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A Deployment Scheme Based Upon Virtual Force for Directional Sensor Networks

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Abstract: A directional sensor network is composed of many directional sensor nodes. Unlike conventional omni-directional sensors that always have an omni-angle of sensing range; directional sensors may have a limited angle of sensing range due to technical constraints or cost considerations. Area coverage is still an essential issue in a directional sensor network. In this paper, we study the area coverage problem in directional sensor networks with mobile sensors, which can move to the correct places to get high coverage. We present distributed self-deployment schemes of mobile sensors. After sensors are randomly deployed, each sensor calculates its next new location to move in order to obtain a better coverage than previous one. The locations of sensors are adjusted round by round so that the coverage is gradually improved. Based on the virtual force of the directional sensors, we design a scheme, namely Virtual force scheme. Simulation results show the effectiveness of our scheme in term of the coverage improvement. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Directional sensors, Mobile sensors, Area coverage.

1. Introduction

In recent years, wireless sensor networks have received a lot of attention due to their wide applications in military and civilian operations, such as fire detection [1], vehicle traffic monitoring [2], ocean monitoring [3], and battlefield surveillance [4]. In wireless sensor networks, target coverage is a fundamental problem and has been studied by many researchers. Most of the past work is always based on the assumption of omni-directional sensors that has an omni-angle of sensing range. However, there are many kinds of directional sensors, such as video sensors [5], ultrasonic sensors [6] and infrared sensors [7]. The omni-directional sensor node has a circular disk of sensing range. The directional sensor node has smaller sensing area (sector-like area) and sensing angle than the omni-directional one. Compared to isotropic sensors, the coverage region of a directional sensor is determined by its location and orientation. This can be illustrated by the example shown in Fig. 1.

Area coverage is a fundamental problem in wireless sensor networks. Therefore, sensor nodes must be deployed appropriately to reach an adequate coverage level for the successful completion of the issued sensing tasks [8-9]. However, in many potential working environments, such as remote harsh fields, disaster areas, and toxic urban regions, sensor deployment cannot be performed manually. Deploying sensors by aircraft may result in the situation that the actual landing positions cannot be controlled. Consequently, the coverage may be inferior to the application requirements no matter how many sensors are dropped. In such a situation, it may need to make the mobile sensors to move to the correct positions for the required coverage.

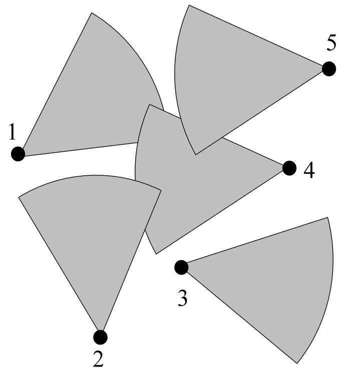


Fig. 1. An example of directional sensors deployed to cover target region.

Most previous research efforts on deploying mobile sensors are based on the omni-directional sensor networks. For example, Howard, *et al.* [10] present a distributed, potential-field-based approach to solve the coverage problem. In their approach, sensor nodes are treated as virtual particles that are subject to force, these forces repel the neighboring sensor nodes from each other and from obstacles. Finally, sensor nodes will spread from dense to sparse area. The concept of potential-field was first proposed in the research of mobile robotic route plan and obstacle avoidance by Khatib [11]. In [12], Wang, *et al.* present a set of Voronoi diagram-based schemes to maximize sensing coverage. After discovering a coverage hole locally, the schemes calculate new position for each sensor to move at next round. They use the Voronoi diagram to discover the coverage holes and design three movement-assisted sensor deployment schemes: VECtor-based (VEC), VORonoi-based (VOR), and Minimax. The VEC approach is motivated by the attributes of electromagnetic and the main idea is to push sensors away from a densely area by the virtual force. The main idea of VOR is to pull sensors to the sparsely covered area. Sensors will move toward its farthest Voronoi vertex and stop when the farthest vertex can be covered. The main idea if Minimax is to fix holes by moving closer to the farthest Voronoi vertex, but it does not move as far as VOR. In [13], Lee, *et al.* designs two movement-assisted schemes: Centroid-based and Dual-Centroid-based. The Centroid algorithm is moving sensors to their local center point of the local Voronoi polygon. Similar to the Centroid algorithm, the Dual-Centroid algorithm is not only moving sensors to their local center point of the local Voronoi point, but also moving to the centroid of the polygon formed by Voronoi neighbor nodes. Based on the Voronoi diagram and centroid (geometric center), the proposed schemes can be used to improve the sensing coverage. In [14], Liang, *et al.* propose a virtual force based moving scheme that can improve the coverage rate after random deployment.

