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Brief paper

Coverage control for mobile sensor networks with limited communication ranges on a circle☆

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ABSTRACT

The coverage control problem for mobile sensor networks with limited communication ranges is addressed in this paper. The goal of the problem is to minimize a coverage cost function which indicates the largest arrival time from the mobile sensor network to the points on a circle. Different input constraints are imposed on the sensors with first-order dynamics due to their different movement capabilities. To deal with this problem, low gain feedback is utilized to develop a distributed coverage control law for each sensor and an upper bound on the low gain is also provided. It is shown that networked mobile sensors can be driven to the configuration minimizing the coverage cost function as long as their communication ranges exceed a threshold and network connectivity of the sensors does not need to be preserved during the coverage task. Finally, a numerical example is given to illustrate the effectiveness of the proposed coverage control law.

1. Introduction

Recently coordination control of autonomous mobile agents has been investigated extensively due to its wide potential applications (Fan, Feng, Wang, & Song, 2013; Fan, Liu, Feng, & Wang, 2015; Nowzari & Cortés, 2012; Susca, Bullo, & Martínez, 2008; Zhai & Hong, 2013). One of the typical coordination control problems is the so-called coverage control problem. Generally, a coverage cost function is introduced in the coverage problem to indicate how well an environment of interest is covered and the ultimate objective is to drive networked mobile agents to the configuration such that the cost function is optimized.

In the past decade, much attention has been paid to improve the overall sensing performance of mobile sensor networks. In Cortés, Martínez, Karatus, and Bullo (2004), Voronoi partition is employed to design distributed coverage control laws to drive a group of mobile sensors to the optimal network configuration, that is, centroidal Voronoi configuration. In Li and Cassandras (2005), a probabilistic sensing model is considered and a distributed gradient-based coverage control scheme is proposed to maximize the joint event detection probability. Artificial potential fields are also utilized to develop distributed coverage algorithms. For example, potential fields are constructed in Howard, Mataric, and Sukhatme (2002) such that mobile sensors are repelled by both obstacles and other sensors, forcing the sensor network to spread over a given mission domain. In Schwager, Rus, and Slotine (2011), a unified optimization framework is proposed to bring together the aforementioned three coverage control schemes.

Reliable communication among mobile sensors is generally critical for successful accomplishment of the coverage task (Song, Liu, Feng, Wang, & Gao, 2013). In Kantaros and Zavlanos (2016), a distributed communication-aware coverage control scheme is developed for a mobile sensor network, under which the information collected by the sensors can be reliably conveyed to desired destinations. For mobile sensors with limited communication ranges, a common approach to guaranteeing their information exchange is to preserve network connectivity of the sensors (Razafindralambo & Simplot-Ryl, 2011; Stergiopoulos, Kantaros, & Tzes, 2012; Van Le, Oh, & Yoon, 2016; Zhong & Cassandras, 2011). In Stergiopoulos et al. (2012), the area coverage problem with radio connectivity constraints is addressed by assuming that only one sensor can move at each time step. Under the same assumption, the work in Li and Cassandras (2005) is reconsidered in Zhong and Cassandras (2011) by taking into account network connectivity preservation.

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In many time-critical applications such as search and rescue missions, the main concern is to provide service or take action as soon as possible, that is, to minimize the arrival time from a group of mobile sensors to any point in environments of interest. For homogeneous mobile sensor networks, it is equivalent to the problem of minimizing the largest distance or weighted distance between the sensors and the points in the mission domain (Cortés & Bullo, 2005; Hu & Xu, 2013; Lekien & Leonard, 2009; Leonard & Olshevsky, 2013; Zuo, Chen, Yan, & Shi, 2016). In practice, heterogeneous sensors with different movement capabilities are often deployed and the arrival time from a mobile sensor to a point not only depends on the distance between them, but also on the sensor's individual movement capability. In Song, Liu, Feng, and Xu (2016), the coverage problem of a circle using mobile sensors with different maximum velocities is addressed and distributed coverage control laws are developed for each sensor such that the largest arrival time from the mobile sensor network to any point on the circle is minimized.

In this paper the work in Song et al. (2016) is extended by taking into consideration mobile sensors' limited communication ranges. Different input constraints are imposed on the sensors due to the existence of different maximum velocities. To deal with this issue, low gain feedback is utilized to develop a distributed coverage control law for each sensor (Lin, 1998; Su, Chen, Lam, & Lin, 2013). It is noted that connectivity preservation prevents the sensors to be far away from each other while the coverage task requires them to spread over the mission domain. A trade-off between the two contradictory objectives often has to be taken into consideration. A natural question arising is whether the coverage task can be accomplished by mobile sensors with limited communication ranges without connectivity preservation. This paper provides a positive answer to this question for a special case, that is, mobile sensors are constrained to move along a circle. It is shown that networked mobile sensors can be driven to the optimal configuration as long as their communication ranges are sufficiently large such that the sensor network is connected in the configuration. Coverage control for mobile sensors with limited visibility radius on a circle is also considered in Flocchini, Prencipe, and Santoro (2008). However, it is noted that their works focus on uniform deployment of the sensors on the circle, which can be regarded as a special case of the work in the present paper. Note also that for easy exposition coverage of a circle is considered in this paper. In fact, our work can be extended to the coverage problem of a closed curve provided that the curve can be parametrized by a single parameter such as the curve arc-length (Zhang & Leonard, 2007). Therefore, the present work can be employed in many potential applications such as perimeter surveillance and cooperative target enclosing.

