Surface Coverage Algorithm in Directional Sensor Networks for Three-Dimensional Complex Terrains

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Abstract: Coverage is an important issue in the area of wireless sensor networks, which reflects the monitoring quality of the sensor networks in scenes. Most sensor coverage research focuses on the ideal two-dimensional (2-D) plane and full three-dimensional (3-D) space. However, in many real-world applications, the target field is a 3-D complex surface, which makes conventional methods unsuitable. In this paper, we study the coverage problem in directional sensor networks for complex 3-D terrains, and design a new surface coverage algorithm. Based on a 3-D directional sensing model of nodes, this algorithm employs grid division, simulated annealing, and local optimum ideas to improve the area coverage ratio by optimizing the position coordinates and the deviation angles of the nodes, which results in coverage enhancement for complex 3-D terrains. We also conduct extensive simulations to evaluate the performance of our algorithms.

Key words: directional sensor networks; surface coverage; simulated annealing; complex terrains

1 Introduction

With the development of wireless communication, microelectronics technology, and embedded systems, wireless sensor networks not only have a wide range of application prospects in traditional fields, but have also become a new tool for information collection, and have deeply affected people’s lives in new domains. In recent years, wireless sensor network research has received a lot of attention. Some research is about data transmission or network lifetime of wireless sensor networks. Lu and Wang[1] proposed a probabilistic routing algorithm for wireless sensor networks and correctness, and analyzed time-space complexity of algorithms. He et al.[2] modeled the solution as an \( \alpha \)-Reliable Maximum Sensor Covers (\( \alpha \)-RMSC) problem and designed a heuristic greedy algorithm to improve WSN reliability. In the future, WiFi signals will be used for both communication and sensing. WiFi-based sensing networks will potentially rank as one of the world’s largest wireless sensor networks. Zhou et al.[3] reviewed the feasibilities and limitations of wireless, sensorless, and contactless sensing via WiFi to explore WiFi-based sensing networks.

As one of the typical research aspects of sensor networks, the coverage problem is still important[4–6]. According to different coverage models, the coverage problem of wireless sensor networks can be divided into omni-directional coverage and directional coverage. Current research has shifted from the omni-directional coverage model of traditional sensor nodes to the directional coverage model of emerging sensor nodes. Omni-directional sensor nodes are usually deployed in two-dimensional (2-D) environments, and thus the study of coverage is also limited to the 2-D environment. Huang and Tseng[7] defined the coverage problem as a decision problem, whose target is to
determine whether every point in the coverage area of a sensor network is covered by at least \( k \) sensors. Also, it gives a polynomial-time algorithm that can be easily transformed into several distributed protocols if the number of sensors is fixed and \( k \) is 1.

In fact, almost all information that is closely related to human life is obtained from three-dimensional (3-D) scenes. Compared to 2-D scenes that are commonly used in current research, realistic 3-D sensing environments are more complex. It is difficult to describe the actual sensing scenes by using the traditional 2-D model. In practical applications, directional sensor nodes are usually deployed in specific 3-D scenes, and sense the 3-D scene to get coverage information. There is little on the problem of coverage in wireless sensor networks for complex 3-D scenes.

For the problem that a traditional 2-D sensing model cannot accurately describe multimedia sensing characteristics in 3-D scenes, Ma et al.\cite{8} were the first to suggest a 3-D sensing model of directional sensor nodes and propose a scene-coverage-enhancing algorithm that was based on virtual potential fields and simulated annealing. In Refs. \cite{9, 10}, four pyramid perception models and circular perception models of directional multimedia sensor nodes were proposed, based on Ref. \cite{8}. Position coordinates, the main sensing direction, the pitch angle, and the deflection angle of the node are definite. And a network coverage enhancement method based on a particle swarm algorithm was designed. Although these references are studies of a 3-D sensing model of sensor nodes, the sensing areas of sensor nodes in the models are the ideal 2-D plane, which is not suited for general purposes.

