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Contents

On the Control of Multi-Agent Systems: A Survey

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ABSTRACT

Recent years have witnessed a trend to use networked multiple autonomous agents to accomplish complex tasks arising from space-based applications, smart grids, and machine learning. Such systems are referred to as multi-agent systems, where a global objective is achieved via the local interactions among the agents. The recent two decades have witnessed a rapid development of MASs in automatic control, but their root can be traced back much earlier. This paper reviews the research progress of MASs in past years. After briefly introducing the basic concepts and definitions, we discuss agents' dynamic models, including both linear and nonlinear models, describe different cooperating tasks, such as consensus, coordinating tracking, formation control, distributed average tracking, distributed estimation, containment control, surrounding control, and distributed optimization. We introduce various research issues for MASs, including time-delays, noise or disturbance, quantization, connectivity maintenance,

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and event-triggered control. We present different MAS control algorithms, including proportional control, proportional-integral control, adaptive control, model predictive control, passivity-based control, and nonsmooth control, and their applications in multi-robot systems, sensor networks, smart grid, machine learning, social networks, and many-core microprocessors.

1

Introduction

Nature has created a large number of multi-agent systems (MASs), where local interaction rules/mechanisms are exploited at different levels by groups of agents to achieve a common group objective. Schools of fish and flocks of birds are typical examples of MASs, which have fascinated scientists from rather diverse disciplines, such as physics, biology, and computer sciences. Thanks to the parallel characteristics, MASs can be used to solve engineering problems that are difficult or impossible for a single agent to accomplish. For example, in a large area, it is not possible to use a camera to cover the whole area; while a network of multiple collaborating cameras can be used to achieve the purpose. MASs are more robust — the malfunction of one agent or a small portion of agents typically will not affect the functionality of the system; MASs are scalable — no matter what the size of the system is, the computation and communication costs of MASs are kept at a reasonably low level.

Although the study of MASs can be traced back long ago [1–3], it was only at the beginning of the 21st century that MASs emerged as a separate research field. In 2005, the paper "coordination of groups of mobile autonomous agents using nearest neighbor rule" won the prestigious George S. Axelby outstanding paper award from IEEE Transactions on Automatic Control, a top-notched journal in systems and control. After that, the International Federation of Automatic Control (IFAC) and American Automatic Control Council (AACC) organized a series of conferences/workshops focusing on MASs. IFAC established several technical committees having close ties with MASs. New journals with a primary interest in MAS or network systems are established, e.g., IEEE Transactions on Control of Network Systems and IEEE Transactions on Network Sciences and Engineering.

As a critical enabler of several research fields, MASs are quintessentially multidisciplinary. In the search for theories and applications, physicists, computer scientists, biologists, and others have all contributed to the development of MASs. Craig Reynold proposed three rules that lead to simulated flocking: collision avoidance, velocity matching, and flock centering [4]. Tamas Vicsek et al. introduced a model where the velocity of the particles is determined by a simple rule with random fluctuations, to investigate the emergence of group behavior [5]. On the other perspective, the study on MASs also provides insights for the related fields, leading to new developments in these fields. A hallmark of MAS control is the mathematical rigor where convergence/stability analysis plays a vital role, perhaps an inheritance from control theory.

Although MAS theory shares some similarities with other branches of natural sciences, there exist some fundamental difference. In natural sciences, methodological reductionism plays a central role and has achieved great success, which attempts to explain entire systems in terms of their components. Reductionism assumes that the interactions among system components (subsystems) are not essential and their effect is negligible. However, the assumption failed to work for MASs. The goal of MAS study is to understand and exploit the local interaction rules among agents, from which a global behavior can emerge. As a result, methodological reductionism becomes less useful for MAS study. Compared with single agent control where there already exists interaction among different systems components, e.g., sensing component and control component, MASs add another layer of interactions at a higher level. How to understand and exploit these interactions is the key to the success of MASs.

Many survey or tutorial papers [6–10] on MASs have been presented, along with a number of special issues and books [11–22]. The Proceedings of IEEE and the IEEE Control System Magazine publishes several overviews on MASs, including information consensus in multivehicle cooperative control [23], motion coordination with distributed information [24], consensus and cooperation in networked multi-agent systems [25], interconnected dynamic systems—an overview on distributed control [26], oscillator models and collective motion [27], motion coordination with distributed information [24], and collective motion, sensor networks, and ocean sampling [28]. Springer Encyclopedia and Wiley Encyclopedia publish a series of tutorial papers on multi-agent systems (e.g., [29–44]). Numerous special issues are published by the IEEE Transactions on Automatic Control [45], the Proceedings of the IEEE [46], and the IEEE Transactions on Robotics and Automation [47].

The first decade of the 21st century has witnessed a very dynamic development of the MAS theory, with rapid growth of applications. The research topics of MASs have been extended from consensus [48–51], formation control [52, 53], and flocking [54] to distributed estimation [55–57] and distributed optimization [58, 59]. The courses on MAS control also appear both at the undergraduate level and graduate level. In many engineering fields, it is not unusual to see that multiple agents work cooperatively to accomplish a complex task. The examples include distributed reconfigurable sensor networks, space-based interferometers, combat, surveillance, and reconnaissance systems, smart grids, and distributed machine learning. Although the problems arise from diverse application domains, they share some fundamental characteristics. First, agents have simple sensing, communication, and computation capabilities and function in a fully autonomously way; second, there is not a central decision maker or coordinator, and each agent makes its own decision by its local information, i.e., the system is distributed. Today, the research scope of MASs is still expanding.

Organization

The remainder of this paper is organized as follows.

- We begin in Chapter 2 with a brief introduction of basic concepts and definitions on MASs, where we will introduce the definitions of agents, autonomy, as well as multi-agent systems. Additionally, we will delineate the preliminaries on graph theory that is relevant in characterizing the network topologies among agents. Among other things, we will point out the difference among the three terms "centralized", "decentralized", and "distributed".
- In Chapter 3, we introduce the models describing the dynamics of agents. The linear models include first-integrator dynamics, double-integrator dynamics, and generic linear systems, while the nonlinear models involve Lagrangian systems, unicycle systems, along with attitude dynamics of rigid bodies.
- In Chapter 4, we describe different multi-agent cooperative tasks, including consensus, leader-following coordination, flocking, formation control, coverage control, distributed average tracking, distributed estimation, containment control and its inverse problem surrounding control, as well as distributed optimization.
- In Chapter 5, we present various research issues of MASs, including time-delays, quantization, packet loss, noise and disturbance, connectivity maintenance, sampled-data control, along with event-triggered control.
- In Chapter 6, we introduce different types of multi-agent control algorithms, including proportional control, proportional-integral control, adaptive control, model predictive control, passivity-based control, sliding-mode control, finite-time control, as well as fixed-time control.
- In Chapter 7, we summarize the applications of MASs in multi-robot systems, sensor networks, smart grids, machine learning, social networks, task migration of multi-core microprocessors, coordination of the charging of multiple electric vehicles, distributed heating, ventilation, and air conditioning optimization.
- Finally, in Chapter 8, we give a conclusion and list some unsolved problems of MASs from the authors' perspective.

The synopsis of this article falls between a survey paper and a book, which is reflected by the length of the article. Compared with a regular survey, our article provides a more thorough coverage on the topics of multi-agent systems, as each one of Chapters 3–7 can serve independently as a survey paper. It is noted that most multi-agent books in the market are monographs, focusing on the specific research interests of the authors. In comparison, our article offers a wider range of coverage, but it omits cumbersome technical details, such as proofs, in order to let the reader get a full picture of the field promptly.

References

[1] E. Eisenberg and D. Gale, "Consensus of subjective probabilities: The pari-mutuel method," *The Annals of Mathematical Statistics*, vol. 30, no. 1, pp. 165–168, 1959.

[2] J. Tsitsiklis and M. Athans, "Convergence and asymptotic agreement in distributed decision problems," *IEEE Transactions on Automatic Control*, vol. 29, no. 1, pp. 42–50, 1984.

[3] J. Tsitsiklis, "Problems in decentralized decision making and computation," *PhD, Massachusetts Institute of Technology*, 1984.

[4] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," in *ACM SIGGRAPH Computer Graphics*, vol. 21, no. 4. ACM, 1987, pp. 25–34.

[5] T. Vicsek, A. Czirók, E. Ben-Jacob, I. Cohen, and O. Shochet, "Novel type of phase transition in a system of self-driven particles," *Physical Review Letters*, vol. 75, no. 6, p. 1226, 1995.

