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A DEPLOYMENT ALGORITHM OF HETEROGENEOUS UNDERWATER SENSOR NETWORK BASED ON ACOUSTIC AND MAGNETIC JOINT SENSING MODEL

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Abstract- In underwater target detection, because the acoustic environment of the shallow sea is extremely complex, the acoustic detection is becoming more and more difficult. A deployment algorithm of heterogeneous sensor network based on joint probabilistic sensing model is proposed which combine the acoustic detection and magnetic detection to detect underwater targets. Expert system knowledge is used to achieve the deployment of acoustic magnetic underwater sensor network which base on the normal working area of submarine and the frequency of target within system work a certain time. The simulation results show that the algorithm can guarantee higher detection probability, and reduce the energy consumption of network and prolong network lifetime.

Index terms: Joint sensing model, expert system, underwater wireless sensor networks, heterogeneous, deployment.

I. INTRODUCTION

Wireless sensor networks have been paid more and more attention by academia and industry because of its great application prospect, but there are still many problems to be solved [1-4]. UWSNs (Underwater Wireless Sensor Networks) [5] is an important part of wireless sensor networks, which can collect marine data, pollution detection, marine exploration, disaster prevention, auxiliary navigation and tactical surveillance, etc; and has caused the attention of many countries and research institutions[6-7]. A large number of micro sensor nodes are deployed to the target waters by using aircraft, ships, submarines, etc. Nodes and base stations should communicate and share information, according to the characteristics of the current surrounding environment to organize network [8].

At present, underwater acoustic positioning is the most mature technology, but still facing great challenges in the regional approaching-sea waters. Because the acoustic environment of the shallow sea is extremely complex, and the rule of acoustic propagation has not been fully mastered, the acoustic detection is becoming more and more difficult with the use of various feature control techniques. Magnetic detecting technology is one of the most reliable and effective detection techniques in the shallow sea area, which is developed earlier and more mature. So it will be an important research direction of underwater sensor network to combine acoustic detection and magnetic detection.

A distributed algorithm FSSD is presented for underwater sensor networks in literature [9]. Through simulate the behavior of fish to move the sensor node to the target area independently, realize the coverage of the event. The algorithm is a non-uniform deployment algorithm, which has a less calculation and high coverage, but the performance of the algorithm is greatly affected by the node's sensing capabilities and movement ability. A underwater sensor network coverage algorithm BT-FIDA is put forward for the amazon river in literature[10] ,which is based on backtracking algorithm; BT-FIDA subsection cover the Amazon river, using the least sensors detect the molar concentration of Amazon river. The algorithm is the barrier coverage, cannot determine the specific location of the source of pollution. There are three algorithms is presented about underwater sensor node localization in literature[11]:(1)Random deployment location method; (2)Multi-dimensional deployment location method; (3)Regular tetrahedron deployment location method. The three methods are based on the exact position of the anchor nodes, but this method is limited by the number of anchor nodes, the more anchor nodes, the better the performance.

For other sensor networks; The deployment algorithm DAWISR is proposed by Zhao [12]. DAWISR is a centralized algorithm, which combine the delaunay triangulation with the grid; because of the difficulty of the reference point fall into the boundary corners in delaunay triangulation method, the boundary compensation mechanism is used which can effectively solve this problem, but it need a large number of redundant nodes to achieve coverage , if sensor nodes are not enough or distributed unevenly the coverage holes will appear. A distributed algorithm CHH for holes filling is put forward in literature [13], CHH does not need the location information, and it can repair the coverage holes, but it needs a very high accuracy for the detection of distance and angle. For the problem of full coverage optimization, there are four algorithms is proposed by M.H[14], which using the Voronoi method: Maxmin-Vertex Strategy, Minmax-Edge Strategy, Maxmin-Edge Strategy and VEDGE Strategy, by calculating the distance between the circumcentre, incentre and the boundary or the vertices of voronoi move the nodes to achieve full coverage, but it increases the average moving distance of the nodes, and also increases the complexity of the algorithm. S. Mini [15] compare the artificial bee colony algorithm and particle swarm optimization algorithm in sensor network to prolong the network lifetime, the artificial bee colony algorithm performs better, and using heuristic method to further improve the lifetime of the sensor network.