In Ref. \cite{11}, a new method of path coverage in wireless sensor networks was presented for complex 3-D terrains. In this scheme, the nodes are deployed evenly and the 3-D terrains are transformed into 2-D planes by using the watershed algorithm. The path-coverage problem is estimated by using a detection factor defined from the optimal path. Feng et al.\cite{12} proposed a strategy for deterministic network coverage optimization based on a genetic algorithm in view of Ref. \cite{11}; the iteration of the genetic algorithm can find the optimal solution. Liu and Ma\cite{13} studied the coverage problem of wireless sensor networks in rolling terrain and obtained the expected coverage ratio. According to different terrain features, two kinds of terrain coverage problems were considered: conventional terrain coverage and irregular terrain coverage. For conventional terrain, two models were presented, a cone model and a cos-revolution model, to estimate the expected coverage ratio of conventional terrain. For irregular terrain, an algorithm based on a digital elevation model was proposed, to estimate the expected coverage ratio of a region of interest. The algorithm uses the contour map of the region of interest. Kong et al.\cite{14} studied two problems: (1) When the nodes are randomly distributed on the surface of terrain, the mathematical expectation of the node number was given. (2) It was proved that computing the minimum number of nodes is an NP-complete problem when the deployment of the nodes is determined, and three approximate algorithms were proposed. Jin et al.\cite{15} designed a general function and used it to measure the reliability of the data that is monitored from the entire sensor network. The general function contains perceived probability of all nodes in the sensor network. Thereby it determines the perceived quality of the best 3-D surface deployment problem and yields the optimal solution.

A new 3-D coverage deployment scheme is proposed in Ref. \cite{16}. Sensor nodes are deployed based on the scheme after the monitor area is subdivided into finite 3-D grids. Abdelsalam and Olariu\cite{17} presented a 3-D localization technique that contains a two-step terrain modeling method. The technique includes RSSI-based distance measurement and a trilateration technique to locate sensors for coverage. Liu et al.\cite{18} investigated the coverage of mobile sensor nodes deployed over convex 3-D surfaces, studied the general convex 3-D surface case, and derived the coverage ratio as a function. They also provided insights into the essence of the coverage hole problem. Yan et al.\cite{19} studied homology-based coverage hole detection for sensor networks on spheres. They chose the proportion of the area of missed coverage holes by Rips complex as a metric to evaluate the accuracy of coverage hole detection approaches.

Although the references studied 3-D terrain coverage deployment of sensor networks, their models of sensor nodes are an omni-directional sensing model. Because there is a big difference between omni-directional sensor nodes and directional sensor nodes in sensing models, the research cannot be directly applied to directional sensor networks.

References \cite{20, 21} study the coverage deployment problem on complex 3-D terrains. Topcuoglu et al.\cite{20} considered that a set of sensors have multiple
conflicting goal properties: the utility of visibility, the utility of stealth, and the utility of cost. Based on multi-attribute utility theory, these conflicting properties were modeled as a total utility function to measure the effect of sensor network deployment. In Ref. [21], a hybrid evolutionary algorithm was proposed for the deployment and configuration of sensor nodes in 3-D complex terrains based on the utility function in Ref. [20].

In previous research works, studies on the combination of directional sensor network coverage problems and 3-D complex scenes are few. In this paper, we study the surface coverage problem of sensor networks for 3-D complex terrains. To solve the problem, we simplify and improve a 3-D directional sensing model of sensor nodes that was designed in Refs. [8, 9]. Three kinds of surface coverage algorithms for complex 3-D terrains are proposed, and the algorithms are compared, verified, and analyzed.

2 Sensing Model and Problem Description

2.1 3-D directional sensing model

In Refs. [8, 9], the authors designed a 3-D directional sensing perception model of directional sensor network nodes. The model is simplified and improved in this section.

The perception model of sensor nodes in a 3-D space depends on the spatial coordinates, the horizontal direction, and the vertical direction. The coverage area of the sensor node is a quadrilateral. In this paper, we uniformly set the sensing direction of nodes as vertically downward, and the model is shown in Fig. 1.