In this paper, we extend the results in [14] of studying the problem of coverage by directional mobile sensor under the random deployment strategy. We develop a solution that maximizes the sensing coverage while minimizing the computation time in term of rounds. Based on the virtual force of directional sensors, we design a moving algorithm: the Virtual Force scheme. Simulation results show that our distributed algorithm is effective in terms of coverage, deployment time, and movement.

The rest of this paper is organized as follows. In Section 2, we introduce some preliminaries. In Section 3, we state the problem formally and make some assumptions regarding the problem. We present our scheme in Section 4. Section 5 shows some simulation results. Finally, we conclude this paper in Section 6.

2. Preliminaries

2.1. Directional Sensing Model

Compared to an omni-directional sensor which has a circular disk of sensing range, a directional sensor has smaller sensing area (sector-like area) and sensing angle. This can be best illustrated in Fig. 2. As shown in Fig. 2, the sensing region of a directional sensor is a sector denoted by a 3-tuple (α, β, R), and the sensing region is called sensing sector. Here R is the sensing radius, α is the sensing angle, and β is the offset angle.

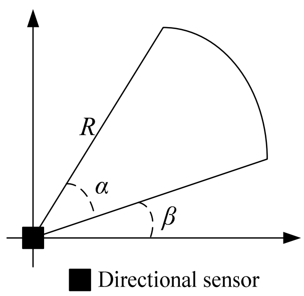


Fig. 2. The directional sensing model.

2.2. Virtual Force Points

We assume that there are many virtual force points around the boundary of sensing sector, as shown in Fig. 3. Without loss of generality, we assume that there are $3m + 1$ virtual force points of each sensor, in which there are m points on the arc, m points on each of the both straight boundary lines of sensing sector, and sensor point itself. We denoted the virtual force points of s_i, as p_{ik}, where $1 \le k \le 3m + 1$. As shown in Fig. 3, there are total $3{\cdot}5 + 1$ virtual force points, in which there are

5 points on the arc and on both straight boundary lines respectively. Each virtual force point on sensors can receive a repulsive force from other sensors.

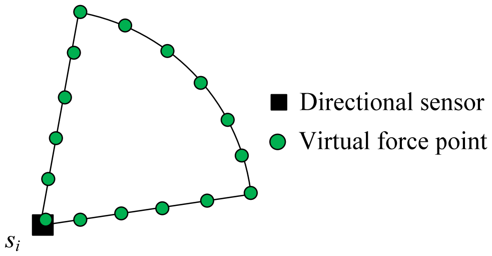
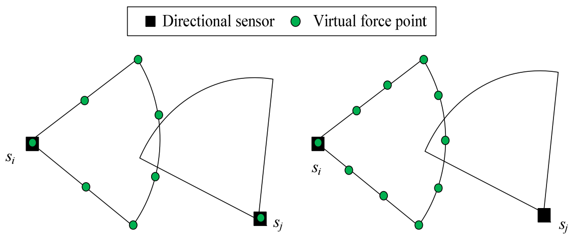


Fig. 3. The virtual force points.

It should be noticed that, as shown in Fig. 4, the more virtual force points a directional sensor has, the more repulsive force that exerted on the directional sensor by its neighboring directional sensors. By applying all of the repulsive forces from its neighbors, the directional sensor can be repelled from dense to sparse area.



(a) Seven virtual force points of a directional sensor.

(b) Ten virtual force points of a directional sensor.

Fig. 4. Illustration of two different number of virtual force points.

