Information Sciences 254 (2014) 69–82

Contents lists available at ScienceDirect

Information Sciences

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

Cooperation of multiple mobile sensors with minimum energy cost for mobility and communication

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ARTICLE INFO

Article history:
Received 13 November 2012
Received in revised form 18 June 2013
Accepted 3 August 2013
Available online 11 August 2013

Keywords:
Wireless sensor networks
Cooperation control
Mobility cost
Communication cost
Optimal control

ABSTRACT

This paper investigates a minimum energy cooperation control problem in mobile sensor networks. Assuming a time-invariant undirected network topology for the sensors, we present a suboptimal solution that guarantees minimum overall energy cost of mobility and communication for the sensors to achieve consensus. The design procedure of the distributed control protocol is composed of two steps. The first step yields the local feedback gain via solving a linear quadratic regulating (LQR) problem, while the second step produces the network feedback gain based on convex optimization technique. The results are extended to formation control problems with and without communication delays. The effectiveness of the proposed methodology is illustrated by numerical examples.

1. Introduction

In the past decade, wireless sensor networks (WSNs), or generally unmanned system networks, received significant research attention. As a special type of networked systems, wireless sensor networks have many benefits, including high efficiency and adaptability, low cost and complexity, easy deployment and maintenance. Due to these advantages, WSNs have found applications spanning vast and varied areas, such as building and home automation, industrial automation, precision agriculture, health monitoring, environment and climate monitoring, traffic monitoring, habitat monitoring, wildlife monitoring and tracking, object tracking, intruder detection, early forest fire detection, earthquake early detection, emergency rescue, space explorations, and military applications in missions such as intelligence, surveillance and reconnaissance, see [1]. In many applications like building monitoring and habitat monitoring, sensors remain stationary after deployment. Recently, there has been a strong desire to deploy sensors mounted on mobile platforms such as unmanned aerial/ground/underwater vehicles and man-made satellites. Such mobile sensor networks are extremely valuable in situations where traditional deployment mechanisms fail or are not suitable, e.g., a hostile environment where sensors cannot be manually deployed.

Devices in WSNs are typically large in number and advanced in sensing, communicational and computational capabilities, demanding nontrivial energy, while at the same time the batteries powering these devices have very low capacity and cannot be replaced or recharged in a convenient way. As a result, reducing energy consumption to extend the battery lifetime of the sensors has emerged as a critical issue in sensor networks [22,14,17]. For stationary sensor networks, communication processes are typically the most energy-expensive in all tasks. Therefore, researchers have developed various schemes in order to reduce the energy consumption due to communication [2]. Outstanding schemes include energy-saving protocols

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0020-0255/$ - see front matter
http://dx.doi.org/10.1016/j.ins.2013.08.001

[23], multi-hop routing, topology control [28], selective communication and cooperative communication [22,14,11], nodes clustering [4] and other resource allocation designs [31]. These strategies are energy-efficient because they are capable of either reducing the number of redundant transmissions or minimizing the total transmission energy required to maintain full connectivity in the network. What makes these schemes possible and useful in practice lies in that the energy consumed by every communication task is typically well-characterized.

While issues in association with stationary sensor networks have been extensively explored, research attention has only recently been focused on mobile sensor networks. Most existing works focus on issues like localization and coverage control of mobile sensor networks. More specifically, researchers have mainly investigated algorithms to reposition sensors in desired locations in order to recover or enhance network coverage or to maximize the covered area [34,25,30]. These studies are limited in at least two aspects: (i) the energy consumption issue is either not considered or falls beyond the primary interest and (ii) they have not counted in the mobility energy consumption, although node mobility has been exploited for different purposes, e.g., to obtain a new network configuration that improves coverage after the sensors move to their desired locations.

