Title: Networked Systems

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Abstract

This article provides a brief overview on networked systems from a systems and control perspective. We pay special attention to the nature of the interactions among agents, the critical role played by information sharing, dissemination, and aggregation, and the distributed control paradigm to engineer the behavior of networked systems.

Keywords and Phrases

Multi-agent systems, autonomous networks, cooperative control, swarms

Introduction

Networked systems appear in numerous scientific and engineering domains, including communication networks [49], multi-robot networks [3; 5], sensor networks [43; 44], water irrigation networks [8], power and electrical networks [10; 9; 17], camera networks [46], transportation networks [1], social networks [23], and chemical and biological networks [27; 47]. Their applications are pervasive, ranging from environmental monitoring, ocean sampling, and marine energy systems, through search and rescue missions, high-stress deployment in disaster recovery, health monitoring of critical infrastructure to science imaging, the smart grid, and cybersecurity.

The rich nature of networked systems makes it difficult to provide a definition that, at the same time, is comprehensive enough to capture their variety and simple enough to be expressive of their main features. With this in mind, we loosely define a networked system as a 'system of systems', i.e., a collection of agents that interact with each other. These groups might be heterogeneous, composed by human, biological, or engineered agents possessing different capabilities regarding mobility, sensing, actuation, communication, and computation. Individuals may have objectives of their own or may share a common objective with others – which in turn might be adversarial with respect to another subset of agents.

In a networked system, the evolutions of the states of individual agents are coupled. Coupling might be the result of the physical interconnection among the agents, the consequence of the implementation of coordination algorithms where agents use information about each other, or a combination of both. There is diversity too in the nature of agents themselves and the interactions among them, which might be cooperative, adversarial, or belong to the rich range between the two. Due to changes in the state of the agents, the network, or the environment, interactions among agents may be changing and dynamic. Such interactions may be structured across different layers, which themselves might be organized in a hierarchical fashion. Networked systems may also interact with external entities that specify high-level commands that trickle down through the system all the way to the agent level.

A defining characteristic of a networked system is the fact that information, understood in a broad sense, is sparse and distributed across the agents. As such, different individuals have access to information of varying degrees of quality. As part of the operation of the networked system, mechanisms are in place to share, transmit, and/or aggregate this information. Some information may be disseminated throughout the whole network or, in some cases, all information can be made centrally available at a reasonable cost. In other scenarios, however, the latter might turn out to be too costly, unfeasible, or undesirable because of privacy and security considerations. Individual agents are the basic unit for decision making but decisions might be made from intermediate levels of the networked system all the way to a central planner. The combination of information availability and decision making capabilities gives rise to an ample spectrum of possibilities between the centralized control paradigm, where all information is available at a central planner who makes the decisions, and the fully distributed control paradigm, where individual agents only have access to the information shared by their neighbors in addition to their own.

Perspective from Systems and Control

There are many aspects that come into play when dealing with networked systems regarding computation, processing, sensing, communication, planning, motion control, and decision making. This complexity makes their study challenging and fascinating, and explains the interest that, with different emphases, they generate in a large number of disciplines. In biology, scientists analyze synchronization phenomena and self-organized swarming behavior in groups with distributed agent-to-agent interactions [34; 38; 13; 14]. In robotics, engineers design algorithmic solutions to help multi-vehicle networks and embedded systems coordinate their actions and perform challenging spatially-distributed tasks [3; 12; 5; 22; 26]. Graph theorists and applied mathematicians study the role played by the interconnection among agents in the emergence of phase transition phenomena [6; 31; 11]. This interest is also shared in communication and information theory, where researchers strive to design efficient communication protocols and examine the effect of topology control on group connectivity and information dissemination [51; 20; 29; 43; 19]. Game theorists study the gap between the performance achieved by global, network-wide optimizers and the configurations that result from selfish agents interacting locally in social and economic systems [40; 33; 18; 30]. In mechanism design, researchers seek to align the objectives of individual self-interested agents with the overall goal of the network. Static and mobile networked systems and their applications to the study of natural phenomena in oceans [37; 21; 50; 15; 36], rivers [41; 48], and the environment [16] also raise exciting challenges in estimation theory, computational geometry, and spatial statistics.

