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Brief paper

Nonuniform coverage control for heterogeneous mobile sensor networks on the line☆

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ABSTRACT

The coverage control problem for networked mobile sensors on a line with different actuation limits is addressed in this paper. The roughness of each point on the line is assumed to be different which makes the concerned problem more challenging. The objective of coverage control considered in this paper is to minimize the largest time required for the sensor network to reach any point on the line via optimizing the sensors' locations on this line. Distributed coverage control laws with input constraints are developed to drive the sensors to the optimal configuration while preserving their spatial ordering on the line. Simulation examples demonstrate the effectiveness of the proposed control laws.

1. Introduction

Networks of sensors and autonomous vehicles have wide applications in many fields, including environment monitoring, surveillance, industrial diagnostics and so on. When the mission domain is remote and/or hostile, such networks must be capable of operating in a fully autonomous and distributed way to adapt to changing environments. The potential of such applications has prompted much interest in coverage control of mobile sensor networks, where the goal is to drive networked mobile sensors to an optimal sensing configuration in a mission field. If the information density or terrain roughness is uniform over the mission field, the problem is referred to as the uniform coverage control problem, whereas for a nonuniform field, the problem is referred to as the nonuniform coverage control problem with a nonuniform metric.

In practice, mobile sensors may have some physical constraints like limited communication or sensing ranges (Laventall & Cortés, 2009), velocity or actuation constraints (Braun et al., 2013; Brezak & Petrovic, 2011). Accordingly, a network of heterogeneous mobile sensors in terms of their different actuation limits is considered in this work. This paper investigates the nonuniform coverage control of a network of heterogeneous mobile sensors located on a line with varying roughness.

1.1. Related work

There is a large volume of works on coverage control problems of sensor networks in the open literature, see for examples Bartolini, Calamoneri, La Porta, and Silvestri (2011), Breitenmoser, Schwager, Metzger, Siegwart, and Rus (2010), Caicedo-Nuez and Žefran (2008), Cortés and Bullo (2005), Cortés, Martınez, and Bullo (2005); Cortés, Martınez, Karatas, and Bullo (2004), Kantaros, Thanou, and Tzes (2015), Laventall and Cortés (2009), Li and Cassandras (2005), MartíNez and Bullo (2006), Pimenta, Kumar, Mesquita, and Pereira (2008), Poduri and Sukhatme (2004), Song, Liu, Feng, Wang, and Gao (2013), Zhai and Hong (2013) and references therein. Based on Voronoi partition and gradient descent algorithms, coverage control laws are developed for a group of mobile sensors in uniform fields in Cortés and Bullo (2005). Uniform coverage control with a constraint on the minimum number of each agent's neighbors is investigated in Poduri and Sukhatme (2004).

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Nonuniform coverage control of sensor networks is addressed in part by using density-dependent gradient descent laws in Cortés et al. (2004), Li and Cassandras (2005) and Pimenta et al. (2008). Nonuniform coverage control of mobile agents with limited sensing or communication range is treated in Cortés et al. (2005), Kantaros et al. (2015) and Laventall and Cortés (2009). The authors in Lekien and Leonard (2009) investigate the nonuniform coverage problem of a planar region with a non-Euclidean distance metric that stretches and shrinks regions of high and low density, respectively. Nonuniform coverage control laws are proposed using cartogram transformation which requires some global information about the region. In addition, nonuniform coverage of a planar region by a group of mobile sensors with stochastically intermittent communications among them is studied in Miah, Nguyen, Bourque, and Spinello (2015).

1.2. One-dimensional coverage problem

This paper focuses on the nonuniform coverage problem when the sensors are arranged on a line, which is motivated by two considerations. First, the one-dimensional coverage problem has several potential applications such as environmental boundary monitoring and target tracking (Jin & Bertozzi, 2007; Susca, Bullo, & Martínez, 2008), and it has attracted increasing attention in recent years, such as Choi and Horowitz (2010), Davison, Leonard, Olshevsky, and Schwemmer (2015), Frasca, Garin, Gerencsér, and Hendrickx (2015). When a group of mobile sensors performs border patrol, they should be optimally positioned on a curve. This problem can be transformed to the line coverage problem investigated in this paper by parametrizing the curve with its arc-length.

Second, the one-dimensional coverage problem can provide a simplified setting for addressing unsettled issues in coverage control. One typical issue is to design control algorithms for mobile agents to minimize the response time or energy cost from the agents to any point in the mission field. The paper Leonard and Olshevsky (2013) develops a distributed coverage control law for a nonuniform field under which a group of mobile agents are optimally positioned on a line, such that the distance from the mobile agents to any point on the line is minimized. Taking into consideration the sensors' velocity constraints, the authors in Song, Liu, Feng, and Xu (2016) study the uniform coverage problem of a circle by networked mobile sensors to minimize the largest time taken from the network to any point on the circle.

