Three-dimensional deployment algorithm based on ideal fluid dynamics model for mobile sensor networks

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Abstract

In the paper, a three-dimensional deployment algorithm based on ideal fluid model for sensor networks is proposed. On this basis, the proposed ideal fluid model is analysed, and the concept of flow field model is applied in deployment of wireless sensor networks. Sensor networks are abstracted as ideal fluid, with nodes as fluid micelles. In the deployment process, motion of nodes follows momentum conservation law of fluid micelle. Moreover, a simulation experiment is performed in this paper with the proposed deployment algorithm as the experimental subject. Coverage and uniformity are 2 indexes employed to evaluate the performance of the proposed algorithm. Shown by the simulation result, the three-dimensional deployment algorithm based on ideal fluid model for sensor networks leads to good deployment effect.

Keywords: three-dimensional deployment, mobile sensor networks, ideal fluid model

1 Introduction

Sensor network deployment refers to the process of adopting proper algorithm to deploy nodes within the target area, so as to conform to certain specified demand. Network deployment is a pre-condition for sensor network to play its role, as well as a premise for the normal operation of network [1-3]. It determines the detection effect of sensor network in the target area, which may further influence the service quality of the network. Node deployment of wireless sensor network is one of the kernel problems in the field. A good deployment method may significantly improve the perception quality of network, reducing resource consumption, and extending service life of network. Related scholars have performed plenty of studies in this connection. Normally, deployment of indoor sensor network nodes often puts to use regular deployment approach [4, 5] and most deployment in outdoor environment adopts random deployment approach [6-8].

Owing to diversified forms wireless sensor network nodes, deployment methods may be divided into three types:

1) Wireless sensor networks completely comprised by static nodes may be deployed manually.

2) As for wireless sensor networks comprised by static and mobile nodes, the mobility of mobile nodes [9] may be utilized to eliminate dead zones in sensor networks.

3) Wireless sensor networks comprised by mobile nodes may be deployed automatically [10, 11]. Owing to the mobility of nodes, deployment of mobile nodes is quite flexible [12].

It is easier to deploy nodes via releasing, spraying or other relevant methods. Yet, in unknown, complicated, and rigor environment, it is impossible to perform deployment manually. Nodes may be unable to be distributed in appropriate positions, leading to overlapping or dead zones, which wastes resources and affects network service quality. By contrast, deployment of mobile nodes perfectly solves the problem. In the algorithm, mobile nodes are designed to move following certain rules, and to elude obstacle accordingly. As for this, deployment in unknown and complicated environment becomes possible. Three-dimensional deployment of sensor network nodes based on ideal flow field model proposed in this paper belongs to this category. In the beginning, nodes may be places at accessible positions. On this basis, nodes will be automatically deployment according to prescribed motion rules, and to elude obstacles when applicable.

Literature [13-15] introduces the concept of potential field, i.e. a deployment method based on potential field. This method takes nodes as virtual particles influenced by virtual forces. One of the virtual forces creates repulsion between node and obstacle, as well as between node and node. As for this, nodes will expand rapidly based on the compact distribution in the beginning, so as to reach maximum coverage of network. Apart from such repulsive force, nodes are also influenced by viscous friction, which guarantees the network with a final static balance, i.e. all nodes will stop moving eventually. When the environment is changed, the network will be reconfigured accordingly to conform to the changed environment, and to reach static balance again.

This method leads to goods coverage rate. However, there is a premise - all nodes have to be put in the deployment environment in advance, i.e. the initial static deployment. What's more, in the initial deployment, the

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number of nodes shall be given. However, in unknown environment, it is impossible to figure out how many nodes are required so as to realize the deployment. Shortage of nodes reduces the coverage, while excessive nodes lead to redundancy, wasting energy. In this paper, the deployment method proposed by Literature [13-15] is improved. As for this, it is unnecessary to know the number of nodes before deployment, and the improved method is proved with high coverage effect.

