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Design of Moving Coverage Algorithm of Ecological Monitoring Network for Curved Surface

Song Liu, Runlan Zhang, Yongheng Shi

Song Liu
Key Laboratory of Information, Computing Science, Guizhou Normal University
Guiyang 550001, China

Runlan Zhang
Information Technology College, Guizhou Vocational Technology Institute
Guiyang 550023, China
Corresponding author: rlzhang@gztvu.cn

Yongheng Shi
Information Technology College, Guizhou Vocational Technology Institute
Guiyang 550023, China

Abstract

Micro-structured sensors that can perceive and communicate at the same time have emerged as a result of the quick growth of microelectronics technology, wireless communication technology, and sensor technology. This sensor has the ability to sense many types of environmental data, gather it at the sink node, and then send it to the data centre. In the civic, industrial, agricultural, military, and other domains, wireless sensor networks are frequently employed. According to the needs of curved surface ecological monitoring such as grasslands, wetlands, deserts, coastal beaches, a virtual force model of moving coverage of curved surface ecological monitoring network is presented, and a moving coverage algorithm of curved surface ecological monitoring network is given. The moving coverage algorithm of curved surface ecology monitoring network, by the virtual force between sensor nodes in the ecological monitoring network, push the sensor nodes to the uncovered area on the monitored surface, and repairs the monitoring blind zone on the monitored surface. To confirm the effectiveness of moving coverage algorithm of curved surface ecological monitoring network, the moving coverage process of the moving coverage algorithm of the ecological monitoring network is simulated. The simulation results show that the moving coverage algorithm proposed in this paper can accurately locate the monitoring blind zone of the ecological monitoring network and push the sensor nodes to the monitoring blind zone for coverage, and effectively improve the coverage of the ecological monitoring network on the monitored surface. The coverage ratio of node deployment phase can reach 85%∼90%, and the final coverage ratio is more than 95%.

Keywords: mobile sensor network; curved surface; coverage; algorithm; simulation.

1 Introduction

The ecological monitoring of curved surfaces, such as grasslands, wetlands, deserts, coastal beaches, can be achieved by a mobile sensor network composed of self-moving vehicles (ships) or unmanned aerial vehicles loaded with ecological monitoring sensors. The curved surface ecological monitoring network consists of several mobile sensor nodes, each of which can monitor the ecological environment around the sensor nodes, collect the ecological environment data around the sensor nodes, and transmit them to the convergence node of the monitoring network. In addition, the ecological monitoring network will also monitor specific targets in the monitored surface through the movement of sensor nodes, so as to continuously and comprehensively monitor the monitored surface [1, 2].

In recent years, the research on coverage control in mobile sensor networks mainly focuses on two-dimensional planar coverage algorithm and three-dimensional spatial coverage algorithm, and many research results have been achieved. Among them, the representative planar coverage algorithms include: Decentralized algorithm for maximizing coverage and lifetime [3], Sweep coverage optimization algorithm [4], Mobile-aware path selection algorithm [5], Improved virtual force relocation coverage enhancement algorithm [6], Hole-healing improved algorithm for mobile sensor networks [7], Redundant hole identification and healing algorithm for homogeneous distributed wireless sensor network [8], and so on. Recent researches on three-dimensional coverage include: Sensor deployment for target coverage in under water mobile sensor network [9], 3D coverage algorithm with adjustable radius [10], Three-dimensional coverage algorithm with multiple moving nodes [11], Three-dimensional spatial target autonomous coverage algorithm [12], Mountainous 3D ring fence coverage algorithm for wireless sensor network [13], Underwater 3D sensor network coverage algorithm based on vertical sampling [14], 3D wireless sensor network coverage enhancement method based on particle swarm optimization algorithm [15], and so on.

