



COVERAGE HOLES RECOVERY ALGORITHM BASED ON NODES BALANCE DISTANCE OF UNDERWATER WIRELESS SENSOR NETWORK

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Abstract-Underwater wireless sensor network nodes deployment optimization problem is studied and underwater wireless sensor nodes deployment determines its capability and lifetime. Underwater wireless sensor network if no wireless sensor node is available in the area due to used up energy or any other reasons, the area which is not detected by any wireless sensor node forms coverage holes. The coverage holes recovery algorithm aiming at the coverage holes in wireless sensor network is designed in this article. The nodes movement is divided into several processes, in each movement process according to the balance distance and location relations move nodes to separate the aggregate nodes and achieve the maximum coverage of the monitoring area. Because of gradually increasing the balance distance between nodes, in each movement process the nodes moving distance is small and reduce the sum of the nodes movement distance. The simulation and experimental results show that this recovery algorithm achieves the goal of the nodes reasonable distribution with improving the network coverage and reducing the nodes movement distance thus extends the lifetime of the network in the initial deployment phase and coverage holes recovery phase.

Index terms: Coverage Holes Recovery, Nodes Balance Distance, Wireless Sensor Network.

I. INTRODUCTION

With low power radio communication technology, embedded computing technology and the rapid development of micro sensors technology, a lot of tiny low-cost wireless sensor nodes through wireless self-organizing mode of wireless sensor network to get more and more widely used [1, 2]. Wireless sensor network (WSN) is a multidisciplinary cross frontier research topic in the military, industrial, medical, transportation and civil has a broad application prospect [3, 4].

Underwater wireless sensor network (UWSN) is widely used in ocean information data collection, marine monitoring, marine pollution monitoring, marine disaster prevention, underwater aided navigation, marine resources exploration, battlefield surveillance, mine detection, underwater target detection, tracking and positioning, and other fields thus underwater wireless sensor network causes widely attention and has become one of the current research hotspot [5, 6]. Based on underwater wireless sensor networks, communication protocol [7, 8] (routing algorithm, the locating and tracking, etc.) of a large amount of research has been conducted, but in view of the underwater wireless sensor nodes deployment optimization research progress is slow [9, 10]. Underwater wireless sensor nodes deployment particularity compared with onshore wireless sensor nodes deployment, the underwater environment is complicated, the goal and the mobile wireless sensor nodes frequently moving with the water flow, therefore how to according to the variation of the underwater environment and for monitoring target adjust the position of the sensor nodes make monitoring effect improved is a worth studying direction [11, 12].

Domestic and foreign scholars have carried out studies to optimize the nodes deployment of wireless sensor network [13, 14]. In order to optimize the movement of the sensor nodes, through using artificial intelligence algorithms such as the differential evolution algorithm [15, 16], the artificial bee colony algorithm [17, 18], the steady state genetic algorithm [19, 20], the fuzzy graph theory algorithm [21, 22], the fuzzy logic controller algorithm [23, 24], the particle swarm optimization algorithm [25, 26] to improve the coverage effect of the network. The deployment algorithms need a lot of iterations calculated thus they own a higher degree of complexity of the algorithm therefore the wireless sensor network nodes need to move the larger distance and consume the more energy. The references [27, 28] introduce wireless sensor nodes deployment algorithm based on virtual force, these algorithms can quickly and efficiently layout optimization of wireless sensor nodes. The movement solutions obtained by the mutual positional relationship

between nodes but the nodes density greater impacts the movement solutions and can't reach the global optimization purposes [29, 30].

Because of the wireless sensor network node energy depletion or other reasons the area which is not covered by any node forms "empty holes" in the target area. How to repair the holes is also a hot research topic. A cover holes repair algorithm based on distance between nodes aiming at covering the holes in the monitoring area is designed in this article. The movement process is decomposed into multiple parts and the wireless sensor nodes coverage as the optimization goal. The wireless sensor node is gradually moving to the right position by increasing the balance of the distance between nodes and improves the network coverage at the same time reduces the moving distance of wireless sensor nodes.

