Centroid-based Movement Assisted Sensor Deployment Schemes in Wireless Sensor Networks

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Abstract—Efficient deployment of sensors is an important issue in wireless sensor networks. If we deploy sensors randomly by our hands or carriers only, some unlucky places are not covered forever. In this paper, we propose distributed self-deployment schemes of mobile sensors. At first, sensors are deployed randomly. They then calculate the next positions locally by utilizing the proposed schemes and move to them. The locations of the sensors are adjusted round by round so that the coverage is gradually improved. By using Voronoi diagram and centroid (geometric center), we design two schemes, named Centroid (centroid-based scheme) and Dual-Centroid (dual-centroid based scheme). We also measure the performance of the proposed schemes and the existing schemes, and show that the proposed schemes get better results.

Index Terms—mobile sensor networks, sensor deployment, Voronoi diagram, centroid.

I. INTRODUCTION

Wireless sensor networks are utilized in many applications, including environment monitoring and controlling. A sensor network consists of a set of distributed sensors to collect data, such as temperature, humidity, pollution level, and so on. For the efficiency of the sensor network, the proper deployment of sensors to maximize the sensor coverage is a very important issue [1]. Since the environment of sensor networks is often unknown or hostile, however, sensor deployment cannot be done by hand. Moreover, in cases of in-building toxic-leaks detection, manual sensor deployments inside a building are not possible. Therefore, it is necessary to make use of mobile sensors which can autonomously move to the correct places to provide the required coverage. In this paper, we consider the following self-deployment problem: given the target sensing field with an arbitrary initial sensor distribution, how to self-deploy the sensors and maximize the sensor coverage.

There have been growing study results about autonomous mobile sensor deployment [2], [3], [4], [5], [6]. Howard et al. [2] and Poduri et al. [3] utilize the Potential field-based techniques which are commonly used in mobile robotics. They are applied to tasks such as local navigation and obstacle avoidance. It imitates the behavior of electro-magnetic particles: when two sensors are too close to each other, a repulsive force pushes them apart. This approach allows the sensors in the networks to move from high density area to low density area.

Wu et al. [4] uses a grid-based structure and tries to balance the workload of sensors by moving sensors to each less covered grid cell through two rounds of scan algorithm. In [5], Tan et al. propose floor-based scheme to self-deploy mobile sensors. The key idea is to divide the target field into floors of common height, and make sensors try to stay in the floor line so that the overlap of the sensing disks is reduced.

In [6], Wang et al. present a set of Voronoi diagram-based schemes to maximize sensing coverage. After discovering a coverage hole locally, the schemes calculate the target position of the sensors where they should move at next round. They use the Voronoi diagram to discover the coverage holes and design three movement-assisted sensor deployment schemes: VEC (VECtor-based), VOR (VORonoi-based), and Minimax. In this paper, we conceive alternate schemes to get better performance than these three schemes.

We only consider VOR and Minimax schemes as the targets of comparison, because they utilize the Voronoi diagram actively and yield better performance than VEC. Fig. 1. (a) shows how VOR works. In the VOR scheme, a sensor moves toward its farthest Voronoi vertex A for the purpose of fixing the largest hole. Then it stops at the point B where the distance between A and B is the sensing range. In the Minimax scheme, on the other hand, a sensor moves toward the point (the circumcenter of the sensor’s local Voronoi polygon) whose distance to the farthest Voronoi vertex is minimized. Fig. 1. (b) shows how Minimax works. It can reduce the variance...
of the distances to the Voronoi vertices, resulting in better utilizing sensor’s sensing circle. Although the two schemes make sensors move and cover the whole target area within a short deploying time and limited movement, but there are still distinct coverage holes after many rounds of movements.

We design and evaluate two new schemes based on the centroid (the geometric center) of Voronoi polygon. The first solution is called the Centroid scheme which moves sensors to their local center point of the local Voronoi polygon. The second solution called Dual-Centroid scheme makes sensors move to the center point of the line formed between the centroid of the local Voronoi polygon and the centroid of the polygon formed by Voronoi neighbor nodes. By simulation, we show that the proposed schemes make the coverage holes covered faster than both VOR and Minimax.