1.3. Our contributions

In this paper, we consider the nonuniform coverage control of a network of heterogeneous mobile sensors with different actuation limits located on a line. The roughness of each point on the line is assumed to be different. Our objective is to minimize a coverage cost function, defined as the largest time required for the sensor network to reach any point on the line. Distributed control laws are designed, under which the sensors are driven to the optimal positions with order preservation. Compared with Leonard and Olshevsky (2013), where nonuniform coverage control laws are designed for homogeneous sensors without actuation constraints, this paper takes into account different actuation limits of mobile sensors and varying roughness of the terrain, and designs distributed control laws with input saturation. The problem investigated in this paper is more general. Compared with Song et al. (2016), where coverage control problem of networked mobile sensors with different velocity constraints positioned on a circle is studied, this paper investigates the coverage problem of mobile sensors with actuation constraints located on a line, and also takes varying roughness of the terrain into consideration.

The remainder of this paper is structured as follows. Section 2 formalizes the nonuniform coverage problem with actuation constraints. Distributed coverage control laws are proposed in Section 3. Section 4 presents the convergence analysis of the coverage control laws. In Section 5, the effectiveness of the results is illustrated by simulations. Finally, Section 6 concludes the paper.

2. Problem formulation

Consider a network of n mobile sensors initially located at arbitrary positions $q_1(0), q_2(0), \ldots, q_n(0)$ which are assumed, without loss of generality, to lie in the interval $[0, 1]$. Denote R^+ as the set of positive real numbers. Let $\rho : [0, 1] \to R^+$, be a positive, piecewise-continuous function, which measures the roughness at each point on the line. We assume that ρ is bounded, i.e., there exist positive constants $\rho_{\max}$ and $\rho_{\min}$ such that for all $z \in [0, 1]$, we have $\rho_{\min} \le \rho(z) \le \rho_{\max}$. In this work, the roughness function ρ is assumed to be known *a priori* by the sensors. Following Leonard and Olshevsky (2013), the distance between a and $b \in [0, 1]$ is defined as

$$d_\rho(a, b) = \int_{\min(a,b)}^{\max(a,b)} \rho(z)dz,$$

and we denote $\bar{d}_\rho(a, b) = \int_a^b \rho(z)dz$. It is easy to see that $d_\rho(a, b) = |\bar{d}_\rho(a, b)|$.

We label the sensors from 1 to n in accordance with their initial order along the line from left to right and assume that no two sensors occupy the same position, that is,

$$0 < q_1(0) < q_2(0) < \cdots < q_n(0) < 1. \quad (1)$$

We introduce the function

$$F(x) = \int_0^x \rho(z)dz.$$

Note that $F(1) = d_\rho(0, 1)$. Furthermore, for any two points $a < b$ in $[0, 1]$, $d_\rho(a, b) = F(b) - F(a)$.

In this paper, we consider the nonuniform coverage problem for heterogeneous mobile sensors with actuation constraints. There exists a maximum actuation α_i for each sensor. Networked mobile sensors are assumed to evolve in discrete time periods. The maximum distance that each sensor can move in one sampling period is limited, which depends on both the sensor's actuation limit and the varying roughness of the terrain. The actuation needed for each agent to move from point p to q on the line is given by $|\int_p^q f(\rho(z))dz|$, where $f(x) : R^+ \to R^+$ is a strictly increasing continuous function with respect to x. This definition captures the fact that the agents need larger actuation for movement in areas where the roughness function ρ is higher, and smaller actuation in areas where ρ is lower. For simplicity, we assume $f(\rho(z)) = \rho(z)$ in this work. As sensor i has the maximum actuation α_i, the actuation for sensor i to move on the line in one period is no larger than α_i, that is, $-\tau\alpha_i \le \int_{q_i(k)}^{q_i(k+1)} \rho(z)dz \le \tau\alpha_i$ for $i = 1, \ldots, n$, and $k \ge 0$, where $q_i(k)$ is the position of sensor i on the line at the discrete-time index k and $\tau > 0$ is the sampling period.

According to the above considerations, the evolution of the mobile sensors' positions depends on not only the control inputs but also the varying roughness of the terrain. For our analysis, each mobile sensor is assumed to evolve according to

$$\int_{q_i(k)}^{q_i(k+1)} \rho(z)dz = \tau u_i(k), \quad (2)$$

where $u_i(k)$ is the control input of sensor i at the discrete-time index k. Since $\tau > 0$ is the sampling period, $u_i(k)$ also can be regarded