The deployment algorithms in the above literature are designed from the perspective of coverage, without considering the change regulation of the target. The activity range of the underwater target may have a certainly regularity or limited by some factors, such as the connection between shoal of fish and season, the relationship between the water quality and the ocean current, the contact of the ship and the sea-route. At present, the research of underwater sensor network seldom considered the target information to optimize the network deployment. In this paper, the sonar sensor and the magnetic sensor are used together to improve the accuracy of the underwater target detection in the shallow sea area, two methods of underwater sensor network deployment based on expert system are presented ;the expert system which include the regulations of submarine ,such as :working depth, time and other information. This method improve the perceived accuracy of sensor network, reduce the number of sensor nodes while meet the coverage quality of the sensor network, and it suitable for the complex area target detection of shallow water acoustic field.

II. BACKGROUND KNOWLEDGE

a. Expert system

ES (Expert System) is the pioneer of all AI (artificial intelligence) technology, has been regarded as the most important branch of AI. In essence, the expert system is intelligent computer program that include the expert knowledge. Expert system mainly includes three parts: knowledge base, reasoning machine and user interface [16]. Knowledge base is a database which includes professional knowledge and metadata and rules. Metadata and rules are formed in experience by learning, can greatly improve the efficiency of the system; the reasoning machine draws a conclusion through matching knowledge base. In this paper, the knowledge base is formed by the laws of the submarine, and the sensor node deployment is deduced by the reasoning machine, to achieve the coverage requirements of the target area.

b. Underwater sensor nodes

There are four types of nodes in the underwater sensor network: ocean bottom sensor nodes, floating nodes, self-moving nodes and sink nodes, where ocean bottom sensor nodes are deployed on the seabed to monitor and collect information. Due to the complexity of the seabed terrain, the communication of ocean bottom sensor nodes is likely to encounter the terrain barrier and form the information isolated island or communication blind area, another feature is that this class nodes are stable relatively; Floating nodes are suspended in the water by means of buoyancy, the depth of its suspension is related to the salinity of the sea water and the properties of the buoyancy device, the characteristics of this kind of nodes are easy influenced by the ocean current, stormy waves, and so on, which can lead to a large displacement; The self-moving nodes is mainly that autonomous underwater vehicle, it is equipped with sensor nodes to monitor and collect the information of the water environment, because this kind of node has the ability of self - moving, it can move independently according to the network requirements or monitoring tasks, so it improves the network structure and dynamic performance; The sink node can be divided into two types, one is the underwater sink node, another one is the water surface sink node, the underwater sink node has a very high energy generally, which is responsible for the data fusion and processing the monitoring data collected by the underwater sensor nodes, and then transmitted to the water surface base station, the water surface base station is responsible for the data fusion and processing the data, and then transmitted to the user through communication with the near shore base station or satellite [17-18].

The sensing model of nodes is the key of the sensor coverage problem, which describes the node's sensing range and detection capability. At present, there are two kinds of sensing models are frequently applied in sensor network coverage: (0-1model) Binary Sensing and Probabilistic Sensing. Because the Binary Sensing is relatively simple and it has a great difference with the actual perception model. For underwater target detection, this paper uses the probability perception model: Sonar sensing model and magnetic sensing model.

b.i The sonar sensing model

Consider the assumption problem of binary, H_0 indicate that no target, H_1 represents the target appears. Assuming the sonar work in the passive reception mode, the receiver set belongs to the Gauss distribution. This assumption is applicable to typical passive sonar receiver, for example the square integral processor. The probability density function of receiver output is [19]:

When H_0

$$P_N(x) = \frac{1}{\sigma_N\sqrt{2\pi}}\exp\left[-\frac{(x-M_N)^2}{2\sigma_N^2}\right] \tag{1}$$

When H_1

$$P_{S+N}(x) = \frac{1}{\sigma_{S+N}\sqrt{2\pi}}\exp\left[-\frac{(x-M_{S+N})^2}{2\sigma_{S+N}^2}\right] \tag{2}$$

M_N, σ_N^2 is the mean and variance of the output noise respectively, M_{S+N}, σ_{S+N}^2 is the mean and variance of signal plus noise respectively.

