Location Dependent Heuristics for Sensor Coverage Planning

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ABSTRACT

The ability of a sensor device is affected significantly by the surroundings and environment in which it is placed. In almost all sensor modalities, some directions are better observed by a sensor than others. Furthermore, the exact impact on the sensing ability of the device is dependent on the position assigned to the sensor. While the problem of determining good coverage schemes for sensors of a field have many good solutions, not many approaches are known to address the challenges arising due to location specific distortion. In this paper, we look at the problem of incorporating terrain specific challenges in sensor coverage, and propose a geometric solution to address them.

Keywords: Sensor Networks, Message Queues, Policy based Security Management, AutoConfiguration

1. INTRODUCTION

Sensor networks are used widely within the military and civilian domains for a variety of monitoring and surveillance purposes. In all of these deployments, algorithms and schemes that can analyze the properties and nature of the coverage provided by a set of sensors over a target area are of key importance. Such algorithms provide a key input to the problem of planning the sensor coverage for an area which is to be subject to surveillance. Mobile sensors also have attracted a lot of attention. See, for example, “Worst and Best-Case Coverage in Sensor Networks”\textsuperscript{1}.

The sensor coverage planning problem can be characterized as follows:

Given a target area to be monitored and a set of sensors with various capabilities, determine the best locations for each sensor so that the area can be monitored completely and effectively.

The problem has been studied in different formulations in a variety of ways. From a theoretical computer science perspective, the Art Gallery Problem addresses the issue of determining the number of observers necessary to cover an art gallery room such that every point is seen by at least one observer. It has found several applications in many domains such as for optimal antenna placement problems in wireless communication. It can be solved optimally in 2D and is known to be NP-hard in the 3D case\textsuperscript{2}. Marengoni et al.\textsuperscript{3} propose heuristics for solving the 3D case using Delaunay triangulations. The treatment of coverage problem in the field varies from theoretical analysis\textsuperscript{4} to pragmatic usage models\textsuperscript{5} and several variations of coverage problem examining aspects such as connectivity maintenance, mobility management, and query optimizations can be found in various papers\textsuperscript{6789}.

In general, most of the treatment of the sensor coverage problem has looked upon sensors as a static entity whose properties and sensing abilities are independent of their location. In practice, most sensors perform differently when located in different environments. The work by Dhillon and Chakrabarty\textsuperscript{10} attempted to model some of the location dependence by approximating the sensor field to a Manhattan grid, but a general approach to formulate the dependency of sensors on the terrain location and incorporating that aspect into solving the coverage problem has received relatively little attention. Dhillon and Chakrabarty approximated the sensor field by a grid and used an asymmetric probability matrix to model the terrain, and proposed two heuristics to address the problem – both using a greedy approach, with one maximizing average coverage with each sensor and the other placing sensors at the point on the grid with least amount of coverage.
While the grid approximation has the benefit of simplicity, modeling a system by means of a grid ignores the fact that some locations in a terrain need more sensing than others, e.g. a road through a forest may require more monitoring than places off the road in a military context. Similarly, a grid approximation requires that the grid be chosen at the right level of granularity – fine enough to model the smallest possible interference, e.g. due to an intervening electric pole, which may result in too many numbers of grid points with an increased computation cost, or a loss in the accuracy of the terrain model.

Another aspect of a practical sensor network placement in any domain is that all regions in an area being observed are not of equal interest. In a military or homeland security domain, one may want to observe some regions, e.g. a highway, an intersection or an entrance more closely than other regions. If an military camp is flanked by a flat region when intruders can be easily observed manually, there may be less value in placing a video sensor observing that region than for a region where trees or dense foliage make human observation more erratic. Not all regions need equal coverage during any deployment of a sensor mission, and we want to incorporate this feature of sensor network planning in our coverage algorithms.

Brown et. al. propose a geometric model for solving the coverage problem, in which sensors coverage is modeled as geometric tiles and the sensor field coverage problem is mapped to the tiling problem. They show that using the wiggle space available in regular tiling allows for a variety of coverage solution. In this paper, we extend the approach to take care of the heterogeneous terrain model. Geometric approaches to solving the coverage model can provide better granularity for sensor coverage without requiring an associated increase in computational complexity.