A 3-D directional sensing model is represented by a triad \((P, C, d)\), where \(P = (x, y, z)\) is the coordinates of the node in 3-D space, and \(C = (\gamma, \theta)\) denotes the main sensing direction, in which \(\gamma\) is the pitch angle for the model and represents the vertical offset angle of the sensing direction, and \(\gamma\) is zero in our paper. \(\theta\) is the deviation angle and represents the horizontal offset angle of the sensing direction. \(\theta\) is uniformly distributed in \([0, 2\pi]\). \(d\) is the side length of a square area that is a projection of the node on the plane.

As can be seen in Fig. 1, the sensing area of the directional sensor nodes in 3-D space is square. Different sensor nodes correspond to different sensing regions. So the corresponding coordinates of the sensing area can be obtained by calculation.

2.2 Surface coverage problem description

In this section, we describe the complex irregular surface coverage problem.

Figure 2 gives a profile map of the area covered by the sensor nodes in the ideal case. In reality, for wireless sensor networks and especially for natural scene monitoring applications, the sensing area is generally an irregular surface with arbitrary distribution. If we regard the covering surface as a simple 2-D plane to deploy sensor nodes, the monitoring area will be covered with holes, which leads to the loss of information. As shown in Fig. 3, the red areas are such coverage holes.

In the actual situation, sensor-node coverage of irregular surfaces is shown in Fig. 4.
3 Surface Coverage Algorithms

Definition 1  Point \(Q(x_Q, y_Q, z_Q)\) on the surface in sensing scene is covered by sensor node \(P(x, y, z)\) if the following formulas are satisfied:

If \((x_Q - x) \cdot \cos(-\theta) - (y_Q - y) \cdot \sin(-\theta) \geq 0;\)
\[z_Q \leq z\cdot(d-(x_Q-x)\cdot\cos(-\theta)+(y_Q-y)\cdot\sin(-\theta))/d\] (1)
If \((x_Q - x) \cdot \cos(-\theta) - (y_Q - y) \cdot \sin(-\theta) < 0;\)
\[z_Q \leq z\cdot(d+(x_Q-x)\cdot\cos(-\theta)-(y_Q-y)\cdot\sin(-\theta))/d\] (2)

If \((x_Q - x) \cdot \sin(-\theta) + (y_Q - y) \cdot \cos(-\theta) \geq 0;\)
\[z_Q \leq z\cdot(d-(x_Q-x)\cdot\sin(-\theta)-(y_Q-y)\cdot\cos(-\theta))/d\] (3)
If \((x_Q - x) \cdot \sin(-\theta) + (y_Q - y) \cdot \cos(-\theta) < 0;\)
\[z_Q \leq z\cdot(d+(x_Q-x)\cdot\sin(-\theta)+(y_Q-y)\cdot\cos(-\theta))/d\] (4)

In Fig. 4, point \(Q\) is covered by node \(P\), and point \(S\) is not covered by node \(P\).

Similar to other coverage studies of directional sensor networks, we assume that,

1. Sensor nodes are isomorphic and in the same plane, with the same height, pitch angle, and side length of the sensing area.
2. Sensor nodes can obtain location information and main sensing direction, and can communicate with each other.
3. Coverage can be enhanced by adjusting the deviation angle and horizontal position of nodes.

The surface coverage enhancement of sensor networks corresponds to the coverage of discrete points on a continuous monitoring area. So we can simplify the coverage of a complex irregular surface area to point coverage in a 3-D scene. Discrete points at intervals of \(\Delta x\) and \(\Delta y\) in the horizontal plane are selected to partition the monitoring region. Every point is linked to a \(z\) coordinate. Thus the coverage ratio of a scene is transformed into the coverage ratio of a discrete point set.

Definition 2  Assume that the point set of the discrete monitoring region is \(\Omega\), and a point set covered by at least one sensor node is \(\Omega_a\); then coverage ratio \(\eta\) is defined as

\[\eta = \|\Omega_a\|/\|\Omega\|\] (5)

Assume that the number of nodes deployed in the monitoring region is \(n\), the coordinate of node \(i\) is \(P_i\), and the deviation angle of node \(i\) is \(\theta_i\). Then the surface coverage problem can be considered as an optimization problem. We need to find an optimal set \((P_1, \theta_1), (P_2, \theta_2), \cdots, (P_n, \theta_n)\) for all other \((P_1, \theta_1), (P_2, \theta_2), \cdots, (P_n, \theta_n)\) such that formula (6) is satisfied:

\[\eta((P_1, \theta_1), (P_2, \theta_2), \cdots, (P_n, \theta_n)^*) \geq \eta((P_1, \theta_1), (P_2, \theta_2), \cdots, (P_n, \theta_n))\] (6)

