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Energy-aware leader-follower tracking control for electric-powered multi-agent systems

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ABSTRACT

This paper aims to extend the operation time/range of an electric-powered multi-agent system (MAS) in leader-follower tracking tasks, through integrating battery-based energy awareness with distributed tracking control synthesis. While MASs have gained much popularity nowadays, their use and deployment are often restricted by the operation time/range, due to the limited battery capacity. In an effort to overcome such a barrier, this work proposes to leverage a battery's *rate capacity effect* to extend its runtime, which states that more energy can be drawn from the battery on less aggressive discharging rates. The battery-aware leader-follower tracking control design is then established in a model predictive control (MPC) framework, which strikes a tradeoff between tracking performance and energy consumption rates, accounts for the battery's rate capacity dynamics, and incorporates the energy and power constraints. A distributed optimization method is used to distribute the MPC across the agents of the MAS. leader-follower tracking based on the proposed distributed MPC algorithm is then evaluated through a case study and compared with an existing algorithm in the literature. The simulation results show its effectiveness in extending the operation.

1. Introduction

Recent years have witnessed a growing interest from both the academia and industry in multi-agent systems (MASs), thanks to their broad application in rescue, surveillance, search, delivery, reconnaissance and mapping missions (Lewis, Zhang, Hengster-Movric, & Das, 2014). The research progress in the past decade is represented by a wealth of literature on MAS coordinated control. However, today's electric-powered MASs can sustain only a relatively short amount of runtime for one charge, fundamentally because the current breed of battery electrochemistries are still unable to offer high energy capacity as often needed in practice. Toward achieving longer-time and wider-range MAS operation, this article for the first time studies how to extend the time/range of an MAS by taking advantage of the battery dynamics in its collaborative mission control synthesis. Specifically, the study considers an unique phenomenon inherent to batteries, namely, the rate capacity effect. Using this effect, it formulates a distributed model predictive control (MPC) approach to enable time/range-extended leader-follower tracking. The research results can find prospective use in many MAS applications and can also be generalized to deal with other types of energy-aware MAS control problems.

Literature review: An MAS is a system composed of multiple agents able to interact with each other, which allows for inter-agent connection and operation, distributed computation and control, and collective response to environment or external conditions (Ferber, 1999). With the wide application spectrum in scientific, commercial and military sectors, it has attracted research effort of both significant breadth and depth. Coordinated control design is central to the successful accomplishment of many MAS missions, having emerged as an active research field in the system and control community. In this vibrant field, problems of prime interest include group consensus (Li & Yan, 2015; Wang & Xiao, 2010; Wu & Shi, 2011; Yang, Meng, Dimarogonas, & Johansson, 2014; Yu & Wang, 2010; Yu, Yan, & Xie, 2017), swarming and flocking (Freeman, Yang, & Lynch, 2006; Olfati-Saber, 2006), formation control (Lin, Francis, & Maggiore, 2005; Mastellone, Stipanović, Graunke, Intlekofer, & Spong, 2008; Mou, Belabbas, Morse, Sun, & Anderson, 2016; Ren & Sorensen, 2008), synchronization (Dörfler, Chertkov, & Bullo, 2013; Jadbabaie, Motee, & Barahona, 2004), rendezvous (Lin, Morse, & Anderson, 2007), coverage control (Cortes, Martinez, Karatas, & Bullo, 2004; Schwager, Rus, & Slotine, 2009), containment control (Li, Ren, Liu, & Fu, 2013b; Yoo, 2013), and leader-follower tracking (Hu & Feng, 2010; Yu, Chen, & Cao, 2010). However, despite these advances, the constrained

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operation time/range of an MAS often makes it unable to meet practical needs, which is a continual challenge in this area.

Most of electric-powered MASs depend on batteries for energy storage. The most favored choice is the lithium-ion batteries (LiBs) because of their high energy density, low self-discharge and long cycle life. Yet, though considered the best among all, LiBs still do not have the energy-weight ratio high enough to support long-duration tasks due to the electrochemistry-imposed constraints. For instance, many off-the-shelf unmanned aerial vehicles can only fly for 30 min at one charge, and ground robotic vehicles mounted with LiBs of much larger capacity will see power depletion in two to three hours, according to our survey. This issue is also pointed out in a few reports, e.g., (Bertani, DeGeorge, Shang, & Aitken, 2014; Cambone, Krieg, Pace, & Linton, 2005), raising concerns about the competence of MASs for long-endurance tasks. While the materials science and electrochemistry communities are making aggressive effort to develop batteries of higher energy and power densities, real-time control of battery use offers another promising way to improve the battery performance, as demonstrated by the rich literature in the area of battery management (Rahn & Wang, 2013). A question of interest then is: can an MAS have an extended operation time and range if its system-wide coordinated control is integrated with the battery control?

