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Brief paper

Fully distributed flocking with a moving leader for Lagrange networks with parametric uncertainties ☆

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ABSTRACT

This paper addresses the leader–follower flocking problem with a moving leader for networked Lagrange systems with parametric uncertainties under a proximity graph. Here a group of followers move cohesively with the moving leader to maintain connectivity and avoid collisions for all time and also eventually achieve velocity matching. In the proximity graph, the neighbor relationship is defined according to the relative distance between each pair of agents. Each follower is able to obtain information from only the neighbors in its proximity, involving only local interaction. We consider two cases: (i) the leader moves with a constant velocity, and (ii) the leader moves with a varying velocity. In the first case, a distributed continuous adaptive control algorithm accounting for unknown parameters is proposed in combination with a distributed continuous estimator for each follower. In the second case, a distributed discontinuous adaptive control algorithm and estimator are proposed. Then the algorithm is extended to be fully distributed with the introduction of gain adaptation laws. In all proposed algorithms, only one-hop neighbors' information (e.g., the relative position and velocity measurements between the neighbors and the absolute position and velocity measurements) is required, and flocking is achieved as long as the connectivity and collision avoidance are ensured at the initial time and the control gains are designed properly. Numerical simulations are presented to illustrate the theoretical results.

1. Introduction

A multi-agent system is defined as a collection of autonomous agents which are able to interact with each other or with their environments to solve problems that are difficult or impossible for an individual agent. In a multi-agent system, the agents often act in a distributed manner to complete global tasks cooperatively with only local information from their neighbors so as to increase flexibility and robustness.

The collective behavior can be observed in nature like flock of birds, swarm of insects, and school of fish. In Reynolds (1987), three heuristic rules are characterized for the flocking of multi-agent systems, namely, flock centering, collision avoidance and velocity matching. In Tanner, Jadbabaie, and Pappas (2007), a flocking algorithm is introduced for a group of agents when there is no leader. A theoretical framework is proposed in Olfati-Saber (2006) to address the flocking problem with a leader, which has a constant velocity and is a neighbor of all followers. Ref. Su, Wang, and Lin (2009) considers both cases where the leader has a constant and a varying velocity. When the leader has a constant velocity, Su et al. (2009) relaxes the constraint that the leader is a neighbor of all followers. However, in the case where the leader has a varying velocity, it still requires that the leader be a neighbor of all followers. Unfortunately, this is an unrealistic restriction on the distributed control design, especially when the number of the followers becomes large. In Cao and Ren (2012), distributed control algorithms for swarm tracking are studied via a variable structure approach, where the moving leader is a neighbor of only a subset of the followers. In Li et al. (2013), the flocking control and communication optimization problems are considered

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for multi-agent systems in a realistic communication environment and the desired separation distances between neighboring agents are calculated in real time.

Note that all above references focus on linear multi-agent systems with single- or double-integrator dynamics. However, in reality, many physical systems are inherently nonlinear and cannot be described by linear equations. Among the nonlinear systems, Lagrange models can be used to describe a large class of physical systems of practical interests such as autonomous vehicles, walking robots, and rotation and translation of spacecraft formation flying. But due to the existence of nonlinear terms with parametric uncertainties, the algorithms for linear models cannot be directly used to solve the coordination problem for multi-agent systems with Lagrange dynamics.

Recent results on distributed coordination of networked Lagrange systems focus on the consensus without a leader (Chopra & Spong, 2006; Hou, Cheng, & Tan, 2009; Min, Sun, Wang, & Li, 2011; Ren, 2009; Wang, 2013, 2014), coordinated tracking with one leader (Chung & Slotine, 2009; Dong, 2011; Mei, Ren, & Ma, 2011), containment control with multiple leaders (Mei, Ren, Chen, & Ma, 2013; Mei, Ren, & Ma, 2012; Meng, Ren, & You, 2010), and flocking or swarming without or with a leader (Cheah, Hou, & Slotine, 2009; Chopra, Stipanovic, & Spong, 2008; Meng, Lin, & Ren, 2012). Ref. Chopra et al. (2008) proposes a control algorithm based on potential functions for networked Lagrange systems to achieve collision avoidance and velocity matching simultaneously in both time-delay and switching-topology scenarios. However, parametric uncertainties are not considered and there is no leader. Ref. Cheah et al. (2009) presents a region-based shape controller for a swarm of Lagrange systems. By utilizing potential functions, the authors design a control scheme that can force multiple robots to move as a group inside a desired region with a common velocity while maintaining a minimum distance among themselves. However, the algorithm relies on the strict assumption that all followers have access to the information of the desired region and the common velocity. A leader–follower swarm tracking framework is established in Meng et al. (2012) in the presence of multiple leaders. However, only a compromised result can be obtained when the group dispersion, cohesion, and containment objectives are considered together. In the proposed algorithms, the variables of the estimators must be communicated among the followers. Furthermore, more information is used in the controller design, for example, the second-order derivatives of the potential functions.