[6] R. M. Murray, "Recent research in cooperative control of multivehicle systems," *Journal of Dynamic Systems, Measurement, and Control*, vol. 129, no. 5, pp. 571–583, 2007.

[7] V. Gazi and B. Fidan, "Coordination and control of multi-agent dynamic systems: Models and approaches," in *International Workshop on Swarm Robotics*. Springer, 2006, pp. 71–102.

[8] P. Y. Chebotarev and R. P. Agaev, "Coordination in multiagent systems and laplacian spectra of digraphs," *Automation and Remote Control*, vol. 70, no. 3, pp. 469–483, 2009.

[9] Y. Cao, W. Yu, W. Ren, and G. Chen, “An overview of recent progress in the study of distributed multi-agent coordination,” *IEEE Transactions on Industrial informatics*, vol. 9, no. 1, pp. 427–438, 2013.

[10] F. Garin and L. Schenato, “A survey on distributed estimation and control applications using linear consensus algorithms,” in *Networked Control Systems*. Springer, 2010, pp. 75–107.

[11] J. Shamma, *Cooperative control of distributed multi-agent systems*. John Wiley & Sons, 2008.

[12] W. Ren and R. W. Beard, *Distributed consensus in multi-vehicle cooperative control*. Springer, 2008.

[13] S. Butenko, R. Murphey, and P. M. Pardalos, *Cooperative control: models, applications and algorithms*. Springer Science & Business Media, 2013, vol. 1.

[14] F. Bullo, J. Cortes, and S. Martinez, *Distributed control of robotic networks: a mathematical approach to motion coordination algorithms*. Princeton University Press, 2009.

[15] Z. Qu, *Cooperative control of dynamical systems: applications to autonomous vehicles*. Springer Science & Business Media, 2009.

[16] H. Bai, M. Arcak, and J. Wen, *Cooperative control design: a systematic, passivity-based approach*. Springer Science & Business Media, 2011.

[17] M. Mesbahi and M. Egerstedt, *Graph theoretic methods in multiagent networks*. Princeton University Press, 2010.

[18] W. Ren and Y. Cao, *Distributed coordination of multi-agent networks: emergent problems, models, and issues*. Springer Science & Business Media, 2010.

[19] F. L. Lewis, H. Zhang, K. Hengster-Movric, and A. Das, *Cooperative control of multi-agent systems: optimal and adaptive design approaches*. Springer Science & Business Media, 2013.

[20] W. Yu, G. Wen, G. Chen, and J. Cao, *Distributed cooperative control of multi-agent systems*. John Wiley & Sons, 2017.

[21] Z. Li and Z. Duan, *Cooperative control of multi-agent systems: a consensus region approach*. CRC Press, 2014.

[22] H. Su and X. Wang, *Pinning control of complex networked systems: Synchronization, consensus and flocking of networked systems via pinning*. Springer Science & Business Media, 2013.

[23] W. Ren, R. W. Beard, and E. M. Atkins, "Information consensus in multivehicle cooperative control," *IEEE Control Systems*, vol. 27, no. 2, pp. 71–82, 2007.

[24] S. Martinez, J. Cortes, and F. Bullo, "Motion coordination with distributed information," *IEEE Control Systems*, vol. 27, no. 4, pp. 75–88, 2007.

[25] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and cooperation in networked multi-agent systems," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 215–233, 2007.

[26] G. Antonelli, "Interconnected dynamic systems: An overview on distributed control," *IEEE Control Systems Magazine*, vol. 33, no. 1, pp. 76–88, 2013.

[27] D. A. Paley, N. E. Leonard, R. Sepulchre, D. Grunbaum, and J. K. Parrish, "Oscillator models and collective motion," *IEEE Control Systems*, vol. 27, no. 4, pp. 89–105, 2007.

[28] N. E. Leonard, D. A. Paley, F. Lekien, R. Sepulchre, D. M. Fratantoni, and R. E. Davis, "Collective motion, sensor networks, and ocean sampling," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 48–74, 2007.

[29] W. Ren, "Averaging algorithms and consensus," *Encyclopedia of Systems and Control*, pp. 55–64, 2015.

[30] J. Cortés, "Networked systems," *Encyclopedia of Systems and Control*, pp. 849–853, 2015.

[31] M. Reza Davoodi, Z. Gallehdari, I. Saboori, H. Rezaee, E. Semsarkazerooni, N. Meskin, F. Abdollahi, and K. Khorasani, "An overview of cooperative and consensus control of multiagent systems," *Wiley Encyclopedia of Electrical and Electronics Engineering*, 2016.

[32] A. V. Proskurnikov and M. Cao, "Consensus in multi-agent systems," *Wiley Encyclopedia of Electrical and Electronics Engineering*, 2016.

[33] F. Chen and W. Ren, "Distributed consensus in networks," *Wiley Encyclopedia of Electrical and Electronics Engineering*, 2016.

[34] A. Torreño, E. Onaindia, and V. Botti, "Planning and coordination in multiagent environments," *Wiley Encyclopedia of Electrical and Electronics Engineering*.

[35] A. Jadbabaie, "Flocking in networked systems," *Encyclopedia of Systems and Control*, pp. 458–463, 2015.

[36] J. P. Hespanha and A. R. Mesquita, "Networked control systems: estimation and control over lossy networks," *Encyclopedia of Systems and Control*, pp. 842–849, 2015.

[37] S. Yüksel, "Information and communication complexity of networked control systems," *Encyclopedia of Systems and Control*, pp. 560–567, 2015.

[38] L. Bushnell and H. Ye, "Networked control systems: architecture and stability issues," *Encyclopedia of Systems and Control*, pp. 835–842, 2015.

[39] M. Mesbahi and M. Egerstedt, "Graphs for modeling networked interactions," *Encyclopedia of Systems and Control*, pp. 510–514, 2015.

[40] A. Nedić, "Distributed optimization," *Encyclopedia of Systems and Control*, pp. 308–317, 2015.

[41] B. A. Francis, "Oscillator synchronization," *Encyclopedia of Systems and Control*, pp. 1015–1020, 2015.

[42] A. D. Domínguez-García and C. N. Hadjicostis, "Coordination of distributed energy resources for provision of ancillary services: Architectures and algorithms," *Encyclopedia of Systems and Control*, pp. 241–246, 2015.

[43] E. Frazzoli and M. Pavone, "Multi-vehicle routing," *Encyclopedia of Systems and Control*, pp. 821–830, 2015.

[44] R. Srikant, "Network games," *Encyclopedia of Systems and Control*, pp. 831–835, 2015.

[45] P. Antsaklis and J. Baillieul, "Guest editorial special issue on networked control systems," *IEEE Transactions on Automatic Control*, vol. 49, no. 9, pp. 1421–1423, 2004.

[46] ——, "Special issue on technology of networked control systems," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 5–8, 2007.

[47] T. Arai, E. Pagello, and L. E. Parker, "Advances in multi-robot systems," *IEEE Transactions on Robotics and Automation*, vol. 18, no. 5, pp. 655–661, 2002.

[48] A. Jadbabaie, J. Lin, and A. S. Morse, "Coordination of groups of mobile autonomous agents using nearest neighbor rules," *IEEE Transactions on Automatic Control*, vol. 48, no. 6, pp. 988–1001, 2003.

[49] R. Olfati-Saber and R. M. Murray, "Consensus problems in networks of agents with switching topology and time-delays," *IEEE Transactions on Automatic Control*, vol. 49, no. 9, pp. 1520–1533, 2004.

[50] W. Ren and R. W. Beard, "Consensus seeking in multiagent systems under dynamically changing interaction topologies," *IEEE Transactions on Automatic Control*, vol. 50, no. 5, pp. 655–661, 2005.

[51] L. Moreau, "Stability of multiagent systems with time-dependent communication links," *IEEE Transactions on Automatic Control*, vol. 50, no. 2, pp. 169–182, 2005.

[52] Z. Lin, M. Broucke, and B. Francis, "Local control strategies for groups of mobile autonomous agents," *IEEE Transactions on Automatic Control*, vol. 49, no. 4, pp. 622–629, 2004.

[53] S. Mastellone, J. S. Mejía, D. M. Stipanović, and M. W. Spong, "Formation control and coordinated tracking via asymptotic decoupling for lagrangian multi-agent systems," *Automatica*, vol. 47, no. 11, pp. 2355–2363, 2011.

[54] R. Olfati-Saber, "Flocking for multi-agent dynamic systems: Algorithms and theory," *IEEE Transactions on Automatic Control*, vol. 51, no. 3, pp. 401–420, 2006.

