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Sensor Networks and Cooperative Control

Christos G. Cassandras and Wei Li
Dept. of Manufacturing Engineering
and Center for Information and Systems Engineering
Boston University, Brookline, MA 02446
cgc@bu.edu, wli@bu.edu

Abstract— **This paper provides a tutorial-style overview of sensor networks from a systems and control theory perspective. We identify key sensor network design and operational control problems and present solution approaches that have been proposed to date. These include deployment, routing, scheduling, and power control. In the case of mobile nodes, a sensor network is called upon to perform a "mission". We present solution approaches to two types of missions, both involving stochastic mission spaces and cooperative control: reward maximization missions, and coverage control missions. We conclude by outlining some fundamental research questions related to sensor networks and the convergence of communication, computing, and control.**

I. Paper summary

The full version paper will appear in the No. 5-6, Vol.11, 2005 issue of the *European Journal of Control*. A summary is provided below.

A sensor network consists of a collection of (possibly mobile) sensing devices that can coordinate their actions through wireless communication and aim at performing tasks such as exploration, surveillance, or monitoring and tracking "target points" over a specific region, often referred to as the "mission space". Collected data are then further processed and often support higher-level decision making processes. Nodes in such networks are generally inhomogeneous, they have limited on-board resources (e.g., power and computational capacity), and they may be subject to communication constraints. It should be pointed out that sensor networks differ from conventional communication networks in a number of critical ways. First, they allow us to interact with the *physical* world, not just computers, databases, or human-generated data. By inserting decision making and control functionality into such networks one can envision closing the loop on remote processes that would otherwise be inaccessible. Thus, sensor networks are expected to realize a long-anticipated convergence of communication, computing, and control. Second, at least some nodes in such a network are "active", e.g., they execute sensing processes or they are are mobile; therefore, they are characterized by dynamics making a sensor network as a whole a challenging dynamic system. In addition, nodes are typically small and inexpensive, operating with limited resources, often in adverse stochastic environments. This implies that optimization in designing and operating sensor networks is a real need and not a mere luxury. Moreover, the limited computational capabilities of nodes often make *distributed* control or optimization methods indispensable. Finally, when it comes to measuring the performance of sensor networks, the metrics can be quite different from those used in standard communcation networks, giving rise to new types of problems. For example, because of limited energy, we recognize that nodes have finite lives and we often seek control mechanisms that maximize an appropriately defined "network lifetime". Part of such mechanisms may involve switching nodes on and off so as to conserve their energy or finding means to periodically replenish their energy supply. When the nodes are mobile, mechanisms are also needed to determine desired trajectories for the nodes over the mission space and *cooperative control* comes into play so as to meet specific mission objectives.

The main goal of this paper is to provide a tutorial-style overview of sensor networks from a systems and control theory perspective. To do so, key sensor network design and operational control problems are identified and some solution approaches that have been proposed to date are discussed. Emphasis is placed on rigorously formulating interesting optimization and cooperative control problems, describing the essential points of solution approaches without getting into technical details whenever these may be found in cited references.

The first part of the paper describes the basic structure of sensor networks and classifies them in a way that distinguishes between (i) those with fixed, known data sources and nodes that are not mobile, and (ii) those where data sources may be unknown and nodes are mobile. Next, the main problems related to the first network type are discussed, including deployment, power control, routing, and scheduling. Subsequently, networks with mobile nodes are considered, which are called upon to perform a "mission". Different types of missions lead to defining different types of problems and two such problems are presented, both involving stochastic mission spaces and cooperative control: reward maximization missions and coverage control missions. The "coverage control" problem, in particular, captures the main features and control challenges encountered in sensor networks: the need to define network performance in an unconventional manner, the involvement of cooperative

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control, the computational limitations of nodes that require a distributed control solution, and the role of communication constraints. Simulation results are presented throughout the paper to illustrate various control schemes and algorithms and open research problems are identified. The conclusion outlines some fundamental research questions related to sensor networks and the convergence of communication, computing, and control, as well as some more specific issues that developments to date have brought forth.