Self-deployment of Mobile Nodes in Hybrid Sensor Networks by AHP

Xiaoling Wu[1], Jinsung Cho[1], Brian J. d'Auriol[1], Sungyoung Lee[1,*], and Hee Yong Youn[2]

[1] Department of Computer Engineering, Kyung Hee University, Korea
{xiaoling,dauriol,sylee}@oslab.khu.ac.kr, chojs@khu.ac.kr
[2] School of Information and Communication Engineering, Sungkyunkwan University, Korea
youn@ece.skku.ac.kr

Abstract. The proper deployment of sensors is very important for the successful completion of the sensing tasks due to the inevitable relation with the physical world. This paper presents a novel method for the redeployment of mobile nodes in a hybrid sensor network consisting of a collection of both static nodes and mobile nodes. In such a sensor network, the locomotion ability of mobile nodes helps the autonomous deployment to enhance the network coverage. An optimal decision of a sensor node moving direction is made based on Analytical Hierarchy Process (AHP). Four factors contributing to the optimal deployment are considered and they are coverage hole, obstacle avoidance, hot spot, and the boundary effect, respectively. The moving style is flip by flip until the stable status is achieved. Simulation results show that our approach can provide high coverage with limited movement distance as well as ensuring connectivity.

1 Introduction

Wireless sensor networks are expected to be widely employed in various applications such as medical care, military, environmental monitoring and industry since they have high flexibility, low production costs, and scalability [1]. Due to the inevitable relation with the physical world, the proper deployment of sensors is very important for the successful completion of the sensing tasks.

Sensor deployment has received considerable attention recently. Some of the work [2], [3], [4] assume that the environment is under control. However, when the environment is inhospitable such as remote inaccessible areas, disaster fields and toxic urban regions, sensor deployment cannot be performed manually. To scatter sensors by aircraft is one possible solution. However, using this scheme, the actual landing position cannot be controlled due to the existence of wind and obstacles such as trees and buildings. Consequently, the coverage may not be able to satisfy the application requirements. Some researchers suggest simply deploying large amount of static

* Corresponding author.

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sensors to increase coverage; however it often ends up harming the performance of the network [5]. In such cases, it is necessary to take advantage of mobile sensor nodes, which can move to the appropriate places to provide the required coverage.

To address this issue, a class of work has recently appeared where sensor nodes with full mobility are utilized to achieve desired deployment [6~11]. Typically in such works, all sensor nodes are fully mobile and they are relocated to maximize the coverage of a given target area with constraints on deployment time, the distance the sensors have to travel and the complexity of the protocol. The sensor network deployment scenario when only some of the sensors are mobile while others are static, that is, hybrid sensor networks [12], has also been under active research, especially in the field of robotics for exploration purposes. The movement capable sensors can help in network maintenance and repair by moving to appropriate locations within the topology to achieve desired level of coverage and connectivity, and to connect a possibly disconnected network.

In [13], Batalin et al. suggest a combined solution for the exploration and coverage of a given target area. The coverage problem is solved with the help of a constantly moving robot in a given target area. The mobile robot first performs the network deployment in the target area as it explores the unknown environment. The deployed static nodes then guide the robot to poorly covered areas. However, the algorithm does not consider the communications between the deployed nodes. All decisions are made by the robot by directly communicating with a neighbor sensor node. In fact, the deployment strategy and network repair policy can also benefit from the multi hop information derived out of a communicating sensor network.

Wang et al. [14] address the single coverage problem by moving the available mobile sensors in a hybrid network to heal coverage holes. The static sensors detect their local coverage holes by using Voronoi diagrams as in [7]. The mobile sensors also calculate coverage holes formed locally if they decide to leave their current position. The static sensors bid for the mobile sensors based on the size of their detected coverage hole. A mobile sensor compares the bids and decides to move if the highest bid received has a coverage hole size greater than the new hole generated in its original location due to its movement. However, the local broadcast may prevent the bid messages reaching mobile sensors if they are located farther than two hops. Moreover, the environment influences are not included in the design.