[55] D. P. Spanos, R. Olfati-Saber, and R. M. Murray, "Dynamic consensus on mobile networks," in *IFAC World Congress*. Prague Czech Republic, 2005, pp. 1–6.

[56] H. Bai, R. A. Freeman, and K. M. Lynch, "Robust dynamic average consensus of time-varying inputs," in *49th IEEE Conference on Decision and Control (CDC)*. IEEE, 2010, pp. 3104–3109.

[57] F. Chen, Y. Cao, W. Ren *et al.*, "Distributed average tracking of multiple time-varying reference signals with bounded derivatives," *IEEE Transactions on Automatic Control*, vol. 57, no. 12, pp. 3169–3174, 2012.

[58] A. Nedic and A. Ozdaglar, "Distributed subgradient methods for multi-agent optimization," *IEEE Transactions on Automatic Control*, vol. 54, no. 1, pp. 48–61, 2009.

[59] A. Nedic, A. Ozdaglar, and P. A. Parrilo, "Constrained consensus and optimization in multi-agent networks," *IEEE Transactions on Automatic Control*, vol. 55, no. 4, pp. 922–938, 2010.

[60] J. Ferber and G. Weiss, *Multi-agent systems: an introduction to distributed artificial intelligence*. Addison-Wesley, Reading, 1999, vol. 1.

[61] "Generation robots," https://www.generationrobots.com, 2018.

[62] P. J. Antsaklis, K. M. Passino, and S. Wang, "An introduction to autonomous control systems," *IEEE Control Systems*, vol. 11, no. 4, pp. 5–13, 1991.

[63] F. Chen, L. Xiang, W. Lan, and G. Chen, "Coordinated tracking in mean square for a multi-agent system with noisy channels and switching directed network topologies," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 59, no. 11, pp. 835–839, 2012.

[64] D. Lee and M. W. Spong, "Stable flocking of multiple inertial agents on balanced graphs," *IEEE Transactions on Automatic Control*, vol. 52, no. 8, pp. 1469–1475, 2007.

[65] T. Rodseth, *Models for multispecies management*. Springer Science & Business Media, 2012.

[66] G. Ferrari-Trecate, L. Galbusera, M. P. E. Marciandi, and R. Scattolini, "Model predictive control schemes for consensus in multi-agent systems with single-and double-integrator dynamics," *IEEE Transactions on Automatic Control*, vol. 54, no. 11, pp. 2560–2572, 2009.

[67] G. S. Seyboth, D. V. Dimarogonas, and K. H. Johansson, "Event-based broadcasting for multi-agent average consensus," *Automatica*, vol. 49, no. 1, pp. 245–252, 2013.

[68] A. Abdessameud and A. Tayebi, "On consensus algorithms design for double integrator dynamics," *Automatica*, vol. 49, no. 1, pp. 253–260, 2013.

[69] J. H. Seo, H. Shim, and J. Back, "Consensus of high-order linear systems using dynamic output feedback compensator: Low gain approach," *Automatica*, vol. 45, no. 11, pp. 2659–2664, 2009.

[70] Z. Lin, B. Francis, and M. Maggiore, "Necessary and sufficient graphical conditions for formation control of unicycles," *IEEE Transactions on Automatic Control*, vol. 50, no. 1, pp. 121–127, 2005.

[71] A. Abdessameud, A. Tayebi, and I. G. Polushin, "Attitude synchronization of multiple rigid bodies with communication delays," *IEEE Transactions on Automatic Control*, vol. 57, no. 9, pp. 2405–2411, 2012.

[72] D. P. Bertsekas and J. N. Tsitsiklis, *Parallel and distributed computation: numerical methods*. Prentice Hall, Englewood Cliffs, NJ, 1989, vol. 23.

[73] J. Tsitsiklis and D. Bertsekas, "Distributed asynchronous optimal routing in data networks," *IEEE Transactions on Automatic Control*, vol. 31, no. 4, pp. 325–332, 1986.

[74] E. Nuno, R. Ortega, L. Basanez, and D. Hill, "Synchronization of networks of nonidentical Euler–Lagrange systems with uncertain parameters and communication delays," *IEEE Transactions on Automatic Control*, vol. 56, no. 4, pp. 935–941, 2011.

[75] E. Nuno, I. Sarras, and L. Basanez, "Consensus in networks of nonidentical Euler–Lagrange systems using P+d controllers," *IEEE Transactions on Robotics*, vol. 29, no. 6, pp. 1503–1508, 2013.

[76] J. CortéS, "Finite-time convergent gradient flows with applications to network consensus," *Automatica*, vol. 42, no. 11, pp. 1993–2000, 2006.

[77] U. Munz, A. Papachristodoulou, and F. Allgower, "Robust consensus controller design for nonlinear relative degree two multi-agent systems with communication constraints," *IEEE Transactions on Automatic Control*, vol. 56, no. 1, pp. 145–151, 2011.

[78] L. Fang and P. J. Antsaklis, "Asynchronous consensus protocols using nonlinear paracontractions theory," *IEEE Transactions on Automatic Control*, vol. 53, no. 10, pp. 2351–2355, 2008.

[79] R. Sepulchre, "Consensus on nonlinear spaces," *Annual Reviews in Control*, vol. 35, no. 1, pp. 56–64, 2011.

[80] K. Krishnanand and D. Ghose, "Theoretical foundations for rendezvous of glowworm-inspired agent swarms at multiple locations," *Robotics and Autonomous Systems*, vol. 56, no. 7, pp. 549–569, 2008.

[81] H. Kopetz and W. Ochsenreiter, "Clock synchronization in distributed real-time systems," *IEEE Transactions on Computers*, vol. 100, no. 8, pp. 933–940, 1987.

[82] B. Sundararaman, U. Buy, and A. D. Kshemkalyani, "Clock synchronization for wireless sensor networks: a survey," *Ad hoc Networks*, vol. 3, no. 3, pp. 281–323, 2005.

[83] C. Xu and F. C. Lau, *Load balancing in parallel computers: theory and practice*. Springer Science & Business Media, 1996, vol. 381.

[84] A. T. Kamal, J. A. Farrell, A. K. Roy-Chowdhury *et al.*, "Information weighted consensus filters and their application in distributed camera networks." *IEEE Transactions on Automatic Control*, vol. 58, no. 12, pp. 3112–3125, 2013.

[85] D. Devarajan, Z. Cheng, and R. J. Radke, "Calibrating distributed camera networks," *Proceedings of the IEEE*, vol. 96, no. 10, pp. 1625–1639, 2008.

[86] U. Niethammer, S. Rothmund, M. James, J. Travelletti, and M. Joswig, "Uav-based remote sensing of landslides," *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 38, no. 5, pp. 496–501, 2010.

[87] N. Biggs, N. L. Biggs, and E. N. Biggs, *Algebraic graph theory*. Cambridge University Press, 1993, vol. 67.

[88] W. Ren and E. Atkins, "Distributed multi-vehicle coordinated control via local information exchange," *International Journal of Robust and Nonlinear Control*, vol. 17, no. 10-11, pp. 1002–1033, 2007.

[89] W. Ren, "Consensus algorithms for double-integrator dynamics," *IEEE Transactions on Automatic Control*, vol. 53, no. 6, pp. 1503–1509, 2008.

[90] Y. Hong, G. Chen, and L. Bushnell, "Distributed observers design for leader-following control of multi-agent networks," *Automatica*, vol. 44, no. 3, pp. 846–850, 2008.

[91] M. Park, O. Kwon, J. H. Park, S. a. Lee, and E. Cha, "Randomly changing leader-following consensus control for Markovian switching multi-agent systems with interval time-varying delays," *Nonlinear Analysis: Hybrid Systems*, vol. 12, pp. 117–131, 2014.

[92] Z. Meng, D. V. Dimarogonas, and K. H. Johansson, "Leader–follower coordinated tracking of multiple heterogeneous lagrange systems using continuous control," *IEEE Transactions on Robotics*, vol. 30, no. 3, pp. 739–745, 2014.

[93] J. Back and J.-S. Kim, "A disturbance observer based practical coordinated tracking controller for uncertain heterogeneous multi-agent systems," *International Journal of Robust and Nonlinear Control*, vol. 25, no. 14, pp. 2254–2278, 2015.

[94] S. Khoo, L. Xie, and Z. Man, "Robust finite-time consensus tracking algorithm for multirobot systems," *IEEE/ASME Transactions on Mechatronics*, vol. 14, no. 2, pp. 219–228, 2009.

[95] M. Egerstedt, S. Martini, M. Cao, K. Camlibel, and A. Bicchi, "Interacting with networks: How does structure relate to controllability in single-leader, consensus networks?" *IEEE Control Systems*, vol. 32, no. 4, pp. 66–73, 2012.

