Research Article

A Sensor Deployment Approach Using Improved Virtual Force Algorithm Based on Area Intensity for Multisensor Networks

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Sensor deployment is one of the major concerns in multisensor networks. This paper proposes a sensor deployment approach using improved virtual force algorithm based on area intensity for multisensor networks to realize the optimal deployment of multisensor and obtain better coverage effect. Due to the real-time sensor detection model, the algorithm uses the intensity of sensor area to select the optimal deployment distance. In order to verify the effectiveness of this algorithm to improve coverage quality, VFA and PSOA are selected for comparative analysis. The simulation results show that the algorithm can achieve global coverage optimization better and improve the performance of virtual force algorithm. It avoids the unstable coverage caused by the large amount of computation, slow convergence speed, and easily falling into local optimum, which provides a new idea for multisensor deployment.

1. Introduction

In recent years, multisensor deployment has been widely used in military reconnaissance [1], environmental monitoring [2], explosion-proof, disaster relief [3], and hypersonic flight vehicle detection [4, 5], but it is difficult to achieve the coverage requirements of monitoring areas, so appropriate deployment methods should be adopted to meet the application needs.

At present, there are a lot of algorithms on multisensor deployment, which are mainly divided into two categories: one is the swarm intelligence algorithms to aim at the global information obtained by the centralized algorithm to supplement and repair the coverage blind area, the widely used centralized coverage algorithms include genetic algorithm, particle swarm optimization, ant colony algorithm and some improved combination algorithms of these algorithms, and these algorithms have a variety of applications in engineering [6–11]. Reference [12] uses genetic algorithm to deploy the sensors; although the coverage effect has been improved, it does not take into account the influence of different sensor positions on coverage efficiency. Reference [13] proposes an

improved coverage control optimization strategy based on genetic algorithm, which optimizes the initial population using density detection mechanism and introduces two taboo operations to achieve the deployment of multisensor. Reference [14] uses dynamic ant colony algorithm to realize the optimal deployment for sensor networks, and the algorithm shows great coverage and connectivity of the sensor networks. Reference [15] presents the particle swarm optimization algorithm based on localization to enhance the coverage after an initial random deployment of the sensors; the results show that the sensor deployment approach can provide high coverage with limited movement of the sensors.

The other is the distributed algorithm, which does not need to obtain global information, reduces energy consumption, and has the characteristics of simple deployment and high degree of autonomy.

Distributed algorithm includes deterministic deployment algorithm and virtual force algorithm. Reference [16] proposes a deterministic deployment scheme, where the sensing field is treated as an arbitrary polygon possibly with obstacles. The simulation shows that the results can be used in indoor environment. To some extent, this algorithm needs prior

information of deployment environment and it is not useful for the application in a battlefield or in dangerous harsh environment, which is not always available. The virtual force algorithm is originally proposed by [17], which aims to allow mobile robots to avoid obstacles in unknown environments. References [18, 19] apply virtual force algorithm to coverage optimization of sensor networks for the first time. On the basis of disc packaging and virtual potential field theory, the node binary perception model and probability perception model were fully considered. On this basis, a classical virtual force algorithm is proposed. However, the algorithm does not take into account the relevant parameters and distance threshold in virtual force model. When the random deployment status cannot be determined beforehand, the appropriate virtual force related parameters cannot be selected, which would affect the deployment effect.

The contribution we have made in this paper is presented as follows:

- (1) Sensor model based on real-time state is established as the basis of this paper;
- (2) An improved virtual force algorithm based on area intensity is proposed to be the core algorithm in this paper;
- (3) The optimal deployment distance is selected by the intensity of sensor area; the parameters related to virtual force are optimized by equation deduction;
- (4) Various algorithms are used to confirm that improved virtual force algorithm based on area intensity (IVFAI) can improve the quality of network coverage.

The structure of the rest paper is organized as follows. The second part introduces the basic theory and methods. First, the sensor model based on real-time state is established. Then, an improved virtual force algorithm based on area intensity is proposed considering the area density on the basis of the basic virtual force algorithm. The third part compares the proposed algorithm with the other two algorithms by simulations to prove the effectiveness of this paper's algorithm. The fourth part summarizes the article and draws conclusions.

2. Methodology

2.1. Sensor Model Based on Real-Time State. Suppose that all kinds of sensors can communicate with each other, the deployment of multisensors is particularly critical to achieve better detection effect. Rational deployment of sensors can improve the communication efficiency between sensors, reduce energy loss, improve detection accuracy, and better complete the whole space's continuous high probability detection.