The rest of this paper is structured as follows. In Sec. 2, we describe our approach to modeling the terrain using a geometric method. In Sec. 3, we discuss a number of heuristics that can be used to solve the coverage problem in a heterogeneous terrain, and then evaluate their performance by means of simulation experiments in Sec. 4.

2. MODELING HETEROGENEOUS TERRAIN

If a terrain being observed were completely homogenous, then the coverage range of each sensor can be modeled as a perfect circle whose radius is determined by the coverage range of the sensor in that modality. However, when the terrain is not homogenous, a sensor located at a specific location may only be able to monitor an area that may be different in different directions. We model the affect of the terrain on a sensor’s coverage by distorting the amount of coverage that it may be able to provide along different directions. Figure 1 shows some of the possible distortions that may happen to a sensor when it encounters the differences in the properties of a different terrain. Because of the difference in the characteristics of the terrain, the coverage area becomes a different shape.

![Figure 1. Possible coverage due to terrain](image)

The shape that results from placing the sensor at any point can be viewed as shrinkage of the original area. The shrinking along the difference dimensions of a sensor coverage is going to be different depending on the properties of the terrain in different dimensions.

Thus, the sensor coverage problem can be defined as the problem of finding the least number of sensors that can be used to cover an area when there are different distortions in the coverage area of a sensor depending on the location of the sensor. Let us assume that we have a set of homogenous sensors such that each sensor can sense a circular area of unit distance on a flat terrain (this assumption does not cause any loss of generality). We can now formally define the problem using the following terms:
Let $F$ be the field that needs to be examined by means of a sensor deployment. Let $S$ be the set of all closed regular geometric shapes such that the shape is fully contained geometrically within a circular area of unit radius.

For each point $p \in F$, let us define a distortion function $f : F \rightarrow S$ which maps a circular area of unit distance into a geometric shape in $S$ such that $f(p)$ represents the coverage area of a sensor placed at point $p$ in $F$.

The sensor coverage problem can now be expressed as:

Given an infinite number of sensors where the original coverage area is a circular zone of unit radius, and a field $F$ characterized by the distortion function $f$, what is the minimum number of sensors required to obtain a coverage of the entire field $F$?

In this paper, we look at the algorithms which will provide us answers to both of these variations of the sensor coverage problem.

### 3. SOLUTION HEURISTICS

Because $f(p)$ is able to express a great deal of variability in a terrain, we used a simple model to examine the assumption that terrain does affect coverage. We therefore assumed that for any $p$, $f(p)$ affects the size of the sensor coverage and not the shape. Our model assumes homogeneous sensors whose sensing area is a disk, with $p$ determining the radius of the sensing range. We further assume that sensors can be positioned on discrete set of points that are arranged as a triangular grid; however, the sensing is continuous. Since it is well known that, for a large flat area with sensors having the same equal range, a triangular arrangement of sensors is optimal in the sense of least overlap, we used this sensor arrangement in our simulation experiments. Finally, the objective goal is to minimize the area that is not covered by any of the sensors.

### 4. PERFORMANCE OF HEURISTICS

In the experiments, terrain effects are modeled by modifying the size of the sensors radius of coverage based on the characteristics of the terrain the sensor is situated on. The experiments used a 400 x 400 unit grid of terrain values (3rd dimension) to model the terrain. Figures 2(a) and 2(b) show examples of the two types of terrain, each using large areas of the same terrain using gray-scale shading. Figure 2(a) shows gray-valued squares of 100 units each; Figure 2(b) shows an example of a contoured terrain. The lightest (white) areas represent areas in which the sensors would have their largest range (i.e., sensor radius); sensors are considered to have the smallest range in the darkest (black) areas, and in between these one gray-scale is used. The experiments used three, five and seven values of sensor ranges.