It also should be noticed that, the more virtual force points a sensor has, the more accurate repulsive force can be applied. In Fig. 4 (a), the directional sensor s_j has the overlapped region with directional sensor s_i, which implies that sensor s_i should be repelled by the sensor s_j. However, sensor s_j will not exert a repulsive force on s_i because that sensor s_j does not cover any virtual force point of sensor s_i. On the contrary, in Fig. 4 (b), we can see that sensor s_j has covered one virtual force point of s_i. Therefore, sensor s_j would exert a repulsive force on s_i.

3. Problem Statement

Problem: Randomly deploying N mobile directional sensors with sensing range R_s and sensing angle α in a given target sensing region, we are asked to maximize the sensor coverage with less time.

To address the above problem, we need to make the following assumptions:

- All directional sensors have the same sensing range (R_s) and sensing angle α, where $0 < \alpha \leq 2\pi/3$. Directional sensors within $2R_s$ of a sensor are called the sensor's neighboring nodes.
- Directional sensors can move to arbitrary orientation, but its sensing direction is not rotatable.
- Each sensor knows its location information and determines the locations of its neighboring sensors.

4. The Proposed Moving Scheme

In order to maximize the sensor coverage, we present a moving scheme for directional mobile sensors, namely the Virtual Force scheme.

4.1. Virtual Force Scheme

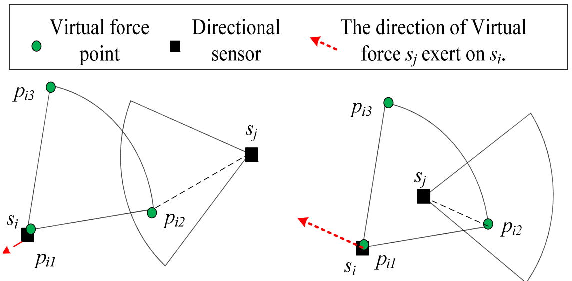
The Virtual Force scheme employs the repulsive force between a directional sensor and each of its neighboring sensors as a basis of movement. The virtual force occurred on a directional sensor is basically generated by the repulsive force between each of its virtual force point and each of its neighboring sensor. The main idea of virtual force scheme aims to repelling a sensor node by its neighboring sensors from dense area to sparse area. We assume that C_{ij} is the set of virtual force points of s_i that are covered by its neighboring sensor s_j. When sensors s_i and s_j are overlapped, they will repel each other by the overlapped region. We denote repulsive force occurred on sensor s_i, which is caused by sensor s_j as $\overrightarrow{F_{ij}}$. Then, $\overrightarrow{F_{ij}}$ can be obtained as follows. If sensor s_j is located inside the sensing sector of s_i, s_j will act as a repulsive force from the virtual force point p_{ik} to the sensor s_j, in which p_{ik} is the virtual force point of s_i that has the maximal distance to s_j, according to the following equation:

$$\overrightarrow{F_{ij}} = \overrightarrow{\rho_{ik} s_j}, \text{where } \rho_{ik} \in C_{ij} s.t. d(\rho_{ik}, s_j) \text{ is maximal.}$$

If sensor s_j is outside the sensing sector of s_i, s_j will act as a repulsive force from sensor s_j to the virtual force point p_{ik}, in which p_{ik} has the minimal distance to s_j, according to the following equation:

$$\overrightarrow{F_{ij}} = \frac{R_s}{\left|\overrightarrow{s_j \rho_{ik}}\right|} \times \overrightarrow{s_j \rho_{ik}} - \overrightarrow{s_j \rho_{ik}},$$ where $p_{ik} \in C_{ij}$ and $d(p_{ik}, s_j)$ is minimal.

Fig. 5 illustrates an example of the repulsion model. From Fig. 5(a), we can observe that s_j is outside the sensing sector of s_i, and p_{i2} has the minimal distance to s_j and $p_{i2} \in C_{ij}$. So, the repulsive force exerts on s_i is $\overrightarrow{F_{ij}} = \frac{R_s}{\left|\overrightarrow{s_j \rho_{i2}}\right|} \times \overrightarrow{s_j \rho_{i2}} - \overrightarrow{s_j \rho_{i2}}$. In Fig. 5(b), s_j is inside the sensing sector of s_i and p_{i2} has the maximal distance to s_j and $p_{i2} \in C_{ij}$. So, the repulsive force exert on S_i is $\overrightarrow{F_{ij}} = \overrightarrow{\rho_{i2} s_j}$.