In order to improve the ratio of target coverage for a monitoring area, we should increase the number of discrete points covered. There are two ways to do this. One is deployment of redundant nodes. Due to the fact that the cost of sensor nodes is high, network budgets will be increased if we use this approach to improve network coverage. So to keep costs down, a second approach is usually adopted. A coverage optimization mechanism is used to improve the coverage ratio for a given number of nodes. The concrete measures are as follows: estimate the required number of nodes before the nodes are deployed; after initial deployment, develop an effective coverage optimization mechanism, adjust the deployed locations and the direction of nodes to make the distribution of nodes more uniform, so that the number of covered discrete points is increased, thereby increasing the network coverage ratio.

The research idea of this paper is: given a certain number of nodes, increase coverage area, reduce blind and overlapping areas, make coverage of the target area even, and increase the number of covered discrete points as much as possible.

3.1 Uniform surface coverage algorithm based on the grid

We first analyze the coordinate information of sensor
nodes. The nodes deployed in complex irregular surfaces should be distributed evenly. The idea of grid division can be used to deploy sensor nodes.

Assume that the complex irregular surface is a square in the XOY plane of the "size" length. The side length of the square area for the directional node projection in the plane is \( d \). We can divide the monitoring scene into \((\text{size}/d) \times (\text{size}/d)\) grids, and deploy \((\text{size}/d) \times (\text{size}/d)\) sensor nodes in the monitoring area. The nodes are placed at the center of each grid, above the uniform height. Under such a deployment, each nodes projection in the XOY plane of its sensing area corresponds to a corresponding divided grid in the XOY plane. Details are shown in Algorithm 1. The time complexity of Algorithm 1 is \( O(m) \), and \( m \) is the number of nodes deployed in the monitoring area.

### 3.2 Surface coverage algorithm based on simulated annealing and local optimum ideas

The problem of surface coverage in directional sensor networks for complex irregular terrains is studied in this paper. In the previous section, a uniform deployment algorithm based on a grid is not optimized for a specific scene. When the number of nodes deployed remains unchanged, there is a lot of room for improvement of the coverage ratio.

Because the sensing perception in sensor networks is for irregular scenes, there will be blind areas between adjacent nodes. We use a simulated annealing algorithm to optimize Algorithm 1. Our simulated annealing algorithm\(^{[22]}\) is based on the theory of solid annealing. A coverage algorithm is designed based on simulated annealing for surface coverage optimization in this section.

In the problem, after Algorithm 1 is implemented, each node has its initial coordinates. The initial coordinates of nodes and control parameter "step" are set at the start, then the iteration of new coordinate generation, calculation of the difference of covered discrete points, judgment of whether node moves continues, and the values of control parameter "step" gradually decay until the stopping criterion is satisfied. Then the current solution is an approximate optimal solution.

Core goal of this algorithm is to select appropriate step to move nodes’ coordinates, if the increased covered discrete points are more than the reduced points due to nodes’ move, the covered discrete number of nodes will be increased, as shown in Figs. 5 and 6. Thus global coverage ratio will be improved. The algorithm details are shown below.

The time complexity of Algorithm 2 is \( O(m^2p) \), \( m \) is the number of nodes deployed in the monitoring area, and \( p \) is the number of iterations of the simulated annealing algorithm for each node. The coordinates of all sensor nodes are optimized in their local area of the monitoring region in Algorithm 2. When the iterative control parameter “step” is set appropriately, Algorithm 2 is better than Algorithm 1 and can improve the target coverage ratio of monitoring scene. But the deviation

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**Algorithm 1** Uniform deployment algorithm based on grid

**Require:**
- The side length of monitoring area “size”, the set of sensor nodes in monitoring area \( D = \{S_1, S_2, \ldots, S_n\} \), and triads representing each node.