Literature [16, 17] put forward a Virtual Force Algorithm (VFA) based on the assumption that nodes are movable, with the aim to improve the coverage of sensor nodes after initial deployment. For a sensor network with explicit number of nodes, virtual force algorithm tries to maximize network coverage rate. The algorithm employs attractive force and repulsive force to determine the path and rate of nodes' virtual motion. Cluster header is designed to calculate the destination position of nodes. Nodes will move accordingly to complete the task, if there is an effective destination position determined.

However, node position in the method is calculated by cluster header, which quite complicated in large-scale sensor networks, and is hereby not applicable. What we need to designed is deployment method applicable to large-scale networks with rigor environment. According to virtual force algorithm, a certain acting force is assumed between nodes, which promote the successful deployment of nodes.

Literature [18] adopts the basic control mechanism from virtual elastic network to deployment sensor networks. In every virtual elastic network, each node is considered as a particle, which moves regularly under the influence of virtual force. If a pair of nodes is too close, the elastic force between them will pull them apart. If the distance between them is too large, the elastic force will then push them closer. This is similar to the previously mentioned deployment method based on virtual force, but is still different in some aspects. The algorithm makes use of elastic force between nodes to expand nodes from the original compact and dense state to the whole area. Decisions are made directly between nodes, free from cluster headers. Literature [19] proposed a deployment algorithm based on ideal fluid model. Inspired by fluid dynamics, the paper proposed a new method to deploy mobile sensor network in unknown area. According to the physical rule of ideal fluid model, mobile sensor network is considered as a sort of fluid, while sensor nodes as micro fluid micelles. In the paper, fluid variables are projected into sensor networks, with equation solution method, initial condition and physical boundary condition given. Based on Literature [19], the method is improved and expanded to 3D deployment field, reaching good deployment effect.

The rest part of this paper is organized as follows: In Section 2, we analyse the ideal fluid dynamics model of three-dimensional deployment for mobile sensor networks. In Section 3, we solve the model mentioned in Section 2 and establish the ideal fluid dynamics algorithm of deployment. In Section 4, we simulate the ideal fluid dynamics algorithm of deployment by using computer software and evaluate its performance. Finally, in Section 5, we reach the main conclusions.

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2 Analysis of ideal fluid control model

Nodes in sensor networks are independent individuals. There is no friction between nodes. In this paper, sensor networks are taken as ideal fluid. Ideal fluid omits dissipation, viscous transport, mass diffusion and heat conduction. Fluid model adopted in this paper defines fluid as a set comprised by flowing infinitesimal fluid micelles. Moreover, the paper is designed to study node motion. For this reason, conservation of momentum shall be considered. In other words, momentum equation followed by fluid micelles is applied in sensor nodes, so as to make nodes move following the rule, so as to realize sensor network deployment.

In this paper, motion of nodes in three-dimensional space Ω is researched. Moreover, the velocity along direction x, y and z is separately represented with u, v and w. Hereby, the three-dimensional expression of Euler equation may be described with Equation (1). It establishes the relation between the force on ideal fluid and the accelerated velocity of fluid motion. This, it is the foundation to study motions of ideal fluid, as well as an important equation in fluid dynamics.

$$\begin{cases} f_x - \dfrac{1}{\rho}\dfrac{\partial p}{\partial x} = \dfrac{du}{dt} \\ f_y - \dfrac{1}{\rho}\dfrac{\partial p}{\partial y} = \dfrac{dv}{dt} \\ f_z - \dfrac{1}{\rho}\dfrac{\partial p}{\partial z} = \dfrac{dw}{dt} \end{cases} . \tag{1}$$

