Game-theoretical methods in control of engineering systems
Special issue introduction

Carlos Ocampo-Martinez and Nicanor Quijano
POC: C. Ocampo-Martinez (cocampo@iri.upc.edu)

There has been increasing interest in the control community in studying large-scale distributed systems, and numerous techniques have been developed to address the main challenges in these problems. One way to approach this type of problems is to use a multi-agent systems framework, which can be cast in game-theoretical terms. Game theory has traditionally been used to describe the behavior of decision makers restricted to the available information from either some or all agents (players). From this perspective, game theory shares some common points with control systems problems, in particular those with distributed topologies, where the interconnection of different elements (agents) leads to a global behavior that depends on the local interaction of these agents. Applications such as games played on networks, the dynamics of consensus/synchronization, energy, transportation networks, combine many techniques of game theory, such as non-cooperative, cooperative, dynamical, mean-field, and evolutionary. Aware of this rising recent interest, this special issue is devoted to collecting different techniques and points of view in the interaction of game-theoretical methods and automatic control, with the aim of closing the gap between the wide background in game theory and related disciplines and their application to solving engineering problems of diverse nature.

Technical Concerns

The key motivation for organizing this special issue was the constant search of bridges among a group of people with different but complementary research backgrounds (game theory and automatic control) but sharing the same objective: efficiently solving real control problems involving large-scale systems with complex dynamics. With that objective, several non-trivial but motivational questions arise, such as:

1) Why is it important to use game-theoretical methods in automatic control problems?

2) What are the main advantages/disadvantages of using these techniques compared to other classical and modern methods?
3) Is there a general methodology that can be followed to use game theoretical methods in dynamic resource allocation problems?
4) What are the main research challenges in control systems that can be solved using game-theoretical methods?
5) What are (some of) the real applications involving automatic control that use techniques such as non-cooperative, cooperative, and evolutionary game theory?

The contributions of this issue relate to control algorithms based on game theory, population dynamics, evolutionary game theory, coalitional control, distributed control, and social integration of engineering problems. All articles address different aspects of the proposed research questions using different methodologies and case studies, enabling the reader to see the relationships between the disciplines involved. Although the articles belonging to this special issue already treat several of the topics related to game theory and control, there much more work is required to discover all of the advantages and strengths of applying game theory to real control problems. However, the hope is that this special issue encourages researchers worldwide to explore this novel line of research, leading to further successful results.

Contributions of the Special Issue

This special issue consists of four research articles focused on presenting or proposing methodologies for learning in games, coalitional games, population/evolutionary games, and networked resource allocation problems. Each article provides an introduction to the methodologies, presenting the analogies necessary to understand how these problems are related to the control systems area. Examples based on dynamical and control systems are presented in order to clarify the utility of the proposed techniques.

The articles all address the fifth motivational question proposed for this special issue since they demonstrate and discuss the effectiveness of the application of their proposed approaches over case studies that reflect real engineering problems: smart energy grids, lighting systems, traffic routing networks, and urban drainage systems. Except for the last article, all papers cover the discussions raised from the motivational questions 2 and 4 since they propose the design of distributed control topologies different to those reported in the literature so far given their flexibility and the scalability of their control architecture, being capable of arranging themselves into proper subsystems as a function of their needs and without a supervisory control layer.

The special issue starts with the article by Vamvoudakis, Modares, Kiumarsi, and

Lewis, entitled "Game Theory-Based Control System Algorithms with Real-Time Reinforcement Learning," which addresses the motivational questions 1, 2, and 4. This article presents and discusses how to solve online multi-player game problems by using adaptive learning in real-time based on data taken from the players. The approach assumes the players communicate using a graph network topology, only receiving information along the graph edges. The considered methods use reinforcement learning (RL), in particular the off-policy RL, to learn, online and in real-time, the solution to both zero-sum and non-zero sum Nash games. Hence, the proposed approach solves the online multi-player game in order to achieve both optimal regulation and optimal control tasks using data measured along the trajectories of the players. The article considers the complete knowledge of the agents state, which leaves for further work the research about the design of output-feedback controllers based only on measured output data, topic not fully investigated yet. The concepts of the article are demonstrated on networked cyber-physical systems.

Then, the article by Felle, Maestre, and Camacho, entitled "Coalitional Control: Cooperative Game Theory and Control," provides a summary of the fundamental concepts of coalitional game theory, in particular those related with control engineering applications in general. Drawing from the well-established framework of the control of large-scale systems, a brief literature survey traces an ideal path from the optimal model partitioning to the distributed control schemes whose principles happen to be close to the idea of coalitional control. The article is framed within this novel theory that emerges by seeking solutions in the multi-agent frameworks formulated into the game theory context. This approach helps to deal with different issues, located at a higher layer in the management of large-scale systems. In order to illustrate the coalitional control algorithm, the authors consider a demand response problem framed within the large-scale systems problem of a smart grid. The article deals especially with motivational questions 1, 2, and 4. It deals with question 1 since game theory is the branch of mathematics that deals with mutual interaction problems, which is often the case in distributed control problems. The local controllers or agents can be independent entities with their own goals and may not have an incentive for cooperation unless they can obtain some benefit. Regarding motivational questions 2 and 4, cooperative game theory establishes the essential conditions for cooperation among local controllers and also means to distribute the corresponding benefits and costs.

