# Distributed Problem Solving in Sensor Networks*

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## ABSTRACT

The difficulties in developing large-scale, distributed sensor networks are discussed and our recent experience in developing and analyzing distributed problem solving methods for applications in sensor networks is overviewed.

## Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—Multiagent systems

## General Terms

Algorithms

## Keywords

sensor, distributed constraint satisfaction, resource allocation

## 1. SENSOR NETWORKS

In recent years, the technology of micro-electro-mechanical systems (MEMS) has made rapid advances. Various smart devices, such as sensors and actuators with some information processing capabilities embedded within, have been developed and deployed in many real-world applications [4, 5]. To meet the needs of vast demands of MEMS in various application domains, such as avionics and plant automation, it becomes critical to connect a large number of sensors and actuators, up to thousands, tens of thousands or even millions of units, and to integrate and embed sensing, signal and data processing and control functions on individual devices.

To make our discussion concrete, we now describe the problem of object detection using MEMS devices. Detecting and tracking mobile objects in large open environments is a topic that has many real applications in different domains, such as surveillance and robot navigation. We are developing such a detection and tracking system using MEMS sensors, each of which is operated under restricted energy sources, i.e., batteries, and has a small amount of memory and restricted computational power. In a typical application of our system, a collection of small sensors are scattered in an open area to detect possible foreign objects moving into the region. Each sensor can scan and detect an object within a fixed radius. However, the overall detecting area of a sensor is divided into three equal sectors, and the sensor can only operate in one sector at a time. The sensors can communicate with one another through radio communication. The radio channel is not reliable, in that a signal may get lost due to, for instance, a collision of signals from multiple sensors, or distorted due to environment noises. Moreover, switching from one scanning sector to another sector and sending and receiving signals take time and energy.

The system needs to meet two conflicting goals. While attempting to detect all objects as quickly as possible, the system must also preserve as much energy as possible in order to prolong its lifetime. The problem is thus to find a distributed scan schedule to optimize an objective function that balances the above conflicting goals. The key to the problem is how individual units should be programmed to work as a coherent piece toward achieving common goals.

## 2. DIFFICULTIES AND FEATURES

Many unique features of MEMS devices and distributed applications make the development of sensor networks difficult. Using a special sensor device, Berkeley Motes [2], and our application of object detection as examples, we discuss some of the difficulties of problem solving in sensor networks.

- **Restricted resources**. MEMS devices are typically developed with a low price in mind. As a result, the computational resources, e.g., the CPU speed and memory, are limited. For example, a Berkeley Mote carries a slow 4 MHZ CPU, only 512 Bytes of memory for instructions, and a small 4 MBytes memory for data. The computational resources on a sensor determines the amount of computation it can provide within a fixed period of time.

- **Faulty devices**. The application environments that sensor networks are applied to may be severe, such as an environment of high temperature and high pressure as in the avionics domain. The reliability of MEMS sensors may be significantly reduced under such environments. Therefore, the lifetime of a single device is reduced, as is the reliability of a sensor network as a whole.

*This research was supported in part by NSF Grants IIS-0196057 and EIA-0113618, and by DARPA under Cooperative Agreements F30602-00-2-0531 and F33615-01-C-1897.

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*AAMAS'02,* July 15-19, 2002, Bologna, Italy.

- **Unreliable communication**. Wireless communication provides much flexibility and extends significantly the applicability of sensor networks. It is one of the most desirable features of sensor networks. However, wireless communication also introduces additional problems to the development of such a system. Reliability of wireless communication is also one of the issues that has to be addressed.

- **Restrictive time bounds**. Sensor networks usually operate under severe time restriction, sometimes within unknown bounds on system response time. Adding information processing capability to sensors alleviates the time issue. Some simple and low-level decision making problems can be solved by coupling sensing and information processing on board. However, it still remains a challenge to fully utilize the onboard information processing functionality to increase the responsiveness of an integrated sensor network.

- **Limited energy**. Due to physical restrictions and the distributed nature of many applications, the sensors and actuators in distributed sensor networks usually operate on limited energy sources, i.e., batteries. It is an important, but difficult, problem to save energy to prolong the life span of a system.

Even though there are many difficult issues involved when using MEMS sensors, they are used to build robust and large-scale networks with many desirable features.

- **Scalability**. It is one of the design objectives to have a sensor network scalable to a large number of components, perhaps to tens of thousands or even a few million components. Scalability means that the system performance does not degrade disproportionally with the size of the system or even does not degenerates at all when the number of components increases.

- **Real-time performance**. Many applications, such as our object detection and tracking, require continuous and spontaneous responses. There are also problems in which the deadline for a response is unknown but can become imminent at any time. Therefore, a good anytime performance is desirable for a sensor network. Here, anytime means that a system can be stopped at any time with a solution.

- **Self-stabilization and fault tolerance**. To tolerate faulty components and support adaptation, it is expected that a sensor network is able to tolerate components' failure. It is also expected that the system be able to stabilize itself in that it is able to eventually converge to legal states, under local perturbations to restricted parts of the system.

# 3. APPROACHES AND INITIAL RESULTS

Multiagent system (MAS) technologies can and will play critical roles in developing effective and efficient problem-solving strategies and methods in large-scale sensor networks. They provide a framework for building and analyzing such systems and offer specific mechanisms for distributed decision making and coordination in the systems . In the past two decades or so, MAS research has produced techniques for distributed problem solving and reasoning [6].

However, many computation- and communication-intensive methods, such as negotiation, may not be suitable for distributed problem solving in sensor networks where computational and communication resources are limited. To accommodate the physical restrictions and provide some of the features needed by high-performance sensor networks, it is desirable to apply distributed problem-solving methods that require little computation and communication. Such methods must use information local to the computational nodes and their neighbors, rather than information related to global states of the overall system.

In our current research, we are building a distributed sensor network for mobile object detection and tracking. We have been focusing on distributed problem-solving methods that use local information. We have considered distributed breakout algorithm [3, 7] and distributed stochastic algorithm (DSA) [1] for solving a few combinatorial optimization problems in sensor networks [8, 9, 10].

Specifically, we proved that DBA is complete on acyclic constraint networks in that it is able to find an optimal solution in $O(n^2)$ steps on a network of $n$ nodes. This implies that DBA can be used for self-stabilization in acyclic networks, a desirable property for distributed problem solving. We also showed a simple ring structure on which DBA may fail to find a solution and proposed stochastic schemes to increase its completeness in cyclic networks [9]. In addition, we investigated the phase-transition or thrashing behavior of DSA on sensor networks [8, 10]. Our experimental evaluation revealed that DSA is usually more effective and efficient than DBA, in terms of solution quality and communication cost.

In summary, our current experience in developing distributed sensor networks leads to the conclusion that simple distributed algorithms that use limited, local information and communication, such as DSA and DBA, are capable and suitable for distributed anytime problem solving in distributed sensor networks.

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