For mobile sensor networks deployed in curved surface, the two-dimensional planar coverage algorithm cannot guarantee that the network can cover the entire monitoring surface. Three-dimensional spatial coverage algorithms are based on full-space mobile coverage, which is effective for sensor networks deployed in air or water, and not fully applicable for curved surface full coverage. For mobile sensor networks of curved surface ecological monitoring, the sensor nodes are not spatially distributed, and the monitoring surface of the network is closer to the three-dimensional surface. Unlike two-dimensional or three-dimensional coverage, moving coverage on curved surface considers not only the horizontal position of sensor nodes, but also the spatial height of sensor nodes. Since the sensor node moves on a curved surface, the trajectory of the sensor node changes with the change of the curved surface terrain.

2 Related Work

In recent research on node deployment and mobile control of mobile sensor networks, under certain conditions, some coverage algorithms can also be used for curved surface coverage of mobile sensor networks, such as Sparrow Search Algorithm [16], Flower Pollination Algorithms [17], Fusion Coverage Algorithm [18], Enhanced Sparrow Search Algorithm [19], Improved Particle Swarm Algorithm [20], and so on. Unlike the design ideas of these coverage algorithms, this paper uses an improved virtual force method to construct a curved surface coverage algorithms for mobile sensor networks in order to make curved surface ecological monitoring more convenient and effective.

Coverage by robots Path planning, or the process of having one or more robots completely traverse a specified area, is a well-known issue in the field of robotics and motion planning. Such planning aims to give almost complete coverage while also reducing areas that are visited twice. In this study, we concentrate on the path planning scenario on general surface, which includes general surface in 3D space, complex terrain, and planar domains with complex topology [26]. Micro-structured sensors that can perceive and communicate at the same time has emerged as a result of the quick growth of micro - electronic technology, wireless communication technology, and sensor technology. This sensor has the ability to sense many types of environmental data, gather it at the sensor nodes, and then send this to the data centre. In the civic, industrial, agricultural, military, and other domains, wireless sensor networks are frequently employed [27].

Considering that most of the existing coverage algorithms cannot be directly applied to moving coverage of curved surfaces, in this paper, according to the needs of curved surface ecological monitoring such as grassland, wetland, desert, coastal beach, the virtual force model of curved surface ecological monitoring network for moving coverage will be built, and the moving coverage algorithm of curved surface ecological monitoring network will be designed. To confirm the effectiveness of the moving coverage algorithm for curved surface ecological monitoring network, the moving coverage process of the moving coverage algorithm of the ecological monitoring network will be simulated.

