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Networked control design for coalitional schemes using game-theoretic methods☆

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ABSTRACT

In this work, we present an iterative design method for a coalitional networked control scheme for linear systems. In this scheme, the links in the communication network are enabled or disabled depending on their contribution to the overall system performance. Likewise, the control law is adapted to these changes. In particular, new conditions are included at the design phase, in order to consider constraints on the links and the agents regarding the game theoretical tools utilized while optimizing the matrices that define the controller.

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1. Introduction

Non-centralized control techniques have been well addressed by the control community: their well-known advantages such as scalability and modularity, are suitable to control large-scale systems such as traffic, water or power networks (Negenborn, De Schutter, & Hellendoorn, 2006). The main idea of these schemes (in comparison with centralized ones) is to divide the overall system into several pieces, each of them governed by a local controller or *agent*. In this way, we refer to decentralized control, if there is no communication among the agents, i.e., the subsystems are isolated; or distributed control, in case the controllers share information to improve the overall system performance.

Focusing on distributed control, it is possible to find in the literature many examples – very specifically under the framework of model based control – which consider that the groups of connected agents, also called *coalitions*, do not vary along the time. In other words, there is no possibility of modifying the way in that the agents are grouped. Examples of these approaches are: Maestre, Muñoz de la Peña, Camacho, and Alamo (2011a), where the agents always send proposals regarding the control actions to the same neighbors; or Lagrangian prices based schemes as Negenborn, van Overloop, Keviczky, and De Schutter (2009), because prices are always updated by the set of agents that share the common resource. See Maestre and Negenborn (2014) and Scattolini (2009) for surveys of these techniques in a distributed model predictive control context.

Recently, different works that consider explicitly interactions among the agents that evolve dynamically with time to reduce the communication burden without compromising the system performance have appeared. To this end, groups of cooperating controllers are merged into dynamic neighborhoods or coalitions that behave as a single agent. Examples of this type of schemes, known as *coalitional control* schemes, can be found in: Jilg and Stursberg (2013), where the coupling of the plant is used to

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partition it into hierarchically coupled clusters; Trodden and Richards (2009), where coalitions are formed using the set of active constraints; Núñez, Ocampo-Martinez, De Schutter, Valencia, López, and Espinosa (2013), Núñez, Ocampo-Martinez, Maestre, and De Schutter (2015), where several possible hierarchical control structures are considered to implement the most appropriate one; or Maestre, Muñoz de la Peña, Jiménez Losada, Algaba, and Camacho (2011b); Maestre, Muñoz de la Peña, Jiménez Losada, Algaba, and Camacho (2014), where the control scheme enables or disables links depending on their contribution to the overall system performance. Recently, this setting has been extended to a MPC framework in Fele, Maestre, Muros, and Camacho (2013), Fele, Maestre, Shahdany, Muñoz de la Peña, and Camacho (2014) and Maestre, Muros, Fele, and Camacho (2015).

The applications of cooperative game theory into engineering problems are becoming more common. For example, Saad, Han, Debbah, Hjørungnes, and Başar (2009) present a tutorial regarding coalitional game theory and its applications in communication networks. Some interesting applications of this framework into control problems have been presented by Bauso and his coworkers, who proposed in Bauso and Timmer (2012) a robust dynamic scheme in which instantaneous and averaged games are analyzed and allocation rules are presented. The problem of robust allocation rules for cooperative games is also considered in Bauso and Timmer (2009). Finally, this line of work is enhanced in Nedić and Bauso (2013), where a distributed bargaining protocol is developed so that an allocation inside the core of the game is provided in different cases.

In particular, in Maestre et al. (2011b, 2014) some game theoretical tools are introduced to consider a bound on the cost function minimized by the control scheme, as the characteristic function of a cooperative game where the players are the links that connect the agents. Once the game is defined in that way, it is necessary to choose a payoff rule to distribute the benefit or cost of the grand coalition among the players (links). From the different solution concepts, there are some recent works Muros, Maestre, Algaba, Alamo, and Camacho (2014a,b) and Muros, Maestre, Algaba, Ocampo-Martinez, and Camacho (2015) that have focused on the Shapley value of the game (Shapley, 1953). This value deals with the averaged contribution of each link, which is interesting to obtain information when considering all the different network configurations by the link-game. In addition, if the cost function has an economical meaning, the position value (Borm, Owen, & Tijs, 1992) also provides a reasonable way of distributing the costs among the agents.