There are many ways to establish the detection model of a single sensor [19–21]. In order to better reflect the real detection environment, a sensor detection model based on real-time state is established in this paper.

Figure 1 shows s_i 's probabilistic sensor detection model [22], where R_d is the detecting radius of s_i and R_s is the sensing radius; in order to describe the sensing range clearly,

FIGURE 1: A sensor detection range model.

we divide it into two parts, certain sensing area and uncertain sensing area; r_e is a measurement of the uncertainty in sensor detection.

Assuming that s_i is deployed at point (x_i, y_i) , for any point P at (x, y) , we denote the Euclidean distance between s_i and P as $d(s_i, P)$, which is shown in Figure 1.

If $R_s + r_e \leq d(s_i, P)$, the sensing probability is 0; if $R_s - r_e \leq d(s_i, P) < R_s + r_e$, the sensing probability is $e^{-\lambda_1 \alpha_1^{\beta_1} \alpha_2^{\beta_2} - \lambda_2}$, where λ_1 , β_1 , and β_2 are the parameters measuring sensing probability, $\alpha_1 = r_e - R_s + d(s_i, P)$, and $\alpha_2 = r_e + R_s - d(s_i, P)$; λ_2 is the disturbing factor; if $R_s + r_e > d(s_i, P)$, the sensing probability is 1. The equation is given below:

$$P_p(s_i) = \begin{cases} 0 & \text{if } R_s + r_e \leq d(s_i, P) \\ e^{-\lambda_1 \alpha_1^{\beta_1} \alpha_2^{\beta_2} + \lambda_2} & \text{if } R_s - r_e \leq d(s_i, P) < R_s + r_e \\ 1 & \text{if } R_s + r_e > d(s_i, P) \end{cases} \quad (1)$$

It can be seen from (1) that the distance among sensors certainly affects the sensing probability of the sensor. The overall trend is decreasing with the increasing probability of the distance. However, due to the differences in the performance of each sensor category, the parameters are different, which would affect the sensing probability to some extent. The specific changes are shown in Figure 2.

2.2. Improved Virtual Force Algorithm Based on Area Intensity

2.2.1. Definition of Area Intensity. Supposing that n sensors are randomly deployed in a two-dimensional plane, the optimal deployment distance between sensors is set to d_{od} . The selection of the optimal deployment distance is related to the intensity of the plane area. The intensity is expressed in

$$\psi_i = \frac{N^2}{\sum_{i=1}^n \sum_{m=1}^N d_{im}} \quad (2)$$

FIGURE 2: Probabilistic sensor detection model.

In (2), ψ indicates the intensity of the area, m is the m th neighbor of s_i , and N is the total number of s_i 's neighbors.

When a sensor has more adjacent sensors, the distance between them is smaller; that is to say, the region's intensity is high, as shown in Figure 3. When the number of sensors deployed in the plane is small, $d_{od} = 2R_s$ and, on the contrary, $d_{od} = \sqrt{3}R_s$.

2.2.2. Improved Virtual Force Algorithm. Physical knowledge shows that the distance between two atoms determines the force between them as positive force or negative force. This paper uses this idea to introduce the concept of virtual force to discuss the force between sensors deployed in two-dimensional plane.

In order to describe it clearly, we assume that there are four sensors s_1, s_2, s_3, s_4 in the two-dimensional plane shown in Figure 4.

Assuming that the force between each sensor is set to $F_{ij}(i, j = 1, 2, \dots, n)$, negative force $F_{ijN}(i, j = 1, 2, \dots, n)$ is generated when the distance between sensors is less than the optimal deployment distance; otherwise positive force $F_{ijP}(i, j = 1, 2, \dots, n)$ is generated, as shown in

$$F_{ij} = \begin{cases} 0 & \text{if } d_{ij} > R_c \\ F_{ijP} = (\lambda(d_{ij} - d_{od}), \theta_{ij}) & \text{if } d_{od} < d_{ij} \leq R_c \\ 0 & \text{if } d_{ij} = d_{od} \\ F_{ijN} = (\delta(d_{od} - d_{ij}), \omega_{ij}) & \text{if } d_{ij} < d_{od} \end{cases} \quad (3)$$

In (3), θ_{ij} and ω_{ij} are the directional angles between s_i and s_j ; in the meantime, $\theta_{ij} = \omega_{ij} + \pi$; λ is the positive parameter; δ is the negative parameter.