Assume that the target sound source is SL, the center frequency is f, environmental noise is NL. All the performance of sonar array are identical: The receiving directivity index is DI; The integral gain of energy detection is $5\lg BT$. The transmission loss model of the acoustic signals in the ocean is:

$$TL(R_i) = 20\lg R_i + \lambda R_i \tag{3}$$

R_i is the distance between the target and the i_{th} sonar receiver(m), λ is the absorption coefficient(dB/m). when $f < 10kHz$, $\lambda = 0.007 f^2 + 0.236 f^2/(2.9 + f^2)(dB/km)$. The equation of passive sonar is:

$$DT = SL - TL(R_i) - NL + DI \tag{4}$$

$DT = 5\lg d_i - 5\lg BT$ is the detection threshold.

b.ii Magnetic sensing nodes

Magnetic sensing nodes will produce a magnetic field, if there is a metal close to it ， the magnetic field will changes, then the surrounding targets will be detected. In some sense, the submarine is a moving metal, when the submarine close to the magnetic sensor node will also cause the change of the surrounding magnetic field, then the submarine will be detected. Due to the existence of the magnetic pole, the magnetic field distribution is non-uniform, the perception model of magnetic sensing node is ellipsoidal, simplified into two-dimensional model as shown in Figure 1.

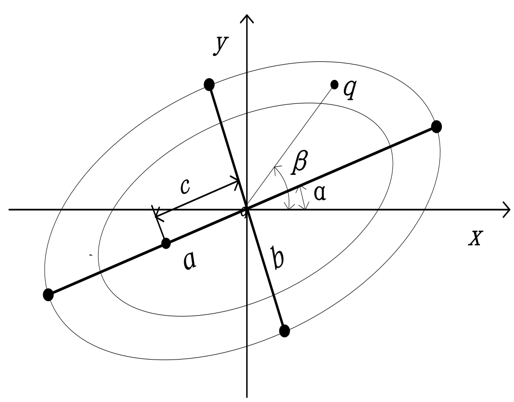

Figure 1. Magnetic Probability Sensing Model

a is the semimajor axis length of the ellipse, b is the semiminor axis of the ellipse, c is the distance between the ellipse focus and the ellipse center. $e = c/a$ is the centrifugal rate, α is the inclination angle of ellipse, β is the angle between the line connecting and the X axis. The probability P of any point q is:

$$P(s,q)=\begin{cases}1, & 0<d(s,q)\le d_1\\ e^{-\alpha[d(s,q)-d_1]}, & d_1<d(s,q)\le d_2\\ 0, & d_2<d(s,q)\end{cases} \quad (5)$$

$d(s,q)$ is the euclidean distance between point s and q , d_1 is the distance between the point of determinate sensing line and center point.

$$d_1=\sqrt{[a\cos(\beta-\theta)\cos\theta-b\sin(\beta-\theta)\sin\theta]^2+[a\cos(\beta-\theta)\sin\theta-b\sin(\beta-\theta)\cos\theta]^2} \quad (6)$$

d_2 is the distance between the point of probable sensing line and center point.