II. RELATED WORKS

The sensing range of each wireless sensor node is limited in the monitored area thus needs to reasonable deploy wireless sensor node according to certain algorithms in order to ensure that the entire area to be monitored within the sensing range in the monitored area.

The position of wireless sensor nodes after randomly deployed is uncertainty in the wireless sensor network coverage problem about mobile wireless sensor nodes and in many cases can't satisfy the requirement of goals.

The mobile wireless sensor nodes moves based on targets in order to improve the coverage effect of wireless sensor network.

The movement processes consume a lot of energy, so reasonable adjust the location of wireless sensor nodes and reduce the movement distance of wireless sensor nodes thereby reduce the consumption energy of wireless sensor network.

2.1 Assumption

To simplify the calculation, randomly deploy the quantity N of the same mobile nodes in the monitored region and mobile wireless sensor node s_j owns wireless sensor network ID number j .

The same wireless sensor nodes in the network own the same sensing radius R_s , the same communication radius R_c , and $R_c=3R_s$.

The wireless sensor node can obtain the location information of itself and its neighbor nodes.

The mobile node owns E_{ini} initial energy and is sufficient to support the completion of the mobile node position migration process.

The mobile node sending 1 byte data consumes E_s energy and receiving 1 byte data consumes E_r energy.

The mobile node migration 1 meter consumes E_m energy.

The distance between the node s_a and the node s_b is $d(s_a, s_b)$.

The time length of the number k movement process is t_k .

The balance distance between the two wireless sensor nodes of the number k movement process is d_k .

Where $d_1 < d_2 < d_3 < \dots < d_k < \dots < d_M$.

2.2 Coverage Model

The monitored area owns $A \times B \times C$ pixels which means that the size of each pixel is the $\Delta x \times \Delta y \times \Delta z$.

The perceived probability of the i-th pixel is perceived by the wireless sensor network is $P(p_i)$, when $P(p_i) \geq P_{th}$ (P_{th} is the minimum allowable perceived probability for the wireless sensor network), the pixels can be regarded as perceived by the wireless sensor network.

The i-th pixel is whether perceived by the wireless sensor node perceived to be used $P_{cov}(P_i)$ to measure, i.e.

$$P_{cov}(p_i) = \begin{cases} 0 & \text{if } P(p_i) < P_{th} \\ 1 & \text{if } P(p_i) \geq P_{th} \end{cases} \quad (1)$$

This article defined the coverage rate is the perceived area and the sum of monitoring area ratio, i.e.

$$R_{area} = \frac{P_{area}}{S_{area}} = \frac{\Delta x \times \Delta y \times \Delta z \times \sum_{x=1}^A \sum_{y=1}^B \sum_{z=1}^C P_{cov}(p_i)}{\Delta x \times \Delta y \times \Delta z \times A \times B \times C} \quad (2)$$

Where, P_{area} is the perceived area while S_{area} is the sum of monitoring area.

2.3 Perceived Model

This article defined the event that the i-th pixel p_i is perceived by the ID number j wireless sensor nodes is r_{ij} and the probability of occurrence of the event is $P(r_{ij})$ which is the perceived probability $P(p_i, s_j)$ that the pixel p_i is perceived by wireless sensor node s_j , i.e.

$$P(p_i, s_j) = \begin{cases} 1 & \text{if } d(p_i, s_j) \leq R_s - R_e \\ \ln\left\{1 - \frac{e-1}{2R_e} [d(p_i, s_j) - R_s - R_e]\right\} & \text{if } R_s - R_e < d(p_i, s_j) < R_s + R_e \\ 0 & \text{if } d(p_i, s_j) \geq R_s + R_e \end{cases} \quad (3)$$

Where, the $d(p_i, s_j)$ is the distance between the i -th pixel p_i and the j -th wireless sensor node s_j , the sensing radius of the k -th type wireless sensor node is R_s , the perceived error range of the k -th type wireless sensor node is R_e .

