Distributed Coordination Control and Industrial Applications

FOR many industrial applications, some complex coordination tasks, such as rendezvous at a common point or move in a specified formation pattern, are required to be achieved with minimal communication between agents, and therefore, with limited information about the global state of the systems. Due to the breakthrough in new cost-effective and advanced instrumentation and communication equipment, the topic of distributed coordination control has gained great interest in the past years, partly due to its wide applications in many industrial systems, including multiple robot systems, sensor networks, industrial processes, unmanned aerial vehicles, transportation systems, as well as power networks. The cooperative systems offer many advantages in terms of flexibility, reliability, manipulability, and scalability that cannot be achieved by an individual system. In light of this, the design and control in networks of coordinated systems is of great theoretical and industrial interests. This special section aims at advancing the technology and methodology and further promoting the research activities in this direction.

This "Special Section on Distributed Coordination Control and Industrial Applications" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS has the goal of providing the reader with the primary research activities that are currently being conducted in the design and control in networks of coordinated systems. The Guest Editors believe that this special section can advance the technology and methodology and further promote the research activities in this direction.

The Special Section includes one state-of-the-art paper and 24 manuscripts, which cover many of the above-mentioned subjects. According to the coordination/cooperation tasks of the manuscripts, they are divided into six groups, each focusing on a specific subject. In item 1) in the Appendix, a comprehensive survey of consensus and coordination of multi-agent systems (MASs) is presented. Focusing on different kinds of constraints on the controller and dynamics of each individual agent, as well as the coordination schemes, the authors categorize the recent results into the following directions: consensus with constraints, event-based consensus, consensus over signed networks, and consensus of heterogeneous agents. In addition, some applications of the well developed consensus algorithms to the topics such as economic dispatch problem in smart grid and k-means clustering algorithms are also reviewed.

The first group deals with the formation (tracking) problem of various control plants, including surface vessels and autonomous underwater vehicles. The formation is realized using the designed coordination algorithms, which can be executed in a distributed manner.

A novel coordinated formation algorithm is presented in item 2) in the Appendix for multiple surface vessels using the guidance-control structure. The proposed coordination algorithm is the combination of the virtual leader strategy and the passivity-based coordination method. The guidance system is used to supply the desired reference signals by designing the controller according to the corresponding marine task.

To achieve high-accuracy formation control of multiple ocean surface vessels, it is important to accommodate the inevitable external disturbance. A novel disturbance estimation scheme is presented in item 3) in the Appendix to solve the disturbance-accommodation problem, and to provide the future formation controller design with precise estimation information. This approach is developed in the theoretical framework of terminal sliding mode observer. The proposed observer is able to precisely estimate external disturbance in finite time. It turns out that a fast and precise estimation for external disturbance can be guaranteed.

The receding horizon formation tracking control problem of a feet of underactuated autonomous underwater vehicles (AUVs) is investigated in item 4) in the Appendix. The follower AUVs are required to track the leader with prescribed formation pattern, and the control inputs of the follower AUVs are subject to practical constraints. An auxiliary stabilizable control law is first designed, based on which a novel optimization problem is proposed and a new receding horizon control algorithm is designed to generate control inputs.

In item 5) in the Appendix, the authors study the time-varying formation tracking analysis and design problems for second-order multi-agent systems with switching interaction topologies. The states of the followers are driven to form a predefined time-varying formation while track the state of the leader. A formation tracking protocol is constructed based on the relative information of the neighboring agents.

The second group addresses the consensus problem of networked systems. The individual systems can be linear or nonlinear (e.g., wheeled mobile robots, and mobile manipulators), which subject to practical constraints including input saturation and limited communication resources. The scenario that the interaction between different individuals can be competitive is also considered.

The investigation of output consensus of multiple nonlinear systems with a directed and fixed interaction topology is reported in item 6) in the Appendix. The followers are subject to saturation and dead-zone input. A distributed adaptive control scheme using neural network is proposed. It is guaranteed that

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all the outputs of the followers asymptotically synchronize to the output of a leader regardless of the unknown system dynamics and external disturbances.

In item 7) in the Appendix, the consensus for a group of two-wheeled mobile robots using nonuniform sampling is discussed. A Rotate & Run Scheme is proposed to update the vehicles' states:

1) the vehicle calculates its goal orientation and the input of each wheel;
2) the vehicle rotates in place;
3) the vehicle moves forward or backward with the calculated wheel velocities.

It is shown that consensus in a group of 2WMRs can be achieved when the switching directed graphs satisfy certain conditions.