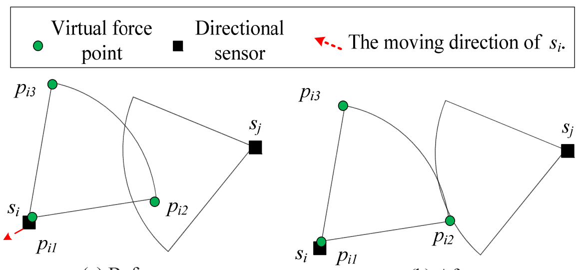


(a) s_j is outside the sensing sector of s_i.
(b) s_j is inside the sensing sector of s_i.

Fig. 5. Illustration of repulsive model s_j exert a repulsive force on s_i.

4.2. Virtual Force Moving Algorithm

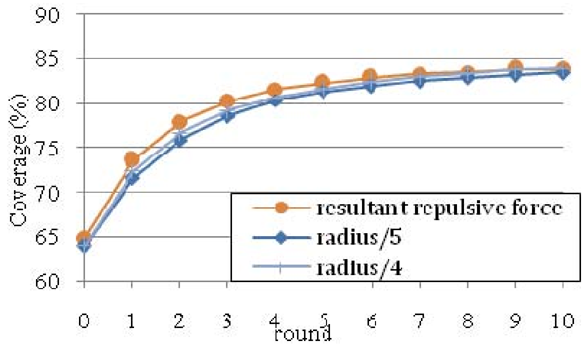
According to the repulsion model, we can compute the repulsive forces of each sensor. Then the resultant repulsive force of each sensor is the direction of the new position that sensor should move toward. Fig. 6 shows an example that the sensor move toward the direction of the new position with its resultant repulsive force. After repelling by its repulsive force, it really can decrease the overlapped region.



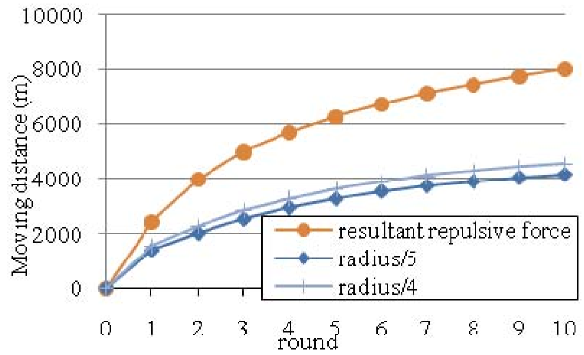
(a) Before s_i move to new position.
(b) After s_i move to new position.

Fig. 6. Illustration of moving direction from resultant repulsive force.

In order to save energy, we observe that each sensor does not need to move too far to have better coverage. This means that the mobile sensors can only move short distances to obtain the improved coverage rate. Thus, in our proposed moving strategy, we take the resultant repulsive force as the moving direction and the moving distance is fixed to radius/5 or radius/4. Fig. 7 shows the effect of our moving strategies. As shown in Fig. 7 (a), the coverage of moving longer distance (i.e. repulsive force) is only a little better than that of moving shorter distance (i.e. radius/5). However, the total moving distance of moving longer distance is much worse than that of moving shorter distance, as shown in Fig. 7 (b). In this example, the total moving distance of using repulsive force strategy is 8003 *m*, which is much worse than the total moving distance of using radius/5 strategy, which is only 4051 *m*.



(a) Coverage (%)



(b) Moving distance (m)

Fig. 7. Illustration of the effect of different moving strategies.

The movement procedure can be stated as follows: First, the directional sensor determines the direction of movement by the repulsion model. Then the directional sensor checks if the overlapped region with neighboring sensors is decreased by moving to the new destination. If the overlapped region is decreased, the directional sensor will start to move; otherwise, it will stay. The above procedure is called the New-movement-adjustment scheme. Fig. 8 illustrates an example of New-movement-adjustment scheme. Then we add an oscillation control on the movement. The purpose of oscillation control is to prevent the sensor from moving back and forth, as shown in Fig. 9.