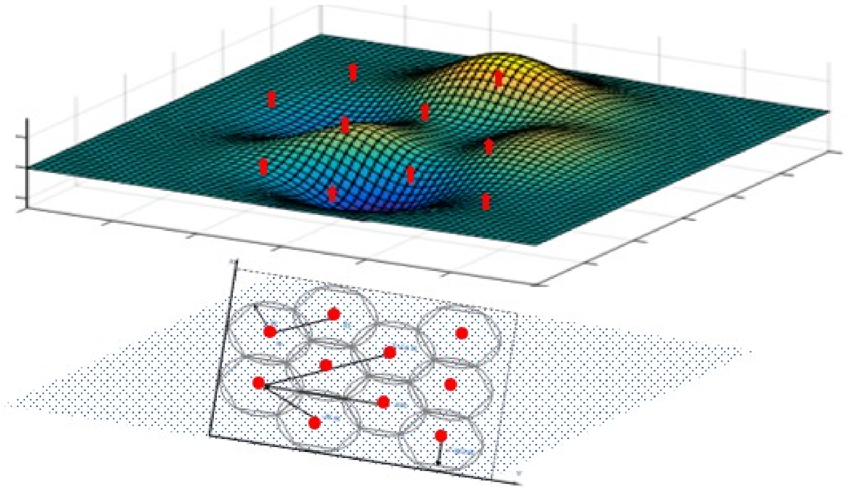

Figure 1: Schematic diagram of moving coverage of ecological monitoring network

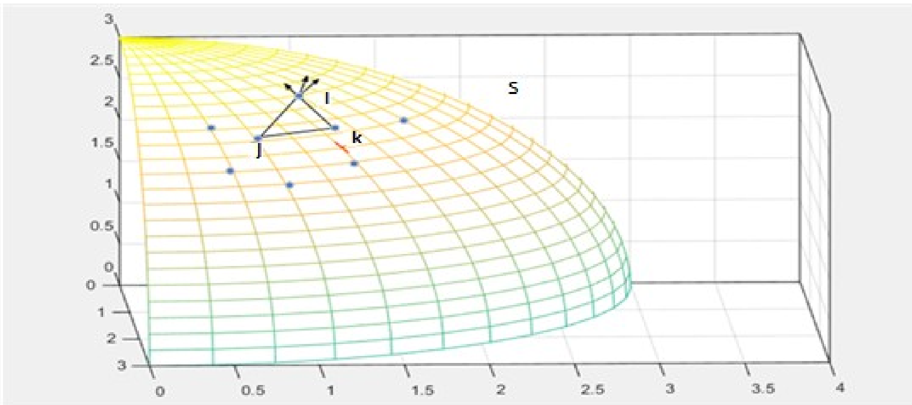

Figure 2: Force model of sensor nodes on curved surface

3 Virtual Force Model for Moving Coverage

A mobile sensor network for ecological monitoring needs to be deployed in the monitored surface in order to fully monitor the ecology of curved surfaces such as grasslands, wetlands, deserts and coastal beaches. A curved surface ecological monitoring network contains several mobile sensor nodes. Each sensor node can monitor the ecological environment around the sensor node, collect the ecological environment data around the sensor node, and transmit them to convergence node of the ecological monitoring network. In addition, the curved surface ecological monitoring network will also monitor specific targets in the monitored surface through the movement of sensor nodes, so as to continuously and comprehensively monitor the monitored surface.

It is assumed that there is some virtual repulsion or suction between the sensor nodes of the curved surface ecological monitoring network. The resultant force of this virtual force acts against the sensor nodes on the network monitoring surface, driving them to move along the monitored surface to cover the monitoring blind zone. Accordingly, the virtual force model of moving coverage of curved surface ecological monitoring network will be established [21].

It is assumed that the curved surface ecological monitoring network has several sensor nodes deployed on the monitored surface shown in Figure 1. Under the continuous action of virtual repulsion or suction, the sensor nodes are moved and positioned to reach their virtual force balance positions, forming the coverage status shown in Figure 1. In this state, the area that the ecological monitoring network can monitor is relatively large and the monitoring blind zones are relatively small.

Set a ecological monitoring network with n nodes is distributed over S-surface, as shown in Figure 2. Any two nodes $i, j \in \{1, 2, \cdots, n\}, i \neq j$ on an S-surface intersect a plane with an S-surface through i, j to obtain a curve S_{ij}. Set the curve distance from j to i to d_{ij} and the normal vector of S-surface at node i to $\overrightarrow{n}_i$, the tangent vector of the curve S_{ij} at node i is $\overrightarrow{e}_{ij}$, the direction is from the j node to the i node. The force $\overrightarrow{VF}_{ij}$ exerted by the j node on the i node can be calculated as equation (1).

$$\overrightarrow{VF}_{ij} = \begin{cases} \frac{{d_{ij}}^{a} - \left(\sqrt{3}R\right)^{a}}{{d_{ij}}^{a}} \cdot \overrightarrow{e}_{ij}, & d_{ij} \le \sqrt{3}R \\ e^{\sqrt{3}R - d_{ij}} \cdot \sin\frac{3R - d_{ij}}{\left(3 - \sqrt{3}\right)R}\pi \cdot \overrightarrow{e}_{ij}, & \sqrt{3}R < d_{ij} \le 3R \\ e^{\sqrt{3}R - d_{ij}} \cdot \sin\frac{d_{ij} - 3R}{\left(2\sqrt{3} - 3\right)R}\pi \cdot \overrightarrow{e}_{ij}, & 3R < d_{ij} \le 2\sqrt{3}R \\ e^{\sqrt{3}R - d_{ij}} \cdot \overrightarrow{e}_{ij}, & d_{ij} > 2\sqrt{3}R \end{cases} \tag{1}$$

In equation (1), $\alpha\,(\alpha \ge 1)$ is the coefficient of gravitation; R is perception radius of sensor nodes. For a ecological monitoring network with n nodes, the sum of the forces exerted by other nodes on node i is $\sum_{j=1,i\neq j}^{n} \overrightarrow{VF}_{ij}$.