In item 8) in the Appendix, the authors address the leader-following consensus for multi-agent systems subject to limited communication resources and unknown-but-bounded process and measurement noise. First, a new distributed event-based communication mechanism is developed. Second, a concept of set-membership leader-following consensus is put forward. Third, a distributed observer-based consensus protocol is presented to provide a set-membership estimation. Then, a convex optimization algorithm is proposed to design the consensus protocol.

In item 9) in the Appendix, event-based semiglobal consensus problem is investigated for linear multi-agent systems subjected to input saturation, by utilizing low-gain feedback technique. Two scenarios for systems with and without updating delays are considered, and fully distributed event-triggered control schemes are proposed to guarantee the semiglobal consensus of the connected systems in which each agent is asymptotically null controllable. Strictly positive lower bounds for both the sampling intervals and the updating delays are captured to eliminate the Zeno behaviors.

The distributed coordination/cooperation control for networked mobile manipulators over jointly connected topology with time delays is addressed in item 10) in the Appendix. With decoupled dynamic control, the task- and null-space of the mobile manipulators can be designed to achieve different missions. For the motion of end-effector, synchronization control mingles with force controls for the network of mobile manipulators to achieve cooperative manipulation and transportation.

When the interaction between the agents can be either cooperative or competitive, the sign-consensus problem of linear multi-agent systems is raised in item 11) in the Appendix. The interaction between agents is modeled by a signed directed graph. The graph is allowed to be structurally unbalanced and its adjacency matrix is assumed to be eventually positive. Two interesting problems are studied, respectively, i.e., conventional consensus over signed graphs and sign-consensus over nonnegative graphs.

In a power system, how to economically generate and distribute the electric power is an on-going and relevant issue. In the third group, with the help of the theories developed in control community, different distributed methods are proposed to solve the problem arising from the power system, especially the problem of power dispatch.

A fully distributed solution for optimal active power dispatch is reported in item 12) in the Appendix. The proposed solution can address not only the constraints of supply–demand balance and generation bounds but also the line flow constraints. To balance computational efficiency and effectiveness, dc power flow was used to check for line flow constraint violations. The operations of projected gradient calculations and global situational awareness acquisition are fully distributed and implemented using a multi-agent system.

In order to solve the economic dispatch problem (EDP) with time-varying topologies and communication delays, an algorithm based on the gradient push-sum method is proposed in item 13) in the Appendix. The authors show that the proposed algorithm is guaranteed to solve the EDP if the time-varying communication network is uniformly jointly strongly connected and time-varying delays are bounded over communication links.

The typical distributed energy management under attacks is considered in item 14) in the Appendix. The necessary and sufficient conditions are provided to guarantee convergence of the economic dispatch protocol when the attacker only injects false data to the broadcast information. It is shown that the offline stealthy attack can be realized under this kind of attack. Then, the authors prove that there exists no stealthy attack injecting false data to the broadcast information for the online case. Further, the authors provide the stealthy attack by merely injecting constant false data to generation cost parameters for the online case. It is proved that for every node, there exists false-data injection to generation cost parameters which reduces the generation efficiency.

For protecting the agents privacy for distributed optimization, a masking method is designed in item 15) in the Appendix. In the proposed method, each agent adds a signal to the own original state to conceal the important information. Additionally, to obtain the correct solution of the optimization problem, they exchange the added signal with each other and subtract the received signals from the own state. Finally, to illustrate the effectiveness of the proposed method, the authors apply it to a microgrid and show that the supply–demand balance is kept via real-time pricing while protecting privacy of agents original states.

The Load Frequency Control problem induced from power system operation and control is the focus of the fourth group. Two frameworks, namely, model predictive control and intelligent control, are developed to solve the Load Frequency Control problem.

A distributed model predictive control (DMPC) scheme is developed for the load frequency control (LFC) problem of the deregulated multi-area interconnected power system with contracted and uncontracted load demands in item 16) in the Appendix. The distributed model predictive controller is designed by posing the LFC problem as a tracking control problem in the presence of both external disturbances and constraints which represent generation rate constraint and load reference setpoint constraint, respectively.

For the load frequency control of the wind-power-incorporated power system, the authors in item 17) in the Appendix propose another distributed model predictive control scheme, which exchanges the power system measurement and predictions through communication, and incorporate the information of other controllers into their local objective to realize the coordination. The controllers can solve the optimal problem subject to constraints, e.g., generation rate constraints, pitch angle, and load input constraints in each area. Since the wind power outputs are quite dependent on the wind speed, diverse optimization modes on DMPC have been established.