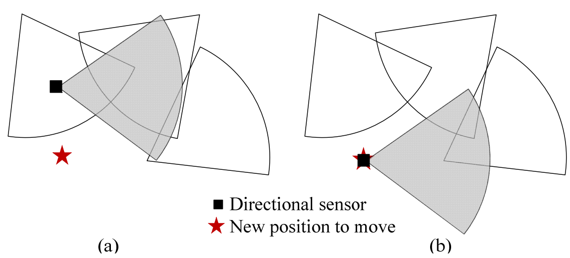


Fig. 8. Illustration of the new movement-adjustment scheme. (a) before movement, and (b) after movement.

Furthermore, we proposed a move-back scheme to prevent sensors move out of the target region. If the virtual force point of a sensor is out of the target region, sensor should move to the new position until its virtual force point is located on the boundary of the target region as shown in Fig. 10.

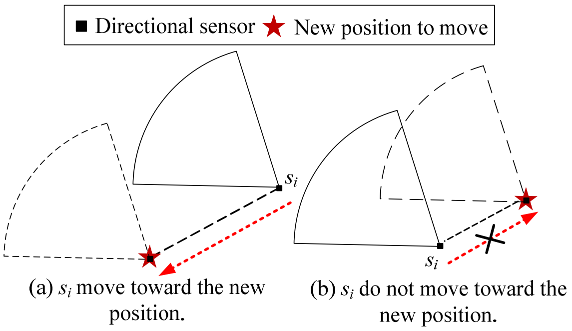


Fig. 9. Illustration of oscillation control.

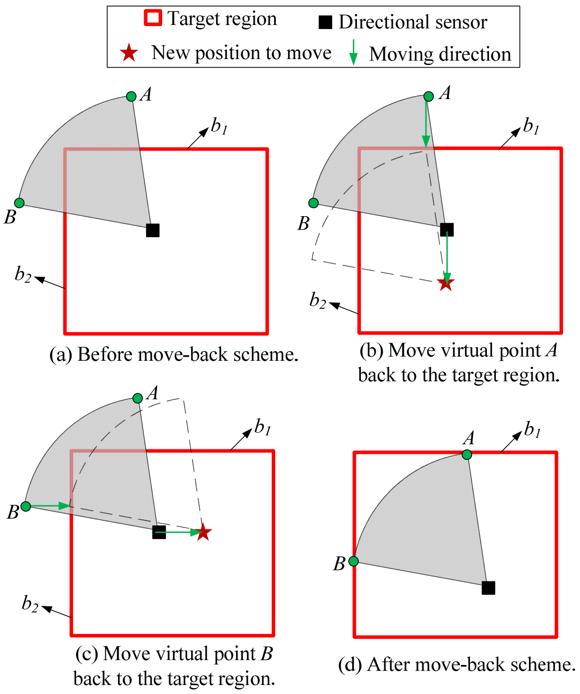


Fig. 10. Illustration of move-back scheme.

From Fig. 10 (a), we can see that the virtual points *A* and *B* are outside the target region. So, we should move these two virtual points into the target region. This can be done by moving down the sensor with the distance between the virtual point *A* and the boundary b_1. After the movement, the virtual point *A* will be just located on the boundary of the target region as shown in Fig. 10 (b). Furthermore, the virtual point *B* is also outside the target region. Thus, the directional sensor will move right with the distance from *B* to the boundary b_2. After that, the virtual point *B* will be also located on the boundary of the target region as shown in Fig. 10 (c). In Fig. 10 (d), the sensing sector of the directional sensor will be all inside the target region after moving to the new position. After determining the new position to move, the directional sensor will execute the New-movement-adjustment until new position is reached. Finally, the proposed moving scheme will stop when it achieves the maximum number of rounds. The complete procedure of Virtual Force Moving algorithm is shown in Fig. 11.

