Automatica 63 (2016) 187–197

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Distributed control of a network of single integrators with limited angular fields of view☆

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ARTICLE INFO

Article history:
Received 4 September 2013
Received in revised form
31 August 2014
Accepted 10 September 2015
Available online 11 November 2015

Keywords:
Multi-agent systems
Cooperative control
Field of view constraint

ABSTRACT

The consensus and containment problems in a multi-agent system consisting of single integrators with angular field of view (FOV) constraints in their sensing capabilities are investigated in this paper. First, it is assumed that all FOVs are half-planes and an impulsive switching strategy is developed such that the underlying sensing graph of the network remains uniformly quasi-strongly connected (UQSC) throughout the system evolution. The control schemes are designed in the framework of switched interconnected systems in such a way that the objectives of consensus and containment are achieved over the entire network. Then, the problem is extended to address a network of single-integrator agents with limited heterogeneous angular FOVs. The FOV of all sensing devices are assumed to rotate with sufficiently large angular velocities, which are controlled independently along with the translational motion of all agents. The velocity vector and the lower bound on the magnitude of the angular velocity of the FOVs are designed such that the agents converge to an arbitrarily small ball, and reach consensus. The convergence of the moving followers to the convex hull of static leaders is addressed for the containment problem as well. Simulation results verify the effectiveness of the proposed control strategies.

1. Introduction

Cooperative control of multi-agent systems has been extensively investigated in the literature recently. It is used in coordination of multi-vehicle systems, formation flight of UAVs, air traffic control, automated highway systems, and reconnaissance missions, to name only a few (Casbeer et al., 2006; Horowitz & Varaiya, 2000; Ryan, Zennaro, Howell, Sengupta, & Hedrick, 2004; Shames, Fidan, & Anderson, 2008; Tomlin, Pappas, & Sastry, 1998). In this type of systems, it is desired to design a local control law for each agent such that a global objective is achieved over the entire network with limited information exchange between agents. Every agent is equipped with sensing and communication devices for exchanging information with its "neighbors". Typical global objectives include consensus, containment, formation, and flocking (Chen, Lü, Yu, & Hill, 2013; Ferrari-Trecate, Egerstedt, Buffa, & Ji, 2006; Lafferriere, Williams, Caughman, & Veerman, 2005; Olfati-Saber, 2006). In the consensus problem, a certain state-dependent quantity of interest of every agent is desired to reach a common value (Olfati-Saber & Murray, 2004). The containment problem is concerned with the coordination of a set of followers in such a way that they converge to the convex hull of the leaders (Ferrari-Trecate et al., 2006). In the formation problem, the agents are aimed to form a desired configuration specified by their relative positions (Lafferriere et al., 2005), while the flocking objective is concerned with an agreement in terms of the agents' velocities and orientations (Olfati-Saber, 2006).

Connectivity of the information flow graph of a multi-agent system plays a key role in achieving the global objectives defined over the network. The interaction topology between agents may change over time in different applications due, for example, to unreliable data exchange and the limitation on the communication range (Fagnani & Zampieri, 2009; Munz, Papachristodoulou, & Allgöwer, 2011). Also, different connectivity conditions on the dynamic interaction graph of a network have been proposed in the literature to perform the desired coordination tasks by a team

☆ This work has been supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) under grant RGPIN-262127-12. The material in this paper was partially presented at the 2012 American Control Conference, June 27–29, 2012, Montréal, Canada and at the 2013 American Control Conference, June 17–19, 2013, Washington, DC, USA. This paper was recommended for publication in revised form by Associate Editor Xiaobo Tan under the direction of Editor Miroslav Krstic.

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http://dx.doi.org/10.1016/j.automatica.2015.09.035

of agents (Jadbabaie, Lin, & Morse, 2003; Moreau, 2005; Ren & Beard, 2005). The connectivity of the union interaction graph over a sufficiently large time interval has been proposed as a necessary and sufficient condition to achieve state agreement in Lin, Francis, and Maggiore (2007) provided a certain sub-tangentiality condition is satisfied by the vector fields describing the network dynamics. The "uniform joint connectivity" of the switching information flow graph is obtained as a necessary and/or sufficient condition to reach robust consensus in a network of single-integrator agents in Shi and Johansson (2011a,b). A variant of uniform connectivity on a fixed or switching directed topology is proposed in Cao, Ren, and Egerstedt (2012) to solve the containment problem over a network of single integrators. The connectivity condition for achieving consensus in a network of high-order integrators with a switching directed topology is studied in Cheng, Wang, Hou, and Tan (2014).