**Ensure:**
- The number \( m \) of nodes deployed in the monitoring area, the ratio of the target coverage \( \eta \).

1. \( \text{snum} = \text{int} (\text{size} / d) \);
2. if \((\text{fabs} (\text{snum} \times d - \text{size}) > \epsilon) \) then
3. \( \text{snum} = +1; \)
4. end if
5. \( m = \text{snum} \times \text{snum}; /\!/ \text{get the number} \ m \text{ of nodes} \)
6. for \( i = 1 \) : \( \text{snum} \) do
7. for \( j = 1 \) : \( \text{snum} \) do
8. the \( x \) coordinate for node \( k \) is \( d / 2 + (i - 1) \times d; \)
9. the \( y \) coordinate for node \( k \) is \( d / 2 + (j - 1) \times d; \)
10. determine whether every discrete point is covered by node \( k \) when the projection of the point on the plane is in the projection of node \( k \) in the monitoring area; calculate the number \( Q_k \) of discrete points covered by node \( k \);
11. end for
12. end for
13. calculate the number \( \Omega_d \) of discrete points covered by at least one sensor node;
14. calculate the ratio of the target coverage \( \eta \)

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**Fig. 5** Nodes before adjustment.
Algorithm 2: Optimization algorithm based on simulated annealing

Require:
The side length of monitoring area “size”, the set of sensor nodes in monitoring area $D = \{S_1, S_2, \ldots, S_n\}$, and a triad for each node.

Ensure:
The number $m$ of nodes deployed in the monitoring area, the ratio of the target coverage $\eta$.

1: snum = int(size/d);
2: if (fabs(snnum \times d - size) $>$ eps) then
3:   snum + +;
4: end if
5: $m = nsum \times nsum; // get the number $m$ of nodes
6: for $i = 1 : snum$ do
7:   for $j = 1 : snum$ do
8:     the x coordinate for node $k$ is $d/2 + (i - 1) \times d$;
9:     the y coordinate for node $k$ is $d/2 + (j - 1) \times d$;
10:    determine whether every discrete point is covered by node $k$ when the projection of the point on the plane is in the projection of node $k$ in the monitoring area; calculate the number $Q_k$ of discrete points covered by node $k$;
11: end for
12: end for
13: for $k = 1 : m$ do
14:   initialize the “step”;
15: while step > eps do
16:   assume move node $k$ “step” distance to the four directions of X axis and Y axis, calculate the number $Q_k^1 \cdot Q_k^2 \cdot Q_k^3 \cdot Q_k^4$ of discrete points covered by node $k$ in new locations;
17:   $Q_k' = \max(Q_k^1 \cdot Q_k^2 \cdot Q_k^3 \cdot Q_k^4)$;
18:   if $Q_k' - Q_k > 0$ then
19:     $Q_k = Q_k'$, move node $k$ to the new location;
20:     else if exp($|Q_k' - Q_k|/\text{step}) > \text{random}(0, 1)$ then
21:       $Q_k = Q_k'$, move node $k$ to the new location;
22: end if
23:   step = step/2;
24: end while
25: end for
26: calculate the number $\Omega_d$ of discrete points covered by at least one sensor node;
27: calculate the ratio of the target coverage $\eta$

angle $\theta$ of all nodes is initialized to 0 in Algorithms 1 and 2, without considering its optimization.

We consider the deviation angle on the basis of Algorithm 2 and propose Algorithm 3. The algorithm considers the overlapping area between every node and its adjacent nodes after the coordinates of all the nodes are optimized, changing the deviation angle of the node to increase the covered discrete points by it and its adjacent nodes. Algorithm details are shown in Algorithm 3.

After the optimization of Algorithm 3, the target surface coverage ratio for complex irregular terrains can reach an optimal value when the number of sensor nodes deployed in the current monitoring area is given.

The time complexity of Algorithm 3 is $O(m^2(p + q))$, $m$ is the number of nodes deployed in the monitoring area, $p$ is the number of iterations of the simulated annealing algorithm for each node, and $q$ is the iterations of the angle optimization algorithm for each node.

4 Simulations

In this section, we perform a series of simulation experiments to analyze the performance of the proposed surface coverage algorithms for complex irregular terrains. We use C++ to write our simulation programs.