Set B_j as the j-th border or impediment the monitored surface of the ecological monitoring network, d_{Bj} is the shortest surface distance from sensor node i to B_j, and $\overrightarrow{VF}_{iBj}$ is the repulsion of the j-th border or impediment in the monitored surface to sensor node i. By equation (2), $\overrightarrow{VF}_{iBj}$ can be calculated [22].

$$\overrightarrow{VF}_{iBj} = \begin{cases} \frac{\left(\frac{\sqrt{3}R}{2}\right)^{ff} - {d_{iBj}}^{\alpha}}{{d_{iBj}}^{\alpha}} \cdot \overrightarrow{e}_{iBj}, & d_{iBj} \le \frac{\sqrt{3}R}{2} \\ 0, & d_{iBj} > \frac{\sqrt{3}R}{2} \end{cases} \tag{2}$$

In equation (2), B_j is the j-th border or impediment on the monitored surface, and $\overrightarrow{e}_{iBj}$ is the unit repulsion vector of B_j acting on sensor node i. $\vec{n}_i$ is the normal vector of sensor node i on the S-surface, and $\overrightarrow{e}_{iBj}$ is perpendicular to $\vec{n}_i$. If the number of borders or impediments in the monitored surface is m, for the sensor node i, the sum of the repulsion forces of borders or impediments in the monitored surface is $\sum_{j=1}^{m} \overrightarrow{VF}_{iBj}$.

To sum up, for an ecological monitoring network with n nodes deployed, the total force suffered by the sensor node i in the network can be calculated as equation (3).

$$\overrightarrow{VF}_i = \sum_{j=1,i\neq j}^{n} \overrightarrow{VF}_{ij} + \sum_{j=1}^{m} \overrightarrow{VF}_{iBj}, i \in \{1, 2, \cdots, n\} \tag{3}$$

4 Moving Coverage Algorithm

According to the virtual force model of moving coverage of curved surface ecological monitoring network, we propose the following moving coverage algorithm of curved surface ecological monitoring network [21, 23].

Assume that in the initial state, $\overrightarrow{VF}_{i0}$ is the force exerted on sensor node i in the network monitoring surface, and $\overrightarrow{L}_{i0}$ is the position vector of sensor node i relative to the coordinate origin. Under the action of $\overrightarrow{VF}_{i0}$, sensor node i moves for the first time, and its position vector is $\overrightarrow{L}_{i1} = \overrightarrow{L}_{i0} + v \cdot \Delta t \cdot \frac{\overrightarrow{VF}_{i0}}{\overrightarrow{VF}_{i0}}$. Then, under the action of $\overrightarrow{VF}_{i(r-1)}$, sensor node i moves $r (r > 1)$ times, and its position vector is $\overrightarrow{L}_{ir}$:

$$\overrightarrow{L}_{ir} = \overrightarrow{L}_{i(r-1)} + \Delta\overrightarrow{L}_{i(r-1)} = \overrightarrow{L}_{i0} + \sum_{j=0}^{r-1} \Delta\overrightarrow{L}_{ij}, i \in \{1, 2, \cdots, n\} \tag{4}$$

After several times of movement, when the force on each sensor node in the curved surface ecological monitoring network has been small enough, it can be considered that each sensor node has moved to a suitable position on the monitored surface. At this time, the movement of sensor nodes of the ecological monitoring network can be stopped and the moving coverage of the ecological monitoring network is completed [24].

The moving coverage process of the curved surface ecological monitoring network consists of the following 7 steps.