Equation (1) is an ideal fluid momentum equation, where, ρ is fluid density, d/dt is derivative of velocity on time, p refers to fluid pressure, f_x, f_y and f_z are component forces along directions of x, y and z; u, v and we are velocity components of an infinitesimal fluid element along directions of x, y and z. Expanding the derivative of velocity on time:

$$\begin{cases} \frac{du}{dt} = \frac{\partial u_i^t}{\partial t} + u_i^t \frac{\partial u_i^t}{\partial x} + v_i^t \frac{\partial u_i^t}{\partial y} + w_i^t \frac{\partial u_i^t}{\partial z} \\ \frac{dv}{dt} = \frac{\partial v_i^t}{\partial t} + u_i^t \frac{\partial v_i^t}{\partial x} + v_i^t \frac{\partial v_i^t}{\partial y} + w_i^t \frac{\partial v_i^t}{\partial z} \\ \frac{dw}{dt} = \frac{\partial w_i^t}{\partial t} + u_i^t \frac{\partial w_i^t}{\partial x} + v_i^t \frac{\partial w_i^t}{\partial y} + w_i^t \frac{\partial w_i^t}{\partial z} \end{cases}. \quad (2)$$

Putting Equation (2) in Equation (1), (superscript and subscript are directly added here) more detailed Euler motion differential equation is shown as (3):

$$\begin{cases} \frac{\partial u_i^t}{\partial t} = -(u_i^t \frac{\partial u_i^t}{\partial x} + v_i^t \frac{\partial u_i^t}{\partial y} + w_i^t \frac{\partial u_i^t}{\partial z} + \frac{1}{\rho_i^t}\frac{\partial p_i^t}{\partial x}) + f_{i,x}^t \\ \frac{\partial v_i^t}{\partial t} = -(u_i^t \frac{\partial v_i^t}{\partial x} + v_i^t \frac{\partial v_i^t}{\partial y} + w_i^t \frac{\partial v_i^t}{\partial z} + \frac{1}{\rho_i^t}\frac{\partial p_i^t}{\partial y}) + f_{i,y}^t \\ \frac{\partial w_i^t}{\partial t} = -(u_i^t \frac{\partial w_i^t}{\partial x} + v_i^t \frac{\partial w_i^t}{\partial y} + w_i^t \frac{\partial w_i^t}{\partial z} + \frac{1}{\rho_i^t}\frac{\partial p_i^t}{\partial z}) + f_{i,z}^t \end{cases}. \quad (3)$$

In Equation (3), time derivative is on the left, and space derivate is on the right. Subscript *i* and Superscript *t* represents fluid element i's parameters of *u, v, w, p, ρ* and *f* at the time of *t*.

3 Applying fluid concept to sensor networks

In order to make use of the liquidity of ideal fluid to analyse the deployment process of sensor network, the network model is assumed as follows:

1) Nodes shall be able to move: Nodes in the network shall be able to move freely, while the energy of nodes shall be able to support nodes to move for a long distance so as to realize the deployment, as well as affairs after the deployment. This is the most fundamental ability of nodes, as well as the basis for self-deployment of network.

2) Nodes shall be designed with the function of self-positioning. Nodes shall be able to know their current position and velocity in every phase. Such positioning function is necessary for each node to determine the next action in the deployment process.

3) Nodes shall be designed with the function to perceive the environment. The perception coverage with each sensor node may be considered as a circle with radius of R_s. As for this, nodes are able to perceive the position of obstacle, etc.

4) Nodes shall be designed with communication function within finite range. The communication coverage of each sensor node is defined by another circle with radius of R_c. A sensor node shall be able to perceive the relative position and velocity of its neighbour nodes within the communication range.

5) Nodes shall be designed with calculation and information fusion function. Useful information may be extracted for decision-making, controlling motion direction and velocity, so as to move freely.

Definition of fluid variables used in Equation (1)-(3) in wireless sensor networks is described in Table 1.