[96] C. D. Godsil, "Compact graphs and equitable partitions," *Linear Algebra and its Applications*, vol. 255, no. 1-3, pp. 259–266, 1997.

[97] S. Martini, M. Egerstedt, and A. Bicchi, "Controllability decompositions of networked systems through quotient graphs," in *47th IEEE Conference on Decision and Control (CDC 2008)*. IEEE, 2008, pp. 5244–5249.

[98] M. Zamani and H. Lin, "Structural controllability of multi-agent systems," in *American Control Conference (ACC'09)*. IEEE, 2009, pp. 5743–5748.

[99] Z. Ji, Z. Wang, H. Lin, and Z. Wang, "Controllability of multi-agent systems with time-delay in state and switching topology," *International Journal of Control*, vol. 83, no. 2, pp. 371–386, 2010.

[100] M. Pósfai, Y.-Y. Liu, J.-J. Slotine, and A.-L. Barabási, "Effect of correlations on network controllability," *Scientific Reports*, vol. 3, p. 1067, 2013.

[101] J. Sun and A. E. Motter, "Controllability transition and nonlocality in network control," *Physical Review Letters*, vol. 110, no. 20, p. 208701, 2013.

[102] C.-L. Pu, W.-J. Pei, and A. Michaelson, "Robustness analysis of network controllability," *Physica A: Statistical Mechanics and its Applications*, vol. 391, no. 18, pp. 4420–4425, 2012.

[103] A. Chapman, M. Nabi-Abdolyousefi, and M. Mesbahi, "Controllability and observability of network-of-networks via cartesian products," *IEEE Transactions on Automatic Control*, vol. 59, no. 10, pp. 2668–2679, 2014.

[104] X. Chen, S. Pequito, G. J. Pappas, and V. M. Preciado, "Minimal edge addition for network controllability," *IEEE Transactions on Control of Network Systems*, 2018.

[105] H. Su, X. Wang, and Z. Lin, "Flocking of multi-agents with a virtual leader," *IEEE Transactions on Automatic Control*, vol. 54, no. 2, pp. 293–307, 2009.

[106] H. G. Tanner, A. Jadbabaie, and G. J. Pappas, "Flocking in fixed and switching networks," *IEEE Transactions on Automatic control*, vol. 52, no. 5, pp. 863–868, 2007.

[107] M. Porfiri, D. G. Roberson, and D. J. Stilwell, "Tracking and formation control of multiple autonomous agents: A two-level consensus approach," *Automatica*, vol. 43, no. 8, pp. 1318–1328, 2007.

[108] T. Balch and R. C. Arkin, "Behavior-based formation control for multi-robot teams," *IEEE Transactions on robotics and automation*, vol. 14, no. 6, pp. 926–939, 1998.

[109] M. A. Lewis and K.-H. Tan, "High precision formation control of mobile robots using virtual structures," *Autonomous robots*, vol. 4, no. 4, pp. 387–403, 1997.

[110] T. H. Van den Broek, N. van de Wouw, and H. Nijmeijer, "Formation control of unicycle mobile robots: a virtual structure approach," in *Proceedings of the 48th IEEE Conference on Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference (CDC/CCC 2009)*. IEEE, 2009, pp. 8328–8333.

[111] W. Dong and J. A. Farrell, "Cooperative control of multiple nonholonomic mobile agents," *IEEE Transactions on Automatic Control*, vol. 53, no. 6, pp. 1434–1448, 2008.

[112] J. A. Fax and R. M. Murray, "Information flow and cooperative control of vehicle formations," *IEEE transactions on Automatic Control*, vol. 49, no. 9, pp. 1465–1476, 2004.

[113] D. V. Dimarogonas and K. J. Kyriakopoulos, "A connection between formation infeasibility and velocity alignment in kinematic multi-agent systems," *Automatica*, vol. 44, no. 10, pp. 2648–2654, 2008.

[114] J. Cortés, "Global and robust formation-shape stabilization of relative sensing networks," *Automatica*, vol. 45, no. 12, pp. 2754–2762, 2009.

[115] A. Abdessameud and A. Tayebi, "On consensus algorithms for double-integrator dynamics without velocity measurements and with input constraints," *Systems & Control Letters*, vol. 59, no. 12, pp. 812–821, 2010.

[116] H. Rezaee and F. Abdollahi, "Pursuit formation of double-integrator dynamics using consensus control approach," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 7, pp. 4249–4256, 2015.

[117] S. E. Tuna, "LQR-based coupling gain for synchronization of linear systems," *arXiv preprint arXiv:0801.3390*, 2008.

[118] L. Consolini, F. Morbidi, D. Prattichizzo, and M. Tosques, "Leader–follower formation control of nonholonomic mobile robots with input constraints," *Automatica*, vol. 44, no. 5, pp. 1343–1349, 2008.

[119] R. Vidal, O. Shakernia, and S. Sastry, "Following the flock [formation control]," *IEEE Robotics & Automation Magazine*, vol. 11, no. 4, pp. 14–20, 2004.

[120] K.-K. Oh, M.-C. Park, and H.-S. Ahn, "A survey of multi-agent formation control," *Automatica*, vol. 53, pp. 424–440, 2015.

[121] B. Hendrickson, "Conditions for unique graph realizations," *SIAM Journal on Computing*, vol. 21, no. 1, pp. 65–84, 1992.

[122] Z. Sun, B. D. Anderson, M. Deghat, and H.-S. Ahn, "Rigid formation control of double-integrator systems," *International Journal of Control*, vol. 90, no. 7, pp. 1403–1419, 2017.

[123] R. Olfati-Saber and R. M. Murray, "Graph rigidity and distributed formation stabilization of multi-vehicle systems," in *Proceedings of the 41st IEEE Conference on Decision and Control, 2002*, vol. 3. IEEE, 2002, pp. 2965–2971.

[124] M. Cao, C. Yu, and B. D. Anderson, "Formation control using range-only measurements," *Automatica*, vol. 47, no. 4, pp. 776–781, 2011.

[125] L. Krick, M. E. Broucke, and B. A. Francis, "Stabilisation of infinitesimally rigid formations of multi-robot networks," *International Journal of Control*, vol. 82, no. 3, pp. 423–439, 2009.

[126] Z. Lin, L. Wang, Z. Han, and M. Fu, "Distributed formation control of multi-agent systems using complex laplacian," *IEEE Transactions on Automatic Control*, vol. 59, no. 7, pp. 1765–1777, 2014.

[127] F. Dorfler and B. Francis, "Geometric analysis of the formation problem for autonomous robots," *IEEE Transactions on Automatic Control*, vol. 55, no. 10, pp. 2379–2384, 2010.

[128] T. Mylvaganam and A. Astolfi, "A differential game approach to formation control for a team of agents with one leader," in *American Control Conference (ACC, 2015)*. IEEE, 2015, pp. 1469–1474.

[129] J. Cortes, S. Martinez, T. Karatas, and F. Bullo, "Coverage control for mobile sensing networks," *IEEE Transactions on robotics and Automation*, vol. 20, no. 2, pp. 243–255, 2004.

[130] A. Gusrialdi, S. Hirche, T. Hatanaka, and M. Fujita, "Voronoi based coverage control with anisotropic sensors," in *American Control Conference, 2008*. IEEE, 2008, pp. 736–741.

[131] I. I. Hussein and D. M. Stipanovic, "Effective coverage control for mobile sensor networks with guaranteed collision avoidance," *IEEE Transactions on Control Systems Technology*, vol. 15, no. 4, pp. 642–657, 2007.

[132] L. C. Pimenta, V. Kumar, R. C. Mesquita, and G. A. Pereira, "Sensing and coverage for a network of heterogeneous robots," in *47th IEEE Conference on Decision and Control (CDC 2008)*. IEEE, 2008, pp. 3947–3952.

[133] K. Laventall and J. Cortés, "Coverage control by multi-robot networks with limited-range anisotropic sensory," *International Journal of Control*, vol. 82, no. 6, pp. 1113–1121, 2009.

[134] Y. Wang and I. I. Hussein, "Awareness coverage control over large-scale domains with intermittent communications," *IEEE Transactions on Automatic Control*, vol. 55, no. 8, pp. 1850–1859, 2010.

[135] R. A. Freeman, P. Yang, and K. M. Lynch, "Stability and convergence properties of dynamic average consensus estimators," in *45th IEEE Conference on Decision and Control, 2006*. IEEE, 2006, pp. 338–343.

[136] M. Zhu and S. Martínez, "Discrete-time dynamic average consensus," *Automatica*, vol. 46, no. 2, pp. 322–329, 2010.

