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A dominance-based stepwise approach for sensor placement optimization

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ABSTRACT

A Wireless Sensor Network (WSN) usually consists of numerous wireless devices deployed in a region of interest, each of which is capable of collecting and processing environmental information and communicating with neighboring devices. The problem of sensor placement becomes non trivial when we consider environmental factors such as terrain elevations. In this paper, we differentiate a stepwise optimization approach from a generic optimization approach, and show that the former is better suited for sensor placement optimization. Following a stepwise optimization approach, we propose a Crowd-Out Dominance Search (CODS), which makes use of terrain information and intersensor relationship information to facilitate the optimization. Finally, we investigate the effect of terrain irregularity on optimization algorithm performances, and show that the proposed method demonstrates better resistance to terrain complexity than other optimization methods.

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1. Introduction

In recent years, territorial security has been studied intensively for various applications, such as environmental monitoring and surveillance, airports, public transit, emergency services, and nuclear facilities. In general, Wireless Sensor Networks (WSN) are used to monitor large geographical areas. A WSN usually consists of numerous wireless devices deployed in a region of interest, each of which is capable of collecting and processing environmental information and communicating with neighboring devices [4,17,29]. As such, it can be regarded as a multi-agent system [12,18,30] for territorial security, in which individual agents cooperate with each other to avoid duplication of effort and to exploit the capacities of other agents [1,30]. Sensor placement is an essential issue in WSN, as it affects how well a region is monitored by sensors, such as national defence [24], home security [31], industrial surveillance [9] and environmental monitoring, among others.

The main objective of sensor placement in a WSN is twofold: the region of interest covered should be as complete as possible, and the network should deploy as few sensors as possible, thereby minimizing its overall cost. Note that this is distinctly different from the objective of path planning problems [8], where sensors are installed on robotic platforms and the sensor path is of primary interest. In our case, the sensors are each placed in a fixed position. One of the most pressing concerns regarding a region of interest monitored by sensors is the region coverage [17,19,20,23,29,32]. In general, one of the basic requirements of a WSN is that every location in a region of interest lie within the sensing range of at least one sensor. An alternative approach is that a region of interest be covered by at least K sensors simultaneously [29,32].

Many methods have been proposed to address the problem of coverage and communication, and some optimal methods have been theoretically proved on the assumption that all the sensors are guaranteed to cover a circular area of equal radius [4,17,19,20,29]. However, this assumption implicitly assumes that the area of interest is flat, and so does not take into account obstacles and terrain effects. The assumption simply does not hold in the real world.

When we do consider terrain effects, the problem becomes rather complex, and there are currently no theoretically optimal methods that can deal with it. Since we have little knowledge of the problem behavior, we must rely on more generic, iterative optimization methods, such as the Gradient Descent and Evolutionary Algorithms, to optimize the sensor placement pattern. Given an initial placement pattern in a region, an iterative optimization algorithm should be able to find a locally optimal placement pattern after a limited number of iterations. These generic optimization methods generate some new placement patterns at each iteration and calculate the coverage of each pattern. Then, at the end of the iteration process, the best sensor placement pattern will be presented as the solution. These generic optimization methods do work to some extent; however, we believe that

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they may not be optimal, because the sensor placement problem is quite different from other optimization problems.

The difference lies in the knowledge we have about the problem. In some optimization problems, we have absolutely no a priori knowledge, and must rely on a heuristic search, such as Evolutionary Algorithms or Simulated Annealing. In contrast, we know about several specific properties of the sensor placement problem: (a) the coverage provided by some positions is better than the coverage provided by others; (b) assuming that the objective of a WSN is to maximize its coverage of a region, a sensor will contribute nothing to the network if it covers an area that is already covered by other sensors. So the question becomes, how can we leverage these two properties to achieve optimal sensor placement?

In our effort to leverage the properties of the sensor placement problem to achieve a more efficient optimization, we structure the problem differently in this paper. We assume that an optimization algorithm will work in an iterative way. Given an initial sensor placement pattern in a region, we differentiate two types of optimization approach: (a) a generic approach, like a Genetic Algorithm, which would, in general, change multiple sensor positions at each iteration without considering each individual sensor and (b) a stepwise approach, which would change only a single sensor position at each iteration. In the latter case, we must know which sensors to move, and where to move them, in an iteration.

We note that in the literature almost all the sensor placement optimization methods used are generic, and only a few of them are stepwise. We believe that a stepwise approach may be worth investigating, because it would allow us to use more specific information, such as redundant coverage and various sensor performances. In this paper, we are interested in investigating the following issues:

(1) Which approach is better for sensor placement optimization, a generic approach or a stepwise approach?
(2) If a stepwise approach is implemented, which sensors should we move in an iteration? What are the possible positions for the selected sensors in an iteration?
(3) What is the effect of terrain irregularities on the performance of search algorithms?