A number of wireless sensor nodes cooperative sensing monitoring method is used in this article and the pixel p_i is perceived by all wireless sensor nodes collaborate perceived probability is

$$P(p_i) = 1 - \prod_{j=1}^N [1 - P(p_i, s_j)] \quad (4)$$

III. ALGORITHM DESCRIPTION

Assuming the wireless sensor nodes are the particulates in the electric field and exist the electric force between the wireless sensor nodes, and move the wireless sensor nodes under the action of the electric force as evenly as possible in order to achieve a reasonable distribution of wireless sensor network in order to improve the coverage effect of the targets in the monitoring area.

3.1 Virtual Force Algorithm

If the distance between the two wireless sensor nodes is too far, the attractive force will play a major role and make the two nodes close to each other. If the distance between the two wireless sensor nodes is too close, the repulsion force will play a major role and make the two nodes separate from each other.

Through calculating the distance $d(s_i, s_j)$ between the two nodes s_i and s_j determines the mobile wireless sensor nodes how to move.

The repulsion $F(p_i, s_j)$ of wireless sensor node s_i to wireless sensor node s_j can be represented as:

$$F(s_i, s_j) = \begin{cases} \frac{k_1}{d(s_i, s_j)^{\alpha_1}} & 0 < d(s_i, s_j) < R \\ 0 & d(s_i, s_j) \geq R \end{cases} \quad (5)$$

Where, k_1 , α_1 is the gain coefficient, $d(s_i, s_j)$ is the distance between the two nodes s_i and s_j , R is the effective distance.

The direction of the force is composed of wireless sensor node s_i to the wireless sensor node s_j , after decomposition the component along the X-axis direction can obtain to $F_x(s_i, s_j)$, the component along the Y-axis direction can obtain to $F_y(s_i, s_j)$ and the component along the Z-axis direction can obtain to $F_z(s_i, s_j)$.

So the sum of the force along the X-axis direction is $F_x(s_j) = \sum_{i=1}^N F_x(s_i, s_j)$, the sum of the force along the Y-axis direction is $F_y(s_j) = \sum_{i=1}^N F_y(p_i, s_j)$ and the sum of the force along the Z-axis direction is $F_z(s_j) = \sum_{i=1}^N F_z(p_i, s_j)$, thus the resultant force from the circular monitoring area whose center is located in the k-th type wireless sensor nodes s_j and radius is R_k is

$$F_{xyz}(s_j) = \sqrt{F_x^2(s_j) + F_y^2(s_j) + F_z^2(s_j)} \quad (6)$$

After force calculation according to the sum of the force, the wireless sensor node s_j moves to the new location $(x_{new}, y_{new}, z_{new})$ from the original location $(x_{old}, y_{old}, z_{old})$:

$$x_{new} = \begin{cases} x_{old} & |F_{xyz}(s_j)| \leq F_{th} \\ x_{old} + \frac{F_x(s_j)}{F_{xyz}(s_j)} \times MaxStep \times e^{-F_{xyz}^{-1}(s_j)} & |F_{xyz}(s_j)| > F_{th} \end{cases} \quad (7)$$

$$y_{new} = \begin{cases} y_{old} & |F_{xyz}(s_j)| \leq F_{th} \\ y_{old} + \frac{F_y(s_j)}{F_{xyz}(s_j)} \times MaxStep \times e^{-F_{xyz}^{-1}(s_j)} & |F_{xyz}(s_j)| > F_{th} \end{cases} \quad (8)$$

$$z_{new} = \begin{cases} z_{old} & |F_{xyz}(s_j)| \leq F_{th} \\ z_{old} + \frac{F_z(s_j)}{F_{xyz}(s_j)} \times MaxStep \times e^{-F_{xyz}^{-1}(s_j)} & |F_{xyz}(s_j)| > F_{th} \end{cases} \quad (9)$$

Where the F_{th} is the virtual force threshold. The wireless sensor node needn't to move when virtual force which the node received is less than the value. MaxStep is the maximum movement distance which is allowed.