$$d_2=\sqrt{[a'\cos(\beta-\theta)\cos\theta-b'\sin(\beta-\theta)\sin\theta]^2+[a'\cos(\beta-\theta)\sin\theta-b'\sin(\beta-\theta)\cos\theta]^2} \quad (7)$$

b.iii Acoustic magnetic joint sensing model

In this paper, the sonar sensor nodes and the magnetic sensor nodes are used to detect the target area, the sensing probability of the sonar nodes $S_i\ (0<i\le n)$ detect the submarine $G_g(0<g\le z)$ is p_{ig} , and the sensing probability of the magnetic nodes $M_j\ (0<j\le m)$ detect the submarine $G_g(0<g\le z)$ is p_{jg} , the joint perception probability P:

$$p=\begin{cases}1 & (if\ \ p_{ig}=1\,or\ \ p_{ig}=1)\\ 1-\prod_{i=0}^{n}(1-p_{ig})\prod_{j=0}^{m}(1-p_{jg}) & (if\ \ 0<p_{ig}<1\,and\ \ 0<p_{jg}<1)\\ 0 & (if\ \ p_{ig}=0\ and\ \ p_{jg}=0)\end{cases} \quad (8)$$

If $p>p_{th}$ the joint sensing model can be considered as the determine perception. p_{th} is a perception thresholds.

c．The diving depth distribution of submarine

The deeper of the submarine diving depth the more easy to hide itself, at the same time bear the pressure is bigger; because of material strength is limited , the submarine has a limit diving depth , there is no submarine beyond the limit depth. The submarine limit diving depth is generally between 400~600m，When the submarine equipment failure, or the crew operational errors, may exceed the limit diving depth of submarine; if the submarine dive in a shallow depth is easy to be detected by surface warship, so the submarine will haunt in a safe dive depth, the maximum probability of dive depth is the limit depth, the submergence depth and submarine infested probability obeys the Gaussian distribution.

$$p(h) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(h-\mu)^2}{2\sigma^2}} \tag{9}$$

μ is the bounding depth, and σ is the variance of depth[20].

According to the submarine dive deep probability distribution, and the target area is layered, store it into the knowledge base of expert system. The target area is divided into ten layers, the maximum probability diving depth (400~600m) of the submarine infested is the center layer. The probability of submarine appeared at each layer:

$$p_i'' = \kappa * p_i + \gamma * (p_i' + \tau) \tag{10}$$

p_i is the submarine appeared probability of the i_{th} layer in the expert system database. p_i' is the actual appeared probability of the submarine, which is calculated by equation (12) after the network work a period of time. τ is a correction parameter, κ, γ are adjustable parameters, $\gamma = 1 - \kappa$.

Table 1: The Information of Submarine Dive Depth

Layer	**Depth of water(m)**	**Expert experience**
1	0~100	0.1
2	100~200	0.2
3	200~300	0.75
4	300~400	0.9
5	400~500	1
6	500~600	1
7	600~700	0.9
8	700~800	0.75
9	800~900	0.2
10	900~1000	0.1

Expert experience indicates that the probability of submarine appears at each layer

d. Dormancy and awakening mechanism

In the large-scale deployment, if unreasonable use of the node will cause energy waste, nodes are usually scheduled by dormancy and awakening mechanism. The wake probability of each layer is related to the expert experience in ES database and the target appears frequency after working a period of time:

$$t = \eta T \tag{11}$$

$$p_i' = \frac{n_i}{N_t} \tag{12}$$

T is the average working time of sensor nodes, $0 < \eta < 1$ is adjustable parameters, p_i' is the actual appeared probability of the submarine in each layer, after the network work a period of time, n_i is the number of monitored targets by the i_{th} layer, N_t is the total number of monitored targets in network.

The node wakening probability:

$$p_{wi} = \frac{\frac{2\sqrt{3}m \times n}{9r^2} \times p_i''}{N_i} \tag{13}$$

p_i'' can be calculated by(10), which is the submarine occurrence probability of the i_{th} layer in the database of the expert system; m, n is the length and width of the target area; N_i is the number of sensor nodes for each layer.