With its practical significance, energy awareness is a recurring subject in control design. It is conventionally handled by formulating a cost function weighing the relative importance of the considered control objective versus that of the input energy (Chen, Hara, & Chen, 2003; Chen, Ren, Hara, & Qin, 2001) or through enforcing hard constraints on control inputs (Hu, Lin, & Chen, 2002; Su, Chen, Lam, & Lin, 2013). These studies only emphasize reducing energy consumption in the control run, regardless of the dynamic features of the power sources. When it comes to MAS control design, a large body of work likewise rarely takes energy storage into consideration and almost unanimously assumes unconstrained power availability to drive an agent, e.g., Hong, Wang, and Jiang (2013), Li, Ren, Liu, and Fu (2013a) and Yu, Yan, Xie, and Xie (2016), which though is not realistic. In reality, a battery not only has limited energy capacity and instantaneous power output but also is not an ideal linear power source as often assumed. A crucial factor contributing to a battery's nonlinear behavior is the well-known *rate capacity effect*, which states that the battery's total usable capacity goes down with an increase in discharging power (Jongerden & Haverkort, 2009). That is, the higher the discharging power, the faster the battery will be drained, or equivalently, the available capacity will decrease at a slower rate given a lower discharging power. This phenomenon implies the promise of extracting more energy from the battery to support longer-time and wider-range operation if the discharging process is controlled to be appropriately conservative yet without much compromise to the mission control objective. Similar to this notion, the literature contains several studies on communication protocol design for wireless sensor networks aware of the rate capacity effect to increase operation time, e.g. Padmanabh and Roy (2006). However, the methodologies proposed therein are not suitable here due to the difference in problem contexts and structures. Meanwhile, the ever-widening use of batteries in electrified transportation, grid and buildings has motivated a growing interest on advanced battery management algorithms, which mainly focus on state-of-charge (SoC) and state-of-health (SoH) estimation (Bartlett et al., 2016; Dey, Ayalew, & Pisu, 2015; Di Domenico, Stefanopoulou, & Fiengo, 2010; Fang, Wang, Sahinoglu, Wada, & Hara, 2014; Fang et al., 2014; Kim et al., 2015; Moura, Chaturvedi, & Krstić, 2014; Smith, Rahn, & Wang, 2010; Weng, Feng, Sun, & Peng, 2016; Zou, Manzie, Nesić, & Kallapur, 2016), charging protocol optimization (Fang, Wang, & Chen, 2017; Liu, Li, & Fathy, 2017; Suthar, Ramadesigan, De, Braatz, & Subramanian, 2014), thermal monitoring (Lin, Perez, Siegel, Stefanopoulou, Li, Anderson, Ding, & Castanier, 2013; Richardson, Ireland, & Howey, 2014), etc. Yet, they usually consider a standalone battery, without integrating the battery control with the system that it powers.

With this motivation, this paper will investigate battery-aware time/range-extended leader-follower tracking. In a leader-follower MAS, the follower agents are distributedly controlled to track the trajectory of the leader agent with real-time information exchange among them according to a communication topology. Differing from the existing work, each follower in this study will be conscious of not only the tracking objective but also the rate capacity effect intrinsic to its battery. The challenge, however, lies in how to design an effective approach to control the joint MAS-battery dynamics in a distributed manner. To overcome it, this work will consider an MPC-based design for two reasons. First, the predictive nature of MPC will allow the battery use to be planned ahead, thus enabling consciousness of battery status. Second, MPC can accommodate state and input constraints (Kerrigan, 2001; Wang, 2009), which makes it a fit for handling battery use limits. Along this line, an MPC strategy based on distributed optimization is thus developed for battery-aware tracking.

Statement of Contributions: The contributions of this work are as follows. (1) Formulation of battery-aware time/range-extended leader-follower tracking problem. It is presented in the form of receding-horizon optimization under constraints relevant to agent and nonlinear battery dynamics embodied by the battery's rate capacity effect. (2) Synthesis of a distributed MPC algorithm to address the problem. With this algorithm, each follower can use exchanged information with its neighbors to decide its control action in order to balance tracking performance and battery energy saving. The design builds on a distributed alternating direction method of multipliers (D-ADMM) method proposed in Mota, Xavier, Aguiar, and Puschel (2013). This study is the first one that we are aware of that exploits the battery's nonlinear dynamics to increase the operation time/range of an MAS.

Organization: The rest of this paper is organized as follows. Section 2 describes the problem of leader-follower tracking with an awareness of the battery's rate capacity effect. Section 3 derives the distributed MPC strategy from the perspective of distributed optimization as a solution to the considered problem. A simulation study is offered in Section 4 to illustrate the effectiveness of the proposed strategy. Finally, Section 5 gathers our concluding remarks.

Notation: The notation throughout this paper is standard. The set of real numbers is denoted by $\mathbb{R}$. The Euclidean norm of a vector is denoted as $\|\cdot\|$, and the Manhattan norm denoted as $\|\cdot\|_1$. Matrices, if their dimensions are not indicated explicitly, are assumed to be compatible in algebraic operations. Consider an MAS with one leader, which is labeled as 0, and N followers, which are labeled from 1 to N. The interaction topology among followers is modeled by an undirected graph. This graph is expressed as $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{1, 2, \ldots, N\}$ is the node set and the edge set $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ contains unordered pairs of nodes. A path is a sequence of connected edges in a graph. The neighbor set of agent i is denoted as $\mathcal{N}_i$, which includes all the agents in communication with it. Furthermore, combination of $\mathcal{G}$ with the leader gives a directed graph $\bar{\mathcal{G}}$ since the information exchange is one-way from the leader to the followers directly connected with it. The graph $\bar{\mathcal{G}}$ of this multi-agent system is said to be connected if at least one agent in each component of $\mathcal{G}$ is connected to the leader by a directed edge For $\bar{\mathcal{G}}$, $\bar{\mathcal{N}}_i$ represents the neighbor set of agent i. Note that $\bar{\mathcal{N}}_i = \mathcal{N}_i \cup \{0\}$ if agent i can directly communicate with the leader and $\bar{\mathcal{N}}_i = \mathcal{N}_i$ otherwise.

2. Problem formulation

This section formulates the problem of MPC-based battery-aware distributed leader-follower tracking control.

For a leader-follower MAS, the followers are expected to track the trajectory of the leader. During the tracking process, the leader and followers will maintain communication according to a pre-specified network topology to exchange their state information. Leveraging the information exchange, the followers will adjust control to themselves to achieve tracking. Suppose that a follower's dynamics is given by

$$z_i(t+1) = z_i(t) + \sigma_i u_i(t), \ i = 1, 2, \ldots, N, \tag{1}$$

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