TABLE 1 Fluid Property and WSNs Property

Fluid Property	Symbol	WSNs Property
Support Domain	Ω	Local neighbourhood within communication range
Position	x	Position vector
Velocity	v	Velocity control vector
Density	ρ	A measure of the number of nodes in Ω
Pressure	p	A parameter generating repulsion among nodes
Body force	f	Flow control force vector

3.1 SOLUTION OF MODEL CONTROL EQUATION

Similar to computations in fluid dynamics, the velocity of sensor nodes may as well be figured out by time iteration. Taking Velocity Component *u* of Node *i* as the example, assuming that the value of velocity component at Time *t* is given, after a small time interval *Δt*, the value of velocity component may be calculated with Taylor expansion, so as to obtain the following equation:

$$u_i^{t+\Delta t} = u_i^t + (\frac{\partial u_i^t}{\partial t})\Delta t + (\frac{\partial^2 u_i^t}{\partial t^2})\frac{(\Delta t)^2}{2} + \ldots . \quad (4)$$

Velocity component may be simply and approximately described as the first two terms in Equation (4), i.e.:

$$u_i^{t+\Delta t} = u_i^t + (\frac{\partial u_i^t}{\partial t})\Delta t . \quad (5)$$

Putting Equation (3) in Equation (5), after a small time interval *Δt*, the value of velocity component may be described as:

$$\begin{cases} u_i^{t+\Delta t} = u_i^t + (-(u_i^t \frac{\partial u_i^t}{\partial x} + v_i^t \frac{\partial u_i^t}{\partial y} + w_i^t \frac{\partial u_i^t}{\partial z} + \frac{1}{\rho_i^t}\frac{\partial p_i^t}{\partial x}) + f_{i,x}^t)\Delta t \\ v_i^{t+\Delta t} = v_i^t + (-(u_i^t \frac{\partial v_i^t}{\partial x} + v_i^t \frac{\partial v_i^t}{\partial y} + w_i^t \frac{\partial v_i^t}{\partial z} + \frac{1}{\rho_i^t}\frac{\partial p_i^t}{\partial y}) + f_{i,y}^t)\Delta t \\ w_i^{t+\Delta t} = w_i^t + (-(u_i^t \frac{\partial w_i^t}{\partial x} + v_i^t \frac{\partial w_i^t}{\partial y} + w_i^t \frac{\partial w_i^t}{\partial z} + \frac{1}{\rho_i^t}\frac{\partial p_i^t}{\partial z}) + f_{i,z}^t)\Delta t \end{cases}. \quad (6)$$

In calculation, equations of u_i^t, v_i^t, w_i^t, ρ_i^t, and p_i^t may be put in Equation (6), so as to calculate the value of velocity component by iteration, and to further figure out the next position of Node *i*. In calculation, momentum conservation law is followed. Motion of nodes abides by the physical rule of fluid micelle.

3.2 CONSTRAINT CONDITION, INITIAL CONDITION AND PHYSICAL BOUNDARY CONDITION

The above has described node motion. However, when the motion begins, there shall be initial conditions give. Moreover, in the motion process, nodes' motion shall be limited. When nodes reach the boundary or encounter obstacles, motion will also be changed. In the following, these problems are to be solved.

1) Initial condition.

Time iteration method in Equation (5) needs to know the initial value of velocity component in advance, as well as present position before calculating the next position. Before deployment, initial velocity and position of any node may be known.

2) Physical boundary condition.

For ideal fluid, as there is no friction, flow velocity on object plane is a finite non-zero value. Moreover, for impervious walls, there is no mass inflow or out-flow object plane. As for this, the velocity of fluid sticking close to object plane shall be tangent with object plane. In other words, the velocity component perpendicular to object plane shall be zero, i.e. flowing on object plane is tangent with object plane. This is the only object plane boundary condition of frictionless flow. The value of velocity on object plane, along with temperature, pressure and density of fluid on object plane, will become a part of the solution. As is shown by Figure 1, when the distance from node to obstacle or boundary is smaller than d, the velocity will be changed.

