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Brief paper

# Persistent awareness coverage control for mobile sensor networks☆

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ABSTRACT

In this paper the persistent awareness coverage problem for mobile sensors with awareness loss is considered, where persistent coverage and awareness coverage are addressed simultaneously. The goal is to cover the mission domain periodically with a finite period and guarantee full awareness coverage of a finite set of points of interest. A closed path is designed such that it is possible to develop periodic speed controllers for mobile sensors. When there is no constraint on the period, the least number of mobile sensors that are needed for the persistent awareness coverage task is derived. Given a network of mobile sensors and a finite period, it is shown that the persistent awareness coverage task can be accomplished if there exists a solution to a set of linear inequalities. Finally, if there is no awareness loss, the proposed approach guarantees full awareness coverage of the whole mission domain even if only one sensor is deployed.



## 1. Introduction

Recently, mobile sensor networks have attracted much attention due to its versatility in many applications (Anisi, Ogren, & Hu, 2010; Casbeer et al., 2006; Fan, Feng, Wang, & Song, 2013; Kingston, Beard, & Holt, 2008; Leonard et al., 2007; Tang & Özgüner, 2005). In this paper we focus on the persistent awareness coverage problem for mobile sensors with awareness loss, where the goal is to guarantee full awareness coverage of a finite set of points of interest and persistent coverage of the mission domain simultaneously. This problem emerges in many practical applications, where some regions are of much more importance with respect to the other regions in the mission domain. Consequently, one needs to discriminate these two classes of regions. For example, in an application where a mobile sensor network is employed to survey a nuclear power plant persistently, the nuclear reactor must be covered with full awareness while the other regions of less importance only need to be revisited frequently.

Coverage control can be generally classified into static coverage control and dynamic coverage control. In static coverage control, the goal is to optimize the locations of sensors to improve the quality of service provided by mobile sensor networks (Cortés, Martínez, & Bullo, 2005; Cortés, Martínez, Karatus, & Bullo, 2004; Kwok & Martínez, 2010; Li & Cassandras, 2005; Schwager, Rus, & Slotine, 2009; Zhong & Cassandras, 2011). In Li and Cassandras (2005), given a probabilistic sensing model and a density function representing the occurring frequency of random events, a distributed gradient-based algorithm is proposed to maximize the joint detection probabilities of these events. In Zhong and Cassandras (2011), coverage control combined with data collection for mobile sensor networks is addressed by solving an optimization problem trading off these two objectives. A Voronoi partition is employed in Cortés et al. (2004) to develop a distributed coverage control law and the resulting optimal network configuration is that each sensor is located at the centroid of its corresponding Voronoi partition. In Cortés et al. (2005), this work is extended to a more realistic scenario where agents have limited sensing and/or communication ranges. In Kwok and Martínez (2010), Voronoi partition based coverage is addressed for a group of nonholonomic agents. A decentralized adaptive controller is developed in Schwager et al. (2009) to accomplish the static coverage task without *a priori* knowledge of the mission domain.

When the mission domain cannot be fully covered by any static configuration of a sensor network, the problem of dynamic coverage (Hokayem, Stipanovic, & Spong, 2007; Hussein & Stipanovic, 2007; Song, Feng, Fan, & Wang, 2011; Wang & Hussein, 2010) arises in which each point in the mission domain is sampled by the mobile sensors until a prescribed coverage level is achieved. In Hussein and Stipanovic (2007), coverage control laws for connected

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networks are developed to achieve satisfactory coverage of the mission domain with guaranteed collision avoidance. An awareness coverage model is proposed in Wang and Hussein (2010), which characterizes how "aware" a network of vehicles is of events occurring over a large-scale domain. A decentralized switching control strategy is proposed to drive all points' awareness coverage to a neighborhood of full awareness when awareness loss is not considered. The persistent coverage problem is addressed in Hokayem et al. (2007), where the goal is to cover all points in the mission domain periodically. An open path is first designed for the agents. Then, the path is divided into several parts and each agent moves along its corresponding part at a constant speed back and forth to cover the mission domain repeatedly.

Problems that are closely related to persistent awareness coverage include persistent surveillance and monitoring, where repetitive motion of the agents is required (Elmaliach, Agmon, & Kaminka, 2007; Nigam, Bieniawski, Kroo, & Vian, 2012; Nigam & Kroo, 2008; Smith, Schwager, & Rus, 2012). In Smith et al. (2012), the changing environment is modeled as an accumulation function defined over a finite set of locations. The function increases at locations that are not covered by any agent and decreases at locations that are covered by an agent. Given several closed paths, agents' speed controllers are computed to prevent the accumulation function from growing unbounded at any location. The persistent surveillance problem is addressed in Nigam and Kroo (2008), where the goal is to minimize the time between visitations to the same region. In Nigam et al. (2012), the authors further take into account endurance constraints of the aerial vehicles in the persistent surveillance problem. In Elmaliach et al. (2007), area patrolling under frequency constraints is addressed, where a given region is required to be continually sampled such that each point in this region is revisited with equal frequency.

