A MDS-based localization algorithm for underwater wireless sensor network

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***Abstract*—This study is to propose a multidimensional scaling localization algorithm based on cluster structure [MDS-MAP (C, E)], and used in underwater wireless sensor networks (UWSN) node self-positioning. MDS-MAP (C, E) algorithm: First, underwater wireless sensor network is divided into more than one cluster head of the local network; Secondly, local positioning, using the Euclidean algorithm to calculate the Euclidean distance between each node and its two-hop neighbors, and then take this Euclidean distance for multidimensional scaling in each cluster, instead of the shortest distance from Dijkstra or Floyd algorithm. Simulation results show that: the localization algorithm achieves self-positioning of the whole network in the case of underwater anchor node sparse sensor nodes; the algorithm can obtain higher positioning accuracy than traditional MDS-MAP algorithm, at the same time reducing the computational overhead.**

Keywords—Cluster structure; Multidimensional scaling (MDS); node localization; Underwater wireless sensor network (UWSN);

I. INTRODUCTION

Most of the applications require location information of nodes in underwater wireless sensor networks (UWSN). In addition, the node position information can be contributed for high-efficient routing algorithm. Therefore, the node self-localization has become an important research direction in UWSN.

Many node localization algorithm have been proposed, but because the underwater acoustic channel particularity and complexity (such as multipath, Doppler shift, large attenuation and a long delay, etc.), making the existing terrestrial wireless network node localization algorithms including which by receiving GPS signals to obtain precise location information, can not be directly applied to underwater acoustic sensor networks (UWSN). To meet the underwater wireless sensor networks in military applications for high-precision positioning requirements, we propose a multidimensional scaling (MDS) localization algorithm based on cluster structure for underwater wireless sensor network.

II. TRADITIONAL MDS-MAP ALGORITHM

Multidimensional scaling analysis (MDS) is a kind of data analysis techniques which expresses the relationship of multi-dimensional data as geometric to study. Traditional MDS-MAP algorithm is proposed by Yi Shang (the University of Missouri-Columbia). The algorithm utilizes the shortest path distance or connectivity information between nodes within the whole network to obtain location information of nodes. Two nodes are considered as connected when the distance between them is shorter than the communication radius. MDS-MAP localization algorithm consists of the following three steps:

① Construct the distance matrix of unknown node within the network: First, according to the connectivity between nodes generate the entire network topology, as well as set value to each edge of the diagram: when any two neighboring nodes have ranging capability, the measuring distance just is the side length of the two nodes; when any two neighboring nodes only have the connectivity, then the side length of the two nodes is set to 1. Secondly use the shortest path algorithm, such as Dijkstra or Floyd algorithm, to calculate the shortest path between any two nodes. Finally use the calculated shortest path value instead of the Euclidean distance between the two nodes to construct the distance matrix for all nodes.

② Solving relative coordinates: suppose sensor network as two-dimensional network, calculate the distance matrix using classical MDS algorithm, then obtain two- dimensional relative coordinates of the entire sensor network.

③ Calculate the absolute coordinates: in the condition of sufficient anchor nodes are given (a minimum of three in two-dimensional coordinates), all the relative coordinates of the unknown node can be converted into absolute coordinates through the coordinate information of anchor nodes after the translation, rotation and mirror etc coordinate transformation.

Traditional MDS-MAP algorithm has two significant drawbacks: First, it is based on the classical MDS centralized computing model, which requires some nodes with high strength calculation capability in the network. It has not only a large time complexity [O (n ^ 3)] but also the algorithm scalability is poor, which can not be applied to large-scale network environment. Second, when the actual geometric distance between the nodes (Euclidean distance) is correct, the solution can be given without error. But when the actual distance between nodes can not be informed, the traditional MDS-MAP algorithm is bound to bring a certain error, as it use the shortest distance to replace the Euclidean distance between two nodes. When the difference between the shortest path distance and the actual distance is large, it will make the traditional MDS-MAP algorithm generate a big positioning error.

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Hereby the improved MDS-MAP(C, E) proposed in this paper reduces the computational complexity and improve the positioning accuracy through clustering and Euclidean algorithm.

