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Brief paper

Optimal control for multi-agent persistent monitoring[☆]

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ABSTRACT

The problem of persistent monitoring using a network of mobile agents is considered in this paper, where the goal is to drive the uncertainty of all targets to zero and patrol the whole mission domain. The uncertainty at each target point is assumed to evolve nonlinearly in time. Given a closed path, it is proved that multi-agent persistent monitoring with the minimum patrol period can be achieved by optimizing the agents' moving speed and initial locations on the path. It is also shown that the proposed approach provides a less conservative condition for persistent tasks with a constraint on the patrol period with respect to the existing works. Simulation results illustrate the effectiveness of the proposed persistent monitoring algorithm.

1. Introduction

This paper focuses on the multi-agent persistent monitoring problem, where the goal is to patrol the whole mission domain while driving the uncertainty of all targets in the mission domain to zero. This problem arises in many applications such as environment surveillance and search and rescue. For example, in the identification of survival in disaster area using mobile robots the robots should be full aware of the regions of significant importance such as schools and sweep the entire disaster area. In this paper, trajectory planning approach is employed to address the multi-agent persistent monitoring problem. Given a closed path, periodic speed controller is designed for each agent to accomplish the persistent monitoring task, where each agent's speed only relies on its current location.

Recently, the multi-agent persistent monitoring problem has received considerable attention. In Smith, Schwager, and Rus (2012), persistent monitoring of a changing environment using mobile robots is addressed. Given a closed path, robot's speed is computed to prevent an accumulation function defined on finite locations from growing unbounded. An optimal control framework for the multi-agent persistent monitoring problem in one dimensional mission space is presented in Cassandras, Lin, and Ding (2013), where the goal is to minimize the sum of the cumulative uncertainty at all sampling points over a fixed time horizon. In Nigam, Bieniawski, Kroo, and Vian (2012), the problem of persistent surveillance using unmanned air vehicle is considered, where the goal is to continuously survey the mission domain and to minimize the time interval between visitations to the same region.

Problems that are closely related to multi-agent persistent monitoring include multi-agent patrol and dynamic coverage. In multi-agent patrol, a network of mobile agents is required to repeatedly visit a mission domain or a set of predefined locations (Cannata & Sgorbissa, 2011; Portugal & Rocha, 2013). A criterion which is often used to evaluate the performance of patrol algorithms is idleness time (Machado, Ramalho, Zucker, & Drogoul, 2002), which is the time elapsed since a node is last observed by an agent. In Chevaleyre (2004), the idleness criterion is employed to compare two classes of patrol strategies, that is, cyclic-based strategy and partition-based strategy. Given a graph to represent the environment, optimal cooperative patrolling algorithms are proposed in Pasqualetti, Franchi, and Bullo (2012) to minimize the refreshing time and latency criteria, which are the time gap between any two visits to the same location and the time needed to inform networked mobile robots about an event occurring in the environment respectively. Frequency-based patrol is addressed in Elmaliach, Agmon, and Kaminka (2009), where the point visit frequency is optimized via constructing an optimal closed path that visits all points in the mission domain.

In dynamic coverage, the goal is to cover all points in the mission domain to the desired coverage level using a network of

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mobile sensors (Hussein & Stipanovic, 2007; Song, Feng, Fan, & Wang, 2011). The main difference between multi-agent persistent monitoring and dynamic coverage lies in that the dynamic coverage task is completed when all points attain satisfactory coverage level while the persistent monitoring task would last forever. In Zhai and Hong (2013), a decentralized algorithm is developed to address the dynamic coverage problem for multi-agent systems in a region with uncertain workload density. An upper bound of the difference between the actual coverage time and the optimal time is also estimated. An awareness coverage model is proposed in Wang and Hussein (2010) which describes how "aware" networked mobile agents are of events occurring in the mission domain. In Song, Liu, Feng, Wang, and Gao (2013), the persistent awareness coverage problem for networked mobile sensors with awareness loss is addressed. When there exists a constraint on the persistent coverage period, it is shown that the persistent awareness coverage task can be accomplished if a set of linear inequalities has a solution. In Song, Feng, and Huang (2013), the optimal speed for mobile sensors along a closed path is designed to guarantee full awareness coverage of all points of interest while maximizing stability margin of awareness coverage or lifetime of a sensor network.

In contrast to the existing works by the authors in Song, Feng et al. (2013) and Song, Liu et al. (2013), given a closed path we focus on designing agents' moving speed and initial locations on the path to guarantee multi-agent persistent monitoring with the minimum patrol period. The main contribution of this work can be summarized as follows. Firstly, in this work the uncertainty is assumed to evolve nonlinearly in time, which is different from the linear-in-time uncertainty model used in Cassandras et al. (2013), Pasqualetti, Durham, and Bullo (2012) and Smith et al. (2012). In addition, the awareness coverage model proposed in Wang and Hussein (2010) can be viewed as a special case of our uncertainty model. From the uncertainty model, a necessary and sufficient condition is derived under which the uncertainty of an arbitrary target can be driven to zero. Secondly, the patrol period of multi-agent persistent monitoring is minimized via optimizing mobile agents' speed and initial locations sequentially. The idea is to first derive the optimal moving speed of agents for multi-agent persistent monitoring to minimize the time period during which an agent completes one cycle of the closed path. Then, an optimal initial location is designed for each agent to minimize the patrol period. Finally, it is also shown that the proposed approach provides a less conservative condition for persistent tasks with a constraint on the patrol period with respect to the existing works.