In [15], a hybrid sensor network is considered and a Voronoi diagram based approach is provided to estimate the amount of coverage holes in a sensing field. They also propose a collaborative algorithm (Coven) to estimate the number of additional mobile nodes to be deployed and relocated to fix the coverage holes. However, their collaborative algorithm doesn't consider any environmental factors such as obstacle and hot spot.

Luo, R.C. et al. [16] propose a mechanism which divides the map into many grids, and sets up weighting fields generated by various environmental effects such that the deployed goal can be determined. Without changing the previous distribution of static nodes, the coverage and uniformity are improved by incrementally placing additional mobile nodes one by one into the monitored environment. Although this "grid method" has inexpensive computation, it provides only approximate result rather than an optimal one.

In this paper, we also solve the coverage problems in hybrid sensor networks by our proposed analytic hierarchy process (AHP) based algorithm. It is different from the previous methods since it not only incorporates various environmental factors such as hot spot and obstacles in the design but also provides the optimal decision for mobile nodes movement. After a random deployment of static sensors, a certain amount of mobile nodes are deployed randomly into the monitored environment without changing the existing deployment of static sensor nodes. In order to increase the network coverage and uniformity, the mobile nodes are relocated according to our proposed scheme. The decision of moving direction of each mobile node is made according to AHP method, in which a set of criteria is evaluated and the optimal alternative is selected.

The rest of the paper is organized as follows. We define the basic assumptions and state the problems in section 2. The third section presents our deployment method. Section 4 evaluates and analyzes the performance of the proposed method. Finally, we draw the conclusion and discuss future work in section 5.

2 Problem Statements

Assume that there have been some static nodes deployed in the monitored region. Then, some mobile nodes are randomly deployed into this system. The problem is how these mobile sensor nodes should be relocated for coverage enhancement under the constraint of environment factors. Fig. 1 is the illustration of our design scenario.

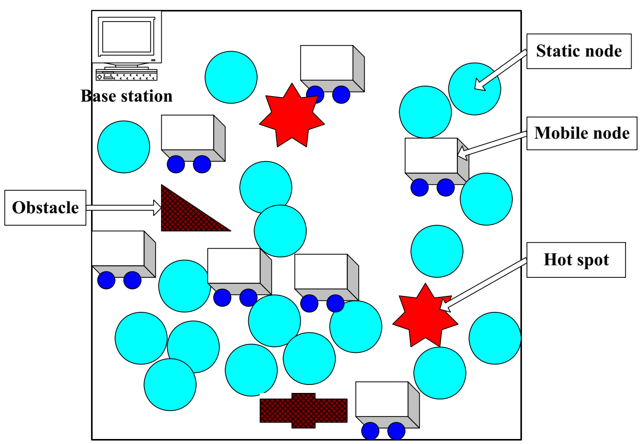

Fig. 1. Illustration of the design scenario

Some basic assumptions are made in our design. First, the networking system is a hybrid sensor network containing both mobile and static nodes. The static nodes must be pre-placed into the environment and the base station records all these locations. All nodes are equipped with the same sensing and communication devices. Second, the map should be well-known in detail including the distribution of obstacles. For example, to monitor a hazardous area suffered from terrible attacking, we need be familiar with the environment pattern and the distribution of static nodes. Third, the mobile nodes have only flip-based mobility as introduced in [17]. This type of model is adopted in most cases and normally trades-off mobility with energy consumption. The object of our proposed relocation scheme is to reduce the coverage holes and improve the network topology in specific environment after redeploying the additional mobile nodes.

To enable desired coverage while satisfying the environment requirements, we move the mobile nodes to proper locations according to their specific situation. In real environment, fours factors influence coverage directly, that is, the location and size of coverage hole in the network, the existence of hot spot and obstacle in the environment, and the boundary effect:

- Coverage hole: Areas not covered by any node. The direction to the nearest and largest coverage hole is preferred to be selected.
- Hot spot: The region in which events happen most frequently. The mobile node should ensure at least single coverage in hot spot. Thus the moving direction towards hot spot is also preferred.
- Obstacle: The mobile nodes need to avoid obstacles on their moving direction.
- Non-boundary: The mobile node is not preferred to move to the boundary since it will cause certain amount of sensing coverage loss.

