followers is undirected, it was proven in [106] by constructing a CLF that leader-following consensus in (22) with controller (25) can be guaranteed if the interaction graph jointly contains a directed spanning tree. Leader-following consensus of MAS (22) with switching jointly reachable interconnection and transmission delays was addressed in [107] by designing the switching laws among topology candidates where the dynamics of the leader are described by first-order integrator. Note that the switching mode for topology evolution of the MASs studied in [107] is a kind of state-dependent switching. The leaderless consensus of (22) with undirected switching topologies was investigated in [108] where the following controller was proposed:

$$u_i(t) = -k_1 v_i(t) + \sum_{j\in\mathcal{N}_i(t)} a_{ij}(t)(x_j(t-\tau) - x_i(t-\tau)) \tag{26}$$

where $k_1 > 0$ is a fixed feedback gain, $\tau > 0$ represents the time-delay, $\mathcal{A}(t) = [a_{ij}(t)]_{N\times N}$ is the adjacency matrix of the switching graph. By constructing a CLFL, it was proven in [108] that consensus of (22) with protocol (26) can be ensured if the underlying interaction graph is jointly connected. Leaderless consensus of MAS (22) with protocol (26) under directed switching topologies was further studied in [109] and [110]. Note that there is no specific restriction for the value of the DT for switching signals in the consensus criteria provided in [106], and [108]–[110] as CLF- and CLFL-based approaches were, respectively, adopted in [106], [108], and [110]. In [111], the following intermittent communication-based protocol was proposed for MAS (22):

$$u_i(t) = \begin{cases} -\alpha\sum_{j=1}^{N} l_{ij}x_j(t) - \beta\sum_{j=1}^{N} l_{ij}v_j(t), & t\in\mathbb{T}\\ \mathbf{0}, & t\in\overline{\mathbb{T}}\end{cases} \tag{27}$$

where $\mathcal{L} = [l_{ij}]_{N\times N}$ is the Laplacian matrix of the strongly connected interaction graph, $\mathbb{T}$ represents the union of time intervals on which the agents could communicate with their neighbors and $\overline{\mathbb{T}}$ represents the union of the time intervals on which the agents could not communicate with their neighbours. The underlying communication topology of the closed-loop MAS (22) with protocol (27) can be seen as a directed switching topologies with two topology candidates: 1) a strong connected graph and 2) the null graph. Some sufficient criteria for consensus of MAS (22) with protocol (27) were derived in [111] by constructing a CLF. Psillakis [112] proposed the following protocol for MAS (22):

$$u_i(t) = b_i\{\kappa R_i(t)\cos(R_i(t))[\rho v_i(t) + \lambda r_i(t)]\} \tag{28}$$

where b_i are the unknown control gains, $R_i(t)$ are PI terms depend on both the absolute position and velocity states of agent i as well as some relative position and velocity states between agent i and its neighbors, κ, ρ, and λ are positive scalars. Under the assumption that each topology candidate is balanced and strongly connected, it is shown that consensus in MAS (22) with protocol (28) can be achieved under switching topologies with any given positive DT. In [113], consensus of MAS (22) with sampled measurement output-based protocol and undirected switching topologies was addressed by proposing the following protocol:

$$u_i(t) = -\sum_{j=1}^{N} a_{ij}[r]\big(k_1 p_{ij}[r] + k_2 p_{ij}[r-1]\big),\quad t\in\big[t_r,\ t_{r+1}\big)$$

of which t_r represents the rth sampling time point, $t_{r+1} - t_r = T$ with some $T > 0$, $p_{ij}[r] = x_i[r] - x_j[r]$, $r\in\mathbb{N}$. Consensus of MAS (22) under pulse-modulated intermittent communication and directed switching topologies was studied in [114] by designing the following protocol:

$$\begin{aligned}u_i(t) = &-\left[\alpha v_i(t_k) + \beta\sum_{j\in N_i} l_{ij}(k)\big(x_j(t_k) - x_i(t_k)\big)\right]\\ &\times a(t - t_k),\quad t\in\big[t_k,\ t_{k+1}\big)\end{aligned}$$

where $\{t_k\}_{k\in\mathbb{N}}$ is the sampling instant sequence satisfying $t_{k+1} - t_k = h > 0$, $\mathcal{L}(k) = [l_{ij}(k)]_{N\times N}$ is the Laplacian matrix of the switching graph at time t_k and $a(t) > 0$ is a piecewise continuous scale pulse function.