As is shown in Figure 4, there is negative force between s_1 and s_2 , positive force between s_1 and s_4 , and no interaction between s_1 and s_3 . And we can conclude the resultant forces acting on s_1 in

$$F_1 = F_{12N} + F_{13} + F_{14P} \quad (4)$$

Because of the negative force effect between the fewer neighbor sensors and the positive force effect between the more nonneighbor sensors, the negative force parameter is set far larger than the positive force parameter in order to achieve the equilibrium state of the nodes. However, if the random deployment state cannot be determined beforehand, only setting a larger negative force parameter and a smaller gravity parameter according to the empirical value cannot achieve a good coverage effect. To this end, Figure 5 shows the relations between λ and δ .

From Figure 5, we can conclude the relations of λ and δ .

$$\lambda = d_{od} - d_{ij} \quad (5)$$

$$\delta = n\sqrt{a^2 + b^2} \quad (6)$$

Theorem 1. According to Figure 5, we can obtain the relations of λ and δ in (5) and (6).

Proof.

$$F_{ijN} = \lambda(d_{od} - d_{ij}) \quad (7)$$

$$F_{ijP} = (n-2)\delta \left[\sqrt{a^2 + b^2} - \sqrt{2(R_{s_i} + R_{s_n})} \right] \quad (8)$$

In (8), $\sqrt{a^2 + b^2} - \sqrt{2(R_{s_i} + R_{s_n})}$ indicates the Euclidean distance between s_i and others.

In area $a \times b$, we ignore the effect of $\sqrt{2(R_{s_i} + R_{s_n})}$ and assume $n-2 \approx n$; we can get the following:

$$F_{ijP} = n\delta\sqrt{a^2 + b^2} \quad (9)$$

When the resultant forces acting on s_i are 0, we can conclude that

$$n\delta\sqrt{a^2 + b^2} = \lambda(d_{od} - d_{ij}) \quad (10)$$

Therefore, we can get the final equations between λ and δ :

$$\lambda = d_{od} - d_{ij} \quad (11)$$

$$\delta = n\sqrt{a^2 + b^2} \quad (12)$$

The proof is completed. $\square$

Based on the above analysis, this paper proposes an improved virtual force algorithm based on area intensity by reasonably setting relevant parameters and choosing the optimal deployment distance by using the intensity of the sensor area. This algorithm can better achieve global coverage and improve the performance of virtual force algorithm, avoiding the unstable coverage caused by the large amount of computation, slow convergence speed, and easily falling into local optimum based on virtual force algorithm, the pseudocode implemented by the algorithm is shown in Algorithm 1.

FIGURE 3: The optimal distance with the sensors.

FIGURE 4: An example of virtual forces with the sensors.

FIGURE 5: The deployment of the sensors' position.

Procedure*Improved Virtual Force Algorithm based on Area Intensity (IVFAI) (Grid $\{s_1, s_2, \dots, s_n\}$)***Input:** monitoring area: $xm=[XMIN \ YMIN; XMIN \ YMAX; XMAX \ YMAX; XMAX \ YMIN]$; axis([0 1000 0 1000]); $n=50$; $Rs=80$; $Rc=2*Rs$; $maxiter=100$; $max_step=2.5$; $max_sensor=3.5$ **Output:** complete solution

```

// Draw the sensing radius of the sensors
1: for i=1:n
2:   x1=x(i,1)+r*cos(w);
3:   y1=x(i,2)+r*sin(w);
4: end
// Compute original coverage rate  $\eta$ 
5: [no_cover, summ, kl]=compute_cover(x1, y1, x, r);
6: q(1,1)=summ/K;
7: for i=1:n
8:   text(x(i,1)+3, x(i,2), ['\fontsize{8}\rm', num2str(i)]); // Mark the position of the sensors
9: end
10: for t=1:maxiter
11:   for i=1:n
12:     for j=1:n
13:       Compute  $\eta$ ;
14:       Compute  $\psi_i$ ;
15:       if  $\psi_i \leq \psi_{max}$ 
16:         continue;
17:       else  $\psi_i > \psi_{max}$ 
18:         break;
19:       end
20:     end
// Compare the distance
21:     if  $d \geq dop$ 
22:       for j=1:n
23:          $dop=2Rs$ ;
24:       end
25:     else  $d < dop$ 
26:       for j=1:n
27:          $dop=\sqrt{3}Rs$ ;
28:       end
29:     end
30:     Move sensors virtually;
31: end
32:   Update  $\eta$ ;
33: end

```

ALGORITHM 1: Pseudocode of the IVFAI.

