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Brief paper

Pursuing an evader through cooperative relaying in multi-agent surveillance networks☆

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ABSTRACT

We provide a distributed control strategy for each mobile agent in a surveillance network in the plane to cooperatively pursue an evader. The pursuit task is relayed from one agent to another when the evader crosses the boundary of the Voronoi regions divided according to the agents' positions. The dynamics of the resulted cooperative relay-pursuit network are described by a novel model of impulsive systems. As a result, to guarantee the stability of the closed-loop network system, the controllers' gains are chosen effectively using the solution of an algebraic Riccati equation. The proof of the stability is based on the construction of a switched Lyapunov function. We also show that the proposed controller is able to deal with delays if some sufficient conditions in the form of a set of linear inequalities are satisfied. A numerical example is provided to validate the performance of the proposed controller.
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1. Introduction

Distributed coordination of mobile agents has attracted increasing attention in recent years due to its wide range of applications, such as distributed tracking, cooperative surveillance, and intrusion detection (Cao, Stephen Morse, & Anderson, 2008; Castanedo, García, Patricio, & Molina, 2010; Cortes, Martinez, Karatas, & Bullo, 2004; Isler, Kannan, & Khanna, 2004; Jadbabaie, Lin, & Stephen Morse, 2003; Martinez, Bullo, & Cortés, 2009; Ren & Beard, et al., 2005; Van der Walle, Fidan, Sutton, Yu, & Anderson, 2008). In particular, tracking and surveillance have given rise to especially important research problems for distributed cooperative control for multi-agent systems. In this context, the agents are usually required to move to their desired positions within a given deployment area where a mobile target of interest is moving around (Cortes et al., 2004; Hong, Hu, & Gao, 2006; Hu & Feng, 2010; Zhu & Cheng, 2010). As a result of the growing research interest, a number of papers have appeared addressing the multi-agent tracking and surveillance problem from different angles. The distributed consensus tracking control of multi-agent systems is studied in Jadbabaie et al. (2003) and Olfati-Saber and Murra (2004) for first-order agent dynamics under a dynamically changing environment. The authors of Ren & Beard, et al. (2005) prove that consensus tracking for such multi-agent systems can be achieved if and only if the time-varying network topology contains a directed spanning tree jointly as the network evolves over time. The distributed relay pursuit of a maneuvering target in the plane is investigated in Bakolas and Tsiotras (2012), where the Voronoi-like partition approach is used to solve such a relay-pursuit problem. In Hong et al. (2006); Hu (2012); Hu and Feng (2010), the tracking control for second-order agent dynamics is investigated by using Lyapunov-like functions to check the systems' invariant sets. Distributed controllers for general linear agent dynamics are designed in Li, Duan, Chen, and Huang (2010) and Zhang, Lewis, and Das (2011), where the network topologies are assumed to be fixed, while in comparison the network topologies considered in Hong et al. (2006); Hu (2012); Hu and Feng (2010); Jadbabaie et al. (2003); Olfati-Saber and Murra (2004); Ren & Beard, et al. (2005) are changing. Delays have not been taken into account in all of the above listed papers except for Olfati-Saber and Murra (2004). To deal with delays, Lyapunov–Krasovskii functionals and inequality techniques are used in Lin and Jia (2010) and Zhu and Cheng (2010), respectively. In addition, multi-agent surveillance and distributed environmental monitoring are investigated in Turpin, Michael, and Kumar (2012), Van der Walle et al. (2008) and Dunbabin and Marques (2012). In Cortes et al. (2004), with the help of Voronoi partitions, Cortés et al. study the coverage control problem for sensor networks.

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It is important to note that the majority of the existing literature on tracking control for multi-agent systems is exclusively devoted to smooth agent dynamics. However, in practice, the closed-loop system dynamics are very likely not to be smooth due to different reasons. For instance, the state of an agent may change abruptly when its interacting agents drop out or an intruding target enters its field of view. Thus, impulsive system models become promising to describe precisely such scenarios that are challenging to be delineated otherwise. It is also worth noting that some works have been done along this line of research. In Jiang, Bi, and Zheng (2012); Zhang, Chen, and Yu (2012), impulsive control strategies for multi-agent systems with second-order agent dynamics are considered, while in Guan, Wu, and Feng (2012), the first-order agent dynamics are investigated. However, those results cannot be applied directly to systems with general linear agent dynamics. In addition, the information used for control may be constrained by several factors, e.g. local information determined by the Voronoi diagram, possible delays in communication and computation etc. Hence, it is in urgent need to design new control strategies for multi-agent tracking and surveillance when modeling the overall closed-loop non-smooth dynamical systems under information constraints.

In this paper, a distributed control strategy is designed for each agent in a surveillance multi-agent network in the plane to cooperatively pursue an evader. The pursuing task is relayed from one agent to another. A novel switched impulsive system is built to describe such a relay-pursuit problem. Although similar problem settings have been considered before in Bakolas and Tsiotras (2012), we consider more general linear agent dynamics in this paper than those of the single integrator type used in Bakolas and Tsiotras (2012). The controller gain in our paper is obtained by solving an algebraic Riccati equation (ARE), which is much easier to implement in practice. In addition, network access and computational delays are also taken into account in this paper. Note that the delay phenomenon is still not considered in most of the related literature (Guan et al., 2012; Jiang et al., 2012) and Zhang et al. (2012), and that in Zhang et al. (2012), the controller design method is not provided. So, compared with the existing literature, our main contributions can be summarized as follows: First, a novel cooperative relay pursuit strategy for agents with general linear dynamics is proposed using Voronoi partitioning, under which only a preset number of agents need to track the evader. Second, a novel impulsive system model is built for the closed-loop network system, for which the relay pursuit control is obtained by solving an ARE.