Each node calculates its wake probability by formula (13), at the same time, a random number is generated which greater than 0 and less than 1. The random number is compared with the awakening probability of this layer, if it is greater than the awakening probability, the node enters the sleep state, if not the node enters the working state; The network enters a new round of scheduling after working for a period of time, then wakes up all the nodes and generates a random number again. If the random number is less than the wake probability, the node enters the working state, otherwise the node will sleep.

e. The moving strategy for nodes

Because the probability of each layer is different, it will lead the energy loss of high probability layers will faster and then the coverage holes will appear. In table1, it can be seen that the probability of target appear in each layer is different , in order to guarantee the monitoring quality of the region which has a high probability of target occurrence, a priority is set: set a high priority to the target area which has a bigger awakening probability, to ensure the node number of it , namely move the nodes to the layer which has a bigger awakening probability, and the number of nodes in each layer is related to the awakening probability. The number of nodes required in per layer N_i':

$$N_i' = \frac{N \times p_{wi}}{\sum_{j=1}^{10} p_{wj}} \tag{14}$$

p_{wi} is the awakening probability of each layer, N is the total number of nodes, $\sum_{j=1}^{10} p_{wj}$ is the sum of the ten layer node wake probability.

If the number of nodes in this layer $N_i < N_i'$, move the sensor nodes to this layer from the low priority area until $N_i = N_i'$.

Definition1.Coverage rate

For submarine detection, there are N submarines in target area $T = \{T_1, T_2, ..., T_n\}$, M submarines $\{T_1, T_2, ..., T_m\}$ are detected by network, the network coverage rate C :

$$C = \frac{M}{N} \tag{15}$$

Definition2.The residual energy of node

There are m sensor nodes $S = \{S_1, S_2, ..., S_m\}$ deployed in the target area $u \times v$, each sensor node has an initial energy $E = \{E_1, E_2, ..., E_m\}$, the energy consumption of the nodes moving unit distance is e_0, the energy consumption of sensor normal work and sleep in unit time is e_1, e_2 respectively.

The energy consumption of node i is:

$$Ec_i(l_i, t) = l_i * e_0 + t_{1i} * e_1 + t_{2i} * e2 \tag{16}$$

l_i is the moving distance of node i, t_{1i} is the working time of the node i, t_{2i} is the sleep time of the node i, $t = t_{1i} + t_{2i}$, t is the network working time, The remaining energy of node i is:

$$Es_i = E_i - Ec_i(l_i, t) \tag{17}$$

III. ALGORITHM DESCRIPTION

A deployment scheme of heterogeneous underwater sensor network is put forward based on the expert system, combine the expert experience and the actual situation of the network to deploy the sensor node, in order to improve the accuracy of sensor network, magnetic sensing node is added to the network. If the node does not move, the algorithm in this paper is non-uniform deployment algorithm, it will cause the energy imbalance of sensor network eventually. By moving the node can make the energy balance of each layer, but it will consume a part of energy in the early stage, ESNDNM (system node does not move expert) and ESFMN (system for mobile node expert) are compared and analyzed in this paper.

In order to build the model better, we make the assumptions as follows:

(1) Assume that each sonar sensor node's communication radius is 2 times the sensing radius of the sensor, and the communication radius of each magnetic sensor node is $2a$ (a is the semimajor axis length of the ellipse)to guarantee the connectivity of network.

(2) In the detection region, the environment noise is stability and belong the uniform distribution; the waveform, amplitude and frequency are kept stable.

(3) Assume that the nodes have two working states: work and sleep, the energy consumption of the nodes in the working state is higher than the sleep state, and the initial deployment of the nodes is random and uniform.

(4) Assume that each sensor node knows its own position, and has ability to move, in order to ensure that the sensor node can reach a predetermined position.

IV. ALGORITHM STEPS

a. ESNDNM

Step1: A large number of sensor nodes are randomly and uniformly deployed in the target area.

Step2: Initialization node parameters, each node according to the water pressure to get their own water depth to determine its own layer (table1), node exchange message, confirm the location of the node and the location of the neighbor node.

Step3: The nodes are scheduled in the target area according to the conventional dormancy and awakening mechanism, and monitoring the target area a period of time t, then calculated the actual probability of each layer.