Casbeer *et al.* [115] studied consensus of MAS (23) with the following protocol:

$$u_i[k] = -\sum_{j=1}^{N} a_{ij}[k+1]\big[\big(x_i[k] - x_j[k]\big) + \gamma_k\big(v_i[k] - v_j[k]\big)\big] \tag{29}$$

of which $\gamma_k > 0$, for $k \in \mathbb{N}$. By assuming that each topology candidate is strong connected and balanced, some DT-based criteria for consensus of MAS (23) with protocol (29) were provided in [115]. Consensus of MAS (23) with nonuniform time-delays was investigated in [116] by proposing the following protocol:

$$u_i[k] = -p_0 v_i[k] + p_1 \sum_{j=1}^{N} a_{ij}[k]\big(x_j\big[k-\tau_{ij}\big] - x_i[k]\big) + p_2 \sum_{j=1}^{N} a_{ij}[k]\big(v_j\big[k-\tau_{ij}\big] - v_i[k]\big) \tag{30}$$

of which τ_{ij} is a non-negative integer representing the communication time delay from agent j to agent i, p_0, p_1, and p_2 are positive scalars. By utilizing the convergence property of infinite products of stochastic matrices, it was shown in [116] that consensus in the MAS under consideration can be guaranteed if the joint graph of all possible interaction graphs candidates frequently contains a directed spanning tree. In [117], consensus of the following discrete-time second-order MAS with heterogeneous sampling periods was studied:

$$\begin{aligned} x_i(t_{k+1}) &= x_i(t_k) + h_k v_i(t_k) \\ v_i(t_{k+1}) &= v_i(t_k) + h_k\left[\alpha \sum_{j=1}^{N} a_{ij}(t_k)\big(x_j(t_k) - x_i(t_k)\big) + \beta \sum_{j=1}^{N} a_{ij}(t_k)\big(v_j(t_k) - v_i(t_k)\big)\right] \end{aligned} \tag{31}$$

where α and β are positive scalars, h_k is the kth sampling period. By assuming that each possible topology is fully connected, some consensus criteria for consensus of second-order MAS (31) were provided by the approach of estimating the eigenvalues of stochastic matrices. Lin *et al.* [118] studied consensus of MAS (23) with nonconvex velocity and control input constraints under directed switching topologies. It was shown in [118] that consensus can be achieved if the joint graph of the switching communication graphs has a directed spanning tree among each time interval of certain bounded length.

3) Consensus of MASs With General Linear Node Dynamics and Switching Topologies: The continuous-time MAS with general linear node dynamics is described as

$$\begin{aligned} \dot{x}_i(t) &= Ax_i(t) + Bu_i(t) \\ y_i(t) &= Cx_i(t) \end{aligned} \tag{32}$$

where $x_i(t) \in \mathbb{R}^n$, and $y_i(t) \in \mathbb{R}^q$ are, respectively, the state and output vectors of agent i, $A \in \mathbb{R}^{n\times n}$ and $B \in \mathbb{R}^{n\times m}$ are, respectively, the system and control input matrices, $C \in \mathbb{R}^{q\times n}$ is the output matrix, $u_i(t)$ is the protocol to be designed. It is worth noting that system (32) represents the MAS with general linear node dynamics, which includes those with first-order, second-order, and high-order integrator-type dynamics as special cases. For example, system (32) will reduce to the nth order integrator-type MAS if the system parameters are selected such that

$$A = \begin{bmatrix} \mathbf{0}_{n-1} & I_{n-1} \\ 0 & \mathbf{0}_{n-1}^T \end{bmatrix}, \quad B = \begin{bmatrix} \mathbf{0}_{n-1} \\ 1 \end{bmatrix}. \tag{33}$$