(1) Set $r = 0$, given the initial position vectors of sensor nodes:

$$\vec{L}_{10},\ \vec{L}_{20},\ \cdots,\ \vec{L}_{n0};$$

(2) Based on the sensor node position vector, the distances between sensor nodes are calculated respectively: $\vec{d}_{(i,j)r} = \vec{L}_{ir} - \vec{L}_{jr}, i, j \in \{1, 2, \cdots, n\}, i \neq j$;

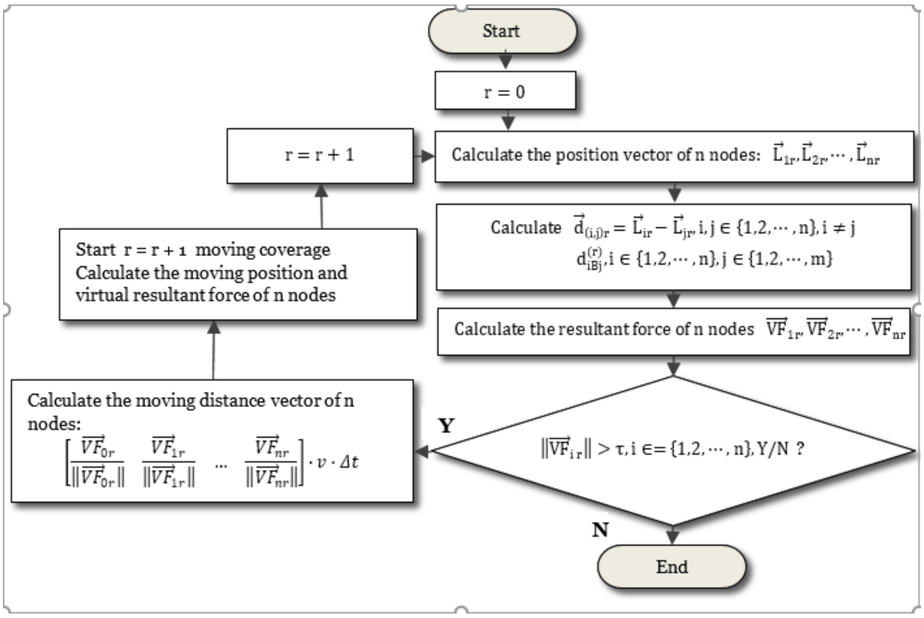

Figure 3: Computational flow diagram of moving coverage algorithm

(3) Based on the sensor node position vector, the distance of sensor nodes to border or impediment in the monitored surface are calculated:

$$d_{iBj}^{(r)}, i \in \{1, 2, \cdots, n\}, j \in \{1, 2, \cdots, m\};$$

(4) According to equation (3), the resultant forces of sensor nodes are calculated:

$$\overrightarrow{VF}_{1r}, \overrightarrow{VF}_{2r}, \cdots, \overrightarrow{VF}_{nr};$$

(5) If $\overrightarrow{VF}_{ir} > ø$, $i \in \{1, 2, \cdots, n\}$, turn (6);
Otherwise, the nodes stop moving, and the moving coverage process end.

(6) Calculate the moving distance vector of sensor nodes:

$$\left[\frac{\overrightarrow{VF}_{0r}}{\overrightarrow{VF}_{0r}} \quad \frac{\overrightarrow{VF}_{1r}}{\overrightarrow{VF}_{1r}} \quad \cdots \quad \frac{\overrightarrow{VF}_{nr}}{\overrightarrow{VF}_{nr}} \right] \cdot v \cdot \Delta t;$$

(7) Set $r = r+1$, according to equation (4), calculates the new position vector of sensor nodes: $\vec{L}_{1r}, \vec{L}_{2r}, \cdots, \vec{L}_{nr}$. turn (2).

The Computational flow diagram of moving coverage algorithm of curved surface ecological monitoring network is shown in Figure 3.

5 Simulation Experiment

To confirm the effectiveness of moving coverage algorithm of curved surface ecological monitoring network, the moving coverage process of the moving coverage algorithm of ecological monitoring network is simulated by using MATLAB simulation tool [21, 25].

5.1 Impediment-Free Moving Coverage

Simulation conditions: The curved surface ecological monitoring network consists of 30 sensor nodes. At the beginning of the simulation, all nodes are randomly deployed on the saddle surface with the spatial surface equation $z = (x^2 + y^2)/18^2$, and the monitored surface is limited to 0-25m, that is, $0 \le x \le 25$, $0 \le y \le 25$. Sensor node perception radius is 3m.

