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An overview of coordinated control for multi-agent systems subject to input saturation☆

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Summary Coordinated control of multi-agent systems has widespread application in engineering such as unmanned aerial vehicles and unmanned ground vehicles. Due to the fact that input saturation can lead a control system to deterioration and instability, a lot of efforts have been devoted to investigating this subject of great importance. The present article offers a survey of recent developments on coordinated control of multi-agents systems subject to input saturation. Some preliminaries about graph theory, stability theory and input saturation are first provided, followed by some important results in the area, which are categorized into semi-global and global coordinated controls. Future research topics are finally discussed.

Introduction

Coordinated control of multi-agent systems is an active research field in both science and engineering, seemingly originated from distributed algorithms (Lynch, 1996) and decision-making (Degroot, 1974) the like. In 1987, Reynolds (1987) suggested a distributed behavioural model, known as the Biod model, to describe the aggregate motion of a flock of birds, a school of fish, and so on, in the natural world. In 1995, Vicsek et al. introduced a simple model with an innovative heading (directional) formula to investigate self-assemble behaviours of flocks, referred to as the Vicsek model today. Thereafter, Olfati and Murray (Saber and Murray, 2002, 2003a,b, 2004, 2007) studied the coordinated

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control of multi-agent systems by designing a specific control protocol for each agent, with formal formulations given in (Saber and Murray, 2003a,b) for flocking of multi-agent systems, which sublimed the Biod model mentioned above.

Briefly speaking, the investigation on coordinated control of multi-agent systems demands integrated knowledge from dynamical systems, control theory, graph theory, mechanics, distributed computation, and so on. Following the works mentioned above, coordinated control of multi-agent systems, including consensus, flocking and swarming, had become a research forefront in the last two decades on which a large volume of literature can be found (Hong et al., 2006; Jiang and Wang, 2010; Li et al., 2010, 2013a,b; Saber and Murray, 2002, 2003a,b, 2004, 2007; Su et al., 2009, 2011, 2014a,b; Tanner et al., 2004; Yu et al., 2010). Among the existing results, coordinated tracking, also called leader-following coordinated control, has received particularly significant attention, which aims at guiding all agents to track virtual/active leaders of the systems.

Roughly, research on coordinated control of multi-agent systems can be considered from three perspectives:

(i) Constructing distributed protocols that are much closer to practicality to drive all agents of the system to achieve consensus. Earlier model for consensus of multi-agent systems is of single-integrator type (Saber and Murray, 2004, 2007), which can be discrete-time or continuous-time single-integrator systems, perhaps with time delays. The consensus problem was then developed to systems with double-integrator dynamics (Hong et al., 2006; Su et al., 2009; Tanner et al., 2004). Lately, the investigation evolved to systems with linear dynamics (Li et al., 2010, 2013a,b) and as well nonlinear dynamics (Su et al., 2011, 2014a,b).

(ii) Developing new methodologies to achieve good performances. Good performances usually mean fast convergence speeds, minimum energy consumptions, great robustness, and so on. To realize these, many control algorithms were designed and tested, including such as pinning control which can guide all the followers to track a leader even only a small fraction of followers are informed directly by the leader (Su et al., 2009, 2014a,b), adaptive control (Li et al., 2013a,b; Su et al., 2011), and intermittent control (Wang and Wang, 2015).

(iii) Exploring the impact of the network topology on coordinated control. The local interactions among agents are influenced by the environment especially their communication network topology. Taking this fact into consideration, a great deal of effort has been devoted to the subject, ranging from undirected networks (Su et al., 2009, 2011) to directed ones (Yu et al., 2010), from fixed topologies (Hong et al., 2006; Saber and Murray, 2003a,b; Tanner et al., 2004) to switching ones (Jiang and Wang, 2010; Yu et al., 2010; Saber and Murray, 2004).

In the existing literature on coordinated control of multi-agent systems, for example those mentioned above and some references therein, it is assumed that no limitation is imposed to the movement of each agent in the consensus algorithms implementation. However, in reality, it is impractical for agents to move with absolutely freely during the process towards consensus. To tackle this kind of problems, Nedic et al. (2010) considered communication constraints, where every agent is restricted lying in a convex set in the motion space, and a distributed ''projected consensus algorithm'' is designed to successfully guide all agents to track the intersection of their individual constraint sets. As a direct extension, Lin and Ren (2014) analyzed the constrained consensus problem for multi-agent systems with an unbalanced topology and time delays.

Compared with the above-discussed communication constraints, input saturation (Lin, 1998, 1999; Saberi et al., 1996) is more important in practical situations, which can induce deterioration or instability of the underlying systems or networks, such as the windup phenomenon. Recently, a large number of works have been devoted to coordinated control of multi-agent systems subject to input saturation. In such a setting, the control input to agent u_i will always be limited within bound interval $[-\omega,\omega]$ and this can be described by a saturation function, $sat(u_i)$. One of the intuitive difficulties induced by input saturation is the nonlinearity. To handle this, the so-called parameterized low-gain feedback technique is introduced (Lin, 1999; Saberi et al., 1996). Roughly speaking, by low-gain feedback, the control input u_i for agent i can be turned to arbitrarily small to within the saturation bound interval so that the saturation nonlinearity can be avoided. There are two kinds of approaches to designing low-gain feedback laws, the eigenstructure assignment based design and the Algebraic Riccati equation based design. The current study on coordination control of multi-agent systems with input saturation mainly relies on the second approach (Chen et al., 2015; Fan, 2015; Su et al., 2013, 2014a,b, 2015a,b,c; Wang et al., 2015a,b; Wang and Wang, 2015; Yang et al., 2014a; Zhang et al., 2015; Zhao and Lin, 2014a,b). On the other hand, as pointed out by (Lin, 1999), parameterized high-gain feedback laws can lead the systems to achieve higher performances beyond consensus tracking, for example to achieve robust consensus tracking or robust swarm tracking (Su et al., 2015a,c; Wang et al., 2015a). With the help of the low-gain and high-gain feedback techniques, semi-global and global coordinated control of multi-agent systems with input saturation were studied in (Chen et al., 2015; Fan, 2015; Su et al., 2013, 2014a,b, 2015a,b,c,d; Wang et al., 2015a,b; Wang and Wang, 2015; Yang et al., 2014a; Zhang et al., 2015; Zhao and Lin, 2014a,b) and in (Meng et al., 2013; Yang et al., 2014b; Zhang and Chen, 2015; Zhang et al., 2014; Zhao and Lin, 2014a,b), respectively. Taking a panoramic view of the existing investigations on coordinated control of multi-agent systems with input saturation, the content of this survey focuses on analyzing the effects of the network topology on the coordinated control performance and finding distributed protocols to achieve consensus effectively, not only for general linear systems (Chen et al., 2015; Fan, 2015; Meng et al., 2013; Su et al., 2013, 2014a,b, 2015a,b,c,d; Wang et al., 2015a,b; Wang and Wang, 2015; Yang et al., 2014a,b; Zhang et al., 2014, 2015; Zhao and Lin, 2014a,b; Zhang and Chen, 2015); but also for nonlinear systems (Zhang et al., 2014).

The rest of the article is organized as follows. ''Preliminaries'' section provides some preliminaries. ''Semi-global coordinated control of multi-agent systems subject to input saturation'' and ''Global coordinated