The virtual force algorithm is in the following:

Step 1: Each wireless sensor node in the monitoring area broadcasts the information which includes the node ID and location information, then go to Step 2.

Step 2: The wireless sensor node updates the neighbor table information if the wireless sensor node receives the broadcast information of the neighbor nodes, then go to Step 3.

Step 3: Use the formula (5) and (6) calculating the resultant force $F(s_j)$ of wireless sensor node s_j , then go to Step 4.

Step 4: Use the formula (7), (8) and (9) calculating the new location where the wireless sensor nodes need to move to, and then go to Step 5.

Step 5: The movement process won't proceed if the new location where wireless sensor node need to move is located outside of the monitoring region and the wireless sensor node needn't move, then go to Step 6; otherwise moved to a new location, then go to Step 6.

Step 6: The algorithm stops if it reaches a pre-set cycles number T; otherwise begin the next movement process, then go to Step 1.

3.2 Problem in Virtual Force Algorithm

The problem in the virtual force algorithm is following:

Randomly deploy 16 wireless sensor nodes in the two dimensional monitoring area and the result is in Figure 1 (The nodes are located in center of the circulars).

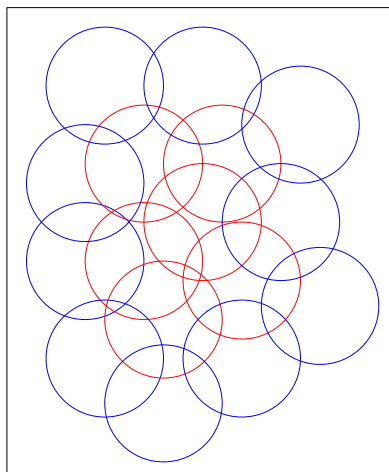


Figure 1: Randomly deploy 16 wireless sensor nodes in the monitoring area

According to the virtual force algorithm, all of the circulars have to move to the new location, in fact the red circulars don't need to move because move the red circulars can't improve the percentage of coverage, but the energy of wireless sensor nodes is consumed.

And the same problem also exists when the wireless sensor nodes are randomly deployed in three dimensional monitoring areas.

So how to solve the problem in the nodes density area is in the next section.

3.3 This Article Algorithm

In the number k period t_k any two wireless sensor nodes s_a, s_b the coordinates of the respectively $(x_a, y_a, z_a), (x_b, y_b, z_b)$ the distance between the two nodes is:

$$d(s_a, s_b) = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2 + (z_a - z_b)^2} \quad (10)$$

In this time period t_k , the distance of repulsive force balance is d_k . If $d(s_a, s_b) < d_k$, the two wireless sensor nodes need to move to balance distance d_k . If $d(s_a, s_b) \geq d_k$, the two wireless sensor nodes is in equilibrium position without moving.

In the time period t_k , if $d(s_a, s_b) < d_k$ then the two wireless sensor nodes s_a, s_b need to move to the new position coordinates $(x'_a, y'_a, z'_a), (x'_b, y'_b, z'_b)$, in order to make the minimum sum of the distance between two mobile wireless sensor node, the new coordinates for calculating available is:

$$x'_a = \frac{d_k \left[x_a - \frac{1}{2}(x_a + x_b) \right]}{2d(s_a, s_b)} + \frac{1}{2}(x_a + x_b) \quad (11)$$

$$y'_a = \frac{d_k \left[y_a - \frac{1}{2}(y_a + y_b) \right]}{2d(s_a, s_b)} + \frac{1}{2}(y_a + y_b) \quad (12)$$

$$z'_a = \frac{d_k \left[z_a - \frac{1}{2}(z_a + z_b) \right]}{2d(s_a, s_b)} + \frac{1}{2}(z_a + z_b) \quad (13)$$