The optimized next step moving direction determination is a multiple factors optimization problem and can be achieved using the AHP approach which is introduced in the next section.

3 Moving Direction Determination by AHP

The Analytical hierarchy process (AHP) is a multiple criteria decision-making method which decomposes a complex problem into a hierarchy of simple subproblems (or factors), synthesizes their importance to the problem, and finds the best solution. In this paper, AHP is used to determine the moving direction of a mobile node and is carried out in three steps:

Step 1: Collect information and formulate the moving direction selection problem as a decision hierarchy of independent factors.

Step 2: Calculate the relative local weights of decision factors or alternatives of each level.

Step 3: Synthesize the above results to achieve the overall weight of each alternative direction and choose the one with the largest weight as the desired direction.

A. Structuring Hierarchy

The goal of the decision "choosing an appropriate moving direction" is at the top level of the hierarchy as shown in Fig. 2. The next level consists of the decision factors which are called criteria for this goal. At the bottom level there are 8 alternative directions to be evaluated.

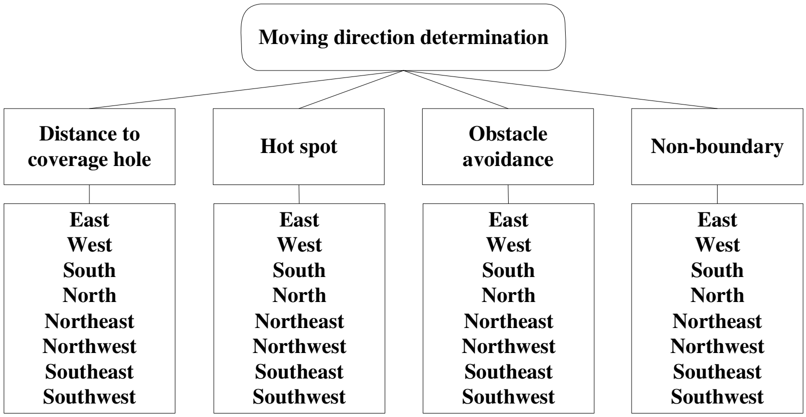

Fig. 2. AHP hierarchy for moving direction selection

B. Calculating Local Weights

Local weights consist of two parts: the weight of each decision factor to the goal and the weight of each nominee to each factor. Both of them are calculated with the same procedure. Taking the former as an example, we describe the procedure as the following three steps.

1) Making Pairwise Comparison

The evaluation matrices are built up through pairwise comparing each decision factor under the topmost goal. The comparison results are implemented by asking the questions: “Which is more important? How much?” and they may be presented in square matrix A as

$$A = \left(a_{ij}\right)_{n\times n} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}, \tag{1}$$

where a_{ij} denotes the ratio of the i^{th} factor weight to the j^{th} factor weight, and n is the number of factors. The fundamental 1 to 9 scale can be used to rank the judgments as shown in Table 1.

Table 1. A fundamental 1 to 9 scale

Number Rating	Verbal Judgment of Preferences
1	Equally
3	Moderately
5	Strongly
7	Very
9	Extremely

2, 4, 6, 8 indicate the medium value of above pairwise comparison.

2) Calculating Weight Vector

For the given matrix A in Eq. (1), we calculate its eigenvalue equation written as AW = λ_{max}W, where W is non-zero vector called eigenvector, and λ_{max} is a scalar called eigenvalue. After standardizing the eigenvector W, we regard the vector element of W as the local weight of each decision factor approximately, which can be denoted as:

$$\mathbf{w}_j^T = \{w_1, w_2, \cdots, w_n\} \tag{2}$$

3) Checking for Consistency

If every element in Eq. (1) satisfies the equations $a_{ij} = 1/a_{ji}$ and $a_{ik} \cdot a_{kj} = a_{ij}$, the matrix A is a consistency matrix. Unfortunately, the evaluation matrices are often not perfectly consistent due to people's random judgments. These judgment errors can be detected by a consistency radio (CR), which is defined as the radio of consistency index (CI) to random index (RI). CI can be achieved by