[137] S. S. Kia, J. Cortés, and S. Martinez, "Dynamic average consensus under limited control authority and privacy requirements," *International Journal of Robust and Nonlinear Control*, vol. 25, no. 13, pp. 1941–1966, 2015.

[138] S. Nosrati, M. Shafiee, and M. B. Menhaj, "Dynamic average consensus via nonlinear protocols," *Automatica*, vol. 48, no. 9, pp. 2262–2270, 2012.

[139] F. Chen, G. Feng, L. Liu, and W. Ren, "Distributed average tracking of networked Euler–Lagrange systems," *IEEE Transactions on Automatic Control*, vol. 60, no. 2, pp. 547–552, 2015.

[140] F. Chen, W. Ren, W. Lan, and G. Chen, "Distributed average tracking for reference signals with bounded accelerations," *IEEE Transactions on Automatic Control*, vol. 60, no. 3, pp. 863–869, 2015.

[141] E. Montijano, J. I. Montijano, C. Sagüés, and S. Martínez, "Robust discrete time dynamic average consensus," *Automatica*, vol. 50, no. 12, pp. 3131–3138, 2014.

[142] F. Chen and W. Ren, "A connection between dynamic region-following formation control and distributed average tracking," *IEEE Transactions on Cybernetics*, 2017.

[143] S. Kar, J. M. Moura, and K. Ramanan, "Distributed parameter estimation in sensor networks: Nonlinear observation models and imperfect communication," *IEEE Transactions on Information Theory*, vol. 58, no. 6, pp. 3575–3605, 2012.

[144] H. T. Banks and K. Kunisch, *Estimation techniques for distributed parameter systems.* Springer Science & Business Media, 2012.

[145] C. Guestrin, P. Bodik, R. Thibaux, M. Paskin, and S. Madden, "Distributed regression: an efficient framework for modeling sensor network data," in *Proceedings of the 3rd International Symposium on Information Processing in Sensor Networks.* ACM, 2004, pp. 1–10.

[146] S. Sundhar Ram, A. Nedić, and V. V. Veeravalli, "A new class of distributed optimization algorithms: Application to regression of distributed data," *Optimization Methods and Software*, vol. 27, no. 1, pp. 71–88, 2012.

[147] R. Olfati-Saber, "Distributed Kalman filter with embedded consensus filters," in *44th IEEE Conference on Decision and Control, 2005 and 2005 European Control Conference (CDC-ECC'05)*. IEEE, 2005, pp. 8179–8184.

[148] R. Olfati-Saber, "Distributed Kalman filtering for sensor networks," in *46th IEEE Conference on Decision and Control, 2007*. IEEE, 2007, pp. 5492–5498.

[149] R. Carli, A. Chiuso, L. Schenato, and S. Zampieri, "Distributed Kalman filtering based on consensus strategies," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 4, 2008.

[150] R. Olfati-Saber, "Kalman-consensus filter: Optimality, stability, and performance," in *Proceedings of the 48th IEEE Conference on Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference (CDC/CCC 2009)*. IEEE, 2009, pp. 7036–7042.

[151] F. S. Cattivelli and A. H. Sayed, "Diffusion strategies for distributed Kalman filtering and smoothing," *IEEE Transactions on Automatic Control*, vol. 55, no. 9, pp. 2069–2084, 2010.

[152] S. Kar and J. M. Moura, "Gossip and distributed Kalman filtering: Weak consensus under weak detectability," *IEEE Transactions on Signal Processing*, vol. 59, no. 4, pp. 1766–1784, 2011.

[153] H. Bai, R. A. Freeman, and K. M. Lynch, "Distributed Kalman filtering using the internal model average consensus estimator," in *American Control Conference (ACC, 2011)*. IEEE, 2011, pp. 1500–1505.

[154] D. P. Spanos, R. Olfati-Saber, and R. M. Murray, "Approximate distributed Kalman filtering in sensor networks with quantifiable performance," in *Fourth International Symposium on Information Processing in Sensor Networks (IPSN 2005)*. IEEE, 2005, pp. 133–139.

[155] J. Cortés, "Distributed Kriged Kalman filter for spatial estimation," *IEEE Transactions on Automatic Control*, vol. 54, no. 12, pp. 2816–2827, 2009.

[156] M. Ji, G. Ferrari-Trecate, M. Egerstedt, and A. Buffa, "Containment control in mobile networks," *IEEE Transactions on Automatic Control*, vol. 53, no. 8, pp. 1972–1975, 2008.

[157] A. Bensoussan and J.-L. Menaldi, "Difference equations on weighted graphs," *Journal of Convex Analysis*, vol. 12, no. 1, pp. 13–44, 2005.

[158] D. V. Dimarogonas, M. Egerstedt, and K. J. Kyriakopoulos, "A leader-based containment control strategy for multiple unicycles," in *45th IEEE Conference on Decision and Control, 2006*. IEEE, 2006, pp. 5968–5973.

[159] S. J. Yoo, "Distributed adaptive containment control of uncertain nonlinear multi-agent systems in strict-feedback form," *Automatica*, vol. 49, no. 7, pp. 2145–2153, 2013.

[160] H. Haghshenas, M. A. Badamchizadeh, and M. Baradarannia, "Containment control of heterogeneous linear multi-agent systems," *Automatica*, vol. 54, pp. 210–216, 2015.

[161] F. Chen, W. Ren, and Y. Cao, "Surrounding control in cooperative agent networks," *Systems & Control Letters*, vol. 59, no. 11, pp. 704–712, 2010.

[162] Y. Lou and Y. Hong, "Distributed surrounding design of target region with complex adjacency matrices," *IEEE Transactions on Automatic Control*, vol. 60, no. 1, pp. 283–288, 2015.

[163] Y. Shi, R. Li, and K. L. Teo, "Cooperative enclosing control for multiple moving targets by a group of agents," *International Journal of Control*, vol. 88, no. 1, pp. 80–89, 2015.

[164] S. Shoja, M. Baradarannia, F. Hashemzadeh, M. Badamchizadeh, and P. Bagheri, "Surrounding control of nonlinear multi-agent systems with non-identical agents," *ISA Transactions*, vol. 70, pp. 219–227, 2017.

[165] Z. Chen and H.-T. Zhang, "No-beacon collective circular motion of jointly connected multi-agents," *Automatica*, vol. 47, no. 9, pp. 1929–1937, 2011.

[166] S. Rahili and W. Ren, "Distributed continuous-time convex optimization with time-varying cost functions," *IEEE Transactions on Automatic Control*, vol. 62, no. 4, pp. 1590–1605, 2017.

[167] M. Zhu and S. Martínez, "On distributed convex optimization under inequality and equality constraints," *IEEE Transactions on Automatic Control*, vol. 57, no. 1, pp. 151–164, 2012.

[168] B. Gharesifard and J. Cortés, "Distributed continuous-time convex optimization on weight-balanced digraphs," *IEEE Transactions on Automatic Control*, vol. 59, no. 3, pp. 781–786, 2014.

[169] K. Srivastava and A. Nedic, "Distributed asynchronous constrained stochastic optimization," *IEEE Journal of Selected Topics in Signal Processing*, vol. 5, no. 4, pp. 772–790, 2011.

[170] J. C. Duchi, A. Agarwal, and M. J. Wainwright, "Dual averaging for distributed optimization: Convergence analysis and network scaling," *IEEE Transactions on Automatic control*, vol. 57, no. 3, pp. 592–606, 2012.

[171] J.-P. Richard, "Time-delay systems: an overview of some recent advances and open problems," *Automatica*, vol. 39, no. 10, pp. 1667–1694, 2003.

[172] R. Sipahi, S.-I. Niculescu, C. T. Abdallah, W. Michiels, and K. Gu, "Stability and stabilization of systems with time delay," *IEEE Control Systems*, vol. 31, no. 1, pp. 38–65, 2011.

[173] U. Munz, A. Papachristodoulou, and F. Allgower, "Consensus in multi-agent systems with coupling delays and switching topology," *IEEE Transactions on Automatic Control*, vol. 56, no. 12, pp. 2976–2982, 2011.

[174] A. Papachristodoulou, A. Jadbabaie, and U. Munz, "Effects of delay in multi-agent consensus and oscillator synchronization," *IEEE Transactions on Automatic Control*, vol. 55, no. 6, pp. 1471–1477, 2010.

[175] A. Seuret, D. V. Dimarogonas, and K. H. Johansson, "Consensus under communication delays," in *47th IEEE Conference on Decision and Control (CDC 2008)*. IEEE, 2008, pp. 4922–4927.