Step4: Sensor node get the submarine appear probability of its own layer from the expert system database; combined with the actual situation, the submarine appear probability of each layer is calculated by the formula (10), and updated it to the database.

Step5: Sensor nodes are scheduled according the dormancy and awakening mechanism from section 1.7.

Step6: End

b. ESFMN

Step1: A large number of nodes are randomly and uniformly deployed in the target area.

Step2: Initialization node parameters, each node according to the water pressure to get their own water depth to determine its own layer (table1), node exchange message, confirm the location of the node and the location of the neighbor node.

Step3: The nodes are scheduled in the target area according to the conventional dormancy and awakening mechanism, and monitoring the target area a period of time t, then calculated the actual probability of each layer.

Step4: Sensor node get the submarine appear probability of its own layer from the expert system database; combined with the actual situation, the submarine appear probability of each layer is calculated by the formula (10), and updated it to the database.

Step5: In order to balance the network's energy, moving sensor nodes to achieve the required nodes number of each layer according to the moving strategy from section 1.8.

Step6: Sensor nodes are scheduled according the dormancy and awakening mechanism from section 1.7.

Step7: End

The sonar nodes and magnetic sensing nodes are deployed by the above steps, in normal working process, the two sensor networks work in different time periods, take turns working for a period of time t. when submarine is found by any one sensor networks, the two networks are activated at the same time to improve the monitoring quality.

V. SIMULATION RESULTS

The software MATLAB is used. In this paper, the algorithm is a dual network joint perception algorithm, compared with VFA double covering algorithm. Simulation parameters: the determined sensing radius of sonar nodes $r=20m$, probability sensing radius $R=30m$. The determined sensing radius of magnetic sensing nodes $r_1=20m$, $r_2=30m$, the probability sensing radius $R_1=30m$， $R_2=40m$. κ =0.8， τ =0.2， ε =0.8， η =0.1, 1000 sonar sensor nodes and 1000 sonar sensor nodes are deployed randomly in the area H (500*1000m). The main simulation work is as follows: the relationship between the number of remaining nodes and the time t , compare joint perception and independent perception, the relationship between coverage and the number of working node, and the relationship between effective coverage and working time t.(Because the sonar network and the magnetic sensing network worked alternately, and the working mechanism and parameters of the two networks are consistent, the network performance is basically the same, so the simulation for the remaining nodes is mainly on the sonar network).