An intelligent controller is designed for "Load Frequency Control" application in "smart grid" environment having changes in communication topology via multi-agent system (MAS) technology in item 18) in the Appendix. A parametric intelligent controller is given, which consists of two levels estimator agent and controller agent in each multi-area system. Particle swarm optimization is then used to tune the controller parameters. Further proposed control strategy and system architecture as MAS for LFC in smart grid is analyzed in detail, verified for various load conditions and different network configurations. In addition, mean square error of power system states with current transformer is also analyzed.

Two telecoperation control frameworks are developed to improve the control performance of the coordinated mobile robots in the fifth group.

In item 19) in the Appendix, the development of the teleoperation control framework of coordinated mobile robots through brain–machine interface. Visual evoked potentials are used to generate EEG motion commands. The online brain-machine interface analyzes the EEG data such that human intentions can be recognized by AdaBoostSVM classifier. Bezier curve is utilized to parameterize the motion commands and leader-following formation control is applied to guarantee tracking performance.

Different from the data-oriented framework of item 19) in the Appendix, the the authors in item 20) in the Appendix develop a control approach in which the robot automatic control is combined with impedance control using stiffness transferred from human operator. The authors employ the incremental stiffness extraction method in operational space with an improved performance by compensation of the nonlinear residual error. The teleoperated robotic exoskeleton is able to replicate the impedance of human operators arm, and simultaneously compensate for external disturbances by the technique of disturbance observer.

In the last group, several important issues in industrial applications are discussed. The topics include the NLOS identification, decentralized implementation of demand response program, the filtering of nonlinear multirate networked industrial processes, the coordinated control of boiler-turbine unit, and decentralized management of power conditioning systems.

To overcome non-line-of-sight (NLOS), which refers to the situation that the transmission of wireless signals can be disrupted by obstacles and walls, an identification algorithm is reported in item 21) in the Appendix based on distributed filtering to mitigate NLOS effects including localization failures. The proposed algorithm distributes the measurements to several local filters. Using distributed filtering and data association techniques and the hybrid particle finite impulse response filter, the distributed HPFF can self-recover by detecting failures and resetting the algorithm.

In order to facilitate implementation of demand response program, the authors in item 22) in the Appendix propose a decentralized control system method. The key of the proposed method is a new decentralized algorithm for determining appropriate control signals (corresponding to prices and/or incentives) by using communication networks provided by smart meters. The effectiveness of the proposed method is illustrated by a numerical example.

The distributed fuzzy H_∞ filtering problem is addressed for a class of nonlinear multirate networked industrial processes in item 23) in the Appendix. The nonlinear industrial plants are described by Takagi–Sugeno (T–S) fuzzy models, whereas the distributed sensor measurements are subject to network-induced delays, stochastic disturbances, and packet dropouts. The sensors of different sampling rates are divided into two groups with different network topologies, and the corresponding filters are designed based on the T–S modeling technique. The major aim is to guarantee the filtering error system to be stochastically stable with a prescribed H_∞ performance index by designing proper filter gains.

In item 24) in the Appendix, based on a typical coal-fired power unit model, a coordinated control scheme with H_∞ performance is proposed for the control of boiler–turbine unit. The LQR is applied to limit the control actions to meet the actuator saturation constraints. Case studies for a practical 500 MW coal-fired boiler–turbine unit model indicate that the designed control system has satisfactory performance in a wide operation range and has a very good boiler–turbine coordination capacity.

The decentralized management problem of Power Conditioning Systems (PCSs), which are used to interconnect the PV system into the power grid, is investigated in item 25) in the Appendix. The real-time pricing strategy of the utility is considered and each PCS determines its own set-points of the active and reactive power injections by solving the individual small size optimization problem that includes conceptual prices provided by the utility. This feedback interaction of the utility and PCSs eventually suppresses the voltage deviation.

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Appendix
Related Work

1) J. Qin, Q. Ma, Y. Shi, and L. Wang, "Recent advances in consensus of multi-agent systems: A brief survey," *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 4972–4983, Jun. 2017.
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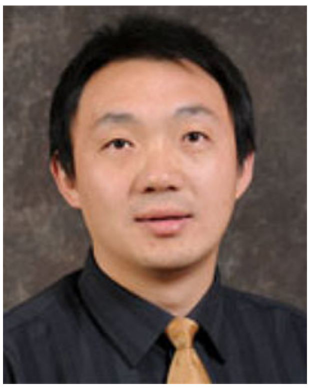

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