Figures 4 and 5 show the moving trajectory of sensor nodes of the curved surface ecological monitoring network. Here, Figure 4 shows the moving trajectory of sensor nodes on the network monitoring surface, while

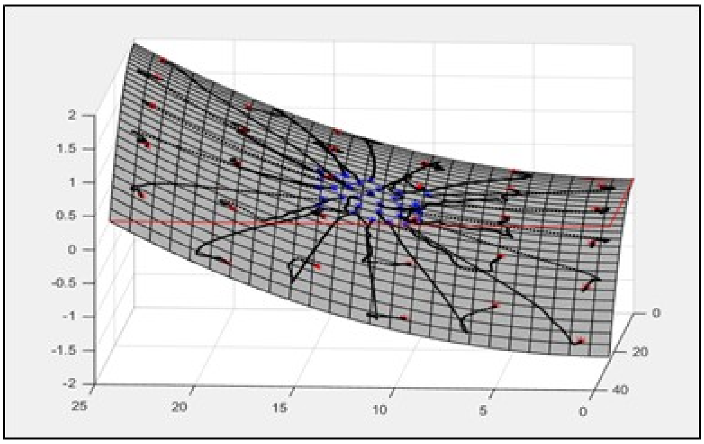

Figure 4: Trajectory of moving coverage of sensor nodes

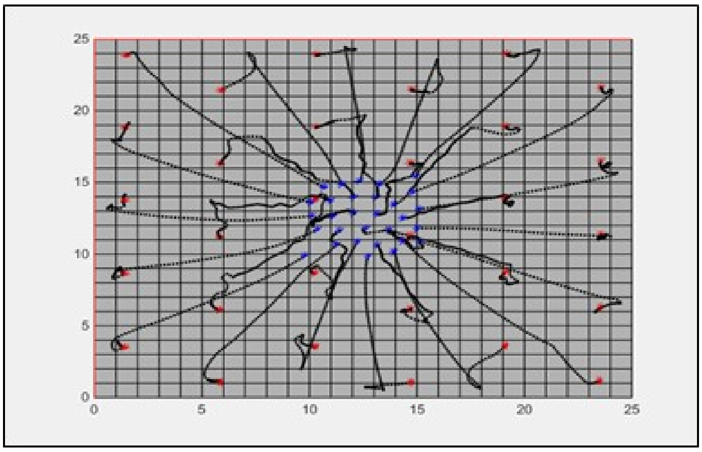

Figure 5: Horizontal projection of moving coverage trajectory of sensor nodes

Figure 5 shows the projection of the moving trajectory of sensor nodes on the network monitoring surface on horizontal plane. As shown in Figures 4 and 5, at the beginning of the simulation, the sensor nodes of the ecological monitoring network are randomly distributed in the center of the monitored surface. During the node deployment phase, the sensor nodes begin to move, and driven by repulsion, the sensor nodes quickly spread around the monitored surface. During the node positioning phase, the sensor nodes approach the balanced position, and there will be position fluctuations of different magnitudes to adjust each sensor node to reach the balanced position with the largest coverage area.

Figure 8 shows the change of coverage ratio of the curved surface ecological monitoring network during moving coverage. As shown in Figure 8, During the node deployment phase, coverage increases rapidly, after 16 moves, the coverage ratio reaches 90%. During the node positioning phase, the network nodes adjust and correct near the balance position on the monitoring surface, coverage increases slowly, after 28 moves, the coverage ratio reaches 98.5%, and the moving coverage process of the curved surface ecological monitoring network can be ended.

5.2 Moving Coverage with Impediment

The moving coverage algorithm of curved surface ecological monitoring network proposed in this paper can be applied to the situation that there are impediments in the network monitoring surface.

The simulation conditions are the same as Section 4.1, the curved surface ecological monitoring network contains 30 sensor nodes, sensor node perception radius is 3m, and the monitored surface is limited to $0 \sim 25$m. As shown in Figures 6 and 7, 7.5m × 5.5m rectangular impediment is set at the lower left corner of the network monitoring surface.