Consensus of high-order integrator-type MAS under directed switching topologies was studied in [119] where the following state-feedback-based protocol was designed:

$$u_i(t) = K_1 x_i(t) + \sum_{j\in\mathcal{N}_i(\sigma(t))} \alpha_{\sigma(t)}^{ij} K_2\big(x_i(t) - x_j(t)\big) \tag{34}$$

of which $\mathcal{N}_i(\sigma(t))$ is the set of neighbors of agent i at time t, $\alpha_{\sigma(t)}^{ij}$ represents the communication weight associated with the communication link from agent j to agent i, K_1 and K_2 are two feedback gain matrices with appropriate dimensions to be designed. By employing a carefully selected transformation, consensus problem of the closed-loop high-order MAS considered in [119] is transformed to that of first-order MAS under directed switching topologies. It has been proven in [119] that consensus can be ensured for MAS with high-order integrator-type dynamics if K_1 and K_2 are suitably selected and the underlying topology uniformly jointly contains a directed spanning tree. Furthermore, consensus of high-order integrator-type dynamics with output-feedback-based protocol under directed switching topologies was also studied in [119].

In [120], leader-following consensus of MAS (32) with the following state-feedback-based protocol under directed switching topologies was studied:

$$u_i(t) = cF \sum_{j=1}^{N} a_{ij}^{\sigma(t)}\big(x_i(t) - x_j(t)\big) \tag{35}$$

where c is a positive scalar, $\mathcal{A}^{\sigma(t)} = [a_{ij}^{\sigma(t)}]_{N\times N}$ is the adjacency matrix of communication graph $\mathcal{G}^{\sigma(t)}$. By assuming that the single leader (labeled as agent 1) in MAS (32) has no neighbor, one gets that the Laplacian matrix $\mathcal{L}^{\sigma(t)}$ associated with the switching graph $\mathcal{G}^{\sigma(t)}$ can be partitioned as

$$\mathcal{L}^{\sigma(t)} = \begin{bmatrix} 0 & \mathbf{0}_{N-1}^T \\ \eta^{\sigma(t)} & \widehat{L}^{\sigma(t)} \end{bmatrix}. \tag{36}$$

Under the assumption that each possible topology candidate has a directed spanning tree rooted at the leader agent, one gets that $\widehat{L}^{\sigma(t)}$ is a nonsingular M-matrix which is also diagonally dominant. Then, the following MLFs were designed in [120]:

$$W(t) = \varphi^T(t)\Big(\Xi^{\sigma(t)} \otimes S^{-1}\Big)\varphi(t) \tag{37}$$

of which $\varphi_i(t) = x_i(t) - x_1(t)$, $i = 2, 3, \ldots, N$, $\varphi(t) = (\varphi_2^T(t), \varphi_3^T(t), \ldots, \varphi_N^T(t))^T$, $\xi^{\sigma(t)} = (\xi_1^{\sigma(t)}, \ldots, \xi_{N-1}^{\sigma(t)})^T = (\widehat{L}^{\sigma(t)})^{-T}\mathbf{1}_{N-1}$, and $\Xi^{\sigma(t)} = \mathrm{diag}\{\xi_1^{\sigma(t)}, \ldots, \xi_{N-1}^{\sigma(t)}\}$. It was shown in [120] that leader-following consensus can be ensured if DT for switchings among different topology candidates is larger than a derived positive scalar.

Wen *et al.* [60] investigated the leader-following consensus problem of MAS (32) with a single leader and control input missing, where the following state-feedback-based protocol was proposed:

$$u_i(t) = \begin{cases} \alpha F \sum_{j=1}^{N} a_{ij}^{\sigma(t)}\big(x_j(t)-x_i(t)\big), & t \in \left[t_k,\ t_k^{h_k-1}\right) \\ \mathbf{0}_m, & t \in [t_k^{h_k-1},\ t_{k+1}), \quad k \in \mathbb{N} \end{cases} \tag{38}$$

