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# On the Control of Multi-Agent Systems: A Survey

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# 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,

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.

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# 1

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## Introduction

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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-notch 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.

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