The rest of the paper is organized as follows. The problem formulation is presented in Section 2. A distributed coverage control law with input constraint is developed in Section 3 and convergence analysis of the coverage control law is provided in Section 4. Finally, simulation results and conclusion are given in Sections 5 and 6, respectively.

2. Problem formulation

Consider a network of mobile sensors i, $i \in \mathcal{I}_n = \{1, \ldots, n\}$ which are deployed on a unit circle initially and are constrained to move on the circle. The position of an arbitrary point q on the circle is denoted by the angle measured counterclockwise from the positive horizontal axis. Let $\mathbb{S}$ be the set of all points on the circle and q_i be the position of sensor i. The distance between sensor i and point $q \in \mathbb{S}$ is defined as $d(q_i, q) = \min\{\bar{d}(q_i, q), 2\pi - \bar{d}(q_i, q)\}$, where $\bar{d}(q_i, q) = (q - q_i) \bmod 2\pi$ is the counterclockwise distance from sensor i to point q.

The mobile sensors are assumed to evolve according to the following discrete-time dynamics

$$q_i(k+1) = q_i(k) + \epsilon u_i(k), \tag{1}$$

where $q_i(k)$ and $u_i(k)$ denote the position and control input of sensor i at step k, respectively and $\epsilon > 0$ is the step-size. In real-world applications, there always exists an upper bound on each sensor's moving velocity and the upper bounds of the sensors are generally different from each other. Denote the maximum velocity of sensor i by λ_i and assume it is known by sensor i *a priori*. For convenience, let $\lambda_0 \equiv \lambda_n$ and $\lambda_{n+1} \equiv \lambda_1$ throughout this paper. Note that in this work $u_i(k)$ also denotes the velocity of sensor i at time step k. Due to the existence of maximum velocities of the sensors, different constraints are imposed on the sensors' control inputs, that is, $-\lambda_i \le u_i(k) \le \lambda_i,\ \forall k \ge 0,\ \forall i \in \mathcal{I}_n$.

For our analysis, label the sensors counterclockwise according to their initial positions on the circle, that is,

$$0 \le q_1(0) < \cdots < q_i(0) < q_{i+1}(0) < \cdots < q_n(0) < 2\pi. \tag{2}$$

The spatial order of the sensors is said to be preserved if the inequalities $q_1(k) < \cdots < q_i(k) < q_{i+1}(k) < \cdots < q_n(k) < 2\pi + q_1(k)$ always hold. Throughout the paper, let $q_0(k) = q_n(k) - 2\pi$ and $q_{n+1}(k) = q_1(k) + 2\pi$. In practice, mobile sensors often possess limited communication capabilities and they communicate with each other only when their distance is within a certain range. Therefore, it is assumed that at each time step sensor i can only communicate with the other sensors whose positions satisfy $|q_j(k) - q_i(k)| \le r$, where r denotes the sensors' limited communication range. The neighbors of the sensor i at time step k are defined by $\mathcal{N}_i(k) = \{j \in \mathcal{I}_n : |q_j(k) - q_i(k)| \le r,\ j \ne i\}$ and the communication topology of the mobile sensors is modeled by an undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with $\mathcal{V}$ being the set of sensors and $\mathcal{E}$ denoting the communication links between them.

Given these assumptions and definitions, a coverage cost function $T(q_1, \ldots, q_n) = \max_{q \in \mathbb{S}} \min_{i \in \mathcal{I}_n} d(q_i, q)/\lambda_i$ can be introduced in this paper, which indicates the largest arrival time from a sensor network to any point on the circle (Song et al., 2016). Note that a smaller T implies that the mobile sensor network could respond more quickly when there exist events occurring on the circle. The goal of this paper is to design distributed coverage control laws to drive networked mobile sensors with limited communication ranges and different input constraints to the optimal configuration such that the coverage cost function $T(q_1, \ldots, q_n)$ is minimized.

3. Distributed coverage control laws

To deal with the limited communication ranges of the senors, the coverage control law proposed in Song et al. (2016) is revised as

$$u_i(k) = \lambda_i \mathrm{sat}(\bar{u}_i(k)),\ i = 1, \ldots, n, \tag{3}$$

where $\mathrm{sat}(\bar{u}_i(k)) = \mathrm{sign}(\bar{u}_i(k))\min\{1, |\bar{u}_i(k)|\}$ and

$$\bar{u}_i(k) = \sigma_i[(\lambda_{i-1} + \lambda_i)\min\{d_i(k), r\} - (\lambda_i + \lambda_{i+1}) \min\{d_{i-1}(k), r\}] \tag{4}$$

with $d_i(k) = q_{i+1}(k) - q_i(k),\ i = 0, \ldots, n$ and $\sigma_i > 0$ being a control gain to be determined.

Note that computation of the above coverage control law for each sensor i requires the maximum velocity information of the sensors $i+1$ and $i-1$. To acquire the maximum velocities λ_{i+1} and λ_{i-1}, each sensor communicates with its neighbors to exchange their positions and maximum velocities. If sensor i has both counterclockwise and clockwise neighbors, it remains static and can obtain the maximum velocities of the sensors $i+1$ and $i-1$ from