III. EUCLIDEAN ALGORITHM

Euclidean algorithm gives a method for calculating the distance between unknown nodes and separated by two-hop beacon node. The main idea of the algorithm is to calculate the distance between nodes separated by two hop through the geometry relations. As shown in Figure 1, where A, B, C are nodes with unknown coordinates; L is the beacon node; node A ,B and C are within one hop; and nodes B, C and L are also within one hop. The distance of AB, AC, BC, BL and CL can be directly measured by ranging technology. For the quadrilateral ABCL, all the sides and a diagonal BC are known, then the length of AL (the distance of node A and L) can be calculated by formula (1) - (3).

$$\cos\alpha = \frac{AB^2 - AC^2 - BC^2}{2AC \bullet BC} \qquad (1)$$

$$\cos\beta = \frac{BL^2 - BC^2 - CL^2}{2CL \bullet BC} \qquad (2)$$

$$AL^2 = AC^2 + CL^2 - 2AC \bullet CL\cos(\alpha+\beta) \qquad (3)$$

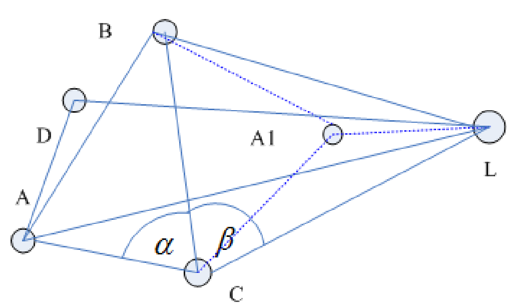

Fig1 Euclidean algorithm Schematic diagram

According to (3) AL has two possible values, that is node A has two possible positions: A and A1. It can use two kinds of ways to solve this problem: □ if there is other neighbor node D next to L, and also next to one of node B and C, then here it can use D instead of B or C to calculate AL again. Two of four results have the same values, the value just is the real AL distance. As shown in figure 1, if there are more neighbor nodes available, node A can be made a more accurate selection. □ based on geometrical principles, the node B shown in figure 1 is the common neighbor nodes of C,D and L, suppose A and B is not adjacent, then A and L can be considered to be in each side of the line BC, that is to say, A is the correct node coordinate. Hereby, it can accurately calculate the distance between the unknown node A and the beacon node L.

IV. CLUSTER-BASED STRUCTURE OF MDS-MAP (C, E) ALGORITHM

This paper proposes a "cluster-based structure of MDS-MAP (C, E) algorithm," to achieve underwater node self-localization. This method is different from the traditional MDS-MAP centralized location algorithm, that is: First, it is a distributed positioning algorithm. This method only requires each local cluster head to calculate the distance between nodes, and then calculate the node coordinates. It not only reduces the computational complexity, but also reduces the calculation error. Secondly, the algorithm introduces Euclidean algorithm to generate more accurate distance of two-hop range than the shortest distance of traditional MDS-MAP algorithm, making the local relative map error reduced, thereby improving the whole network positioning accuracy.

4.1 Design Process

Assumptions: 1. UWSN is deployed on the seabed as the two-dimensional sensor networks, there are a small number of buoys as sea anchors; 2. Anchor node receives GPS signals, to obtain accurate geographical coordinates, underwater sensor nodes have ranging capability ; 3 network has a unified global time, the node has a timer, each node maximum communication radius is R.

The node executes MDS - MAP (C, E) algorithm in the following steps:

1. Perform clustering algorithm to divide the network into several clusters, each cluster is referred to as a local network.
2. Establish D distance matrix: the distance for 1-hop nodes in the cluster is obtained by measuring, and for 2-hop nodes the distance is obtained through the Euclidean algorithm.
3. Generate the local relative coordinates map by performing MDS localization algorithm
4. Merge the local relative coordinates into global relative map coordinates performed by cluster head which has more energy and larger beacon nodes.
5. The cluster head executing fusion algorithm utilizes the true location information of horizontal anchor nodes to calculate absolute coordinates for all the unknown nodes in the entire network.

4.2 Clustering process

Clustering algorithm is executed in nodes. The network is divided into multiple clusters; each cluster is called a local network. The local coordinate system of each cluster is fused into the global coordinate system through inter-conversion. In this process, neighboring clusters must have a certain degree of overlap. In this study, rigid transformation is applied to two adjacent coordinate systems; cluster requires overlapping of greater than 2. Cluster node to the cluster head does not exceed the number of 2 hops. Each node computes its own hop and the total number of two-hop neighbors, including the connectivity and energy information as a cluster head selection parameters. Defined corresponding weights for each parameter, and finally determine the cluster head by selecting the appropriate weights. Once a node is selected as the cluster head, its one-hop and two-hop neighbors cease to constitute its own local network. If a node finds itself also in other clusters within two-hop, it will be recorded as the basis for integration behind.