$$x'_b = \frac{d_k \left[x_b - \frac{1}{2}(x_a + x_b) \right]}{2d(s_a, s_b)} + \frac{1}{2}(x_a + x_b) \quad (14)$$

$$y'_b = \frac{d_k \left[y_b - \frac{1}{2}(y_a + y_b) \right]}{2d(s_a, s_b)} + \frac{1}{2}(y_a + y_b) \quad (15)$$

$$z'_b = \frac{d_k \left[z_b - \frac{1}{2}(z_a + z_b) \right]}{2d(s_a, s_b)} + \frac{1}{2}(z_a + z_b) \quad (16)$$

Because in the movement process the wireless sensor nodes could be removed out of monitoring area and reduce the monitoring effect. If the new position is out of the monitoring area for mobile wireless sensor node, it will not be moved.

This article algorithm is in the following:

Step 1: Initialization parameters, in monitoring area randomly deploy N wireless sensor nodes, and $a = 1$, $b = 1$, $k = 1$, and then go to Step 2.

Step 2: Each wireless sensor nodes in the region into the number k time period t_k broadcasts information and the information included the node ID number and location information. If the node s_a received neighbor s_b broadcast information, update the information in the neighbor list L_a , and then go to Step 3.

Step 3: Make s_b as the smallest ID number of the wireless sensor nodes in the neighbor list L_a , and then go to Step 4.

Step 4: Wireless sensor node s_a according to the neighbor node s_b information in the list L_a , use the formula (10), calculating the distance between node s_a and the neighbor node s_b , and then go to Step 5.

Step 5: Compare $d(s_a, s_b)$ with the time balance distance d_k , if $d(s_a, s_b) < d_k$, use the formula (11)-(16) calculating need to move to a new location coordinates (x'_a, y'_a, z'_a) , (x'_b, y'_b, z'_b) , and then go to step 6.

Step 6: If the new position for mobile wireless sensor node is out of monitoring area, it will not be moved, and then go to step 7; Or move to the new location, and then go to step 7.

Step 7: If $a = N$, turn to step 9; Otherwise enter step 8.

Step 8: If the wireless sensor nodes of neighbor list L_a are according to the node ID from small to large is finished, make $a = a + 1$, turn to step 3; Otherwise make $b = b + 1$, turn to step 4.

Step 9: When $k = M$ time period t_M is finished, the algorithm ended; Otherwise $k = k + 1$ to step 2, after enter the period to the next mobile sensor node process.

IV. SIMULATION

This article uses MATLAB software to simulate the algorithm and the monitoring area is $100m \times 100m \times 100m$.

Randomly deploy the quantity N mobile nodes in the monitoring area and all nodes sensing radius $R_s = 10m$, perceived error range $R_e = 1m$, communication radius $R_c = 3 R_s = 30m$ and $R = R_s + R_e = 11m$, $E_{ini} = 1000J$, $E_s = 0.01J$, $E_r = 0.001J$, $E_m = 1J$.

The various parameters of virtual force algorithm: $k_1 = 2$, $\alpha_1 = 2$, $F_{th} = 1$, $P_{th} = 1$, $T = 10$, $MaxStep = 10m$.

The various parameters of this article algorithm: $R_c = 3 R_s = 30m$, $d_M = 2 R_s = 20m$, $M = 10$, $d_k = d_M \times k/M$.

In order to prevent the wireless sensor nodes removed from the monitoring area if the node will move to a new location where located in the monitoring area 5m wide edge, the node won't move and stay in the original location.

In the deployment phase simulate 100 times when $N = 100$, $N = 120$, $N = 140$, $N = 160$, $N = 180$, $N = 200$.

The results are averaged and shown in Figure 2, Figure 3 and Figure 4.