[176] R. Cepeda-Gomez and N. Olgac, "An exact method for the stability analysis of linear consensus protocols with time delay," *IEEE Transactions on Automatic Control*, vol. 56, no. 7, pp. 1734–1740, 2011.

[177] P.-A. Bliman and G. Ferrari-Trecate, "Average consensus problems in networks of agents with delayed communications," *Automatica*, vol. 44, no. 8, pp. 1985–1995, 2008.

[178] U. Münz, A. Papachristodoulou, and F. Allgöwer, "Delay robustness in consensus problems," *Automatica*, vol. 46, no. 8, pp. 1252–1265, 2010.

[179] D. F. Delchamps, "Stabilizing a linear system with quantized state feedback," *IEEE Transactions on Automatic Control*, vol. 35, no. 8, pp. 916–924, 1990.

[180] N. Elia and S. K. Mitter, "Stabilization of linear systems with limited information," *IEEE Transactions on Automatic Control*, vol. 46, no. 9, pp. 1384–1400, 2001.

[181] A. Kashyap, T. Başar, and R. Srikant, "Quantized consensus," *Automatica*, vol. 43, no. 7, pp. 1192–1203, 2007.

[182] R. Carli, F. Bullo, and S. Zampieri, "Quantized average consensus via dynamic coding/decoding schemes," *International Journal of Robust and Nonlinear Control*, vol. 20, no. 2, pp. 156–175, 2010.

[183] J. Lavaei and R. M. Murray, "Quantized consensus by means of gossip algorithm," *IEEE Transactions on Automatic Control*, vol. 57, no. 1, pp. 19–32, 2012.

[184] K. Cai and H. Ishii, "Quantized consensus and averaging on gossip digraphs," *IEEE Transactions on Automatic Control*, vol. 56, no. 9, pp. 2087–2100, 2011.

[185] S. Kar and J. M. Moura, "Distributed consensus algorithms in sensor networks: Quantized data and random link failures," *IEEE Transactions on Signal Processing*, vol. 58, no. 3, pp. 1383–1400, 2010.

[186] M. Franceschelli, A. Giua, and C. Seatzu, "Quantized consensus in hamiltonian graphs," *Automatica*, vol. 47, no. 11, pp. 2495–2503, 2011.

[187] F. Ceragioli, C. De Persis, and P. Frasca, "Discontinuities and hysteresis in quantized average consensus," *Automatica*, vol. 47, no. 9, pp. 1916–1928, 2011.

[188] A. Speranzon, C. Fischione, B. Johansson, and K. H. Johansson, "Adaptive distributed estimation over wireless sensor networks with packet losses," in *46th IEEE Conference on Decision and Control, 2007*. IEEE, 2007, pp. 5472–5477.

[189] M. Huang and J. H. Manton, "Stochastic consensus seeking with noisy and directed inter-agent communication: Fixed and randomly varying topologies," *IEEE Transactions on Automatic Control*, vol. 55, no. 1, pp. 235–241, 2010.

[190] Y.-H. Ni and X. Li, "Consensus seeking in multi-agent systems with multiplicative measurement noises," *Systems & Control Letters*, vol. 62, no. 5, pp. 430–437, 2013.

[191] D. Bauso, L. Giarré, and R. Pesenti, "Consensus for networks with unknown but bounded disturbances," *SIAM Journal on Control and Optimization*, vol. 48, no. 3, pp. 1756–1770, 2009.

[192] T. C. Aysal and K. E. Barner, "Convergence of consensus models with stochastic disturbances," *IEEE Transactions on Information Theory*, vol. 56, no. 8, pp. 4101–4113, 2010.

[193] M. Franceschelli, A. Pisano, A. Giua, and E. Usai, "Finite-time consensus with disturbance rejection by discontinuous local interactions in directed graphs," *IEEE Transactions on Automatic Control*, vol. 60, no. 4, pp. 1133–1138, 2015.

[194] R. Rajagopal and M. J. Wainwright, "Network-based consensus averaging with general noisy channels," *IEEE Transactions on Signal Processing*, vol. 59, no. 1, pp. 373–385, 2011.

[195] M. Franceschelli, A. Giua, A. Pisano, and E. Usai, "Finite-time consensus for switching network topologies with disturbances," *Nonlinear Analysis: Hybrid Systems*, vol. 10, pp. 83–93, 2013.

[196] J. A. Bondy, U. S. R. Murty *et al.*, *Graph theory with applications*. Citeseer, 1976, vol. 290.

[197] Y. Kim and M. Mesbahi, "On maximizing the second smallest eigenvalue of a state-dependent graph Laplacian," *IEEE transactions on Automatic Control*, vol. 51, no. 1, pp. 116–120, 2006.

[198] M. M. Zavlanos and G. J. Pappas, "Controlling connectivity of dynamic graphs," in *44th IEEE Conference on Decision and Control, 2005 and 2005 European Control Conference (CDC-ECC'05)*. IEEE, 2005, pp. 6388–6393.

[199] M. Ji and M. Egerstedt, "Distributed coordination control of multiagent systems while preserving connectedness," *IEEE Transactions on Robotics*, vol. 23, no. 4, pp. 693–703, 2007.

[200] A. Ajorlou, A. Momeni, and A. G. Aghdam, "A class of bounded distributed control strategies for connectivity preservation in multi-agent systems," *IEEE Transactions on Automatic Control*, vol. 55, no. 12, pp. 2828–2833, 2010.

[201] S. Bhattacharya, T. Başar, and N. Hovakimyan, "Singular surfaces in multi-agent connectivity maintenance games," in *50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC'11)*. IEEE, 2011, pp. 261–266.

[202] L. Sabattini, N. Chopra, and C. Secchi, "Decentralized connectivity maintenance for cooperative control of mobile robotic systems," *The International Journal of Robotics Research*, vol. 32, no. 12, pp. 1411–1423, 2013.

[203] S. Bhattacharya and T. Başar, "Graph-theoretic approach for connectivity maintenance in mobile networks in the presence of a jammer," in *49th IEEE Conference on Decision and Control (CDC 2010)*. IEEE, 2010, pp. 3560–3565.

[204] P. Robuffo Giordano, A. Franchi, C. Secchi, and H. H. Bülthoff, "A passivity-based decentralized strategy for generalized connectivity maintenance," *The International Journal of Robotics Research*, vol. 32, no. 3, pp. 299–323, 2013.

[205] L. Sabattini, C. Secchi, and N. Chopra, "Decentralized connectivity maintenance for networked lagrangian dynamical systems," in *IEEE International Conference on Robotics and Automation (ICRA 2012)*. IEEE, 2012, pp. 2433–2438.

[206] G. F. Franklin, J. D. Powell, and M. L. Workman, *Digital control of dynamic systems*. Addison-Wesley, Menlo Park, CA, 1998, vol. 3.

[207] Y. Cao and W. Ren, "Multi-vehicle coordination for double-integrator dynamics under fixed undirected/directed interaction in a sampled-data setting," *International Journal of Robust and Nonlinear Control*, vol. 20, no. 9, pp. 987–1000, 2010.

[208] D. V. Dimarogonas, E. Frazzoli, and K. H. Johansson, "Distributed event-triggered control for multi-agent systems," *IEEE Transactions on Automatic Control*, vol. 57, no. 5, pp. 1291–1297, 2012.

[209] Y. Fan, G. Feng, Y. Wang, and C. Song, "Distributed event-triggered control of multi-agent systems with combinational measurements," *Automatica*, vol. 49, no. 2, pp. 671–675, 2013.

[210] W. Lu, Y. Han, and T. Chen, "Synchronization in networks of linearly coupled dynamical systems via event-triggered diffusions," *IEEE Transactions on Neural Networks and Learning Systems*, vol. 26, no. 12, pp. 3060–3069, 2015.

[211] E. Garcia, Y. Cao, and D. W. Casbeer, "Decentralized event-triggered consensus with general linear dynamics," *Automatica*, vol. 50, no. 10, pp. 2633–2640, 2014.

[212] W. Zhu, Z.-P. Jiang, and G. Feng, "Event-based consensus of multi-agent systems with general linear models," *Automatica*, vol. 50, no. 2, pp. 552–558, 2014.

[213] G. Shi and K. H. Johansson, "Multi-agent robust consensus-part ii: Application to distributed event-triggered coordination," in *50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC, 2011)*. IEEE, 2011, pp. 5738–5743.

[214] C. Nowzari and J. Cortés, "Zeno-free, distributed event-triggered communication and control for multi-agent average consensus," in *American Control Conference (ACC, 2014)*. IEEE, 2014, pp. 2148–2153.