The remainder of this paper is organized as follows. Section II makes the assumptions and defines the problem we are going to solve. Section III introduces the preliminaries about Voronoi diagram and centroid. Section IV will describe the proposed autonomous self-deployment schemes of mobile sensors. Both simulation results and concluding remarks are given in Section V and Section VI, respectively.

II. PROBLEM FORMULATION

Problem: Given N mobile sensors with sensing range Rs and radio communication range R_c and given the target sensing field with an arbitrary initial sensor distribution, how to maximize the sensor coverage with less time.

We make the following assumptions:
1) All sensors have the same communication range R_c and sensing range Rs; sensors within R_c of a sensor are called the sensor’s neighbor nodes.
2) The sensors are capable of omni-directional motion and move in rounds of variable distance.
3) For coverage and connectivity model, we use the binary model where the quality of sensing (communication) is constant within R_s (R_c) and is zero outside the sensing (communication) range.
4) Each sensor knows their location information by an arbitrary method and determines neighbor nodes’ location by communication.
5) The sensing field is on a two-dimensional plane with no obstacle. The boundary of field, however, is regarded as a wall-like obstacle.

III. PRELIMINARIES

A. Voronoi Diagram

The Voronoi diagram is a fundamental tool for resolving the coverage problems of wireless sensor networks [6], [7]. The Voronoi diagram of a collection of sensors partitions the given place into several polygons. Fig. 2 shows an example of Voronoi diagram construct. Given a set of sensor S = \{s_1, s_2, s_3, ..., s_n\}, the Voronoi diagram divides a two-dimension plane into N convex polygons. Each polygon c_i has only one sensor s_i and consists of the set of edges that are equidistant from neighbor nodes. That is, the Voronoi edges of polygon c_i are the vertical bisectors of the line passing the sensor s_i and its Voronoi neighbor nodes. It is noted that any point in the polygon c_i is closer to s_i than any other sensors. Thus, if s_i cannot detect the expected phenomenon occurred in the polygon c_i, no other sensor can detect it, and thus each sensor is responsible for the sensing task in its Voronoi polygon.

By using the Voronoi diagram, we translate the region coverage problem into the coverage problem of each Voronoi polygon and reduce the complexity of the problem [7]. In this paper, each sensor uses only local information, the locations of neighbor nodes, for calculating its Voronoi polygon and determining the next position, so the proposed algorithm can be executed concurrently by all sensor nodes.

B. Centroid

The centroid (or the geometric center) of a polygon is the intersection point of all lines that divide the polygon into two part of equal area. So, the point is the average of all points of the polygon. Fig. 3 shows the centroid of a triangle polygon. A line \overline{AF} divides the triangle ABC into two equal parts: triangle ABF and triangle AFC. In the case of polygon by n vertices \((x_i, y_i)\), the closed-form expression representing the centroid \((C_x, C_y)\) can be calculated as follows:

\[
C_x = \frac{1}{6A} \sum_{i=0}^{n-1} (x_i + x_{i+1})(x_iy_{i+1} - x_{i+1}y_i),
\]

\[
C_y = \frac{1}{6A} \sum_{i=0}^{n-1} (y_i + y_{i+1})(x_iy_{i+1} - x_{i+1}y_i)
\]

where the area A of the polygon is as follows:

\[
A = \frac{1}{2} \sum_{i=0}^{n-1} (x_iy_{i+1} - x_{i+1}y_i).
\]
(a) Round 0 (70.12%) (b) Round 1 (87.40%) (c) Round 2 (91.78%)

Fig. 4. Execution snapshot of Centroid scheme

1.5V

In [8], the authors refer to the advantage of centroid that moving to the centroid of a Voronoi polygon can be beneficial in terms of coverage and uniform arrangement of sensors. [9] also utilizes the centroid for the coverage optimization. In this paper, we take advantage of the centroid’s power to develop distributed self-deployment schemes for mobile sensors.