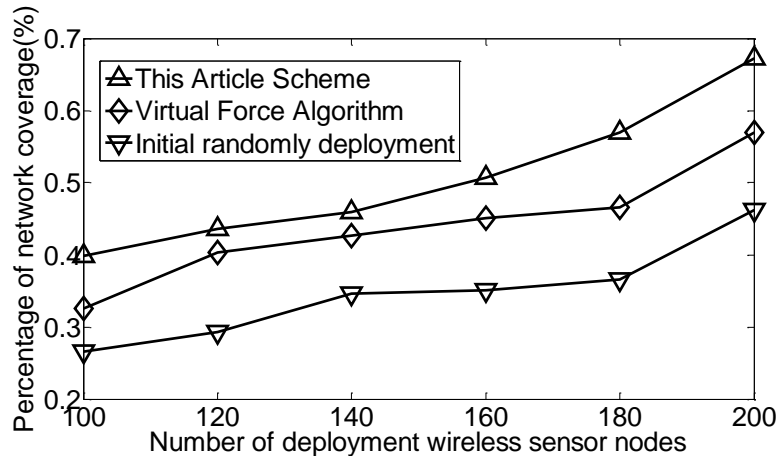


Figure 2: Percentage of coverage after deployment in different algorithms

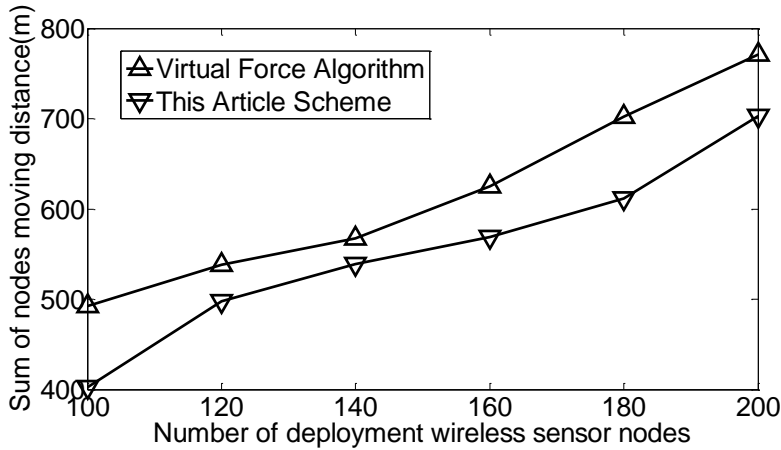


Figure 3: Sum of nodes moving distance after deployment in different algorithms

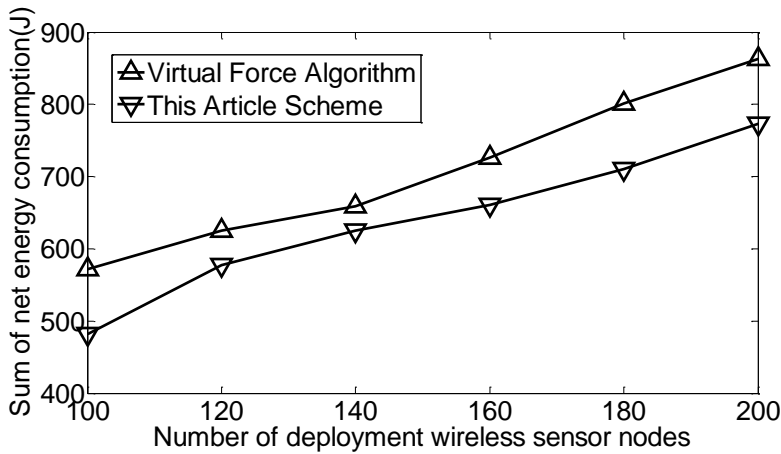


Figure 4: Sum of net energy consumption after deployment in different algorithms

Randomly lose 10 nodes after initial deployment and using their algorithm in wireless sensor network to recovery coverage holes. The simulation 100 times results are averaged and shown in Figure 5, Figure 6 and Figure 7.