[215] R. Aragues, J. Cortes, and C. Sagues, "Distributed consensus on robot networks for dynamically merging feature-based maps," *IEEE Transactions on Robotics*, vol. 28, no. 4, pp. 840–854, 2012.

[216] Y. Fan, L. Liu, G. Feng, and Y. Wang, "Self-triggered consensus for multi-agent systems with zeno-free triggers," *IEEE Transactions on Automatic Control*, vol. 60, no. 10, pp. 2779–2784, 2015.

[217] H. Yu and P. J. Antsaklis, "Output synchronization of networked passive systems with event-driven communication," *IEEE Transactions on Automatic Control*, vol. 59, no. 3, pp. 750–756, 2014.

[218] R. Carli, A. Chiuso, L. Schenato, and S. Zampieri, "A pi consensus controller for networked clocks synchronization," *IFAC Proceedings Volumes*, vol. 41, no. 2, pp. 10 289–10 294, 2008.

[219] D. A. B. Lombana and M. Di Bernardo, "Distributed pid control for consensus of homogeneous and heterogeneous networks," *IEEE Transactions on Control of Network Systems*, vol. 2, no. 2, pp. 154–163, 2015.

[220] D. Burbano and M. di Bernardo, "Consensus and synchronization of complex networks via proportional-integral coupling," in *IEEE International Symposium on Circuits and Systems (ISCAS 2014)*. IEEE, 2014, pp. 1796–1799.

[221] P. De Lellis, M. Di Bernardo, F. Sorrentino, and A. Tierno, "Adaptive synchronization of complex networks," *International Journal of Computer Mathematics*, vol. 85, no. 8, pp. 1189–1218, 2008.

[222] L. Cheng, Z.-G. Hou, M. Tan, Y. Lin, and W. Zhang, "Neural-network-based adaptive leader-following control for multiagent systems with uncertainties," *IEEE Transactions on Neural Networks*, vol. 21, no. 8, pp. 1351–1358, 2010.

[223] M. M. Polycarpou, "Stable adaptive neural control scheme for nonlinear systems," *IEEE Transactions on Automatic Control*, vol. 41, no. 3, pp. 447–451, 1996.

[224] W. Chen, X. Li, W. Ren, and C. Wen, "Adaptive consensus of multi-agent systems with unknown identical control directions based on a novel Nussbaum-type function," *IEEE Transactions on Automatic Control*, vol. 59, no. 7, pp. 1887–1892, 2014.

[225] G. Droge and M. Egerstedt, "Distributed parameterized model predictive control of networked multi-agent systems," in *American Control Conference (ACC, 2013)*. IEEE, 2013, pp. 1332–1337.

[226] H. Terelius, U. Topcu, and R. Murray, "Decentralized multi-agent optimization via dual decomposition," in *18th IFAC World Congress, 28 August 2011 through 2 September 2011, Milano, Italy*, 2011, pp. 11 245–11 251.

[227] A. Rantzer, "Dynamic dual decomposition for distributed control," in *American Control Conference (ACC'09)*. IEEE, 2009, pp. 884–888.

[228] N. Chopra and M. W. Spong, "Passivity-based control of multi-agent systems," *Advances in Robot Control: From Everyday Physics to Human-like Movements*, vol. 107, p. 134, 2006.

[229] M. Arcak, "Passivity as a design tool for group coordination," *IEEE Transactions on Automatic Control*, vol. 52, no. 8, pp. 1380–1390, 2007.

[230] Y. Igarashi, T. Hatanaka, M. Fujita, and M. W. Spong, "Passivity-based attitude synchronization in $se(3)$," *IEEE Transactions on Control Systems Technology*, vol. 17, no. 5, pp. 1119–1134, 2009.

[231] H. Wang, "Passivity based synchronization for networked robotic systems with uncertain kinematics and dynamics," *Automatica*, vol. 49, no. 3, pp. 755–761, 2013.

[232] H. Yu and P. J. Antsaklis, "Passivity-based output synchronization of networked Euler–Lagrange systems subject to nonholonomic constraints," in *American Control Conference (ACC, 2010)*. IEEE, 2010, pp. 208–213.

[233] S. Knorn, A. Donaire, J. C. Agüero, and R. H. Middleton, "Passivity-based control for multi-vehicle systems subject to string constraints," *Automatica*, vol. 50, no. 12, pp. 3224–3230, 2014.

[234] V. Gazi, "Swarm aggregations using artificial potentials and sliding-mode control," *IEEE Transactions on Robotics*, vol. 21, no. 6, pp. 1208–1214, 2005.

[235] L. Wang and F. Xiao, "Finite-time consensus problems for networks of dynamic agents," *IEEE Transactions on Automatic Control*, vol. 55, no. 4, pp. 950–955, 2010.

[236] Y. Cao and W. Ren, "Finite-time consensus for multi-agent networks with unknown inherent nonlinear dynamics," *Automatica*, vol. 50, no. 10, pp. 2648–2656, 2014.

[237] S. Parsegov, A. Polyakov, and P. Shcherbakov, "Fixed-time consensus algorithm for multi-agent systems with integrator dynamics," *IFAC Proceedings Volumes*, vol. 46, no. 27, pp. 110–115, 2013.

[238] Q. Hui, W. M. Haddad, and S. P. Bhat, "Finite-time semistability and consensus for nonlinear dynamical networks," *IEEE Transactions on Automatic Control*, vol. 53, no. 8, pp. 1887–1900, 2008.

[239] S. Sundaram and C. N. Hadjicostis, "Finite-time distributed consensus in graphs with time-invariant topologies," in *American Control Conference (ACC'07)*. IEEE, 2007, pp. 711–716.

[240] J. M. Hendrickx, G. Shi, and K. H. Johansson, "Finite-time consensus using stochastic matrices with positive diagonals," *IEEE Transactions on Automatic Control*, vol. 60, no. 4, pp. 1070–1073, 2015.

[241] H.-L. Choi, L. Brunet, and J. P. How, "Consensus-based decentralized auctions for robust task allocation," *IEEE transactions on robotics*, vol. 25, no. 4, pp. 912–926, 2009.

[242] M. Rubenstein, A. Cabrera, J. Werfel, G. Habibi, J. McLurkin, and R. Nagpal, "Collective transport of complex objects by simple robots: theory and experiments," in *Proceedings of the 2013 International Conference on Autonomous Agents and Multi-agent Systems*. International Foundation for Autonomous Agents and Multiagent Systems, 2013, pp. 47–54.

[243] I. D. Couzin, J. Krause, N. R. Franks, and S. A. Levin, "Effective leadership and decision-making in animal groups on the move," *Nature*, vol. 433, no. 7025, pp. 513–516, 2005.

[244] I. R. Nourbakhsh, K. Sycara, M. Koes, M. Yong, M. Lewis, and S. Burion, "Human-robot teaming for search and rescue," *IEEE Pervasive Computing*, vol. 4, no. 1, pp. 72–79, 2005.

[245] J. S. Jennings, G. Whelan, and W. F. Evans, "Cooperative search and rescue with a team of mobile robots," in *8th International Conference on Advanced Robotics (ICAR'97)*. IEEE, 1997, pp. 193–200.

[246] P. Song and V. Kumar, "A potential field based approach to multi-robot manipulation," in *IEEE International Conference on Robotics and Automation (ICRA'02)*, vol. 2. IEEE, 2002, pp. 1217–1222.

[247] J. Wawerla and R. T. Vaughan, "A fast and frugal method for team-task allocation in a multi-robot transportation system," in *IEEE International Conference on Robotics and Automation (ICRA, 2010)*. IEEE, 2010, pp. 1432–1437.

[248] L. Schenato and F. Fiorentin, "Average timesynch: A consensus-based protocol for clock synchronization in wireless sensor networks," *Automatica*, vol. 47, no. 9, pp. 1878–1886, 2011.

[249] L. Xiao, S. Boyd, and S. Lall, "A scheme for robust distributed sensor fusion based on average consensus," in *Proceedings of the 4th International Symposium on Information Processing in Sensor Networks*. IEEE Press, 2005, p. 9.

[250] D. P. Spanos, R. Olfati-Saber, and R. M. Murray, "Distributed sensor fusion using dynamic consensus," in *IFAC World Congress*, Prague Czech Republic, 2005.

[251] A. Simonetto and G. Leus, "Distributed maximum likelihood sensor network localization." *IEEE Transactions on Signal Processing*, vol. 62, no. 6, pp. 1424–1437, 2014.