Figure 6 is the moving track of sensor nodes on the monitored surface with impediment, while Figure 7 shows the projection of the moving trajectory of sensor nodes on the monitored surface with impediment on horizontal plane. As shown in Figure 6 and 7, during the node deployment phase, driven by the virtual repulsion between the sensor nodes of the ecological monitoring network, the sensor nodes move quickly to

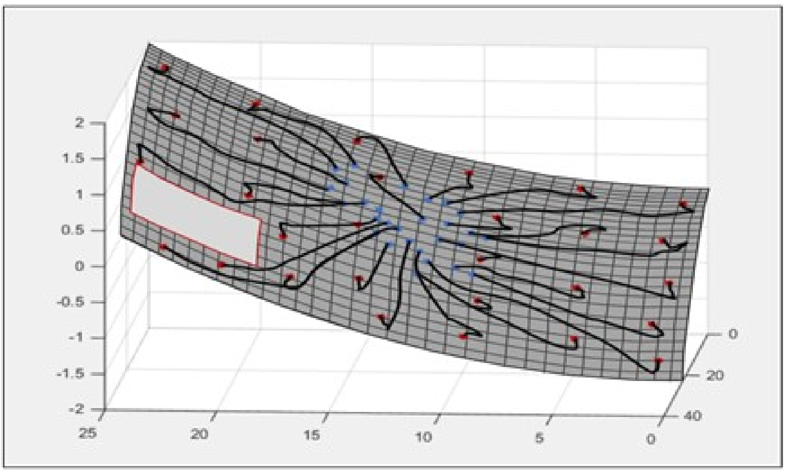

Figure 6: Trajectory of moving coverage of sensor nodes (with impediment)

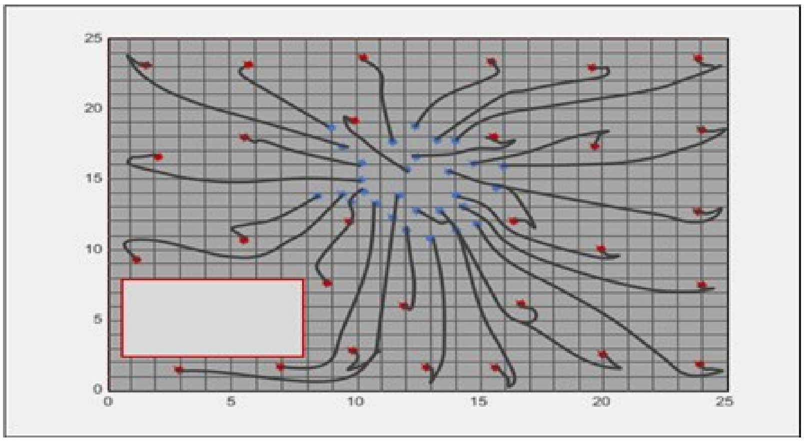

Figure 7: Horizontal projection of moving coverage trajectory of sensor nodes (with impediment)

the balance position nearby. During the node positioning phase, the network nodes adjust and correct near the balance position on the monitored surface. When the sensor node approaches the border or impediment of the monitored surface, driven by the virtual repulsion of the border or impediment, the sensor node will turn back to the nearby balanced position.

As shown in Figure 8, the moving coverage process of the monitored surface with impediments is different from that of the monitored surface without impediments. Due to the influence of impediments, the number of mobile location adjustment of sensor nodes near impediments will be increased, the moving coverage efficiency will be reduced, and the network coverage will be reduced. As shown in Figure 8, after 16 moves, the coverage ratio is 85%, after 28 moves, the coverage ratio is 95%, and after 30 moves, the coverage ratio is only 96%.