Figures 3(a) and 3(b) shows the result of one of our first series of experiments in which the benefit of additional coverage if simple terrain information is used to lengthen the distance between sensors that are larger vs. none was compared. In the experiments labeled "uniform lattice placement," sensors were placed on our standard grid without regard to their placement radius. Approximately 290 sensors were randomly placed with sizes of 24, 18 and 12 units. In comparison, Figure 3(b), called “weighted lattice,” shows the sensor coverage when terrain which determines the sensors range is used to modify the distance between sensors using the following naive algorithm: the horizontal distance between grid points is directly related to the sensors range of the sensor that falls on that grid point. The weighted lattice algorithm is simple, but effective, since it takes into account the need for fewer sensors when the terrain allows it. By lengthening the grid distance across a row for the white and gray areas only the coverage is improved. Notice that the uncovered areas only occur in the areas covered by the smallest radii sensors in both pictures. (The uncovered region is Figure 3(a) is 5.7% and that of Figure 3(b) is 1.7%.) Even though this is true, using the more intelligent weighted sensor location algorithm does significantly reduce the uncovered areas.

Figures 4(a), 4(b), and 4(c) compare one of the results of 50 simulations under the uniform lattice placement and the weighted placement algorithms on tiled terrain with square tile size 50. The optimal label stands for using approximately 290 sensors, which by experiment, was found could cover the entire terrain. The experiments
Figure 2. Sample terrain

(a) Tiled  
(b) Contoured

Figure 3. Sensor placement

(a) Uniform lattice  
(b) Weighted lattice
were done with 3, 5 and 7 sensor coverage sizes. These three graphs show that the weighted lattice placement outperforms the uniform lattice throughout the range of values, even when there are 250 sensors placed. The largest difference occurs when there are about 8% less than the optimal number of sensors placed on the grid. Figures 5(a), 5(b), and 5(c) repeat these experiments with a larger square tile size (100) and, as shown, the same conclusions result. Figures 6(a), 6(b), and 6(c) repeat these experiments using 50 randomly created contour maps similar to the one in Figure 2(b). As shown, except when there are 3 sensor sizes and about 17% less sensors than optimal, adjusting sensor distance based on terrain improves coverage.

Figure 4. Lattice placement coverage for tiled (size 50) terrain

![Graphs showing lattice placement coverage for tiled (size 50) terrain](image)

Figure 5. Lattice placement coverage for tiled (size 100) terrain

![Graphs showing lattice placement coverage for tiled (size 100) terrain](image)

What happens if a sensors were able to move to a better grid location (one where its range is larger), or, equivalently, could be placed there rather than on the one it is originally assigned to? This is the premise for the next series of simulations. In these, a sensor moves as little as possible, up to a fixed distance (a parameter) in any direction looking for a grid point that would improve its coverage. It will not move if there is no improvement. To minimize the amount of communication that would have had to take place, we had each move independently of other sensors, even though this could create conflicts in their final position. Figures 7(a)–7(d) shows these results. The figures show the amount of remaining uncovered area (measured in grid points not covered) for different size square tiles. There are at least two interesting results. Interestingly, but not surprising upon reflection, the exposure decreases to zero quickly if the square tiles are of unit length. Moreover, with larger square tiles, when a sensor is able to look and move further, it ends up on a conflicting grid point reducing the coverage.
Figure 6. Lattice placement coverage for contoured terrain

Figure 7. Exposure for tiled terrain with movement allowed
5. SUMMARY

Little research has been done incorporating a third dimension, the terrain, into sensor coverage, yet the unevenness, slope, small objects, etc. of a terrain will affect the distance a sensor can cover as well as its communication ability. In this paper, we have reported on some simulation experiments on a few simple artificial terrains to provide some understanding of the consequences of incorporating terrain information into sensor coverage. They all show that, taken into consideration, terrain can improve coverage. We intend to generalize the coverage model to make the results more realistic. In the future, we will use actual terrain information. One way is to copy already mapped terrains. Another is to measure surface attributes by using computer vision techniques. This can be achieved by convolving standard templates with surface data (viz: an image) to guide the sensor placement process. Clearly, first-order difference operators can be used to derive estimates of surface gradient. Equally, we could use second order operators (such as Laplacian or Gaussian) to derive additional information concerning the rate of change of the surface gradient. At a higher level we could use image-processing curvature operators to gain higher order surface topologies.

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