Virtual Force Moving Algorithm

Notations:

$VPCov_{ij}$, VP_{ik}, $\left|\overrightarrow{S_jP_{ik}}\right|$, FR_{ij}: defined before

N_i: the neighbor of sensor S_i

$\vec{V}_i$: moving vector of 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 *discovery interval* and enter *discovery phase* upon timeout

(2.2) Compute the resultant repulsive force

(2.2.1) $\vec{V}_i = 0$

(2.2.2) for each S_j in N_i

If neighbor node is outside the sensing sector

and $VPCov_{ij} \neq \emptyset$ and $VP_{ik} \in VPCov_{ij}$

FR_{ij}=radius–min $(\left|\overrightarrow{S_jVP_{ik}}\right|)$; $\vec{V}_i = \vec{V}_i + FR_{ij}$;

If neighbor node is inside the sensing sector and

$VPCov_{ij} \neq \emptyset$ and $VP_{ik} \in VPCov_{ij}$

FR_{ij}= –max $(\left|\overrightarrow{S_jVP_{ik}}\right|)$; $\vec{V}_i = \vec{V}_i + FR_{ij}$

(2.2.3) The distance between the new position of

S_i and S_i is radius/5 by the moving direction $\vec{V}_i$

(2.3) do oscillation control

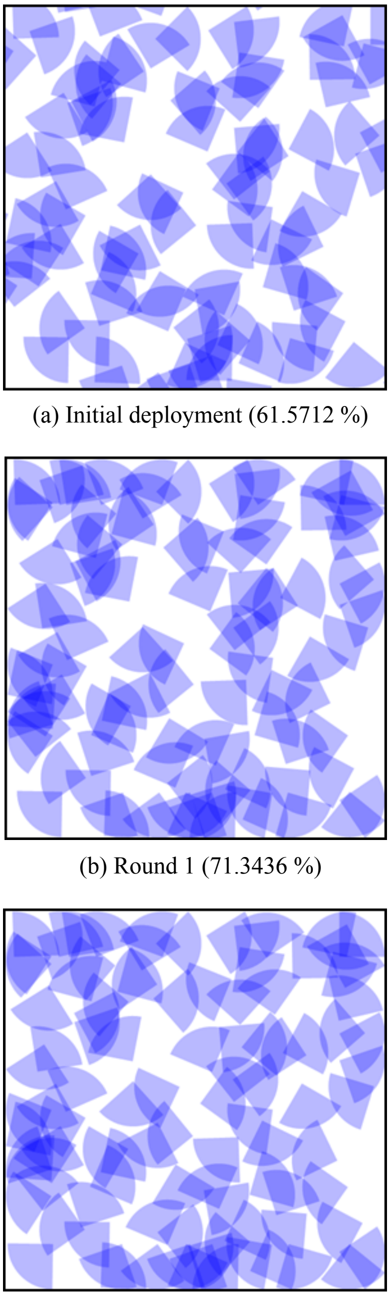
(2.4) do New-movement-adjustment

(2.5) do move-back scheme

(2.6) Done when satisfying stop criteria

Fig. 11. Procedure of virtual force moving algorithm.

We utilize a case to illustrate the Virtual Force scheme. As shown in Fig. 12, we have 100 directional sensors which are randomly deployed in a region of 500×500 m^2. For each directional sensor, the sensing radius is 60 *m* and the sensing angle is 90°. In Fig. 12 (a), the initial coverage rate is 61.5712 %. After Round 1 (Fig. 12 (b)) and Round 2 (Fig. 12 (c)), it can be seen that the coverage ratios are increased to 71.3436 % and 76.2856 %, respectively.



(a) Initial deployment (61.5712 %)

(b) Round 1 (71.3436 %)

(c) Round 2 (76.2856 %)

Fig. 12. Illustration of an example of executing first two rounds of proposed virtual force moving algorithm.

5. Simulation Results

In this section, we simulate and analyze the performance of Virtual Force scheme from two aspects: coverage and moving distance. Each simulation is executed 10 times then gets the average value. The simulation program is written by *C#* programming language on .NET platform. We deployed 100 directional sensor of a region of 500×500 m^2 in our simulation. The sensing radius is 60 *m*, the, the sensing angle is 90º and the number of virtual force point around the boundary of sensing sector is 31. Experimental environment is shown in Table 1.