The simulation shows that whether there are impediments on the monitored surface or not, the movement of sensor nodes in the surface ecological monitoring network is "fast in front and slow in back". During the node deployment phase, the sensor nodes begin to move, and driven by repulsion, the sensor nodes quickly spread around the monitored surface. During the node positioning phase, the sensor nodes approach the balanced position, and there will be position fluctuations of different magnitudes to adjust each sensor node to reach the balanced position with the largest coverage area. In addition, the simulation results also show that the moving coverage algorithm of the curved surface ecological monitoring network can accurately locate the monitoring blind zone of the ecological monitoring network on the monitored surface, and push the sensor node to the monitoring blind zone for coverage, which effectively improve the coverage of the ecological monitoring network. During the node deployment phase, after about 15 moves, the coverage ratio reaches 85%∼90%. At the end of the mobile coverage (about 30 moves), the coverage ratio reaches 95% or more.

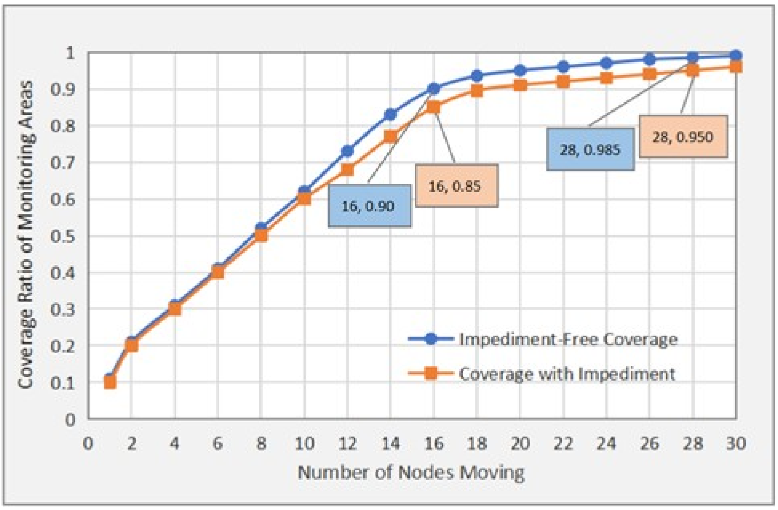

Figure 8: Change of the coverage ratio in network monitoring surface

6 Conclusion

The ecological monitoring of curved surfaces, such as grasslands, wetlands, deserts, coastal beaches, can be achieved by a ecological monitoring network composed of self-moving vehicles (ships) or unmanned aerial vehicles loaded with ecological monitoring sensors. For ecological monitoring networks deployed in curved surface, the two-dimensional planar coverage algorithm cannot guarantee that the network can effectively cover the entire monitored surface. Three-dimensional spatial coverage algorithms are based on moving coverage in full space and are not suitable for ecological monitoring of full coverage on curved surface. For the curved surface ecological monitoring network, the sensor nodes are not spatially distributed, and the monitored surface of the ecological monitoring network is closer to the three-dimensional surface. Moving coverage on a three-dimensional surface considers not only the horizontal position of the sensor nodes, but also the spatial height of the sensor nodes.

According to the needs of curved surface ecological monitoring such as grasslands, wetlands, deserts, coastal beaches, a virtual force model of curved surface ecological monitoring network for moving coverage is constructed, and a moving coverage algorithm for curved surface ecological monitoring network is presented. The moving coverage algorithm of curved surface ecological monitoring network, by the virtual force between sensor nodes in the monitoring network, push the sensor nodes to the uncovered area on the monitored surface, and repairs the monitoring blind zone on the monitored surface, so as to improve the coverage of ecological monitoring network on the monitored surface.

To confirm confirm the effectiveness of the moving coverage algorithm of curved surface ecological monitoring network, the moving coverage process of the coverage algorithm of curved surface ecological monitoring network is simulated and analyzed. The simulation results show that the moving coverage algorithm of the curved surface ecological monitoring network proposed in this paper can accurately locate the monitoring blind zone of the ecological monitoring network on the monitored surface, and push the sensor nodes to the monitoring blind zone for coverage, which effectively improve the coverage of the ecological monitoring network on the monitored surface. The coverage ratio of node deployment phase can reach 85%∼90%, and the final coverage ratio is more than 95%.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflict of interest

The authors declare no conflict of interest.

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