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Coordinate-free formation stabilization based on relative position measurements ☆

Miguel Aranda [a,1], Gonzalo López-Nicolás [a], Carlos Sagüés [a], Michael M. Zavlanos [b]

[a] Inst. de Investigación en Ingeniería de Aragón - Universidad de Zaragoza, C/ María de Luna 1, E-50018 Zaragoza, Spain

[b] Department of Mechanical Engineering and Materials Science, Duke University, Durham, NC 27708, United States

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ABSTRACT

This paper presents a method to stabilize a group of agents moving in a two-dimensional space to a desired rigid geometric configuration. A common approach is to use information of relative interagent position vectors to carry out this specific control task. However, existing works in this vein either require the agents to express their measurements in a global coordinate reference, or generally fail to provide global stability guarantees. Our contribution is a globally convergent method that uses relative position information expressed in each agent's local reference frame, and can be implemented in a distributed networked fashion. The proposed control strategy, which is shown to have exponential convergence properties, makes each agent move so as to minimize a cost function that encompasses all the agents in the team and captures the collective control objective. The coordinate-free nature of the method emerges through the introduction of a rotation matrix, computed by each agent, in the cost function. We consider that the agents form a nearest-neighbor communications network, and they obtain the required relative position information via multi-hop propagation, which is inherently affected by time-delays. We support the feasibility of such distributed networked implementation by obtaining global stability guarantees for the formation controller when these time-delays are incorporated in the analysis. The performance of our approach is illustrated with simulations.

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1. Introduction

We address in this paper the problem of controlling a multiagent group, which has many interesting applications, e.g. autonomous multivehicle control, cooperative sensing, surveillance, or search and rescue missions. In particular, we are interested in the stabilization of a team of mobile agents to a desired geometric configuration. Diverse methods have been proposed to carry out this task. Approaches typically rely on defining the multiagent formation in terms of absolute positions the agents must reach (Dong & Farrell, 2008; Ren & Atkins, 2007; Sabattini, Secchi, & Fantuzzi, 2011; Zavlanos & Pappas, 2007) or in terms of relative quantities such as position vectors or distances between the agents (Mesbahi & Egerstedt, 2010). In particular, relative position-based formation stabilization (Coogan & Arcak, 2012; Cortés, 2009; Dimarogonas & Kyriakopoulos, 2008; Ji & Egerstedt, 2007; Kan, Dani, Shea, & Dixon, 2012; Lin, Francis, & Maggiore, 2005; Oh & Ahn, 2014; Olfati-Saber, Fax, & Murray, 2007) specifies the formation in terms of relative distances and bearings between agents. This leads to a unique desired shape and, by using linear consensus-based control laws, permits global stabilization when the formation graph (i.e. the graph encapsulating the interactions between agents) is connected. However, methods based on position information (either absolute or relative) require the agents' measurements used for the control to be expressed in a global reference frame. In particular, in relative position-based approaches, the agents must share a common sense of orientation. For flexibility (i.e. in GPS-denied environments), simplicity and autonomy of the agents, a scenario where they can rely on their independent onboard sensors, i.e. use only locally referred information, is interesting.

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E-mail addresses: marandac@unizar.es (M. Aranda), gonlopez@unizar.es (G. López-Nicolás), csagues@unizar.es (C. Sagüés), michael.zavlanos@duke.edu (M.M. Zavlanos).

[1] Tel.: +34 876555075.

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Distance-based formation control (Dimarogonas & Johansson, 2009; Hendrickx, Anderson, Delvenne, & Blondel, 2007; Krick, Broucke, & Francis, 2008; Oh & Ahn, 2011; Olfati-Saber & Murray, 2002) addresses this scenario. Since the relative bearings between the agents cannot be expressed in a common reference, this methodology resorts to specifying the formation in terms of interagent distances only, and requires the formation graph to be rigid (Anderson, Yu, Fidan, & Hendrickx, 2008). Still, when generic numbers of agents are considered, no leader agents are used, and the desired task is for the team to acquire a rigid shape, these schemes provide only local stability guarantees, even with a complete formation graph. Global stabilization to a rigid formation is not achievable using negative-gradient, distance-based formation control (Anderson, 2011; Dimarogonas & Johansson, 2009). In addition, using distances to specify the formation implies that the target shape is always defined up to a reflection of the pattern, i.e. it is not unique. Even if only distances are used in the specification, knowledge of the directions to the neighboring agents is required in these methods to compute the control inputs.

We present here an approach that requires the same knowledge as distance-based controllers (i.e. locally expressed relative positions), but achieves global stability. The final positions of the agents form a specified rigid shape, defined up to translation and rotation. The control task is accomplished via minimization of a cost function defined for each agent in terms of global information, i.e. the relative positions of all other agents. We address the misalignment between orientation references by introducing in the cost function a local rotation matrix acting on the relative interagent vectors. These rotations, on which the agents implicitly agree, capture the method's independence of any global reference.