$$CI = (\lambda_{max} - n)/(n-1)\ , \tag{3}$$

where

$$\lambda_{max} = (1/n)\sum_{i=1}^{n}(AW)_i / W_i \tag{4}$$

The *RI* is given in Table 2 [18]. When $CR \le 0.1$, the judgment errors are tolerable and the weight coefficients of the global weight matrix W_j are the weights of decision factor under the topmost goal. Otherwise, the pairwise comparisons should be adjusted until matrix A satisfies the consistency check.

Table 2. Random index

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

C. Calculating Global Weights

From above steps, we can obtain not merely the weights of decision factors towards the topmost goal from W_j but also the weights of alternative directions towards each factor. It is assumed that there are eight directions. All the eight weight matrixes of alternatives under four factors construct a 8×4 matrix, denoted as $W_{n_i/j}$, i=1, 2, … 8, j=1, 2, 3, 4.

The global weight of each senor node can be achieved through multiplying the local weight by its corresponding parent. So the final weight matrix in the symbol of W_{n_i} is calculated as

$$W_{n_i} = W_{n_i/j} \cdot W_j\ , \tag{5}$$

where the final weight of each alternative is calculated as

$$W_{n_i} = \sum_{j=1}^{4} W_{n_i/j} \cdot W_j \tag{6}$$

The larger the final weight of the direction, the more important it towards enhancing the network topology quality. Thus, the direction with the largest weight is selected as next step moving direction of the mobile node.

4 Performance Evaluations

4.1 Simulation Environment

In order to evaluate the relocation scheme by AHP, we compare it with random deployment case. In our simulation, the 50m by 50m square monitored area is divided into 100 uniform square grids. Each grid has the same length of 5m, and all nodes equip with identical sensors with sensing radius equal to 5m. The communication range is set as 10m to ensure the network connectivity. The moving style of a mobile node is flip by flip until the stable status is achieved. One flip distance is assumed to be 2m.

In AHP modeling, the matrix A is determined as follows according to Section 3:

$$A = \begin{array}{r c} & \begin{array}{cccc} \text{Coverage hole} & \text{Hot spot} & \text{Obstacle} & \text{Non-boundary} \end{array} \\ \begin{array}{r} \text{Coverage hole} \\ \text{Hot spot} \\ \text{Obstacle} \\ \text{Non-boundary} \end{array} & \begin{bmatrix} 1 & 3/1 & 2/1 & 5/1 \\ 1/3 & 1 & 1/2 & 3/1 \\ 1/2 & 2/1 & 1 & 4/1 \\ 1/5 & 1/3 & 1/4 & 1 \end{bmatrix} \end{array}$$

The computed eigenvector W = [0.4729 0.1699 0.2844 0.0729]. It indicates the local weight of coverage hole, hot spot, obstacle and non-boundary, respectively, so that we can see clearly that coverage hole is the most important criterion, and non-boundary is the least. According to Eq. (4), we can get the eigenvalue $\lambda_{max} = 4.0505$. Consequently, consistency radio can be calculated as $CR= 0.02 < 0.1$, thus matrix A satisfies the consistency check.

Each mobile sensor node determines the weight matrixes of alternatives under four factors[1] and then gets global weight based on its specific location and environment characteristics. Its moving direction can be finally selected by the AHP model.

4.2 Simulation Results

In contrast to random deployment which achieves desired coverage with 70 static sensors deployed, the proposed AHP based scheme can achieve the same amount of coverage (k coverage can be guaranteed in hot spot with $k \geqslant 1$) using only a combination of approximate 20 static and 20 mobile sensors.

In Fig. 3, the static node locations and coverage of the initial random deployment before running the algorithms are shown. Tiny points with red numerical label beside represent the positions of 20 static nodes. The 2 red small disks denote the hot spots,

[1] Coverage holes positions and area can be calculated by using Voronoi diagrams as in [7].