Trajectory planning for mobile sensors has been studied extensively in literature (Choi & How, 2010; Kant & Zucker, 1986; Tang & Özgüner, 2005). In Tang and Özgüner (2005), trajectory planning for multiple target surveillance is addressed by solving an optimization problem whose objective is the minimization of the average time between two consecutive observations of each target. The continuous trajectory of mobile sensors is planned in Choi and How (2010) to reduce the uncertainty in quantities of interest. In Kant and Zucker (1986), it is established that decoupling path planning from speed control is an efficient approach to the complex trajectory planning problem. Following this idea, we first construct a closed path for mobile sensors based on the pioneering work in Hokayem et al. (2007) such that when a sensor completes one cycle of the path all points in the mission domain can be covered by this sensor. Then, the agents' speed controllers are designed to accomplish the persistent awareness coverage task. The main contributions of this work are threefold. Firstly, based on a necessary and sufficient condition for achievement of full awareness coverage of an arbitrary point in the mission domain, it is shown that the least number of sensors that are needed for persistent awareness coverage can be derived by solving a mixed-integer nonlinear programming problem (MINLP). Secondly, a formal formulation of persistent coverage of an arbitrary point in the mission domain is provided such that it is possible for us to consider the case of persistent coverage with a given period. When a mobile sensor network and a finite period are given, it is shown that the persistent coverage task can be accomplished if a set of linear inequalities has a solution. Finally, if there is no awareness loss, the proposed approach can drive all points' awareness coverage to full awareness exactly rather than to a neighborhood of full awareness even if only one mobile sensor is deployed.

The remainder of this paper is organized as follows. In Section 2, the problem of persistent awareness coverage is formulated. In Section 3, trajectory planning of mobile sensors is presented to accomplish the persistent awareness coverage task with and without a given period. A simulation example is given in Section 4 to illustrate the main results. Finally, Section 5 concludes the paper.

## 2. Problem formulation

Consider a mobile sensor network operating in workspace $\mathbb{R}^2$. The position of each sensor $A_i,\ i \in S = \{1, 2, \dots, n\}$ is denoted by $q_i$. The mission domain $D$ is a convex polygonal region and an arbitrary point in $D$ is denoted by $q$. $\mathcal{P} = \{p_1, \dots, p_m\}$ is a finite set of points of interest in $D$.

In this paper, we use the sensor model proposed in Hussein and Stipanovic (2007) and Wang and Hussein (2010)

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

where $r_i > 0$ is the limited sensing range. We assume the sensors have uniform sensing function, that is, $r_i$ and $G_i$ are identical for all sensors.

In this work, we consider a mobile sensor network's awareness coverage (Wang & Hussein, 2010) of the mission domain which is a distribution $x(q, t)$ describing how "aware" the mobile sensor network is of events occurring at a specific location $q$ at time $t$. Without any loss of generality, we assume that $x(q, t) \in (-\infty, 0]$. When $x(q, t) = 0$ it indicates that the point $q$ attains full awareness coverage. For each point $q \in D$, the awareness coverage $x(q, t)$ is assumed to satisfy the following differential equation

$$\dot{x}(q, t) = -\left(\sum_{i=1}^{n} M_i(q_i, q) - \alpha\right) x(q, t),$$
$$x(q, 0) = x_0(q), \tag{2}$$

where $\alpha \ge 0$ is a constant awareness loss.

In practice, full awareness coverage of the whole mission domain may not be necessary because not all points in the mission domain are of the same importance. Moreover, in the case that agents' resource and capability are limited it is often unaffordable to be fully aware of all points in the mission space. Thus, in this work we focus on guaranteeing full awareness coverage of a set of points of interest while covering the mission domain periodically with a finite period $T^*$. Note that a point $q$ is covered by the mobile sensor network in time interval $[t_s, t_f]$ if and only if

$$\int_{t_s}^{t_f} \sum_{i=1}^{n} M_i(q_i, q) d\tau > 0. \tag{3}$$

Then, the goal of persistent awareness coverage is to plan a network of mobile sensors' trajectory such that $x(p_j, t) \to 0,\ \forall p_j \in \mathcal{P}$ as $t \to \infty$ and there exists a finite period $T^*$ satisfying $\int_{t_0}^{t_0+T^*} \sum_{i=1}^{n} M_i(q_i, q) d\tau > 0,\ \forall t_0 \ge 0,\ \forall q \in D$. Furthermore, we consider the persistent awareness coverage problem with a given period of time, where all points in the mission domain are needed to be covered by the mobile sensor network in the time period.

## 3. Trajectory planning for persistent awareness coverage

In this section, we plan the mobile sensor network's trajectory to cover the mission domain periodically and guarantee full awareness coverage of all points of interest simultaneously. Path planning is decoupled from speed control to solve this trajectory planning problem as suggested in Kant and Zucker (1986).

### 3.1. Path planning

In Hokayem et al. (2007), an open path has been designed for the persistent coverage problem. In this subsection, a closed path is constructed based on the work in Hokayem et al. (2007) such