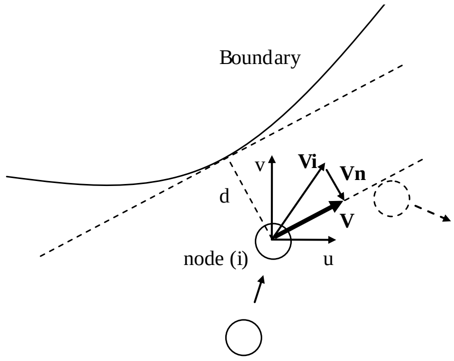

FIGURE 1 Object plane boundary condition

3) Constraint control condition.

Velocity component method in Equation (6) may be used to calculate the velocity of sensor node. In reality, owing to mobile equipment or other problems, the motion velocity of network sensor nodes may be limited. As for this, calculated velocity and accelerated velocity of sensor nodes shall be mandatorily constrained, in case that they exceed the threshold of velocity V_{th} and accelerated velocity a_{th}.

3.3 IDEAL FLUID DEPLOYMENT ALGORITHM

The entire Deployment Algorithm of Ideal Fluid Model is shown in Algorithm 1.

ALGORITHM 1 Deployment Algorithm of Ideal Fluid Dynamics

Algorithm : Deployment Algorithm of Ideal Fluid Model

Requirement: Ω, N, C, Rc, Rs.

1: Estimate number of nodes N based on expected Coverage Ratio C and volume of Ω
2: At time t_0, all of the N nodes are located at their initial positions
3: For each node node_i at time t
4: Parameters in Euler equation may be figured out by calculating the distance with neighbor nodes;
5: Accelerated velocity a_i of node along different direction may be calculated with parameters obtained from 4;
6: Calculating node velocity v_i;
7: Judging if the velocity is larger than the prescribed threshold v_{th}; if so, turn to 8; if not, turn to 9;
8: Changing node velocity to threshold velocity;
9: Calculating the position of the next step;
10: Judging if the distance from node to obstacle or boundary is smaller than the prescribed distance; if so turn to 11; if not turn to 12;
11: Changing velocity according to boundary condition, and turning to 9;
12: Node moves to the calculated position;
13: Judging if the target coverage is reached; if so, turn to 14; if not, turn to 4;
14: End For
15: All nodes have reached equilibrium, algorithm ends.

With a 3D plot, the principle of the algorithm in this paper can be clearly demonstrated, as is shown in Figure 2. This is a 3D plot simulated with software, and the deployment area Ω is a space with the dimension of 10x10x10. The initial deployment position of node is a corner in the area, as is shown in the left plot. The small black dots are exactly the mobile nodes to be deployed. The right plot shows the spatial distribution of nodes after deployment. It can be seen from the plot that, nodes have been expanded from the initial positions to the whole space.

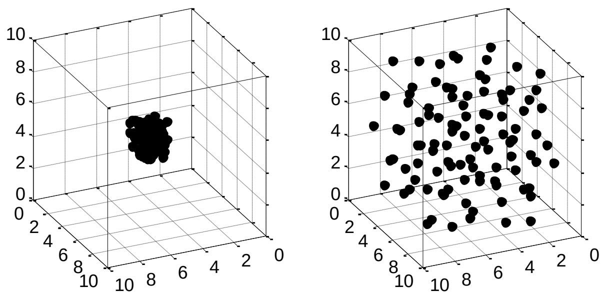

FIGURE 2 Demonstration of the Deployment Process

4 Simulation results

Numerous simulations have been carried out in various environments to investigate the performance of our approach. Parameter settings of our simulations are indicated in Table 2 with reference to the related figure number.