IV. THE PROPOSED SENSOR DEPLOYMENT SCHEMES

Our sensor deployment schemes are based on the Voronoi diagram which represents the proximity information about a set of sensors. Each sensor is responsible for the sensing and detecting an expected phenomenon in its local Voronoi polygon. We also utilize the centroid of the Voronoi polygon in order to get better coverage of mobile sensors. Because all of Voronoi vertices are used without exception to calculate the centroid, it is intuitively obvious that a scheme utilizing the centroid of the Voronoi polygon works better than both VOR and Minimax. VOR takes into account only one Voronoi vertex and Minimax utilizes at most three Voronoi vertices. After the initial random deployment to a given field, each sensor runs the proposed scheme repeatedly until it reaches the pre-defined maximum round. As in [6], to terminate the deployment procedure earlier, we can also use a threshold $\epsilon$, defined as the minimum increase in coverage below which a sensor will not move.

Now we present two new self-deployment schemes, Centroid and Dual-Centroid, of mobile sensors in details.

A. The Centroid Scheme

Every beginning of each round, a sensor calculates its local Voronoi polygon using the neighbor’s location information. If the polygon is fully covered by the sensor’s sensing range, the sensor will do nothing for this round. Fully covered polygon means that all distances from the local Voronoi vertices to the sensor are less than $R_s$. If not, the sensor calculates the centroid of the local polygon by using the Equations (1) and (2). The centroid is decided as the next location of the sensor. Prior to the final decision, the sensor checks whether the local coverage will increase by its movement to the new location.

Fig. 4 shows how the Centroid scheme works when $R_s$ is 6m and $R_c$ is 20m. Round 0 is the initial random deployment of 30 sensors in a 50m by 50m field and coverage is 70.12%. After Round 1 and Round 2, the coverage is improved to 87.40% and 91.78%, respectively. We can see that sensors in the field become more and more evenly distributed every round.

If the local coverage increases at the new location, the sensor will move; otherwise, it will stay. This is introduced by [6] and called movement-adjustment scheme. In Fig. 5, the sensor $O$ draws its local Voronoi polygon and knows that the polygon is not fully covered by itself. Therefore, sensor $O$ will move to the point $G$, the centroid of the local polygon (the marked area). The complete procedure of the Centroid scheme is shown in Fig. 6.

Notations:

$G_p(s_i)$: Voronoi polygon of sensor $s_i$

cover$_i$: boolean variable indicating whether $G_p(s_i)$ is completely covered by sensor $s_i$

MAX_ROUND: pre-defined maximum number of round

Procedure:

(1) enter Discovery phase:
   (1.1) set timer to be discovery interval and enter Moving phase upon timeout
   (1.2) broadcast hello after a random time slot

(2) enter Moving phase:
   (2.1) set timer to be moving interval and enter Discovery phase upon timeout
   (2.2) if cover$_i$ = false, call Centroid()
   (2.3) Done when satisfying the stop criteria

(3) Upon receiving hello message from a neighbor node $s_j$:
   (3.1) Update $G_p(s_i)$
   (3.2) if $G_p(s_i)$ is newly covered, set cover$_i$ = true

(4) Centroid():
   (4.1) Calculate the centroid of $G_p(s_i)$
   (4.2) Do movement-adjustment

Fig. 5. The Voronoi polygon of the sensor $O$ and the next location $G$ based on the Centroid scheme

Fig. 6. The procedure of Centroid scheme
B. The Dual-Centroid Scheme

As each round of Centroid scheme runs, we can see that the mobile sensors become gradually distributed evenly so that the distances between a sensor and its neighbor nodes are almost equalized (see Fig. 7 (a)). From this observation, we can assert that each sensor should also move so that it is located at the center between their neighbor nodes. Although the centroid of a Voronoi polygon represents the point where a sensor covers the polygon at maximum, it does not stand for the central point between the topological locations of neighbor nodes. So, we develop a new centroid representing such a central point.