where $\alpha > 0$ represents the coupling strength, $F \in \mathbb{R}^{m\times n}$ is the feedback gain matrix to be designed, $\mathcal{A}^{\sigma(t)} = [a_{ij}^{\sigma(t)}]_{N\times N}$ is the adjacency matrix of communication graph $\mathcal{G}^{\sigma(t)}$, the underlying topology switches over time points t_k for $k \in \mathbb{N}$, the control input is assumed to be missing over time interval $[t_k^{h_k-1},\ t_{k+1})$. By utilising tools from the nonsingular M-matrix theory, a class of MLFs were constructed to study the leader-following consensus problem of MAS (32) under protocol (38). Then, two new kinds of MLFs were developed in [121] to deal with the leader-following consensus problem of MAS (32) with, respectively, a single autonomous and nonautonomous leader under directed switching topologies. The MLFs utilized in [121] were constructed by solving some linear matrix inequalities and performing an optimization algorithm. Under the circumstance with an autonomous leader, it was verified that the criteria derived in [121] for leader-following consensus are less conservative than most existing ones established by directly constructing the M-matrix-based MLFs. An outstanding yet challenging issue is how to construct some new kinds of MLFs for MASs with inherent nonlinear dynamics and directed switching topologies to yield some less conservative criteria (compared with those derived by constructing MLFs based on tools from nonsingular M-matrix theory) for leader-following consensus.

Under the condition that each possible interaction graph has a directed spanning tree, leaderless consensus of MAS (32) with state-feedback-based protocol and directed switching topologies was studied in [61]. By proposing a state transformation, leaderless consensus problem of the MAS considered in [61] is transformed to the global stability problem of the following switched dynamical system about its zero fixed point:

$$\dot{e}(t) = \Big[I_{N-1} \otimes A - \alpha\Big(\Xi\mathcal{L}^{(\sigma(t))}\Pi \otimes BK\Big)\Big]e(t) \tag{39}$$

of which $\alpha > 0$ is a positive scalar, $\mathcal{L}^{(\sigma(t))}$ is the Laplacian matrix of the coupling topology at time t, $\Xi\mathcal{L}^{(\sigma(t))}\Pi$ is an antistable matrix with $\Xi = [I_{N-1}, -\mathbf{1}_{N-1}]$ and $\Pi = \begin{bmatrix} I_{N-1} \\ \mathbf{0}_{N-1}^T \end{bmatrix}$. Then, a kind of MLFs was proposed based on the antistable property of $\Xi\mathcal{L}^{(\sigma(t))}\Pi$ to seek some sufficient criteria for achieving leaderless consensus in MAS under consideration. It is remarkable that the labels of the roots for spanning trees of different topology candidates do not need to be the same in the MAS model considered in [61].

Under the conditions that (A, B) is controllable and the inherent linear dynamics of each agent is marginally stable, both the leaderless consensus and the leader-following consensus problems for linear MASs (32) under switching communication topology were addressed in [62] by using a generalized Barbalat's Lemma. For the leaderless case, it was shown in [62] that consensus can be reached if the underlying undirected topology is jointly connected and the consensus protocol is suitably designed. Under the condition that the communication topology among the followers is undirected all the time and the communication topology for the leader-following MASs jointly contains a directed spanning tree rooted at the leader, it was proven in [62] that leader-following consensus can be ensured under some appropriately designed protocols. With the conditions that the system matrix A does not have positive real part eigenvalue and each possible subgraph describing the topology among followers is undirected, event-triggered leader-following consensus problem for linear MASs (32) under switching communication topologies was addressed in [122] by utilising tools from CLF-based stability analysis theory and Cauchy convergence criterion.

In [123], leaderless consensus of single input linear MASs with undirected switching topologies was investigated by using the CLF-based approach. Under the assumption that the inherent linear dynamics of agents are stabilizable and each possible topology candidate is undirected and connected, it was proven in [123] that consensus in the closed-loop MASs with an arbitrarily given switching signal for underlying topology can be achieved if the feedback gain matrix of the consensus protocol is suitably designed. Leaderless consensus of multiple input linear MASs with directed switching topologies as well as its disturbance rejection issue were addressed in [124] by assuming that the possible strongly connected topology graphs share a common left eigenvector of the Laplacian matrices associated with zero eigenvalue.