The third article by Quijano, Ocampo-Martinez, Barreiro-Gomez, Obando, Pantoja, and Mojica-Nava, entitled "The Role of Population Games and Evolutionary Dynamics in Distributed Control Systems," uses a multi-agent systems framework, which may be cast in game-theoretic terms, in order to perform the distributed control of large-scale complex systems in which the availability of information plays a crucial role. Some of these problems can be seen as dynamic resource allocation problems, which can be solved using dynamic games. In this type of games, there is a learning mechanism that helps to modify past decisions using a model of the environment, the objectives that are pursued, and the order and amount of information needed to modify the actions. In this paper, a special class of dynamic games that describe the change of behavior of the players is used: evolutionary game theory (EGT). Even though this EGT approach has been widely studied in biology and behavioral ecology, the authors use the fact that there is an analogy between the evolution of the behavior of agents and the population games to design controllers for different dynamic resource allocation problems. This article presents a useful mathematical formalism of the population games and evolutionary dynamics and their main features and properties to address the motivational questions 1, 3, and 4. In order to show the effectiveness of the proposed approaches, simulation and/or implementation results from three real engineering applications are presented.

Adding a complementary perspective to the game-theory-based control statements, the article by Brown and Marden, entitled “Studies on Robust Social Influence Mechanisms” addresses the way the engineering problems are integrated into a social environment and how the strategic behavior from the users of such problems affect the system performance. The discussion arises from the the fact that the incentives of the users as individuals may be against the global objectives of the entire system. The questions this article seeks to solve reads: “how can behavior-influencing mechanisms be designed such that they are robust to a variety of mis-characterization/variations in models of social behavior?” The proposed approach, through a traffic routing case study, investigates the definition of robust social influence reaching analytical results for the particular example able to be conceptually applied to engineering systems where the social systems can be enmeshed. This paper tackles the motivational questions 3, and 4 since, apart of covering the problem from a nominal point of view, the proposal discusses the robustness in the performance of the engineering problems in a social framework, which is in general one of the most interesting challenging issue in the analysis of control systems.

Suggested Highlights

Modeling interactions between different decision-makers is an important dynamical systems concept that can be addressed from a game-theoretical perspective.

Game theory shares some common points with control systems problems, in particular of distributed topology, where the interconnection of different elements leads to a global behavior depending on local interactions.

Networked dynamic resource allocation problems can be tackled using different type of game-theoretical approaches.

Author Information

Carlos Ocampo-Martinez (cocampo@iri.upc.edu) received his Electronics Engineering degree and his MSc. degree in Industrial Automation from Universidad Nacional de Colombia, Campus Manizales, in 2001 and 2003, respectively. In 2007, he received his Ph.D. degree in Control Engineering from the Technical University of Catalonia (Barcelona, Spain). Since 2011, he is with the Technical University of Catalonia, Automatic Control Department (ESAII) as Associate Professor in automatic control and model predictive control. Since 2014, he is also Deputy Director of the Institut de Robòtica i Informàtica Industrial (CSIC-UPC), a Joint Research Center of UPC and CSIC. His main research interests include constrained model predictive control, large-scale systems management (partitioning and non-centralized control), and industrial applications (mainly related to the key scopes of water and energy). He is Senior Member of the IEEE.

Nicanor Quijano (nquijano@uniandes.edu.co) received his B.S. degree in Electronics Engineering from Pontificia Universidad Javeriana (PUJ), Bogotá, Colombia, in 1999. He received the M.S. and PhD degrees in Electrical and Computer Engineering from The Ohio State University, in 2002 and 2006, respectively. In 2007 he joined the Electrical and Electronics Engineering Department, Universidad de los Andes (UAndes), Bogotá, Colombia as an Assistant Professor. In 2008 he obtained the Distinguished Lecturer Award from the School of Engineering, UAndes. He is currently Full Professor and the director of the research group in control and automation systems (GIAP, UAndes). On the other hand, he has been a member of the Board of Governors of the IEEE Control Systems Society (CSS) for the 2014 period, and he was the Chair of the IEEE CSS, Colombia for the 2011-2013 period. Currently his research interests include: hierarchical and distributed optimization methods using bio-inspired and game-theoretical techniques for dynamic resource allocation problems, especially those in energy, water, and transportation. He is Senior Member of the IEEE.