Our second scheme, Dual-Centroid, utilizes the new centroid as well as the existing centroid to expedite the coverage expansion. For describing the Dual-Centroid scheme, we define the Voronoi neighbor nodes of a sensor as the nodes involved in the construction of the sensor’s Voronoi polygon. In the Dual-Centroid scheme, as in the Centroid scheme, a sensor first calculates the centroid of the local Voronoi polygon to cover coverage hole. Moreover, it constructs a local polygon where each vertex represents the Voronoi neighbor nodes. It is called Voronoi neighbor polygon (the marked area in Fig. 7 (b)). The sensor also calculates a new centroid of the Voronoi neighbor polygon. And then it obtains the next position $G$ as follows:

$$G = \alpha C_1 + (1 - \alpha) C_2 \quad (\alpha \in (0, 1))$$

where $C_1$ and $C_2$ are the centroids of the Voronoi polygon and the centroid of the Voronoi neighbor polygon, respectively.

The procedure of Dual-Centroid scheme is shown in Fig. 8. It is noted that the Dual-Centroid scheme is performed only when the Voronoi polygon is completely covered by the Voronoi neighbor polygon. This strategy prevents mobile sensors from false movement because when a Voronoi vertex is out of the Voronoi neighbor polygon, it is highly possible that there is a big coverage hole in the proximity of the Voronoi vertex. So, such a big coverage hole should be covered just by using the Centroid scheme. If the Dual-Centroid scheme is used at this case, the coverage hole will become rather bigger.

Fig. 9 shows how Dual-Centroid scheme works. Round 0 is the initial random deployment of 30 sensors in a 50m by 50m field and coverage is 70.12% (the initial locations of sensors are the same as the sensor locations in Fig. 4. (a)).

Fig. 7. (a) $O \approx OBC \approx \ldots \approx OP$, (b) The neighbor polygon of the sensor $O$’s Voronoi neighbor nodes and the next location $G$ based on the Dual-Centroid scheme

V. PERFORMANCE EVALUATION

We measure the performance of the proposed schemes and the existing schemes, VOR and Minimax. In the measurement, we run the simulation 10 times per parameter set and get the average value. We use 0.5 as the value of $\alpha$ in Equation (3).

Fig. 10 shows the increment of average coverage at each round. The sensor coverage are measured under four system parameter sets: 30 sensors in 50m by 50m, 40 sensors in 50m by 50m, 120 sensors in 100m by 100m and 160 sensors in 100m by 100m. $R_c$ and $R_e$ are 6m and 20m, respectively. As can be seen, we confirm that the proposed schemes yield better coverage performance than VOR and Minimax irrespectively of the number of sensors and the field size. We can also know that the Dual-Centroid scheme is a little better than the Centroid scheme. The reason is that the Dual-Centroid scheme tries to not only cover the coverage hole but also equalize each distance to the Voronoi neighbor nodes.

Fig. 11 shows the coverage and moving distance after ten rounds under different $R_e$. We randomly deploy 40 sensors in 50m by 50m and change $R_e$ from 14m to 26m to evaluate its impact on the performance. When the $R_e$ increases, we can see the tendency that the coverage also increases, but the moving...
distance decreases. This is because when the $R_c$ is low, each sensor draws its local Voronoi polygon incompletely and the Voronoi polygons of sensors will be overlapped. It increases the probability that sensors decide a wrong location to move. We can also observe that the proposed schemes are better than Minimax and VOR in terms of the coverage, but they are better than Minimax and worse than VOR in terms of the moving distance. It indicates that the proposed schemes are quite good to maximize the sensor coverage and moderate in the moving distance.

VI. CONCLUSION

This paper addresses the problem of placing sensors in a target field to maximize the sensing coverage. Based on the Voronoi diagram and centroid, we present new distributed self-deployment schemes, Centroid and Dual-Centroid, for mobile sensors. We choose the existing schemes, VOR and Minimax, as the targets of comparison and show that the proposed schemes make the coverage holes covered faster than both VOR and Minimax and the moving distance does not increase much.

REFERENCES