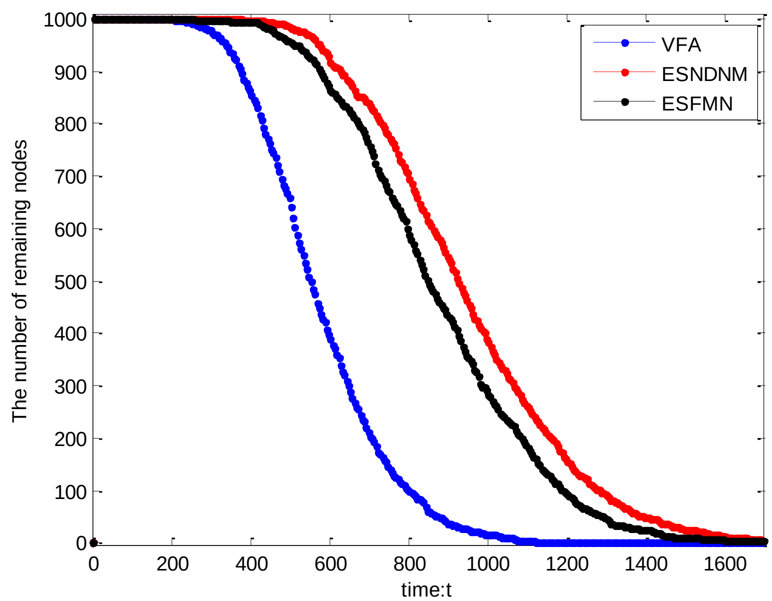

Figure 2. The Number of Remaining Nodes and Time t

Figure 2 shows that at the time of t>500, the remaining number of nodes of ESFMN and VFA algorithm is smaller than the ESNDNM algorithm, VFA algorithm has the least number of remaining nodes. This is because the ESFMN and ESNDNM algorithm based on the submarine appear frequency in a certain depth to determine the awakening probability of nodes, a large number of unnecessary nodes are saved in the areas which has a small appear probability of submarine, so that the number of remaining nodes is more than VFA. Because of the movement of ESFMN algorithm consumed a portion of the energy in the early stage, so the number of the remaining nodes of ESFMN algorithm is less than ESNDNM algorithm.

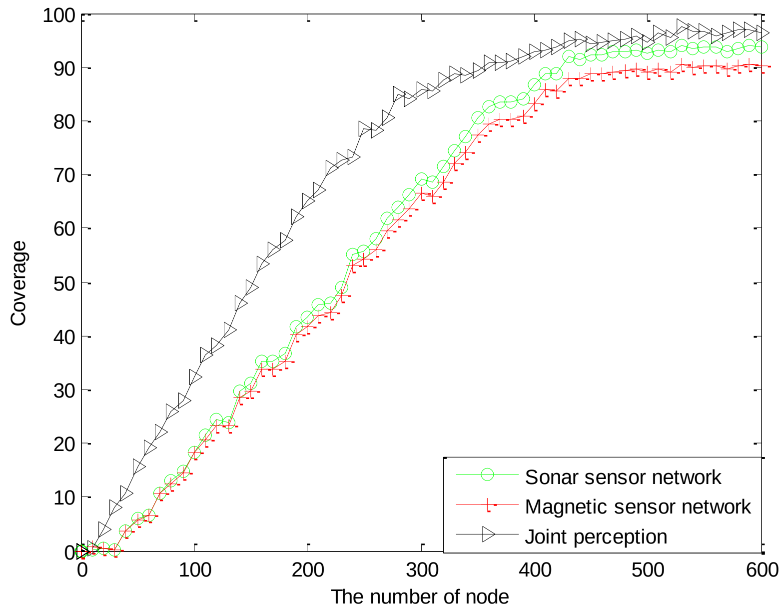

Figure 3. Joint Perception and Independent Perception

Figure 3 is the comparison of joint perception and independent perception. In case of low redundancy of nodes, we can see that the coverage of the joint perception is higher than independent perception about 10%~20%, this is because the joint perception reduces the coverage holes, improves the sensing accuracy of the network, and also improves the coverage of the network. It can be seen from the fig.3 that the coverage of the magnetic sensor network is significantly lower than the sonar network, there are exist overlapping phenomenon of the major axis of ellipse, so the coverage of the magnetic sensing network is lower.