The rest of this paper is organized as follows. In Section 2, the problem is formulated. In Sections 3 and 4, the cooperative relay pursuit problem without and with delays are investigated, respectively. A simulation example is presented in Section 5 followed by the section of concluding remarks.

2. Problem formulation

In this paper, we study the cooperative relay pursuit problem in a bounded area in the plane. We distribute N_a mobile agents in this area at distinct locations by partitioning the area into N_a Voronoi cells, each containing an agent monitoring this cell. This can be done after solving the dynamic Voronoi-like partition problem (Bakolas & Tsiotras, 2012), where the positions of the agents are taken as the corresponding Voronoi sites. We call all these agents *monitoring agents*. We consider the problem, when an evader intrudes this area, how to guide a preset number of agents to cooperate with each other to catch such an intruder. We call those agents carrying out the pursuing task the *pursuers*.

Within this region $\mathcal{S}$, we now have two types of agents: pursuers and monitoring agents. The roles of the pursuers and monitoring agents may switch back and forth. This can be thought of as the police–thief game, in which the monitoring agents are mobile police stations, a Voronoi cell reflects the effective range of a police station, and the pursuers are the policemen with the mission to capture the thief. Once an evader enters this monitoring region $\mathcal{S}$, a predefined number of agents which are nearest to it will cooperate to catch it.

Suppose that the agents placed in the monitoring region $\mathcal{S}$ are identical and the kinematic equation of agent i is given by

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t),\ i \in \mathcal{N}_a := \{1, \dots, N_a\}, \tag{1}$$

where $x_i(t) \in \mathbb{R}^2$ and $u_i(t) \in \mathbb{R}^m$ represent the position and the control input of agent i, respectively, and $A \in \mathbb{R}^{2\times 2}$, $B \in \mathbb{R}^{2\times m}$ are constant matrices with $\mathbb{R}$ denoting the set of real numbers. The motion of the evader is described by

$$\dot{x}_0(t) = Ax_0(t), \tag{2}$$

where $x_0(t) \in \mathbb{R}^2$ denotes the position of the evader.

We make the following standard assumption.

Assumption 1. The pair (A, B) is stabilizable.

The precise goal of this paper is then to design a cooperative relay pursuit strategy that can ensure the tracking agents to effectively pursue the evader in the monitoring region. In such a strategy, only a preset number $N < N_a$ of pursuers need to track the evader, while the others are kept stationary.

Let $\mathcal{G} = \{\mathcal{V}, \mathcal{E}, \mathcal{A}\}$ be an undirected graph, where $\mathcal{V} = \{1, \dots, N\}$ is the set of all the indices of N vertices, and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the set of the edges. The graph is used to describe the neighbor relationships of the N pursuers in the cooperative pursuit network where each vertex corresponds to a pursuer. The set of neighbors of vertex i is denoted by $\mathcal{N}_i = \{j \in \mathcal{V} : (i,j) \in \mathcal{E}, j \neq i\}$. An edge of $\mathcal{G}$ is denoted by e_{ij}, which in our context of the multi-agent cooperative pursuit problem means that pursuers i and j can exchange information with each other. $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N\times N}$ denotes the adjacency matrix. The evader is labeled by vertex 0 and the neighbor of this evader can sense the target in real time. Then, we have a graph $\bar{\mathcal{G}}$, for both of the N pursuers and the moving evader. A diagonal matrix $\mathcal{D} = \{d_1, \dots, d_N\}$, is specified by its diagonal elements $d_i = \sum_{j\in\mathcal{N}_i} a_{ij}$. The Laplacian of the graph is defined by $\mathcal{L} = \mathcal{D} - \mathcal{A}$.

Apparently, in such a relay cooperative pursuit control problem, the pursuers are not fixed. Thus, results from graph theory on fixed graphs will not be applicable, and one has to deal with the switching topologies. The dependence of the graphs upon time can be characterized by a left piecewise continuous function $\sigma(t) : [0, \infty) \to \mathcal{P} = \{1, \dots, m\}$. Here, m denotes the total number of all possible topologies of the multi-agent system during the pursuit. The relationship $\sigma(t_s) = i$ and $\sigma(t_s^+) = j$ implies that the topology switches from the ith to the jth at the time instant t_s.

Now, we define a set of piecewise continuous functions indicating at time t, the mapping to the indices of the pursuers

$$\alpha_i(t) : [0, +\infty) \to \mathcal{N}_a,\ i = 1, \dots, N, \tag{3}$$

where $\alpha_i(t) \neq \alpha_j(t)$, $\forall i \neq j$ at any time instant t.

Research problem: design a cooperative relay pursuit control law $u_{\alpha_i(t)}(t)$ such that N pursuers among the monitoring agents will pursue the evader successfully.

Formally, we say the relay pursuit strategy is successful if, there exist a time-varying subset $\Omega_t \subset \mathcal{N}_a$ of N pursuers and a control input $u_{\alpha_i(t)}(t)$ such that

$$\lim_{t\to\infty} \|x_{\alpha_i(t)}(t) - x_0(t)\| = 0,\ i = 1, \dots, N, \tag{4}$$

for the pursuers and the evader in this monitoring region.

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