In this work, we enhance and present in a more formal way the preliminary results given in Muros et al. (2014a,b). More specifically, we will focus on the following directions:

- We derive conditions to consider Shapley and position value constraints in the overall control problem. In particular, we introduce a matrix notation that extends the Shapley standard matrix concept (Xu, Driessen, & Sun, 2008) to the position value. Ultimately, this setting will make possible to bound or establish comparisons for each link or agent inside the network and also combine constraints for the links and the agents.
- We propose an iterative design algorithm which optimizes the matrices that define the controller. In addition, we present a new suboptimality index, which gives a measure of the convergence achieved.

In order to achieve the objectives mentioned above, we will use linear matrix algebra and linear matrix inequalities (LMIs) to model the optimization problem. The key idea is to minimize a linear objective under LMI constraints. In this way, if there exists a set of matrices that simultaneously satisfy all the LMIs, this set is convex and hence the *interior point methods* (IPMs) find a solution of the optimization problem with an affordable computational time (Alamo, Normey-Rico, Arahal, Limon, & Camacho, 2006; Boyd, El Ghaoui, Feron, & Balakrishnan, 1994). In this work, we will use a Matlab® solver which implements the IPMs proposed in Nesterov and Nemirovskii (1994). Nevertheless, in the context of design, there are other solvers in the literature, such as the *active set methods*. In this sense, the choice of the optimization method will depend on the specific problem to solve in each case. A comparative analysis of the different solvers available can be found in Bartlett, Wätchet, and Biegler (2000), Geletu (2007), Leyffer and Mahajan (2010) and Wright (1997).

Another relevant topic in this context is that of networked control systems (NCSs), which consider spatially distributed systems for which the communication between their parts is supported by a shared communication network. These control systems deal with the issues derived from the communication, e.g., packet data rates, networking technology, sampling, network security, packet dropout or network delays (see Gupta & Chow, 2010; Hespanha, Naghshtabrizi, & Xu, 2007 for surveys about these topics). Nevertheless, in this particular work, we will not deal with these challenges, but we will focus on analyzing control architecture changes that depend on the state, by considering game theory tools. Another noteworthy point in this regard is that some schemes proposed in the NCSs literature are also designed by means of LMIs (Millán,Orihuela,Vivas,Rubio,Dimarogonas & Johansson, 2013), which may simplify its integration with the design method presented in this article.

Note that this work contains significant differences with respect to Muros et al. (2014a,b). First, the design algorithm has been generalized to consider constraints on the agents by the position value, and the corresponding position value LMI conditions have been derived. In addition, an extension for multiplayer constraints is also considered. Likewise, the steady state is studied, the limit case conditions for the LMIs are also given and the decentralized case has been analyzed more explicitly. Moreover, performance indices have been redefined and proofs for the theorems have been provided. Finally, new examples and figures are presented to enhance and illustrate the explanation of the scheme proposed.

The rest of the paper is organized as follows. In Section 2 the problem setting and the game theory tools are presented. In Section 3, a controller design procedure based on LMIs, which integrates conditions on the Shapley and the position values, is introduced. In Section 4, a very simple numerical example is used to illustrate the proposed approach. Finally, conclusions and comments about future research are presented in Section 5.

2. Problem formulation

In this section, we present the model used to represent the system dynamics, a description of the control scheme and how some cooperative game theory tools can be applied to distributed control.

2.1. System description

Consider the class of distributed linear systems composed of a set of $\mathcal{N} = \{1, 2, \ldots, |\mathcal{N}|\}$ interconnected subsystems. The dynamics of subsystem $i \in \mathcal{N}$ can be described mathematically as[1]

$$\begin{aligned} \mathbf{x}_i(k+1) &= \mathbf{A}_{ii}\mathbf{x}_i(k) + \mathbf{B}_{ii}\mathbf{u}_i(k) + \mathbf{d}_i(k), \\ \mathbf{d}_i(k) &= \sum_{j \neq i} \left[\mathbf{A}_{ij}\mathbf{x}_j(k) + \mathbf{B}_{ij}\mathbf{u}_j(k)\right], \end{aligned} \quad (1)$$

[1] In Section 3.4 the possibility of including extra state or input constraints is considered.

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