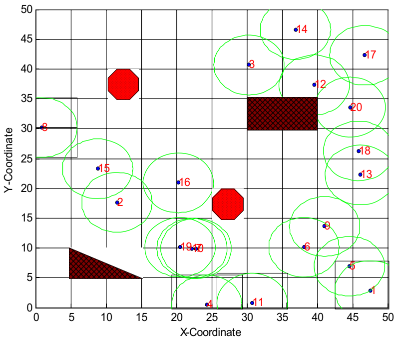

Fig. 3. Initial static sensor nodes placement

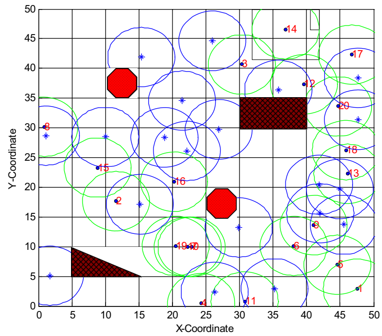

Fig. 4. Random mobile nodes deployment

the rectangle and triangle denote the obstacles in the environment. It's obvious that many uncovered areas exist and the hot spots are not well covered. Fig. 4 shows the random 20 mobile nodes deployment without change of original static sensors placement. The tiny stars denote the mobile node positions, and the green and blue circles represent the sensing range of the static sensor and mobile sensor respectively. The final mobile node positions with desired coverage after executing AHP based algorithm are shown in Fig. 5.

Fig. 6 provides the coverage ratio comparison between proposed AHP based redeployment and random deployment. The proposed scheme is only compared with the random deployment case because of our different assumptions from other existing mobile node relocation schemes. In AHP based redeployment, the coverage is achieved by deploying a hybrid sensor network in which mobile nodes occupy a half and the environment has a 3% obstacle area. The coverage here is defined as the ratio of the union of all sensor nodes' sensing areas to the whole monitored environment excluding obstacles. For the detailed explanation of coverage ratio calculation method, please refer to [10]. Note that, as the number of mobile nodes increases (the total number of nodes also increase), the coverage increases sharply because the sensing field becomes more flexible by movement of sensors.

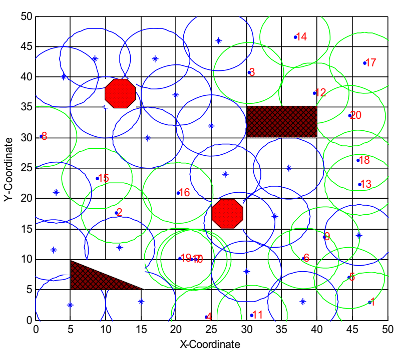

Fig. 5. Mobile nodes relocated

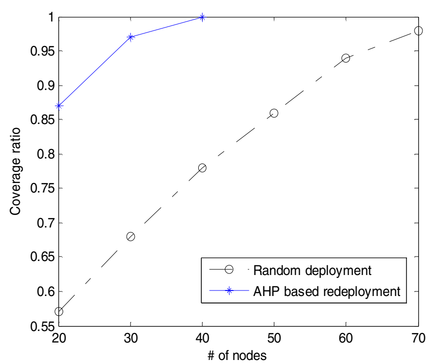

Fig. 6. Coverage vs. total number of nodes

5 Conclusion and Future Work

In this paper, a novel method for the redeployment of mobile nodes in a hybrid sensor network which consists of a collection of both static nodes and mobile nodes were proposed. An optimal decision of the mobile sensor node moving direction is made based on Analytical Hierarchy Process (AHP). Four factors contributing to the optimal deployment are considered which are coverage hole, obstacle avoidance, hot spot, and the boundary effect, respectively. The moving style is flip by flip until the stable status is achieved. Simulation results showed that our approach could provide high coverage with limited movement distance without compromising connectivity.

In the future work, we may consider mobile energy consumption and communication overhead between the sensor nodes and test more realistic sensing and communication range.

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