In this paper we focus on the distributed leader–follower flocking problem with a moving leader for networked Lagrange systems with unknown parameters under a proximity graph defined according to the relative distance between each pair of agents, expanding on our preliminary results presented in Ghapani, Mei, and Ren (2014). Here a group of followers move cohesively with the moving leader to maintain connectivity and avoid collisions for all time and also eventually achieve velocity matching. The leader can be a physical or virtual vehicle, which encapsulates the group trajectory. We consider two cases: (i) the leader moves with a constant velocity, and (ii) the leader moves with a varying velocity. In the first case, a distributed continuous adaptive control algorithm accounting for unknown parameters and a distributed continuous estimator are proposed for each follower. In the second case, we first propose a distributed discontinuous adaptive control algorithm and estimator, where we use a common control gain that is sufficiently large for all followers. Hence the system is not completely distributed. We then improve the algorithm by further proposing gain adaption schemes to implement a fully distributed algorithm. In all proposed algorithms, only one-hop neighbors' information is used, and flocking is achieved as long as the connectivity and collision avoidance are ensured at the initial time and the control gains are designed properly. Compared with the results in the existing literature, this paper has the following novel features.

(1) This paper considers each agent as a nonlinear Euler–Lagrange system with parametric uncertainties and is more realistic. While in Cao and Ren (2012), Li et al. (2013), Olfati-Saber (2006) and Tanner et al. (2007), the agents' dynamics are assumed to be single or double integrators. The results for single- or double-integrator dynamics are not applicable to Lagrange systems with parametric uncertainties.
(2) This paper considers the combination of flocking (considering connectivity maintenance, collision avoidance, and velocity matching with a moving leader in the meantime) and the constraint that the leader's information is available to only the followers in its proximity. The above constraint introduces further complexities since not all followers know the leader's velocity. Even for the case with single- or double-integrator agents, the problem is very challenging (Cao & Ren, 2012), not to mention the case of nonlinear Lagrange systems with parametric uncertainties. In contrast, in Chopra et al. (2008), parametric uncertainties are not considered and there is no leader and in Cheah et al. (2009), it is assumed that the leader's information is available to all followers (against the local interaction nature of the problem).
(3) To overcome the coexistence and coupling of the above mentioned challenges, in the current paper, we propose an adaptive control law in combination with a new distributed estimator for each follower. The novelty of the estimators is that the partial derivatives of the potential functions are integrated into the estimators. In Cao and Ren (2012) and Meng et al. (2012), the variables of the estimators must be communicated between the neighbors. For the case of a moving leader with varying velocity, the proposed algorithms in Cao and Ren (2012) and Mei et al. (2011) require both one-hop and two-hop neighbors' information. In contrast, in our proposed algorithms, only one-hop neighbors' information (e.g., the relative position and velocity measurements between the neighbors and the absolute position and velocity measurements) is required. These measurements can be obtained by the sensing devices carried by the agents and hence the need for communication can be removed. Further, a fully distributed algorithm without global information is proposed in the current paper, while the results in Cao and Ren (2012), Mei et al. (2011) and Meng et al. (2012) rely on some global information.

Notations: Let $\mathbf{1}_n$ denote the $n \times 1$ column vector of all ones. Let $\lambda_{\min}(.)$ denote the minimum eigenvalue of a square real matrix with real eigenvalues. Let $\mathrm{diag}(z_1, \ldots, z_p)$ be the diagonal matrix with diagonal entries z_1 to z_p. For symmetric square real matrices A and B with the same order, $A > B$ or equivalently $B < A$ (respectively, $A \geq B$ or equivalently $B \leq A$) means that $A - B$ is symmetric positive definite (respectively, semi-definite). Throughout the paper, we use $\|\cdot\|$ to denote the Euclidean norm, $\otimes$ to denote the Kronecker product, and $\mathrm{sgn}(\cdot)$ to denote the signum function defined component-wise. For a vector function $f(t) : \mathbb{R} \mapsto \mathbb{R}^m$, it is said that $f(t) \in \mathbb{L}_l$ if $(\int_0^\infty \|f(\tau)\|^l d\tau)^{\frac{1}{l}} < \infty$ and $f(t) \in \mathbb{L}_\infty$ if for each element of $f(t)$, noted as $f_i(t)$, $\sup_{t \geq 0} |f_i(t)| < \infty$, $i = 1, \ldots, m$.

2. Background

2.1. Lagrange dynamics

Suppose that there exist $n+1$ agents (e.g., autonomous vehicles) consisting of one leader and n followers. The leader is labeled as agent 0 and the followers are labeled as agent 1 to n. The n followers are described by Lagrange equations of the form (Kelly, Davila, & Perez, 2006)

$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + g_i(q_i) = u_i, \quad i = 1, \ldots, n, \tag{1}$$