The field of systems and control brings a comprehensive approach to the modeling, analysis, and design of networked systems. Emphasis is put on the understanding of the general principles that explain how specific collective behaviors emerge from basic interactions, the establishment of models, abstractions, and tools that allow us to reason rigorously about complex interconnected systems, and the development of systematic methodologies that help engineer their behavior. The ultimate goal is to establish a science for integrating individual components into complex, self-organizing networks with predictable behavior. To realize the 'power of many' and expand the realm of what is possible to achieve beyond the individual agent capabilities, special care is taken to obtain precise guarantees on the stability properties of coordination algorithms, understand the conditions and constraints under which they work, and characterize their performance and robustness against a variety of disturbances and disruptions.

Research Issues – and How the Articles in the Encyclopedia Address Them

Given the key role played by agent-to-agent interactions in networked systems, several Encyclopedia articles ≪link to "Graphs for modeling networked control systems," Mesbahi Mesbahi and Magnus Egerstedt≫, ≪link to "Connectivity of dynamic graphs," Michael Zavlanos and George Pappas≫ deal with how their nature and effect can be modeled through graphs. This includes diverse aspects such as deterministic and stochastic interactions, static and dynamic graphs, state-dependent and time-dependent neighboring relationships, and connectivity. The importance of maintaining a certain level of coordination and consistency across the networked system is manifested in the various articles that deal with coordination tasks that are, in some way or another, related to some form of agreement. These include consensus ≪link to "Averaging algorithms and consensus," Wei Ren≫, formation control ≪link to "Vehicular strings," Mihailo Jovanović≫, cohesiveness ≪link to "Steering laws for interacting particles," P. S. Krishnaprasad≫, flocking ≪link to "Flocking in Networked Systems," Ali Jadbabaie≫, synchronization ≪link to "Oscillator synchronization," Bruce Francis≫, and distributed optimization ≪link to "Distributed optimization," Angelia Nedić≫. A great deal of work ≪link to "Optimal deployment and spatial coverage," Sonia Martínez≫, ≪link to "Multi-vehicle routing," Emilio Frazzoli and Marco Pavone≫ is also devoted to the design of cooperative strategies that achieve spatially-distributed tasks such as optimal coverage, space partitioning, vehicle routing, and servicing. These articles explore the optimal placement of agents, the optimal tuning of sensors, and the distributed optimization of network resources. The article ≪link to "Estimation and control over networks," Vijay Gupta≫ explores the impact that communication channels may have on the execution of estimation and control tasks over networks of sensors and actuators. A strong point of commonality among the contributions is the precise characterization of the scalability of coordination algorithms, together with the rigorous analysis of their correctness and stability properties. Another focal point is the analysis of the performance gap between centralized and distributed approaches in regard to the ultimate network objective.

Further information about other relevant aspects of networked systems can be found throughout this Encyclopedia. Among these, we highlight the synthesis of cooperative strategies for data fusion, distributed estimation, and adaptive sampling, the analysis of the network operation under communication constraints (e.g., limited bandwidth, message drops, delays, and quantization), the treatment of game-theoretic scenarios that involve interactions among multiple players and where security concerns might be involved, distributed model predictive control, and the handling of uncertainty, imprecise information, and events via discrete-event systems and triggered control.

Summary and Future Directions

In conclusion, this article has illustrated ways in which systems and control can help us design and analyze networked systems. We have focused on the role that information and agent interconnection play in shaping their behavior. We have also made emphasis on the increasingly rich set of methods and techniques that allow to provide correctness and performance guarantees. The field of networked systems is vast and the amount of work impossible to survey in this brief article. The reader is invited to further explore additional topics beyond the ones mentioned here. The monographs [39; 7; 32; 2], edited volumes [25; 45; 42], and manuscripts [35; 4; 28; 24], together with the references provided in the Encyclopedia articles mentioned above, are a good starting point to undertake this enjoyable effort. Given the big impact that networked systems have, and will continue to have, in our society, from energy and transportation, through human interaction and healthcare, to biology and the environment, there is no doubt that the coming years will witness the development of more tools, abstractions, and models that allow to reason rigorously about intelligent networks, and for techniques that help design truly autonomous and adaptive networks.

Cross-References

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- ≪link to "Connectivity of dynamic graphs," Michael Zavlanos and George Pappas≫
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