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Tutorial Article

A framework for receding-horizon control in infinite-horizon aggregative games☆

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ABSTRACT

A novel modelling framework is proposed for the analysis of aggregative games on an infinite-time horizon, assuming that players are subject to heterogeneous periodic constraints. A new aggregative equilibrium notion is presented and the strategic behaviour of the agents is analysed under a receding horizon paradigm. The evolution of the strategies predicted and implemented by the players over time is modelled through a discrete-time multi-valued dynamical system. By considering Lyapunov stability notions and applying limit and invariance results for set-valued correspondences, necessary conditions are derived for convergence of a receding horizon map to a periodic equilibrium of the aggregative game. This result is achieved for any (feasible) initial condition, thus ensuring implicit adaptivity of the proposed control framework to real-time variations in the number and parameters of players. Design and implementation of the proposed control strategy are discussed and an example of distributed control for data routing is presented, evaluating its performance in simulation.

Contents

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1. Introduction

This work studies the interactions between self-interested agents that autonomously pursue their individual benefit. It is supposed that the pay-off of the single agent is exclusively a function of its strategy and of the overall population behaviour. These scenarios are usually described as aggregative games (Jensen, 2010; Kukushkin, 2004), which have been recently applied in multiple contexts, including economics, power systems and transportation networks. Most of the studies in this area have focused on characterizing the game equilibria and devising distributed control strategies for the agents' coordination that ensure convergence and (possibly) global optimality.

The proposed analyses have mostly considered a static setting, with all the agents operating over the same finite-time horizon. This modelling framework does not fully capture realistic scenarios where the constraints and preferences of the agents, and possibly the size of the population, are expected to vary over time. Furthermore, due to the cyclic nature of most economic, industrial, and social processes, a periodic operation can be an essential factor in pursuing optimal economical performance (Angeli, Amrit, & Rawlings, 2012; Huang, Harinath, & Biegler, 2011; Limón et al., 2016; Müller & Grüne, 2016; Zanon, Gros, & Diehl, 2013). However, a static framework cannot account for multiple agents that repeatedly perform heterogeneous tasks over time, as this cannot be meaningfully incorporated in a single limited time frame. To the best of the authors' knowledge, this is the first paper that tries to tackle these current limitations in the literature, extending the analysis of aggregative games to a periodic infinite-time horizon, proposing a receding horizon scheme for the distributed coordination of the agents and deriving analytical conditions for its convergence to equilibrium.

The remaining part of this introduction contains an overview on the state of the art for aggregative games and receding horizon control schemes. In addition, it summarizes the main contributions of the paper. Section 2 details the chosen modelling framework for infinite-horizon aggregative games with periodic constraints and characterizes the associated equilibria. Section 3 presents the proposed receding horizon scheme and derives sufficient conditions for feasibility and convergence to equilibrium of better-response coordination algorithms. Finally, Section 4 presents a possible application of the proposed scheme to a data routing problem and Section 5 contains some conclusive remarks.

1.1. Relevant work – aggregative games and distributed coordination schemes

Noncooperative Nash games in which the objective function of a single player depends exclusively on its strategy and on some aggregation of all players' strategies have been considered in multiple papers. Although this aggregation typically reduces to some linear function of the population strategy, much broader definitions are allowed (Jensen, 2010). In addition to theoretical works that investigate existence and uniqueness of Nash equilibria in aggregative games (Dindos & Mezzetti, 2006; Kukushkin, 2004; Martimort & Stole, 2011), many applications and studies have been proposed in the area of economics (Cornes & Hartley, 2005; Novshek, 1985), communication networks (Altman, Boulogne, El-Azouzi, Jiménez, & Wynter, 2006; Başar, 2007), network congestion (Alpcan & Başar, 2005; Barrera & Garcia, 2015; Gentile, Parise, Paccagnan, Kamgarpour, & Lygeros, 2017) and power systems (Chen, Li, Louie, & Vucetic, 2014; De Paola, Angeli, & Strbac, 2017b; Ma, Callaway, & Hiskens, 2013). Several studies have recently analysed aggregative games within the context of mean field theory (Huang, Caines, & Malhamé, 2007; Lasry & Lions, 2007). Research has not only focused on theoretical characterizations of the equilibrium as the population size tends to infinity, but it has also considered the design of decentralized control schemes (Bauso & Pesenti, 2013; Grammatico, Parise, Colombino, & Lygeros, 2016; Nourian, Caines, Malhame, & Huang, 2013), with specific applications in several engineering-related areas (Djehiche, Tcheukam, & Tembine, 2017), specifically power grids (Bagagiolo & Bauso, 2014; De Paola, Angeli, & Strbac, 2016), crowd dynamics (Aurell & Djehiche, 2018; Lachapelle & Wolfram, 2011) and economics (Lachapelle, Salomon, & Turinici, 2010). Further research has considered the related framework of population games, characterizing the evolutionary dynamics of infinitely large collections of interacting agents (Fox & Shamma, 2013; Quijano et al., 2017; Sandholm, 2010).

In the context of aggregative games, increasing interest has been directed towards the development of distributed coordination mechanisms with suitable convergence properties. Specific classes of games show an intrinsic convex structure which facilitates the design and analysis of noncooperative response schemes (Belgioioso & Grammatico, 2017a; Fox & Shamma, 2013; Hofbauer & Sandholm, 2009; Marden, Arslan, & Shamma, 2009). The well-established convergence properties of these games are exploited, for example, by Candogan, Ozdaglar, and Parrilo (2013) for characterizing the limiting behaviour of general Nash games in terms of their distance from a closer potential game. Different individual improvement paths have been considered in the literature, ranging from best-response (Jensen, 2010; Kukushkin, 2004) to other more general (possibly stochastic) strategy revision trajectories (Dindos & Mezzetti, 2006; Kukushkin, 2010; Lahkar, 2017; Poveda, Brown, Marden, & Teel, 2017). Other standard techniques include gradient-based schemes (Grammatico et al., 2016) and variational inequality formulations (Belgioioso & Grammatico, 2017b; Scutari, Palomar, Facchinei, & Pang, 2010). Current research is also focusing on the problem of coupling constraints (Grammatico, 2017a).

Two main architectures for the implementation of these mechanisms can be distinguished. In one case, agents iteratively modify their strategy in response to an updated aggregated signal (De Paola, Angeli, & Strbac, 2017a; Gan, Topcu, & Low, 2013; Koshal, Nedić, & Shanbhag, 2010). An alternative setup with a higher degree of decentralization—suitable whenever an aggregate signal broadcast is not available to the agents—adopts consensus-based techniques. In this case, the problem is addressed through the more general set up of network games, which include an underlying game topology and characterize the agents' interactions through a graph (Koshal, Nedić, & Shanbhag, 2016; Parise & Ozdaglar, 2017). Each agent independently modifies its strategy (either synchronously or asynchronously) according to an estimate of the aggregate signal, based on local information exchange (Gharesifard, Başar, & Domínguez-García, 2016; Grammatico, 2017b; Ye & Hu, 2017).

1.2. Relevant work – dynamic environment and receding horizon control

Most of the aforementioned works on distributed coordination of the players in an aggregative game consider a finite-time horizon and a static set up. To the best of our knowledge, there is a limited number of studies that have expanded this modelling framework in order to consider a dynamic environment or explicitly account for cyclic operation. In economics,