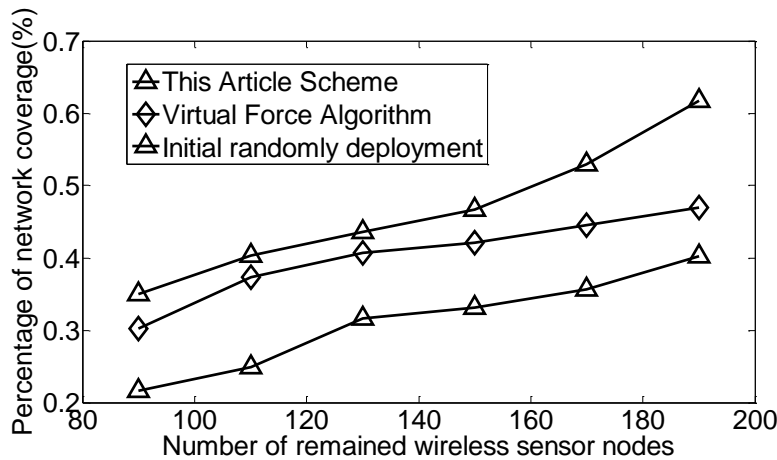


Figure 5: Percentage of network coverage after recovery coverage holes in different algorithms

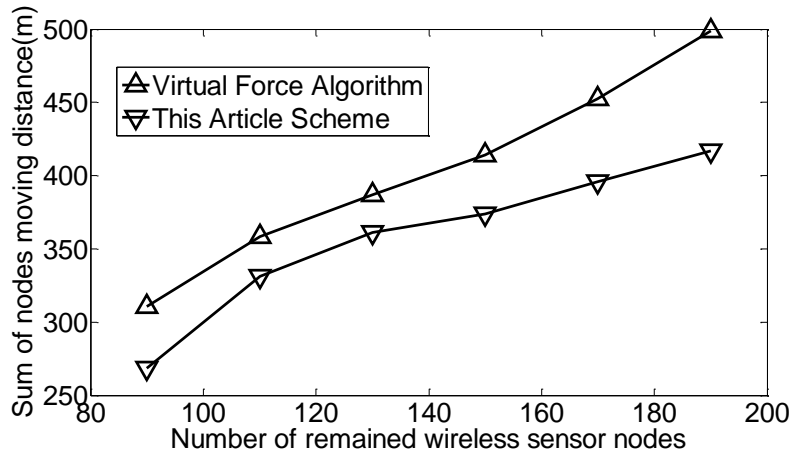


Figure 6: Sum of nodes moving distance after recovery coverage holes in different algorithms

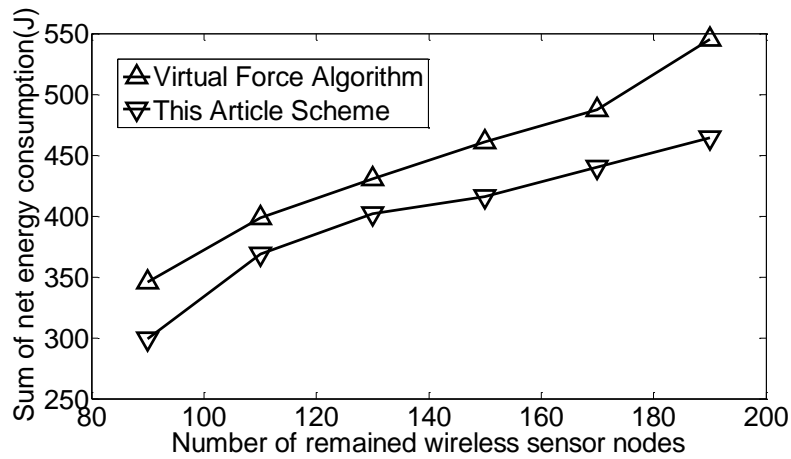


Figure 7: Sum of net energy consumption after recovery coverage holes in different algorithms

The monitoring area coverage percentage increases; the sum of nodes moving distance increases and the sum of nodes energy consumption increases with the number of wireless sensor nodes increasing can be derived from Figure 2 to Figure 7.