4.1 Generation of irregular complex 3-D terrain

In this section, we generate irregular complex 3-D terrains. We use the open source 3-D terrain class provided by Ref. [23]. The class cannot only generate an irregular terrain topographic map, but also can set up some of its parameters, such as width of the height map, the smallest possible radius for a hill, the largest possible radius for a hill, the number of hills in the terrain, the power to raise height map values to flatten, whether hills should be positioned to create an island, and height range of the height map.

The parameters of the simulation experiments are shown in Table 1.

The terrain is generated randomly according to parameters in Table 1. It is shown in Fig. 7.

4.2 Performance evaluation

We perform several sets of simulation experiments of the surface coverage for irregular complex 3-D terrains and analyze the data results.

Different numbers of sensor nodes are deployed in the sensing area according to the side length of
Algorithm 3 Algorithm with deviation angle been considered

Require:

The side length of monitoring area “size”, the set of sensor nodes in monitoring area $D = \{S_1, S_2, \ldots, S_n\}$, nodes represented as triads.

Ensure:

The number $m$ of nodes deployed in the monitoring area, the ratio of the target coverage $\eta$.

1: $\text{snnum} = \text{int}(\text{size}/d)$;
2: if $(\text{fabs}(\text{snnum} \times d - \text{size}) > \text{eps})$ then
3:   $\text{snnum} += +$;
4: end if
5: $m = \text{snnum} \times \text{snnum};$ // get the number $m$ of nodes
6: for $i = 1 : m$ do
7:    for $j = 1 : m$ do
8:       the $x$ coordinate for node $k$ is $d/2 + (i-1) \times d$;
9:       the $y$ coordinate for node $k$ is $d/2 + (j-1) \times d$;
10:      determine whether every discrete point is covered by node $k$ when the projection of the point on the plane is in the projection of node $k$ in the monitoring area; calculate the number $Q_k$ of discrete points covered by node $k$;
11: end for
12: end for
13: for $k = 1:m$ do
14:    initialize the “step”;
15:    while step $> \text{eps}$ do
16:       assume move node $k$ “step” distance to the four directions of $X$ axis and $Y$ axis, calculate the number $Q_k', Q_{k'}^1, Q_{k'}^2, Q_{k'}^3, Q_{k'}^4$ of discrete points covered by node $k$ in new locations;
17:       $Q_k' = \max(Q_k^1, Q_k^2, Q_k^3, Q_k^4)$;
18:       if $Q_k' - Q_k > 0$ then
19:          $Q_k = Q_k'$, move node $k$ to the new location;
20:       else if $\exp((Q_k' - Q_k)/\text{step}) > \text{random}(0, 1)$ then
21:          $Q_k = Q_k'$, move node $k$ to the new location;
22:       end if
23:       step = step/2;
24:    end while
25: end for
26: for $k = 1:m$ do
27:    calculate the number cnt of discrete points covered by node $k$ and its all neighbor nodes;
28:    initialize the angle increment variable $y$;
29:    for $i = 0 : y : 2/\pi$ do
30:       calculate the number cnt of discrete points covered by node $k$ and its all neighbor nodes after the $\theta$ is changed;
31:       if cnt $> \text{cnt}$ then
32:          cnt = cnt’, update the deviation angle $\theta$ of node $k$;
33:    end if
34: end for
35: end for
36: calculate the number $\Omega_{\Delta \theta}$ of discrete points covered by at least one sensor node;
37: calculate the ratio of the target coverage $\eta$

Table 1 Parameters of height map.

| Parameter                          | Value       |
|-----------------------------------|-------------|
| Width of the height map           | 256         |
| Smallest possible radius for a hill| 2           |
| Largest possible radius for a hill | 40          |
| Number of hills in the terrain    | 200         |
| Power to raise height map values to flatten | 1          |
| Whether hills should be positioned to create an island | False |
| Height range of the height map    | 0–50        |

Fig. 7 Height map of irregular 3-D terrain.

the square area for node projection. Five sets of experiments are done. The experimental scene is a complex irregular terrain of $256 \times 256 \times 50$ m. The number of nodes and the side length of the square area for the node projection are shown in Table 2.