Note that most of the aforementioned criteria for consensus of general linear MASs with (directed) switching topologies are derived based on the assumption that the switching frequency among different topology candidates is sufficiently slow, i.e., the DT for switchings among different interaction graph candidates should be larger than a positive quantity depending on both the inherent dynamics of agents and the properties of interaction graph candidates (see [60], [61], [120]). However, in some cases, it is possible to achieve consensus in general linear MASs with fast switching topologies [125], [126]. By using tools from the stability of time-varying differential equations, the leader-following consensus of general linear MASs with fast switching topologies was studied in [125]. Under the assumption that the inherent linear dynamics of agents are stabilizable and the interaction graphs among followers are undirected, it was shown in [125] that leader-following consensus in linear MASs with fast switching topologies can be ensured if the underlying interaction graph jointly has a directed spanning tree rooted at the leader and the protocols are appropriately designed. In [126], the leaderless consensus of general linear MASs with output-coupling under fast switching directed topologies was studied by using averaging theory. It has been shown in [126] consensus in the linear MASs with output-coupling can be guaranteed under sufficiently fast switching topologies if the consensus problem of the MASs with the corresponding fixed averaging network topology can be solved via designing output-coupling protocols.

Compared with consensus of the continuous-time general linear MASs with switching topologies, the consensus of discrete-time general linear MASs with switching topologies has received relatively less attention in the last years. In [127], with the assumption that the system matrix of the inherent dynamics of agents is neutrally stable, both leaderless consensus problem and leader-following consensus problem of discrete-time general linear MASs under switching topologies were studied based on a generalized version of Barbalat's lemma. By assuming that the inherent linear dynamics of each agent are controllable and observable, output consensus problem for a class of discrete-time heterogeneous linear MASs with directed switching topologies and time delays was investigated in [128] by designing a kind of distributed predictor-based controller.

Most of the above-mentioned works focused on addressing consensus problem of linear MASs with deterministically switching topologies. Note that the consensus of linear MASs with randomly switching topologies has also been considered in [129] and [130]. Specifically, consensus problems of continuous- and discrete-time linear MASs with Markovian switching topologies were studied in [129] by constructing stochastic MLFs. Then, the robust consensus of continuous-time linear MASs with Markovian switching topologies subject to unknown jumping modes was investigated in [130].

4) Consensus of MASs With Nonlinear Dynamics and Switching Topologies: In [63], leader-following consensus of MASs with Lipschitz-type nodes and directed switching topologies was investigated where the dynamics of the followers and the leader are described, respectively, by

$$\dot{x}_i(t) = Ax_i(t) + Cf(x_i(t), t) + Bu_i(t) \tag{40}$$

of which $i = 2, 3, \ldots, N$, and

$$\dot{x}_1(t) = Ax_1(t) \tag{41}$$

where $x_i(t) \in \mathbb{R}^n$ is the state vector of agent i ($i = 1, 2, \ldots, N$), A, B, and C are constant real matrices with compatible dimensions, f is a nonlinear function satisfying the Lipschitz condition. To achieve leader-following consensus, the following relative-state-based protocol was designed in [63]:

$$u_i(t) = \alpha BF \sum_{j=1}^{N} a_{ij}^{\sigma(t)}\big(x_j(t) - x_i(t)\big) \tag{42}$$

of which α is a positive scalar, $\mathcal{A}^{\sigma(t)} = [a_{ij}^{\sigma(t)}]_{N\times N}$ is the adjacency matrix of communication graph $\mathcal{G}^{\sigma(t)}$ describing the communication structure among the N agents. Under the condition that each possible topology contains a directed spanning tree with the leader as the root, distributed leader-following consensus of MASs with leader given by (41) and followers given by (40) under protocol (42) were studied in [63]. Then, leader-following consensus for MASs with Lipschitz-type nodes and directed switching topologies was addressed in [131] by designing observer-type protocols where only the relative outputs between neighboring agents are available. By assuming that each possible subgraph describing the interaction relationships among followers is undirected and the switching graph containing both the leader and followers is jointly connected, leader-following consensus for MASs with leader given by (41) and followers given by (40) was studied in [132] by using a CLF-based approach. Distributed output leader-following consensus problem was studied in [64] for a class of nonlinear MASs where the dynamics of followers and the single leader are heterogeneous. With the condition that the θ-digraph containing both the followers and the leader jointly has a directed spanning tree rooted at the leader, some new sufficient output tracking criteria were obtained and analyzed in [64]. Under the assumption that each possible topology candidate has a directed spanning tree rooted at the leader, practical leader-following consensus for heterogeneous MASs with a high-dimensional leader and unknown followers' dynamics was studied in [133] by constructing MLFs for the tracking error systems. Then, in [134], leader-following consensus for a class of first-order MASs with nonlinear dynamics and event-triggered communication was investigated where the underlying topology is assumed to switch among a set of directed graphs with each having a directed spanning tree rooted at the leader. Leader-following attitude consensus for a class of multiple rigid spacecraft systems with directed switching topologies was studied in [135] by developing tools for convergence analysis of linear time-varying system and constructing a kind of CLF.