The energy consumption of a mobile sensor network depends not only on the network configuration, but also on the mobility behavior of the sensors. Therefore, node mobility can be exploited as a complementary means for reducing energy consumption [13,32]. One demonstrating example is to let a mobile sensor with sufficient energy move about a sensor field to collect data from its neighbors, reducing communication energy consumption at those nodes. This paper aims to investigate energy-efficient designs for mobile sensor networks from the viewpoint of cooperative control [21], taking into consideration both communication expenditure and mobility cost. To be specific, we will study this problem in the context of consensus seeking and formation control, which to the best of the authors' knowledge is the first time. Consensus issue, meaning that all agents' states converge to the same value via mutual interaction, has been extensively investigated by researchers. For example, various consensus algorithms for systems with single-integrator, double-integrator or higher order dynamics can be seen, e.g., in [6,7,16,19,26], results on optimal consensus protocol design and applications to formation control problems can be seen in [15,35].

In this paper, we consider a collection of mobile sensors operating under a given communication topology. The dynamics of these sensors are described by linear state space equations. The problem is interesting in that the energy consumption for mobility and communication tasks is simultaneously counted in for analysis and design. To give an energy-efficient cooperative control methodology, we will introduce a new definition for the overall energy cost, which is composed of two energy models describing respectively the mobility energy and communication energy. Based on the novel energy model (which plays the role of the cost function for optimization), we will give a two-step design method for the newly defined distributed consensus protocol and derive the exact agreement state at which the consensus is to be achieved. To be more precise, the consensus problem will be converted to a stabilization problem by transforming the original systems into their reduced-order state error systems; then, by solving the latter problem in a sub-optimal way, we will derive the controller gains that can stabilize the error systems, which guarantees consensus of the original systems describing the mobile sensor network. Finally, we will extend the results to formation control problems with and without communication delays.

It should be emphasized that our problem formulation differs from the existing ones in that we consider both the communication energy and mobility energy in each of the sensor nodes. Also, in obtaining the results we have used a two-step procedure by combining convex optimization and the linear quadratic regulating technique. The presented framework makes it possible for the mobile sensor nodes to decide whether to communicate or to move at each time, guaranteeing the energy consumption as low as possible.

The remainder of this paper is organized as follows. In Section 2 we give some preliminaries of graph theory and the problem formulation. Section 3 contains the main results on consensus controller design. In Section 4 we extend the presented results to formation control of sensor networks. Some numerical examples are given in Section 5 to illustrate the obtained method, followed by the concluding remarks in Section 6.

Notations: R^ndenotes n dimensional Euclidean space, $R^{n\times m}$ denotes the family of $n \times m$ dimensional real matrices. I_n denotes the identity matrix of dimension n. For a given vector or a matrix X, X^{T} denotes its transpose, $\|X\|$ denotes its Euclidean norm. For a square nonsingular matrix X, X^{-1} denotes its inverse matrix. And $diag\{\cdots\}$ stands for a block-diagonal matrix. The sign $\otimes$ represents matrix Kronecker product. $\mathbf{1}$ denotes a column vector whose entries equal to one. The symmetric elements of a symmetric matrix are demoted by $*$.

2. Preliminaries and problem formulation

2.1. Preliminaries of graph theory

We use an undirected graph $G(\nu, \varepsilon, \gamma)$ to model the interactions among agents, where $\nu \in \{1,\ldots,N\}$ is the set of N agents, $\varepsilon \subseteq \nu \times \nu$ is the set of edges, $\gamma = [a_{ij}]$ is the adjacency matrix with its elements associated with the edges being positive, i.e., $(i, j) \in \varepsilon$, $a_{ij} = a_{ji} > 0$, otherwise $(i, j) \notin \varepsilon$, $a_{ij} = 0$. An unordered pair $(i, j) \in \varepsilon$ if there exists an edge between agent i and agent j. A sequence of successive edges $(i, l),(l, k),\ldots,(m, j)$ is called a path from agent i to agent j. A graph G is said to be connected if for any two agents $i, j \in \nu$, there is a path from agent i to agent j. The set of neighbors of node i is denoted by $N_i = (i \in \nu\colon (i, j) \in \varepsilon)$. The Laplacian of the undirected graph G is defined as $L = \Delta - \gamma$, where $\Delta = diag\{d_1,\ldots,d_n\}$ is the degree matrix with