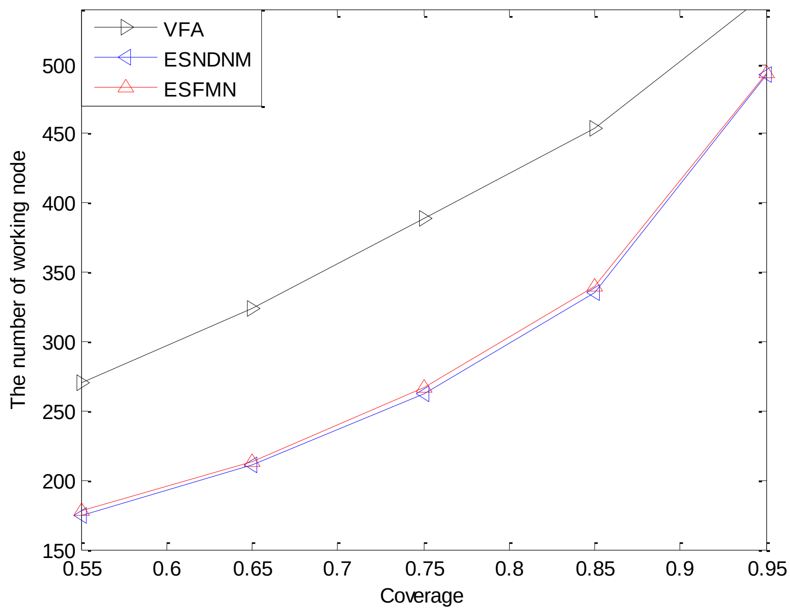

Figure 4. Coverage and Working Nodes

Fig.4 is the number of required working nodes in the case of the same coverage; In the case of the same coverage, the required nodes number of the ESNDNM algorithms and ESFMN algorithms are less than the VFA algorithm. The required number of nodes of the ESNDNM algorithms and ESFMN algorithms are almost the same. Therefore, the non-uniform deployment algorithm of this paper can save a large number of sensor nodes.

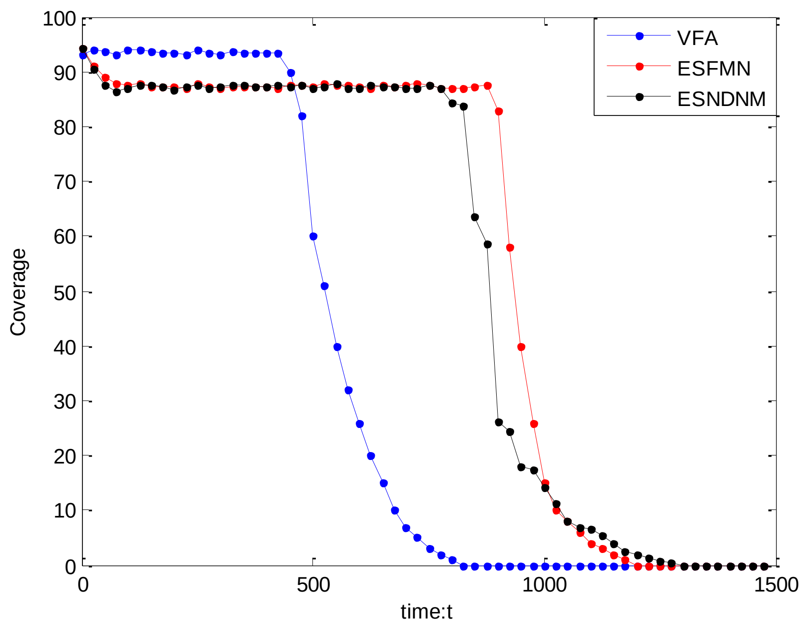

Figure 5. Effective Coverage and Working Time

Fig.5 is the relationship between effective coverage and working time t. When t<100, the proposed algorithm calculate and adjust the probability of sleep. In the fig.5, the coverage rate of VFA is higher than the two proposed algorithms about 6%, and it is stable at around 94%; When t>500, in the VFA algorithm, a large number of nodes are depleted and death, which makes the coverage rate drops sharply. The two proposed algorithms can maintain high coverage for longer time than the VFA algorithm, because the use of the dormancy and awakening mechanism. The ESFMN algorithm can maintain high coverage for longer time than the ESNDNM algorithm, because the ESNDNM algorithm does not balance the network energy. The proposed algorithm can prolong the lifetime of network.

VI. CONCLUSION AND OUTLOOK

In this paper, two distributed algorithms for the underwater heterogeneous sensor network deployment were proposed, which based on the expert system. The two algorithms sum up the experience of the submarine, and store it into the expert system database, and the target area is divided into ten layers. Each node determines its own layer according the depth, and calculates its own wakening probability through database, and use the joint perception to improve the perception accuracy of the network. The simulation results show that the algorithm can guarantee higher detection probability, reduce the energy consumption of network and prolong network lifetime.

In this paper, the model was built on the two-dimensional model, there was a certain gap with the 3 dimensional real model, and didn't consider the direction of magnetic sensing node, the simulation results were not ideal enough. In the future work the model of magnetic sensing nodes will be improved gradually and the 3-D model will be used into the research work.

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