Leaderless consensus of MASs with Lipschitz-type dynamic agents [as shown in (40)] and undirected switching topologies was addressed in [136]. By utilizing a CLF-based approach, it was shown in [136] that leaderless consensus in the considered nonlinear MASs can be guaranteed under a jointly connected topology if some linear matrix inequalities are satisfied and the protocol is suitably designed. Leaderless guaranteed-cost consensus for MASs with Lipschitz-type dynamic agents over undirected switching topologies was studied in [137]. Without assuming that the inherent nonlinear dynamics of agents satisfy the Lipschitz condition, leaderless consensus of a class of second-order nonlinear MASs under jointly connected topologies was studied in [138] by using tools from input-to-state stability of switched systems.

Consensus problems of first-order and second-order MASs with Lipschitz-type nonlinear dynamics and directed switching topologies were, respectively, studied in [139] and [140] by designing rules for determining the switchings among different topology candidates.

Remark 3: Research on consensus of MASs with nonlinear dynamics with switching topologies is still at its infancy stage as most of the existing results are generally assumed that the inherent nonlinear dynamics are Lipschitz-type. It hoped that the efficient tools developed for analyzing and controlling nonlinear plants, e.g., the neural network-based control method [141], [142], will promote the advances of research on this topic in the near future.

D. Containment Control

Containment control of first-order multileader multifollower MASs (18) with directed switching topologies was addressed in [28]. Specifically, the following control laws were designed in [28] for each follower i, $i \in \mathcal{F}$, to achieve containment under the cases with, respectively, stationary and dynamic leaders:

$$u_i(t) = -\sum_{j\in\mathcal{F}\bigcup\mathcal{R}} a_{ij}(t)\big[x_i(t) - x_j(t)\big] \tag{43}$$

$$u_i(t) = -\alpha \sum_{j\in\mathcal{F}\bigcup\mathcal{R}} a_{ij}(t)\big[x_i(t) - x_j(t)\big] - \beta\,\mathrm{sgn}\left\{\sum_{j\in\mathcal{F}\bigcup\mathcal{R}} a_{ij}(t)\big[x_i(t) - x_j(t)\big]\right\} \tag{44}$$

of which $\mathcal{A}(t) = [a_{ij}(t)]_{N\times N}$ is the adjacency matrix of the interaction graph which jointly has a united directed spanning tree (i.e., for each follower i, $i \in \mathcal{F}$, there exists at least one leader j, $j \in \mathcal{R}$ such that there is a directed path from leader j to the follower i) as MASs evolve with time, $\alpha = 1$ and β should be larger than the maximum absolute values of the external inputs acting on the leaders, and the dynamics of each agent are one-dimensional systems. Furthermore, the cases with discrete-time dynamics were also addressed in [28]. Note that the analysis approach adopted in [28] is a CLF-based approach. Containment control of first-order high-dimensional multileader multifollower MASs under directed switching topologies was further studied in [29]. It was revealed in [28] that the states of the followers under control law (43) will converge to the convex hull spanned by those of the stationary leaders if the union graph for the underlying directed switching graph frequently has a united directed spanning tree. It was interestingly found that the states of followers might not converge onto the dynamic convex hull formed by those of the dynamic leaders under control law (44) but will converge onto the dynamic minimal hyper-rectangle that contains the dynamic leaders. It is worth noting that there is no constraint on the DT of switchings among different topology candidates in the containment criteria provided in [28] and [29]. By using LaSalle's Invariance Principle (LaSalle's IP) for switched systems, containment control for first-order multileader MASs with undirected switching communication topologies among followers was studied in [143]. Containment control for a kind of second-order MAS in the presence of multiple leaders with random switching topologies was investigated in [144]. By developing tools from stochastic process theory and convex analysis, some necessary and sufficient conditions were derived in [144] to ensure that the dynamic following agents converge asymptotically to the static convex leader set in the almost sure convergence sense. Then, containment control for continuous-time first-order multileader multifollower MASs in the presence of interactive leaders and directed switching topologies was studied in [145]. By using the convergence property of infinite products of stochastic, indecomposable, and aperiodic (SIA) matrices, it was shown in [145] that the states of leaders will converge to the desired formation while the states of followers will move onto the convex hull formed by those the leaders under directed switching topologies. The summary of analysis approaches for containment control of multileader MASs is illustrated in Fig. 2.