Table 1. Experimental parameters.

Network size	500×500 m^2
Sensing radius (R_s)	60 *m*
Sensing angle (α)	90º
Number of directional sensors	100
Number of virtual force points	31

The first experiment examines the effect that the number of rounds makes to the performance of coverage rate of our proposed approach on different number of virtual force points. Fig. 13 shows the results. In Fig. 13, we can see that the more virtual force point a directional sensor has, the more target region can be covered. Thus, we set the number of virtual force points to be 31 in the following experiments.

The second experiment evaluates the effect that the number of rounds makes to the performance of accumulated coverage rate of our moving algorithm with 31 virtual force points. Fig. 14 shows the results. We can see that our proposed virtual force scheme can increase the coverage rate effectively as rounds increase. This is due to that the directional sensors repel each others from dense to sparse area. Therefore, as rounds increase, the mobile sensors will move to the sparse area. As a result, the coverage holes in the sparse area will be reduced and coverage rate will be increased.

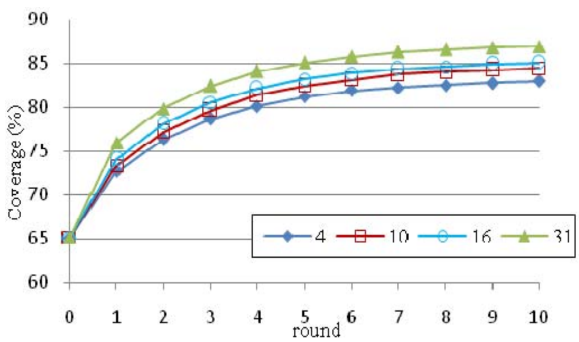


Fig. 13. Coverage rate vs. number of rounds.

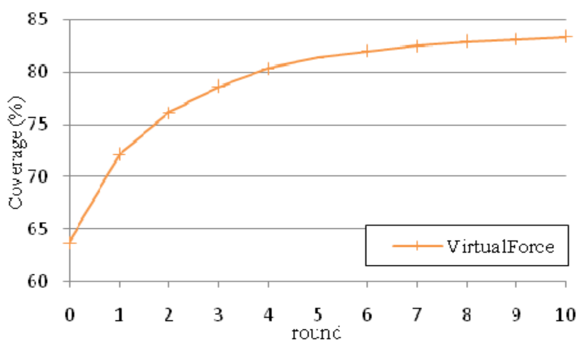


Fig. 14. Coverage rate vs. number of rounds – 31 virtual points.

The final experiment examines the effect that the number of rounds makes to the performance of accumulated moving distance of our moving algorithm with 31 virtual force points. Fig. 15 shows the results.

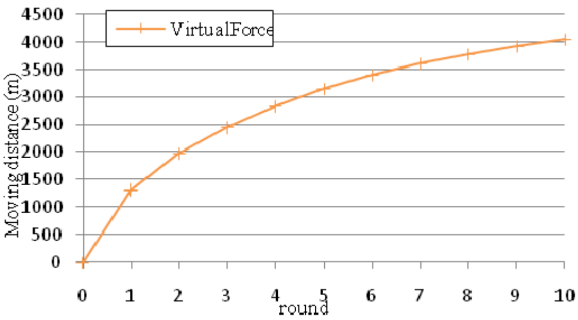


Fig. 15. Moving distance vs. number of rounds – 31 virtual points.

We can see that our proposed virtual force scheme will increase the moving distance as rounds increase. This is due to that our approach will move mobile sensors to the sparse area in order to cover the hole area. Therefore, as rounds increase, the moving distance will be increased as well.

6. Conclusions

In this paper, we define a new problem regarding how to maximize the area coverage with less moving distance by mobile directional sensors. We propose a scheme, namely the Virtual Force scheme, to improve the coverage. We adopt the virtual force points as the basis of repulsion. Then directional sensor can move toward new position to get better coverage by this repulsion. Simulation results show that virtual force scheme will increase the area coverage round by round, and the moving distance will be increased when the coverage increases. Specifically, the improvement can be obtained by our proposed Virtual Force scheme up to 30 % coverage rate more than initial random deployment.

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