TABLE 2 Simulation settings by figure number

Parameter	Figure 3	Figure 4	Figure 5
Deployment(Ω)	10×10×10	10×10×10	10×10×10
Node number (NN)	100	100	100
R_s, R_c	2; 4	2; 4	2; 4
damping factor (Df)	2.0	2.0	2.0
a_{th}, V_{th}	2; 1	2; 1	2; 1
Time (T)	15	15	15
Δt	0.1	0.1	0.1
Obstacles	0	1	0
ROIs	0	0	1

4.1 COVERAGE AND UNIFORMITY

Generally, coverage can be considered as the service quality of a sensor network. Gage invented the concept of coverage in the research of multi-robot systems [20]. This paper defines it as the ratio between the sum of the coverage volume of all nodes and the volume of the entire target region, as is shown in Equation (7). The definition of the sum of the coverage volume is taken from the concept of union in the Set Theory, thus the coverage is usually no larger than 1.

$$Coverage = \frac{\bigcup_{i=1,\dots,N} \Omega_i}{\Omega}. \quad (7)$$

The uniformity of coverage is a well-defined standard to measure the service life of a network. Article [21] describes the concept as the standard deviation of distance between nodes. Smaller standard deviation means better coverage uniformity of the network. However, this approach for measuring uniformity is under perfection. We take the grid approach to calculate uniformity in this paper, i.e. dividing the whole region into N small cubes with the same volume, and then figuring out the standard deviation of the nodes contained in these small cubes, as is shown in Equation (8).

$$U = \left[\frac{1}{N}\sum_{i=N}^{N}(n_i - \bar{n})^2\right]^{\frac{1}{2}}. \quad (8)$$

In the equation, n_i is the total number of nodes in the ith small cube and $\bar{n}$ is the mean of nodes number in each cube. So far, we have discussed the relation between communication and coverage. Article [22] has proved that when the communication range of node is twice or larger than the sensing range, coverage will contain pure connections. In practical deployment, we only have to consider the coverage so as to ensure the connection. At the moment, coverage contains connection problems.

Please refer to Table 2 for simulation parameters in Figure 3. The circumstance after deployment is shown in the left plot. In the plot, the cube represents the volume of the region (area *Ω*). Tiny black dots represent the positions of nodes; blue spheres are used to indicate the sensing radius. In order to watch them clearly, only the sensing radius of partial nodes are displayed. Nodes can probe the environment and collect information in its sensing radius R_s. Similarly, it may be influenced by the Coulomb's force from its adjacent nodes, and repulsive force from the obstacles as well. The communication radius of Node R_c is greater than the sensing radius R_s. Nodes are able to exchange information mutually within the communication radius. The initial positions of the nodes are in the centre of Region *Ω* (being close to the coordinates [5,5,5]). Imaginably, node density at the beginning is practically very large. When deployment is started, all the nodes are forced by un-balanced Coulomb's force, starting to move to fill the entire region, and eventually reaching equilibrium, as is shown in Figure 3. The right plot shows the change in Coverage and Uniformity versus time during the deployment process described in the left plot. The x-coordinate is the simulation time T; the y-coordinate on the left is the uniformity; the y-coordinate on the right represents the coverage. We can see from the right plot that, at the initial moment of deployment, the nodes only cover a small part of the region because they are all initially positioned in the centre of *Ω*. Therefore the coverage is practically low (<20%). With time elapsed and all nodes are in motion, the coverage tends to grow, and reaches equilibrium after a certain moment (about Time=9). This begins when the coverage reaches maximum (about 100%), and lasts until the simulation is over. The value of uniformity is initially around 1.8 when the simulation begins. Then it decreases rapidly shortly after the deployment begins, eventually, tends to be around 0.3. Because uniformity represents standard deviations, so the smaller it is, the more uniform the network is.