4.3 Establish the distance matrix D

1. The distance of one-hop nodes in the cluster is obtained by ranging. As characteristics of the underwater environment, usually a sound signal is used as the main means of communication. So we utilize the TOA method to measure the relative distance between nodes, the ranging formula is:

$$D = T_{proc} * v_s \qquad (4)$$

$$v_s = 1410 + 4.21P - 0.037P^2 + 1.41s + 0.018h \qquad (5)$$

$$T_{proc} = T_{sig} - T_{tran} = (T_c - T_p) - \frac{L_p}{R_t} \qquad (6)$$

In formula (4), D is the distance between the nodes, T_{proc} is the acoustic signal propagation delay calculated by the formula (6). v_s is propagation speed of sound in water calculated by the formula (5). In formula (5), P is the water temperature, s is the salinity, h is the depth. In formula (6), T_c is the time of the node finish data receiving, T_p is the timestamp of sending information packet, L_p is the packet length, R_t is the data transfer rate.

2, The distance of two hop in the cluster is calculated by two-hop Euclidean algorithm [see section 3] .

4.4 Generate the local relative coordinates map

From distance matrix D, using the classical MDS algorithm to calculate relative coordinates of each node within the cluster:

(1) The square of each element of D, denoted by $D^{(2)}$;

(2) dual centralized of $D^{(2)}$, and receive a positive definite symmetric matrix B, which is

$$B = -\frac{1}{2} J \cdot D^{(2)} \cdot J \qquad (7)$$

$$J = E_{n\times n} - \frac{1}{n} e_n^T \cdot e_n \qquad (8)$$

Where: $E_{n\times n}$ is n unit matrix, $e_n = [1,1,\ldots\ldots 1]_{1\times n}$

(3) The singular value decomposition of matrix B, take the largest m eigenvector $(\lambda_1, \lambda_2, \ldots\ldots \lambda_m)$, to obtain the corresponding m eigenvectors $(w_1, w_2, \ldots\ldots w_m)$, m eigenvector compose a m-dimensional diagonal matrix Λ, m eigenvectors compose n × m matrix V, assuming m = 2, the relative coordinates $X = V_m \Lambda_m^{\frac{1}{2}}$

4.5 Merge the local relative coordinates map into global relative coordinates, and then transform to be absolute coordinates

1. Cluster head with more energy and larger beacon nodes executes the integration algorithm, which is based on the overlapping nodes between the clusters. Using optimal linear transformation, based on overlapping nodes, it achieves the transformation from a relative coordinate map to another one, until the global relative coordinates map is generated. The algorithm is as follows:

Suppose r, l are two localized networks, if $NB(r) \cap NB(l)$ contains more than three nodes, using the following conversion formula to transform the note coordinate of $NB(l)$ to the r coordinate system:

$$x_r = sR(x_l) + x_0 \qquad (9)$$

where s is the scaling factor, $R(\cdot)$ is the rotation transformation, x_0 is the translation transformation.

Suppose E is the coordinate matrix of the node of $NB(r) \cap NB(l)$ in r (one per line node), which the i row vector is represented by $x_{r,i}$; S is the node of $NB(r) \cap NB(l)$ as the coordinate matrix of l, $x_{l,i}$ is the i node row vector; D is the node of $NB(l) - NB(r) \cap NB(l)$ in the coordinates of the l matrices. E and S, respectively, assuming that there are n nodes. First, the node r to l extend to three-dimensional coordinate space, and make three-dimensional coordinate value of all 1's. Respectively make the central points of r and l are:

$$\overline{x_r} = \frac{1}{n}\sum_{i=1}^{n} x_{r,i}, \overline{x_l} = \frac{1}{n}\sum_{i=1}^{n} x_{l,i} \qquad (10)$$

suppose $x'_{r,i} = x_{r,i} - \overline{x_r}, x'_{l,i} = x_{l,i} - \overline{x_l}$, Scaling factor s is given by the following formula:

$$s = \sqrt{\sum_{i=1}^{n} \left\| x'_{r,i} \right\|^2 / \sum_{i=1}^{n} \left\| x'_{l,i} \right\|^2} \qquad (11)$$

the covariance matrix of E and S can be expressed as:

$$C = \sum_{i=1}^{n} x'_{l,i} {x'_{r,i}}^T = \begin{bmatrix} C_{xx} & C_{xy} & C_{xz} \\ C_{yx} & C_{yy} & C_{yz} \\ C_{zx} & C_{zy} & C_{zz} \end{bmatrix} \qquad (12)$$