Our multiagent team constitutes a networked system, in which the agents interact via communications. If they have up-to-date relative position information, we show that our controller has exponential convergence properties. Realistically, the mobile agents are subject to strict limitations in terms of power consumption, computational resources and communication ranges, which require the use of a distributed, nearest-neighbor network scheme. With such setups, system scalability is greatly enhanced, but multihop communication causes the information used by the agents to be affected by significant time-delays. This effect needs to be introduced in the model of our system, which then becomes a nonlinear time-delay system (Gu, Kharitonov, & Chen, 2003; Richard, 2003) that is, in addition, interconnected (Hua & Guan, 2008; Nedic & Ozdaglar, 2010; Papachristodoulou, Jadbabaie, & Munz, 2010). As illustrated by this relevant literature, obtaining stability results for such a system in general conditions (e.g. varying delays, or switching network topologies) is a complex problem. We present a Lyapunov-based study of our system's convergence, considering that the network's communication pattern, in terms of active links and time-delay values, is fixed. Constant point-to-point delays are a usual assumption in the study of nonlinear time-delay systems (Papachristodoulou et al., 2010; Richard, 2003), while the consideration of a fixed interaction/communication graph topology is ordinary in multiagent formation stabilization methods (Cortés, 2009; Dimarogonas & Johansson, 2009; Dimarogonas & Kyriakopoulos, 2008; Guo, Lin, Cao, & Yan, 2010; Oh & Ahn, 2011). Then, by assuming the agents' motions satisfy certain bounds regarding maximum accelerations and minimum interagent separations, we establish an upper bound for the system's worst-case point-to-point time-delay such that global stability is ensured.

Other relevant work addressing coordinate-free multiagent motion using not merely distances includes López-Nicolás, Aranda, Mezouar, and Sagüés (2012), where a formation is stabilized using a central coordinator which employs visual sensing. In Zhang (2010), each agent computes its motion using global information and both relative position and velocity information are employed, while here we use only positions. Distributed schemes have been presented addressing behaviors different from rigid-shape stabilization, e.g. rendezvous (Cortés, Martínez, & Bullo, 2006; Yu, LaValle, & Liberzon, 2012), flocking (Jadbabaie, Lin, & Morse, 2003) and other coordinated motion patterns (Moshtagh, Michael, Jadbabaie, & Daniilidis, 2009), or assuming the agents agree on (and then maintain) a common orientation reference before or during the control execution (Cortés, 2009; Oh & Ahn, 2014). Although formation schemes based on leader agents (Desai, Ostrowski, & Kumar, 2001; Guo et al., 2010) have also been very popular, leaderless approaches, such as the one we propose, provide greater robustness and flexibility.

To summarize, our contribution is an approach implementable in a distributed networked fashion that globally stabilizes a multiagent group to an arbitrary unique rigid shape in the absence of a global coordinate system, and not relying on central coordinators or leader agents.

The rest of this paper is organized as follows: In Section 2 we define the formation control problem and discuss the communication patterns in the underlying networked system. In Section 3, we describe the proposed coordinate-free control method. Section 4 presents the stability analysis of our approach, addressing both a scenario where the agents have instantaneous global information, and the case where they form a distributed networked system in which information propagation is affected by time-delays. Simulation results are presented in Section 5. Finally, a brief discussion and the conclusion of the paper are given in Section 6.

2. Problem formulation

Consider a group of N agents in $\mathbb{R}^2$ having single integrator kinematics, i.e. satisfying:

$$\dot{\mathbf{q}}_\mathbf{i} = \mathbf{u}_\mathbf{i}, \tag{1}$$

where $\mathbf{q}_\mathbf{i} \in \mathbb{R}^2$ denotes the position vector of agent i and $\mathbf{u}_\mathbf{i} \in \mathbb{R}^2$ is its control input. We define a desired configuration, or formation shape, by a certain, fixed, reference layout of the N agents in their configuration space. The way in which we encode the desired configuration is through a set of interagent relative position vectors. To capture the existence or absence of an interaction in our control method between every pair of agents, we define an undirected formation graph, $\mathcal{G}_f = (\mathcal{V}, \mathcal{E}_f)$, where $\mathcal{V}$ is a set of N vertices, each one associated with an agent, and $\mathcal{E}_f$ is a set of links, each one expressing the connection between a pair of agents. Then, for every neighbor j of agent i in $\mathcal{G}_f$, we denote as $\mathbf{c}_\mathbf{ji} \in \mathbb{R}^2$ the vector from i to j in the reference layout of the agents that defines the desired configuration. The agents are not interchangeable, i.e. each of them has a fixed place in the target formation. We then consider that the agents are in the desired configuration if the reference layout has been achieved, up to a rotation and translation.

The problem that we set out to solve in this paper is specified as follows:

Problem 1. Given an initial configuration in which the agents are in arbitrary positions, the control objective is to stabilize them in a set of final positions such that the group is in the desired configuration.

We also define a graph $\mathcal{G}_c = (\mathcal{V}, \mathcal{E}_c)$ to capture the communications in our distributed networked system. The edges $\mathcal{E}_c$ express the presence or absence of a direct communication link between every pair of nodes (associated with agents) in $\mathcal{V}$. Each agent in the system is assumed to be able to obtain an estimation of the relative positions of its set of neighbors in $\mathcal{G}_f$. This is the only information used by the proposed control strategy, which is described in the following section.

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