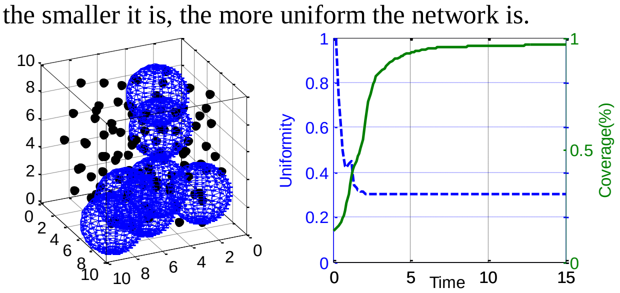

FIGURE 3 Normal deployment

In the left plot in Figure 4, the solid spheres represent obstacles. In the previous sections we mentioned that obstacle can be considered stationary charge with same sign. But the charge it carries is proportional to its size, which means the larger it is, the more charge it carries. There is only one obstacle in the left plot. We can adjust the distance from nodes to the obstacles by configuring the amount of charges that the obstacle carries. It is shown in the left plot that, due to the repulsive force from the obstacles, nodes will be deployed at a distance with the obstacle to avoid them. This is highly meaningful in applications. To keep the nodes away from hazard or unreachable region can minimize node damage, indicating the algorithm's self-adaption. The right plot shows the change in coverage and uniformity versus time during the deployment process. We can see that because of the obstacles, the region is not completely covered by nodes. The maximum coverage is less than 1. In the meantime, compared with Figure 3, the value of uniformity is higher after nodes have reached equilibrium, due to reduction of uniformity because of obstacles.

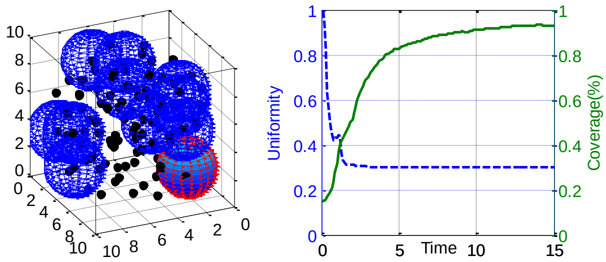

FIGURE 4 Deployment with Obstacles

In the left plot in Figure 5, the black little solid spheres represent sensor nodes while the three big spheres represent the ROIs (Range of Interesting). We noted that ROI can be considered stationary charge with opposite sign. While the charge ROI carries is proportional to its size, which means the larger it is, the more charge it carries. There are three ROIs in the left plot. We can adjust the distance from nodes to the ROIs by configuring the amount of charges that the ROI carries. It is shown in the left plot that, due to the attractive force from the ROIs, nodes will be deployed close to them. This is highly meaningful in applications. To put more attentions to the region needed monitor. The right plot shows the change in coverage and uniformity versus time during the deployment process. We can see that because of the ROIs, the region is completely covered by nodes. When the maximum coverage is reached, it decreases slowly with time for nodes tend to move toward to the ROIs. In the meantime, compared with Figured 3, the value of uniformity is higher after nodes have reached equilibrium, due to reduction of uniformity because of ROIs.

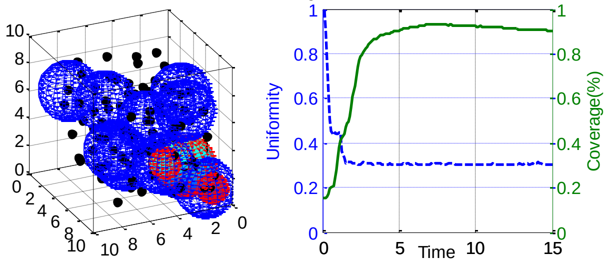

FIGURE 5 Deployment with ROIs

5 Conclusion

Most previous researches on sensor networks are limited to 2d planes, neglecting the vertical fall of the deployment area, while taking the area as a flat plane. With people's continual exploration on space, underwater, underground and other regions, 3D sensor networks are gradually becoming a research hot spot. Yet, 2D algorithms are no longer applicable to 3D deployment. As for this, deployment algorithms under 3D environment have to be researched.

The proposed ideal fluid model is analysed in this paper, and the concept of flow field model is applied in deployment of wireless sensor networks. Sensor networks are abstracted as ideal fluid. In the deployment process, motion of nodes follows momentum conservation law of fluid micelle. A simulation experiment is performed in this paper with the proposed deployment algorithm as the experimental subject. Coverage and uniformity are 2 indexes employed to evaluate the performance of the proposed algorithm. Shown by the simulation result, the deployment algorithm based on ideal fluid model for sensor networks leads to good effect.

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