The remainder of this paper is organized as follows. In Section 2, problem formulation is given. In Section 3, trajectory planning of mobile agents is presented to achieve multi-agent persistent monitoring with the minimum patrol period. A simulation example is provided in Section 4 to illustrate the main results. Finally, Section 5 concludes the paper.

2. Problem formulation

Consider a compact mission domain D in $\mathbb{R}^2$. A network of holonomic mobile agents is required to move along a given closed path to repeatedly visit every point in the mission domain. Without loss of generality, we assume that the agents move counterclockwise on the path. Denote the mobile agents by $A_i,\ i \in S = \{1, 2, \dots, n\}$. Each agent possesses limited sensing capability which is described by

$$M_i(q_i, q) = \begin{cases} \dfrac{G_i}{{r_i}^4}(\|q_i - q\|^2 - r_i^2)^2 & \text{if } \|q_i - q\| \le r_i, \\ 0 & \text{otherwise}, \end{cases} \tag{1}$$

where q_i is the location of agent A_i and $r_i > 0$ is the limited sensing range (Hussein & Stipanovic, 2007).

It is noted that an arbitrary point q in the mission domain is visited by the multi-agent system in time interval $[t_s, t_f]$ if and only if the following inequality holds

$$\int_{t_s}^{t_f} \sum_{i=1}^{n} M_i(q_i, q) d\tau > 0. \tag{2}$$

Then, a finite period $\bar{T}$ is called as a patrol period if the following inequality holds

$$\int_{t_0}^{t_0+\bar{T}} \sum_{i=1}^{n} M_i(q_i, q) d\tau > 0, \quad \forall t_0 \ge 0,\ \forall q \in D. \tag{3}$$

Due to the definition of the patrol period, it is easy to check that if $\bar{T}$ is a patrol period for a multi-agent system, any period $\tilde{T}$ satisfying $\tilde{T} \ge \bar{T}$ is also a patrol period.

In the mission domain, there exists a finite set of stationary targets $\mathscr{P} = \{p_1, \dots, p_m\}$ to be monitored. An uncertainty function $X(p_j, t) \in [0, \infty)$ is defined on the target points, which characterizes the multi-agent system's uncertainty about the state of each target. In this work, it is assumed that $X(p_j, t)$ increases as long as p_j is not covered by any mobile agent and evolves according to the following differential equation

$$\dot{X}(p_j, t) = \left(C(p_j) - \sum_{i=1}^{n} M_i(q_i, p_j) \right) g(X(p_j, t)),$$
$$X(p_j, 0) = X_0(p_j), \tag{4}$$

where $C(p_j) \ge 0,\ j = 1, \dots, m$ is a constant and $g(X(p_j, t)) = \sum_{l=1}^{L} a_l X(p_j, t)^l$ with $a_l \ge 0,\ l = 1, \dots, L$ being constants, $X_0(p_j)$ is the initial uncertainty of target p_j. In fact, $g(X(p_j, t))$ characterizes the impact of the current value of $X(p_j, t)$ on the change rate of $X(p_j, t)$. Note that in our model the target points' uncertainty increases or decreases nonlinearly in time, which is different from the linear-in-time uncertainty model in Cassandras et al. (2013), Pasqualetti et al. (2012) and Smith et al. (2012). The nonlinear uncertainty model arises in many practical applications, where the changing rate of a quantity of interest is closely related to the current value of the quantity of interest. For example, during cyanobacteria break cyanobacteria concentration increases more rapidly in the regions of high cyanobacteria concentration. It is also noted that the mobile sensor network's awareness coverage model proposed in Wang and Hussein (2010) can be regarded as a special case of the nonlinear uncertainty model.

In practice, it is often desirable to be full aware of all target points and patrol the whole mission domain as frequently as possible. In consequence, the goal of our work is to plan the mobile agents' trajectories such that the uncertainties of all target points are driven to zero as time goes to infinity and the whole mission domain is patrolled with the minimum patrol period.

3. Optimal control for multi-agent persistent monitoring

Decoupling path planning from speed control has been established as an efficient approach to the complex trajectory planning problem (Kant & Zucker, 1986). In Elmaliach et al. (2009) and Song, Liu et al. (2013), several closed paths are constructed for agents such that when the agents move along the path perpetually all points in the mission domain are revisited persistently. In this work, instead of designing the optimal path for mobile agents we focus on addressing multi-agent persistent monitoring with the minimum patrol period via optimizing agents' moving speed and initial locations on a given closed path.