Automatica 63 (2016) 209–220

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Distributed communication-aware coverage control by mobile sensor networks ☆

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ARTICLE INFO

Article history:
Received 21 November 2014
Received in revised form
21 May 2015
Accepted 8 October 2015
Available online 11 November 2015

Keywords:
Mobile robot networks
Communication networks
Coverage control
Distributed optimization

ABSTRACT

The purpose of this paper is to propose a distributed control scheme to maximize area coverage by a mobile robot network while ensuring reliable communication between the members of the team. The information that is generated at the sensors depends on the sensing capabilities of the sensors as well as on the frequency at which events occur in their vicinity, captured by appropriate probability density functions. This information is then routed to a fixed set of access points via a multi-hop network whose links model the probability that information packets are correctly decoded at their intended destinations. The proposed distributed control scheme simultaneously optimizes coverage and routing of information by sequentially alternating between optimization of the two objectives. Specifically, optimization of the communication variables is performed periodically in the dual domain. Then, between communication rounds, the robots move to optimize coverage. Motion control is due to the solution of a distributed sequential concave program that handles efficiently the introduced nonlinearities in the mobility space. Our method is illustrated in computer simulations.

1. Introduction

The area coverage problem is related to the development of a control plan that allows a group of mobile agents equipped with sensing and communication capabilities to spatially configure themselves in a way that maximizes the cumulative probability that events are detected in an area of interest. While the area coverage problem has recently received a lot of attention, ensuring that the collected rates of information can be efficiently relayed to a desired set of access points for subsequent processing is, to the best of our knowledge, still an open problem. In this paper, we provide a distributed solution to this problem of joint coverage and communication control.

The literature related to coverage problems is quite extensive. In Cortés, Martinez, Karatas, and Bullo (2004), the authors propose a distributed controller based on Lloyd's algorithm for sensing a convex area. In this work, it is assumed that the sensing performance degrades as the distance from the sensor increases. The case where the robots are equipped with range-limited sensors is discussed in Cortés, Martinez, and Bullo (2005). Distributed controllers for coverage optimization have been proposed in Zhu and Martínez (2013) that minimize the energy needed for sensing and data processing. Coverage optimization for anisotropic sensors, whose performance depends on both the distance from the sensor and its orientation, is studied in Gusrialdi, Hatanaka, and Fujita (2008), Hexsel, Chakraborty, and Sycara (2011) and Stergiopoulos and Tzes (2013, 2014), while Caicedo-Nuez and Zefran (2008), Kantaros, Thanou, and Tzes (2015), Pimenta, Kumar, Mesquita, and Pereira (2008) and Renzaglia, Doitsidis, Martinelli, and Kosmatopoulos (2012) discuss coverage of non-convex areas.

The area coverage problems discussed above typically ignore the requirement that the information collected by the robot sensors needs to be routed to a desired set of destinations. Introducing this capability in the system gives a new twist to the problem on the interface with communication control and networking. Most of the existing approaches to communication control of mobile robot networks employ proximity graphs to model information exchange between robots and, therefore, consider the problem of preserving graph connectivity. Such approaches involve, for example, maximization of the algebraic connectivity of the graph (DeGennaro & Jadbabaie, 2006; Kim & Mesbahi, 2006), potential fields that model loss of connectivity as an obstacle in the free space (Zavlanos & Pappas, 2007), tools from reachability

☆ The material in this paper was partially presented at the 53rd IEEE Conference on Decision and Control, December 15–17, 2014, Los Angeles, CA, USA and at the 2nd IEEE Global Conference on Signal and Information Processing (GlobalSIP), December 3–5, 2014, Atlanta, GA, USA. This paper was recommended for publication in revised form by Associate Editor Wei Ren under the direction of Editor Ian R. Petersen.

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http://dx.doi.org/10.1016/j.automatica.2015.10.035

analysis to ensure connectivity in networks of mobile sensors (Gil, Feldman, & Rus, 2012), and distributed hybrid approaches that decompose control of the discrete graph from continuous motion of the robots (Zavlanos & Pappas, 2008). Distributed algorithms for graph connectivity maintenance have also been implemented in Ji and Egerstedt (2007) and Notarstefano, Savla, Bullo, and Jadbabaie (2006). A comprehensive survey of this literature can be found in Zavlanos, Egerstedt, and Pappas (2011).

A more realistic communication model between mobile robots, compared to the above graph-theoretic approaches, is presented in Zavlanos, Ribeiro, and Pappas (2010, 2013) that takes into account the routing of packets as well as desired bounds on the transmitted rates. In this model, edges in the communication graph are associated with the probability that packets delivered through the corresponding links are correctly decoded by their intended receivers. This formulation gives rise to optimization problems to determine the desired rates and routes. Related methods for the control of wireless robot networks are proposed in Ghaffarkhah and Mostofi (2011) and Le Ny, Ribeiro, and Pappas (2012), where the wireless channels are modeled using path loss, shadowing, and multi-path fading, or evaluated using on-line techniques, respectively. Similarly, the Signal to Interference ratio (SIR) is utilized in Gil, Schwager, Julian, and Rus (2010) to model communication links between mobile aerial vehicles and ground sensors that perform collaborative tasks.