In some applications, there is a constraint on the field of view (FOV) of the sensing/communication devices used in multi-agent systems, and this can have a fundamental impact on the overall performance and controller design of the network. Typically, the FOV limitation is characterized by a radial and/or angular constraint, where the former has been addressed in the cooperative control literature (Ganguli, Cortés, & Bullo, 2009). The angular FOV limitation appears in multi-agent networks equipped with certain sensing devices such as vision-based cameras, laser range finders, and sonar arrays (Gerkey, Thrun, & Gordon, 2006; Lee & Chong, 2011; Ma & Liu, 2007). The cooperative control problem over a network of mobile agents with limited FOV has been investigated in the literature. For example, the collective circular motion of a team of nonholonomic vehicles is addressed in Ceccarelli, Di Marco, Garulli, and Giannitrapani (2008), where the local perception of each vehicle is constrained to a sector-shaped visibility region and the connectivity of the sensing graph is presumed. The problem of distributed motion coordination for a team of mobile robots is studied in Moshtagh, Michael, Jadbabaie, and Daniilidis (2009), where the controller of each robot requires local vision-based measurements of its neighbors. However, it is assumed in the above work that the information flow graph of the network remains fixed and connected, and that the cameras used by the agents are omnidirectional. In Ibuki, Hatanaka, Fujita, and Spong (2010), on the other hand, attitude synchronization in a network of rigid bodies using visual measurements is investigated, where the underlying leader–follower visibility graph of the network is assumed to be a static directed spanning tree and some distinction between leaders and followers is required. Attitude consensus in a group of nonholonomic robots using vision-based sensors with constrained angular FOVs is addressed in Montijano, Thunberg, Hu, and Sagues (2011), where the undirected sensing graph of the network is assumed to be fixed and connected at all times. Distributed topology control for a multi-agent network is investigated in Di Paolo, De Asmundis, Gasparri, and Rizzo (2012), where all sensors are assumed to have limited FOVs which are not necessarily identical. Moreover, it is presumed in Di Paolo et al. (2012) that a bidirectional communication link is established between a pair of agents if a directed sensing link exists between them. In addition, a rotating FOV is proposed in Gerkey et al. (2006); Lee (2008); Lee and Chong (2011); Plett, Bahl, Buss, Kühnlenz, and Borst (2012) to cope with the limitation in the FOV of sensing devices. In the pursuit-evasion problem for a team of mobile robots (Gerkey et al., 2006), the notion of the ϕ-searcher is introduced to represent a mobile robot equipped with a visual sensor whose FOV can freely rotate with a bounded angular velocity independent of the robot's motion. Moreover, a distributed algorithm for the rotation of the FOV of a network of directional sensors is developed in Lee (2008) to improve the overall sensing performance. A fly-inspired visual rotating sensor with limited FOV is also presented in Plett et al. (2012), which is capable of accurate measurements while maintaining the practical constraints required for the operation of micro aerial vehicles (MAV).

As discussed in the previous paragraph, the control laws developed in the literature for the cooperative control of multi-agent systems with limited FOVs have a number of shortcomings. Furthermore, they often make strong assumptions such as: (i) availability of global knowledge of the network by each agent, and the connectivity of the underlying network (Ceccarelli et al., 2008; Moshtagh et al., 2009); (ii) a fixed topology for the information flow graph (Montijano et al., 2011; Moshtagh et al., 2009); (iii) labeling the agents in such a way that different agents are distinguishable (Ibuki et al., 2010), and (iv) the existence of communication links for information exchange in addition to the sensor measurements (Di Paolo et al., 2012). In this paper, the consensus and containment problems for a network of single-integrator agents are investigated, where each agent has a sensor with a constrained angular FOV. The flow of information between agents is represented by a dynamic sensing directed graph, with no assumption on its connectivity (it could be disconnected at any point in time). Moreover, it is assumed that the agents are identical and indistinguishable; hence, no labeling of the agents is required. Also, no communication link is needed between agents because each agent obtains the required information from its sensor. Two steps are taken to tackle the problem. In the first step, an impulsive switching control strategy is proposed for the case of half-plane FOVs to drive a group of single-integrator agents toward a common location (consensus), while preserving uniform quasi-strong connectivity of the network by instantaneous rotation of the FOVs (Asadi, Ajorlou, & Aghdam, 2012). The proposed controller is then generalized to address the containment problem in such a way that the required connectivity condition is satisfied over sufficiently large time intervals. In the second step, the consensus and containment problems are investigated for a network composed of single integrators with limited heterogeneous angular FOVs. It is assumed that the FOV of every agent rotates with a constant angular velocity (independent of the agents' motion) to cover a sufficiently large area. Then, the velocity vectors are designed and a lower bound on the angular velocity of the FOVs is obtained such that the agents asymptotically converge to an arbitrarily small ball in the consensus problem while the angular velocity of the FOVs remains below a certain value (Asadi, Ajorlou, & Aghdam, 2013). Moreover, a trade-off between the size of the convergence ball, the lower bound on the magnitude of the angular velocity of the FOVs, and the upper bound on the magnitude of the velocity vector of every agent is introduced. The control law is modified subsequently to solve the containment problem as well. The effectiveness of the results is confirmed by simulations.

The remainder of the paper is organized as follows. Some useful preliminaries and definitions are presented in Section 2. The consensus and containment problems for a network of single-integrator agents with half-plane FOVs are investigated in Section 3. Then, the results are extended to a team of single-integrator agents with limited heterogeneous angular FOVs in Section 4. Simulations are provided in Section 5, and the concluding remarks are given in Section 6.

2. Preliminaries

Throughout this paper, $\mathbb{N}$, $\mathbb{Z}_{\geq 0}$, and $\mathbb{R}_{\geq 0}$ denote the set of natural, nonnegative integer, and nonnegative real numbers, respectively. The inner product of two arbitrary m-dimensional vectors $\mathrm{v}, \mathrm{w} \in \mathbb{R}^m$ is represented by $\langle \mathrm{v}, \mathrm{w} \rangle$, and $\|\mathrm{v}\|$ indicates the Euclidean norm of v on $\mathbb{R}^m$. Moreover, the cardinality of a finite set Φ is denoted by $\mathrm{card}(\Phi)$.

An m-dimensional *switched interconnected system* composed of n agents can be described as

$$\dot{\mathrm{q}}(t) = f_{\sigma(t)}(\mathrm{q}(t)), \tag{1}$$