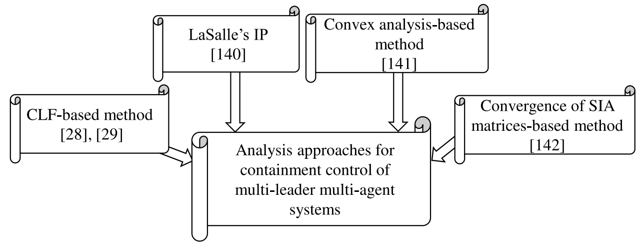

Fig. 2. Analysis approaches for containment control of multileader MASs.

IV. Conclusion

We have surveyed some recent developments on coordination and control of CNSs with switching topologies. However, this survey is by no means complete. Note also that there are still many interesting and yet critical issues concerning CNSs with switching topologies the deserve further study although a variety of efficient tools have been successfully developed to solve various challenging problems in this active research field. Some interesting yet important future research issues are provided as follows.

1) *Bridging the Gap Between Consensus/Synchronization Under Fast Switching Topologies and That Under Slow Switching Topologies:* Consensus or synchronization of CNSs under fast switching topologies has been studied from averaging theory while that with slow switching topologies has been generally studied from MLFs-based approaches. An interesting topic is to provide a unified approach to deal with consensus/synchronization problem under fast switching topologies and slow switching topologies. Another interesting problem is to study how to reduce the conservatism of the consensus/synchronization criteria derived by tools from averaging theory or MLFs-based stability analysis.
2) *Distributed Optimization of CNSs With Switching Topologies:* Distributed optimization problem of CNSs with fixed topology has been studied under various scenarios where only the information about local objective function and relative state (or output) information between its own and the neighbors' are available to each individual. An interesting yet challenging problem is how to efficiently solve the distributed optimization problem over CNSs with switching topologies.
3) *Finite-Time Coordination Control of CNSs With Switching Topologies:* To date, many distributed protocols have been developed to solve asymptotical coordination problems (including consensus, synchronization, rendezvous, and flocking problems) of CNSs with switching topologies. However, in some practical applications, it is desirable to design distributed protocols for CNSs such that the coordination objectives can be completed in a finite time. For CNSs with fixed topology, various efficient protocols have been designed based on tools from sliding mode control theory to complete the goal of finite-time coordination. However, it is interesting but challenging to see how to design sliding mode controller-based protocols for CNSs with

switching topologies such that the goal of finite-time coordination can be guaranteed.

4) *Resilience Analysis and Control of Complex Cyber-Physical Networks:* Most of the units in various network infrastructures are cyber-physical systems in the era of the Internet of Things. Complex cyber-physical network as a next-generation of CNS has recently received a drastic attention. Any successful cyber or physical attacks on complex cyber-physical networks may introduce undesired switching dynamics (e.g., loss of links) to the operation of these networks. In this context, resilience analysis and control of complex cyber-physical networks become increasingly important and thus deserve future study.

We sincerely hope that the present survey paper stimulates further research on the analysis and synthesis of CNSs with switching topologies, both on the theoretical side and in the practical applications.

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