The nodes movement distance is larger and the coverage effect is worse when using virtual force algorithm in wireless sensor nodes dense area, because the virtual force algorithm can't reasonably move the wireless sensor nodes in the initial deployment phase and coverage holes recovery phase.

V. EXPERIMENTAL

The same various parameters which are used in the section of the simulation are also used in the experimental processes of this article.

The experimental results are shown in the table 1 to table 6.

Table 1: Percentage of coverage after deployment in different algorithms

Number of deployment wireless sensor nodes	Initial randomly deployment	Virtual Force Algorithm	This Article Algorithm
100	27.8%	32.1%	40.2%
120	28.8%	37.9%	42.4%
140	31.1%	39.9%	44.5%
160	32.3%	41.1%	46.6%
180	33.5%	43.6%	51.2%
200	43.1%	56.3%	67.9%

Table 2: Sum of nodes movement distance after deployment in different algorithms

Number of deployment wireless sensor nodes	Virtual Force Algorithm	This Article Algorithm
100	489m	412m
120	532m	478m
140	556m	510m
160	576m	535m
180	612m	562m
200	723m	617m

Table 3: Sum of net energy consumption after deployment in different algorithms

Number of deployment wireless sensor nodes	Virtual Force Algorithm	This Article Algorithm
100	589J	479J
120	621J	587J
140	653J	595J
160	682J	601J
180	762J	636J
200	867J	672J

Table 4: Percentage of network coverage after recovery coverage holes in different algorithms

Number of remained wireless sensor nodes	Initial randomly deployment	Virtual Force Algorithm	This Article Algorithm
90	22.3%	30.3%	36.9%
110	24.5%	33.5%	40.1%
130	27.8%	36.6%	41.3%
150	30.2%	39.7%	44.5%
170	32.1%	41.2%	49.3%
190	40.2%	47.7%	62.6%

Table 5: Sum of nodes movement distance after recovery coverage holes in different algorithms

Number of remained wireless sensor nodes	Virtual Force Algorithm	This Article Algorithm
90	309m	278m
110	352m	312m
130	396m	339m
150	416m	365m
170	461m	392m
190	472m	417m

Table 6: Sum of net energy consumption after recovery coverage holes in different algorithms

Number of remained wireless sensor nodes	Virtual Force Algorithm	This Article Algorithm
90	339J	297J
110	362J	357J
130	435J	395J
150	468J	410J
170	492J	433J
190	536J	452J

This article algorithm according to the nodes balance distance moves the nodes, so each movement distance is smaller, thus gradually move to the best location of monitoring, and sum movement distance of each mobile node in the process is not large, so the sum distance of nodes movement is smaller.

VI. CONCLUSION

The energy consumption of the wireless sensor network directly determines the lifetime of the wireless sensor network. Reasonably deploying the wireless sensor nodes can improve the coverage effect of the wireless sensor network and reduce the movement distance of the wireless sensor nodes. A nodes deployment algorithm based on the monitoring area perceived probability model of underwater wireless sensor network is designed in this article.

The nodes movement algorithm is designed in this article, the nodes movement process is decomposed into several parts, each part of the node according to the nodes balance distance and the relationship with the neighbor nodes position. If they need to move, they will move to the new location. Because the nodes balance distance is gradually increasing between nodes, each mobile node movement distance in the process is smaller and the sum distance of mobile nodes movement is also smaller.

The simulation and experimental results show that this article algorithm is better than the virtual force algorithm at improving the coverage effect of underwater wireless sensor network and reducing the movement distance of the wireless sensor nodes. This article algorithm achieves the goal of wireless sensor network nodes reasonable distribution to reduce energy in the initial deployment phase and coverage holes recovery phase.

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