[252] Z. Wang, S. Zheng, S. Boyd, and Y. Ye, "Further relaxations of the SDP approach to sensor network localization," *SIAM Journal on Optimization*, vol. 19, no. 2, pp. 655–673, 2008.

[253] S. Boyd, "Alternating direction method of multipliers," in *Talk at NIPS Workshop on Optimization and Machine Learning*, 2011.

[254] M. K. Maggs, S. G. O'keefe, and D. V. Thiel, "Consensus clock synchronization for wireless sensor networks," *IEEE Sensors Journal*, vol. 12, no. 6, pp. 2269–2277, 2012.

[255] R. Carli and S. Zampieri, "Network clock synchronization based on the second-order linear consensus algorithm," *IEEE Transactions on Automatic Control*, vol. 59, no. 2, pp. 409–422, 2014.

[256] R. Tron and R. Vidal, "Distributed image-based 3-D localization of camera sensor networks," in *Proceedings of the 48th IEEE Conference on Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference (CDC/CCC 2009)*. IEEE, 2009, pp. 901–908.

[257] A. J. Wood and B. F. Wollenberg, *Power generation, operation, and control*. John Wiley & Sons, 2012.

[258] S. Yang, S. Tan, and J.-X. Xu, "Consensus based approach for economic dispatch problem in a smart grid," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4416–4426, 2013.

[259] S. Kar, G. Hug, J. Mohammadi, and J. M. Moura, "Distributed state estimation and energy management in smart grids: A consensus + innovations approach," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 6, pp. 1022–1038, 2014.

[260] G. Mateos, I. D. Schizas, and G. B. Giannakis, "Distributed recursive least-squares for consensus-based in-network adaptive estimation," *IEEE Transactions on Signal Processing*, vol. 57, no. 11, pp. 4583–4588, 2009.

[261] F. Dorfler and F. Bullo, "Synchronization and transient stability in power networks and nonuniform Kuramoto oscillators," *SIAM Journal on Control and Optimization*, vol. 50, no. 3, pp. 1616–1642, 2012.

[262] D. Romeres, F. Dorfler, and F. Bullo, "Novel results on slow coherency in consensus and power networks," in *European Control Conference (ECC, 2013)*. IEEE, 2013, pp. 742–747.

[263] Z. Zhang and M.-Y. Chow, "Incremental cost consensus algorithm in a smart grid environment," in *IEEE Power and Energy Society General Meeting, 2011*. IEEE, 2011, pp. 1–6.

[264] P. A. Forero, A. Cano, and G. B. Giannakis, "Consensus-based distributed support vector machines," *Journal of Machine Learning Research*, vol. 11, no. May, pp. 1663–1707, 2010.

[265] R. Tron and R. Vidal, "Distributed computer vision algorithms through distributed averaging," in *IEEE Conference on Computer Vision and Pattern Recognition (CVPR, 2011)*. IEEE, 2011, pp. 57–63.

[266] M. H. DeGroot, "Reaching a consensus," *Journal of the American Statistical Association*, vol. 69, no. 345, pp. 118–121, 1974.

[267] N. Fredkin and E. Johnson, "Social influence networks and opinion change," *Adv Group Process*, vol. 16, pp. 1–29, 1999.

[268] V. Amelkin, F. Bullo, and A. K. Singh, “Polar opinion dynamics in social networks,” *IEEE Transactions on Automatic Control*, 2017.

[269] D. Acemoglu and A. Ozdaglar, “Opinion dynamics and learning in social networks,” *Dynamic Games and Applications*, vol. 1, no. 1, pp. 3–49, 2011.

[270] C. Altafini, “Consensus problems on networks with antagonistic interactions,” *IEEE Transactions on Automatic Control*, vol. 58, no. 4, pp. 935–946, 2013.

[271] A. Jadbabaie, P. Molavi, A. Sandroni, and A. Tahbaz-Salehi, “Non-bayesian social learning,” *Games and Economic Behavior*, vol. 76, no. 1, pp. 210–225, 2012.

[272] D. Acemoglu, A. Ozdaglar, and A. ParandehGheibi, “Spread of (mis) information in social networks,” *Games and Economic Behavior*, vol. 70, no. 2, pp. 194–227, 2010.

[273] Z. Liu, X. Huang, S. X.-D. Tan, H. Wang, and H. Tang, “Distributed task migration for thermal hot spot reduction in many-core microprocessors,” in *10th International Conference on ASIC (ASICON, 2013)*. IEEE, 2013, pp. 1–4.

[274] M. U. Sardar, O. Hasan, M. Shafique, and J. Henkel, “Theorem proving based formal verification of distributed dynamic thermal management schemes,” *Journal of Parallel and Distributed Computing*, vol. 100, pp. 157–171, 2017.

[275] S. A. A. Bukhari, F. K. Lodhi, O. Hasan, M. Shafique, and J. Henkel, “FAMe-TM: Formal analysis methodology for task migration algorithms in many-core systems,” *Science of Computer Programming*, vol. 133, pp. 154–174, 2017.

[276] Y. Yang, Q.-S. Jia, and X. Guan, “Stochastic coordination of aggregated electric vehicle charging with on-site wind power at multiple buildings,” in *IEEE 56th Annual Conference on Decision and Control (CDC, 2017)*. IEEE, 2017, pp. 4434–4439.

[277] T. Hatanaka, X. Zhang, W. Shi, M. Zhu, and N. Li, “Physics-integrated hierarchical/distributed HVAC optimization for multiple buildings with robustness against time delays,” in *IEEE 56th Annual Conference on Decision and Control*. IEEE, 2017, pp. 6573–6579.

[278] T. Hatanaka, X. Zhang, W. Shi, M. Zhu, and N. Li, “Physics-integrated hierarchical/distributed HVAC optimization for multiple buildings with robustness against time delays,” in *IEEE 56th Annual Conference on Decision and Control (CDC, 2017)*. IEEE, 2017, pp. 6573–6579.

[279] T. Mylvaganam, M. Sassano, and A. Astolfi, "Constructive ϵ-Nash equilibria for nonzero-sum differential games," *IEEE Transactions on Automatic Control*, vol. 60, no. 4, pp. 950–965, 2015.

[280] E. Semsar-Kazerooni and K. Khorasani, "Multi-agent team cooperation: A game theory approach," *Automatica*, vol. 45, no. 10, pp. 2205–2213, 2009.

[281] K. G. Vamvoudakis, F. L. Lewis, and G. R. Hudas, "Multi-agent differential graphical games: Online adaptive learning solution for synchronization with optimality," *Automatica*, vol. 48, no. 8, pp. 1598–1611, 2012.

[282] C.-T. Lin, "Structural controllability," *IEEE Transactions on Automatic Control*, vol. 19, no. 3, pp. 201–208, 1974.

[283] Y.-Y. Liu, J.-J. Slotine, and A.-L. Barabási, "Controllability of complex networks," *Nature*, vol. 473, no. 7346, p. 167, 2011.

[284] S. Gu, F. Pasqualetti, M. Cieslak, Q. K. Telesford, B. Y. Alfred, A. E. Kahn, J. D. Medaglia, J. M. Vettel, M. B. Miller, S. T. Grafton *et al.*, "Controllability of structural brain networks," *Nature Communications*, vol. 6, p. 8414, 2015.

[285] T.-S. Tay and W. Whiteley, "Generating isostatic frameworks," *Structural Topology, 1985, Núm. 11.*

[286] W. Whiteley, "Some matroids from discrete applied geometry," *Contemporary Mathematics*, vol. 197, pp. 171–312, 1996.

[287] T.-S. Tay and W. Whiteley, "Recent advances in the generic rigidity of structures," *Structural Topology, 1984, Núm. 9.*

[288] T.-S. Tay, "A new proof of Laman's theorem," *Graphs and combinatorics*, vol. 9, no. 2, pp. 365–370, 1993.

[289] A. Recski, "A network theory approach to the rigidity of skeletal structures part II. Laman's theorem and topological formulae," *Discrete Applied Mathematics*, vol. 8, no. 1, pp. 63–68, 1984.

[290] J. Choi, S. Oh, and R. Horowitz, "Distributed learning and cooperative control for multi-agent systems," *Automatica*, vol. 45, no. 12, pp. 2802–2814, 2009.

[291] A. H. Sayed *et al.*, "Adaptation, learning, and optimization over networks," *Foundations and Trends® in Machine Learning*, vol. 7, no. 4-5, pp. 311–801, 2014.

[292] S. Kapetanakis and D. Kudenko, "Reinforcement learning of coordination in cooperative multi-agent systems," *AAAI/IAAI*, vol. 2002, pp. 326–331, 2002.