3. Simulation

All the simulations in this paper are carried out on MATLAB R2014a platform, and the simulation results are obtained from a large number of simulations.

The hypothesis of simulation is as follows [23]:

- (1) Each sensor can find its best position in the deployed airspace.
- (2) Each sensor can acquire its own position information and the position relationship between itself and other sensors.
- (3) Each sensor can sense and acquire the position of other sensors within its communication radius.

When the sensors are deployed, the coverage rate is used to measure the effect of deployment. Assuming that S_c is the

area covered by the sensor s_i and S_m and is the size of the monitoring area, the coverage rate η is defined as the coverage rate and (13) can be obtained.

$$\eta = \frac{S_c}{S_m} \quad (13)$$

The simulation parameters are set as shown in Table 1.

In order to verify the effectiveness of the proposed algorithm in improving coverage quality, the basic virtual force algorithm [24] (VFA) and particle swarm optimization algorithm [25] (PSOA) are selected for comparative analysis and discussion. According to the parameter settings, the simulation results are presented in Figures 6–8.

Figures 6–8 represent the deployment of 50 sensors by three algorithms. It can be concluded that PSOA can adjust the initial deployment of sensors, but there are still some

FIGURE 6: Sensor positions with PSO.

FIGURE 7: Sensor positions with VFA.

TABLE 1: Simulation parameter settings.

Parameter	Value
Monitoring area	$1000 \times 1000 m^2$
Initialization method	Random
Number of sensors	50
Sensing radius	80 m
Detecting radius	160 m
Uncertain distance	2 m
Number of iterations	100
Max step	2.5
Max sensor	3.5
Intensity threshold	0.625

sensors. Compared with PSO, VFA has better effect on sensor deployment, but some sensors are distributed at the edge of the region, resulting in waste of sensor resources; IVFAI has the best effect on sensor deployment, high effective coverage, and high resource utilization, while all sensors are

more evenly distributed in the region and among sensors. Distance optimization is more reasonable.

Figures 9(a) and 9(b) are the diagrams of the coverage and running time of the three algorithms. Figure 10(a) is a curve of the impact of changing the number of sensors on coverage. Figure 10(b) is a curve of the impact of changing the number of sensors of IVFAI on coverage.

From Figure 9(a), it can be inferred that the initial coverage rate is 70%. With the increase of iterations, the coverage rate of the three algorithms is improved. PSO achieves the maximum coverage rate of 90% in 70 iterations, VFA achieves the maximum coverage rate of 94% in 60 iterations, and IVFAI achieves the maximum coverage rate of 98% in 39 iterations. At the same time, from the running time of the three algorithms in Figure 9(b), it can be concluded that IVFAI runs in the shortest time and reaches the maximum coverage in 30 seconds, while PSO needs at least 70 seconds to achieve the maximum coverage.

From Figure 10(a), we can conclude that when the number of initial sensors is changed, the coverage increases with the increase of the number of sensors, but the coverage

FIGURE 8: Sensor positions with IVFAI.

FIGURE 9: Comparison of three algorithms.

of IVFAI to the region changes slightly, and the coverage of PSOA to the region changes greatly, which shows that the stability and optimization ability of the algorithm is worse than that of IVFAI.

From Figure 10(a), it is obvious that, with the number of the sensors of IVFAI varying from 35 to 50, the coverage is getting higher and higher, which shows that when the number of sensors is 50, the coverage of the region comes to about 98%.

4. Conclusion

This paper mainly introduces the virtual force algorithm based on area intensity to realize the deployment of multisensors. Firstly, a multisensor detection model based on real-time state is established to describe the detection range of sensors in details. Secondly, an improved virtual force

algorithm based on area intensity is proposed. By selecting the best deployment distance of the interaction force attributes between sensors in the virtual force model through intensity, the basic virtual force algorithm is improved, and the convergence effect is better, which reflects better optimization accuracy and higher coverage in the later period. At the same time, the algorithm is compared with other two algorithms to prove the effectiveness of the proposed algorithm, which makes up for the problems of poor coverage and long running time of the basic algorithm. Besides, by changing the algorithm's parameters, this paper confirms that the improved algorithm can reach better coverage of the target area, which has better practical application prospects.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

FIGURE 10: Comparison of different variables.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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