In this paper, we assume a team of mobile robot sensors responsible for covering a convex area of interest with the additional requirement that the sensory information collected by the robots can be efficiently routed to a desired set of fixed access points (APs). The rate of information generated at every sensor depends on the quality of sensing as a function of the sensing range as well as on the probability that events occur in the vicinity of that sensor, captured by an appropriate probability density function over the area of interest. This information is then routed to the APs via a multi-hop network whose links model the probability that information packets are correctly decoded at their intended destinations.

The key idea in this work is to formulate the area coverage problem as a *constrained optimization problem* in the robot positions, associated area partitions, and routing decisions. We can then use the routing decisions to control the feasible set so that it contains the Voronoi partition as a solution, which is well-known to be optimal for the unconstrained problem (Cortés et al., 2005). Substituting the Voronoi partition in the constrained problem, we obtain an optimization problem in the robot positions and routing decisions, which we solve in a way similar to our prior work (Zavlanos et al., 2013); we decouple coverage and routing control and alternate between optimization of the two objectives. In particular, given a spacial configuration of the robots in the area of interest, the communication variables are updated using a distributed subgradient algorithm in the dual domain. The update of the communication variables is then followed by robot motion in a direction that optimizes the coverage objective. Robot motion is formulated as a distributed sequential concave program, that allows us to handle nonlinearities in the coverage objective as well as the nonlinear dependence of the communication constraints on the robot positions. As the robots move, the optimal solution in the communication space drifts, which introduces a possible infeasibility gap in the primal variables. While such infeasibility gaps persist, the affected robots remain stationary until feasible routing variables are determined by the optimization in the communication space. Following the analysis in Zavlanos et al. (2013), we obtain bounds on the robot velocities that characterize the performance of communications. The proposed control scheme is distributed, utilizing only information that is locally available at the sensors.

The problem of simultaneous coverage and communication control is also addressed in Kantaros and Zavlanos (2014a), although in a centralized setting. In that work, the routing variables are updated periodically in discrete time while the robot motion is performed along the negative gradient of a function that combines the coverage objective and a barrier potential function to ensure satisfaction of the imposed communication constraints. A distributed solution to this problem is presented in Kantaros and Zavlanos (2014b). In this work, we provide theoretical guarantees to support the framework proposed in Kantaros and Zavlanos (2014b), as well as extensive simulation studies. A related problem that considers the minimization of the aggregate information delivered directly, in one hop, from the robots to a sink node is addressed in Jiang and Zefran (2013). Multi-hop communication in the context of coverage is considered in Li and Cassandras (2005) and Stergiopoulos, Kantaros, and Tzes (2012a,b). Specifically, in Li and Cassandras (2005) the objective is to minimize the energy consumption in the network, so paths are sought that ensure this minimum energy objective. In Stergiopoulos et al. (2012a,b) a joint coverage and graph connectivity framework is developed for robots that have limited, proximity-based communication ranges. These latter approaches differ from the one proposed here in that we consider more realistic models of wireless communication that involve routing of information over a network of varying link reliabilities, and we also ensure desired information rates that depend on the frequency with which events occur in the sensors' vicinity.

The rest of this paper is organized as follows. Section 2 presents the coverage problem in the presence of communication constraints. The proposed control scheme is presented in Section 4 while its efficiency is examined in Section 6 through a simulation study. Conclusive remarks are provided in the last section.

2. Problem formulation

Assume a team of N mobile robots responsible for the sensing coverage of a convex and compact area $\mathcal{A} \subset \mathbb{R}^2$ and for the transmission of packets of information to a fixed set of K access points (APs). The positions of all nodes are stacked in the vector $\mathbf{x} = [\mathbf{x}_1^T, \ldots, \mathbf{x}_i^T, \ldots, \mathbf{x}_{N+K}^T]^T$, where $i \in \{1, \ldots, N\}$ for the robots and $i \in \{N+1, \ldots, N+K\}$ for the APs. The motion of the robots is assumed to be governed by the first order differential equation:

$$\dot{\mathbf{x}}_i = \mathbf{u}_i, \quad i = 1, \ldots, N, \tag{1}$$

where $\mathbf{u}_i \in \mathbb{R}^2$ stands for the control input associated with the ith robot.

To achieve area coverage, each robot is equipped with an isotropic sensor whose accuracy is captured by a radially decreasing function f that is maximal at the sensor location $\mathbf{x}_i$. In this context, a larger value of f means better sensing accuracy. In particular, we choose

$$f(\mathbf{x}_i, \mathbf{q}) = e^{-\|\mathbf{q}-\mathbf{x}_i\|^2}. \tag{2}$$

Moreover, let $\phi(\mathbf{q}) : \mathcal{A} \to \mathbb{R}_+$ be an integrable density function representing the probability that an event takes place at the point $\mathbf{q} \in \mathcal{A}$. Then, the coverage problem can be formulated as follows:

$$\underset{\mathbf{x}}{\text{maximize}} \left[\mathcal{H}(\mathbf{x}) = \int_{\mathcal{A}} \max_{i=1,\ldots,N} f(\mathbf{x}_i, \mathbf{q}) \phi(\mathbf{q}) \mathrm{d}\mathbf{q} \right]. \tag{3}$$

A common geometric approach to simplify the area cost function $\mathcal{H}$ is via the tessellation of the area of interest into subregions $\mathcal{W}_i$, $i \in \{1, \ldots, N\}$ according to some distance metric, and the assignment of those regions to the robots for sensing purposes. Requiring that $\bigcup_{i=1}^N \mathcal{W}_i = \mathcal{A}$ and that the sets $\mathcal{W}_i$ are disjoint except