We use four kind of simulation algorithms for each experiment: (1) random deployment; (2) deployment using Algorithm 1; (3) deployment using Algorithm 2 (initial step $= d/2$ ); (4) deployment using Algorithm 2 (initial step $= 0.5$ ). Experimental results are shown in Fig. 8.

Setting the side length of square area $d$ to 8, the experimental results of the four algorithms are shown in Figs. 9–12.

Algorithm 1 performs better than random deployment, no matter what the side length of the
square area for the node projection is from Fig. 8. There is a clear connection between the deployment results and the initial “step” of Algorithm 2. When the value of the initial “step” is set large and the side length of square area for node projection $d$ is also large, the sensing area coverage is not ideal. When the “step” is too large, the moving distance for the node is generally large. This makes it easy to produce many overlapping coverage areas after optimization by moving the nodes. Then the overall ratio of target coverage for monitoring area is greatly reduced. When the initial “step” is set appropriately, the overall ratio of target coverage is still improved by Algorithm 1, and the results are satisfying.

Using Algorithm 2 (initial “step” $= 0.5$) to deploy nodes, and then using Algorithm 3 (initial angle increment variable $\gamma = 0.1^\circ$) to adjust nodes for the coverage optimization problem, we get the results shown in Table 3.

We can know that the number of covered discrete points can be increased by about 100 points, and the coverage ratio can be increased by about 0.15%, after optimization with Algorithm 3, compared with Algorithm 2 optimization, from Table 3. Algorithm 3 can further improve the overall ratio of target coverage for the monitoring area.

For Algorithm 3, we set the initial “step” at 0.5, and set the different angle increment variable $\gamma = 1^\circ$ and $\gamma = 0.1^\circ$ to optimize the coverage problem. The comparison of results is shown in Table 4. From Table 4, we know that when the node size and the initial “step” are determined, the angle increment variable has an effect on the optimization of the coverage. When $\gamma$ is smaller, the coverage ratio is higher.
Table 3 Comparison between Algorithms 2 and 3.

| Side length of square area $d$ | Number of nodes $m$ | Coverage ratio by Algorithm 2 (%) | Number of covered discrete points by Algorithm 2 | Coverage ratio by Algorithm 3 (%) | Number of covered discrete points by Algorithm 3 |
|-------------------------------|---------------------|-----------------------------------|-----------------------------------------------|-----------------------------------|-----------------------------------------------|
| 4                            | 4096                | 99.54                             | 65235                                         | 99.76                             | 65379                                         |
| 8                            | 1024                | 95.76                             | 62757                                         | 95.93                             | 62869                                         |
| 16                           | 256                 | 87.32                             | 57226                                         | 87.47                             | 57324                                         |
| 32                           | 64                  | 85.01                             | 55712                                         | 85.16                             | 55810                                         |
| 64                           | 16                  | 86.33                             | 56577                                         | 86.41                             | 56630                                         |

Table 4 Comparison between different angle increments in Algorithm 3.

| Side length of square area $d$ | Number of nodes $m$ | Coverage ratio by Algorithm 3 for $\theta = 1^\circ$ (%) | Coverage ratio by Algorithm 3 for $\theta = 0.1^\circ$ (%) |
|-------------------------------|---------------------|----------------------------------------------------------|----------------------------------------------------------|
| 4                            | 4096                | 99.70                                                    | 99.76                                                    |
| 8                            | 1024                | 95.87                                                    | 95.93                                                    |
| 16                           | 256                 | 87.42                                                    | 87.47                                                    |
| 32                           | 64                  | 85.11                                                    | 85.16                                                    |
| 64                           | 16                  | 86.37                                                    | 86.41                                                    |

5 Conclusion

This paper studies the problem of surface coverage in directional sensor networks for complex 3-D terrains. Addressing the problem of overlapping and blind node perception areas in directional sensor networks, an improved 3-D directional sensing model of sensor nodes is proposed. Three kinds of surface coverage algorithms are proposed to enhance coverage for complex 3-D terrains. A series of simulation experiments verify the validity of our algorithms.

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