To answer these questions, we propose a Crowd-Out Dominance Search (CODS), which follows a stepwise approach, and so makes use of terrain information and individual sensor information. The proposed optimization methodology is based on the concept of a static dominance and a dynamic dominance that we have designed to tackle the irregular terrain problem in sensor placement. Moreover, our method indicates clearly which sensor to move at each iteration, as well as the possible positions to which this sensor may be moved. In order to validate our proposed method, as well as to evaluate the performance of the generic approach relative to that of the stepwise approach, we compare our results with those of a number of heuristic methods, including Random Search, a Genetic Algorithm, and Simulated Annealing.

The paper is organized as follows. In the next section, we introduce some related works in sensor placement optimization. In Section 3, we formulate the problem statement. The methodology is proposed in Section 4. Experimental protocols and results are presented in Section 5, followed by a discussion, our conclusions, and suggestions for future work.

2. Related works

The sensor placement problem has been researched extensively in simplified settings in the literature. Usually, terrain effects and obstacles are ignored in these studies. Some deterministic methods have been proposed to address the problem of coverage, and it has been shown that covering a region with disks of equal radius can be achieved in an optimal way [4,10,15,17,19,22]. Similar as simplification of the environment makes it possible to be design and validate an optimal method, the majority of these proposed optimization methods are deterministic, as shown in Fig. 1.

Other, more realistic scenarios have been created, such as the Art Gallery problem [11,21,26], where there are fixed obstacles. In this case, the purpose of sensor placement is to achieve maximum coverage with a minimum number of sensors taking these obstacles into account, as shown in Fig. 2. The Art Gallery problem portrays a more realistic setting than a simple plane. Sensors in such a setting should be deployed in such a way as to minimize the disadvantage of the presence of obstacles. Note that the Art Gallery is a 2D environment, where a position is considered either completely flat or an obstacle, and this makes it a binary environment. Moreover, an obstacle in the Art Gallery problem is an obstacle from the perspective of all the sensors, no matter what their position, and,

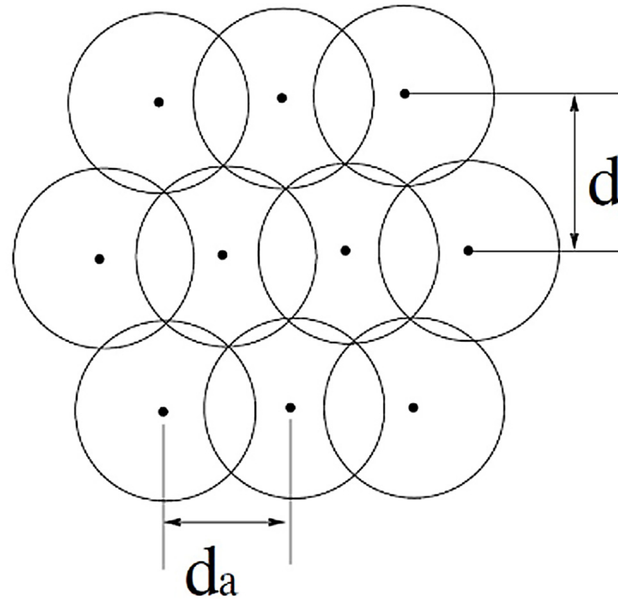

Fig. 1. Pattern of the deterministic method [4,17] implemented in the paper, where $d_a = \sqrt{3}r_s$, $d_b = \frac{3}{2}r_s$, and r_s is the sensing range of a sensor. The pattern is optimal for a zero-obstacle environment. Circles represent sensor sensing ranges, and dots represent sensor positions.

conversely, a change in the position of a sensor will not affect the status of an obstacle. This is not the case in a 3D problem, where the environment is no longer binary. Furthermore, the number of obstacles seen by a network depends on the positions of the sensors. A sensor placed in a valley may perceive the presence of a different number of obstacles than a sensor placed on a summit, for example. Terrain information can therefore greatly increase the complexity of the problem [29].

The direct consequence of oversimplification in a sensor placement environment is that the theoretically perfect coverage shown by these deterministic methods may not hold true in practice. Most sensor placement optimization methods assume that the sensors are placed on a 2D plane, and topographical details about the terrain, such as hills, valleys, vegetation, and buildings, are not considered [4,10,15,17,19,22]. However, the region of interest that requires sensor activity is rarely completely flat, as both natural and urban environments usually contain some obstacles. The conventional deterministic approaches do not consider environmental factors such as terrain topology, and may lead to the production of incorrect optimization results. While a WSN created using a deterministic method may seem to achieve full coverage on a target

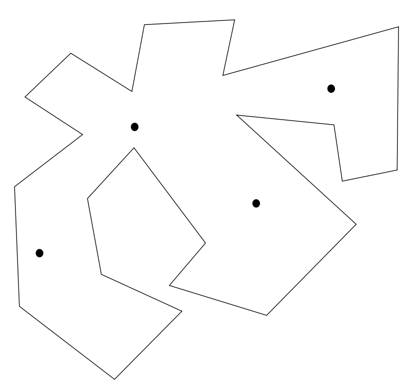

Fig. 2. An example of the Art Gallery problem: the polygon is an area bounded by obstacles, and the dots are sensor positions. Unlike Fig. 1, this 2D environment contains obstacles and they remain where they are, regardless of the sensor positions.

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