where $C_{xx} = \sum_{i=1}^{n} x'_{l,i} x'_{r,i}, C_{xy} = \sum_{i=1}^{n} x'_{l,i} y'_{r,i}$, matrix U Calculated by the C:

$$U = \begin{bmatrix} C_{xx} + C_{yy} + C_{zz} & C_{yz} - C_{zy} & C_{zx} - Cxz & C_{xy} - C_{yx} \\ C_{yz} - C_{zy} & C_{xx} - C_{yy} - C_{zz} & C_{xy} + C_{yx} & C_{zx} + C_{xz} \\ C_{zx} - C_{xz} & C_{xy} + Cyx & -C_{xx} + C_{yy} - C_{zz} & C_{yz} + C_{zy} \\ C_{xy} - C_{YX} & C_{zx} + C_{xz} & C_{yz} + C_{zy} & -C_{xx} - C_{yy} + C_{zz} \end{bmatrix}$$

(13)

Calculate the maximum eigenvalue of U corresponding eigenvectors λ_m : $\lambda_m = (q_0, q_1, q_2, q_3)$, The rotational transformation matrix can be calculated by the following formula:

$$R = \begin{bmatrix} q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_2q_1+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3-q_0q_1) \\ 2(q_3q_1-q_0q_2) & 2(q_3q_2+q_0q)_1 & q_0^2-q_1^2-q_2^2+q_3^2 \end{bmatrix} \quad (14)$$

Translational transform to be

$$x_0 = \overline{x_r} - \overline{x_l} R^T \quad (15)$$

By the formula (9), (11), (14), (15), D can be transformed into the r coordinate system, as shown in formula (16):

$$F = DR^T + Ix_0 \quad (16)$$

where I is the All one column vector having the same number of lines with D.

2. According to the two beacon nodes of not in the same line, using the above method it can further transform the two-dimensional global relative coordinates into global absolute coordinates, and no longer needs to optimize the coordinates, finally achieve the positioning results.

V. Simulation and Discussion

The simulation area is a rectangular area of 1000m X 1000m, random uniform deployment of 100 nodes, the node communication radius of 200m. As shown in Figure 2, a red asterisk represents an anchor node, the hollow circle represents the unknown node, the average connectivity of network: 9.44.

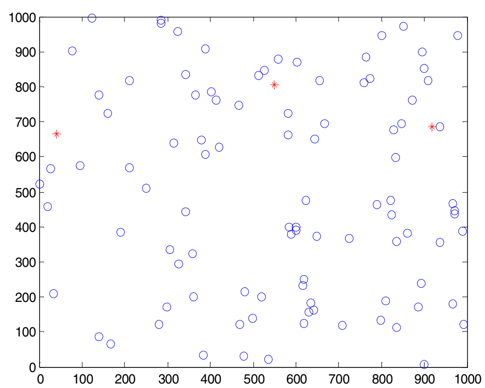

Figure 2: Node Distribution

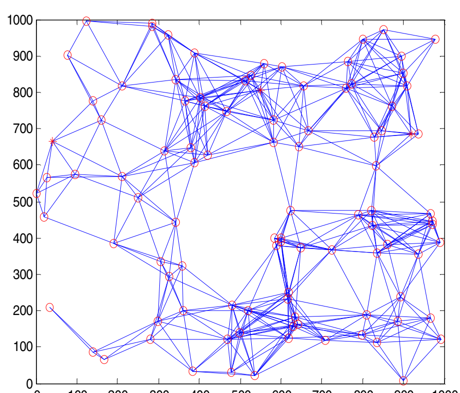

Figure 3: Neighbor relationship diagram (node communication radius 200m)

Table 1 clustering algorithm simulation results

Communication radius /m	380	340	300	260	240	200
The number of sub-clusters	3	3	4	5	6	7

Table 1 show the clustering results on above network in different communication radius condition. From the results, along with communication radius decreases, the clustering algorithm significantly reduces the number of nodes within a local network, which provides favorable condition to reduce the positioning error.

Simulate the improved algorithm MDS-MAP (C, E) in Matlab, being compared with the MDS-MAP (P) algorithm. Using the average positioning error evaluate algorithm performance. Average positioning error: the ratio of the Euclidean distance of estimated position to the true position with communication radius.

$$E = \left(\sum_{i=1}^{n} \left\| x_{esti}(i) - x_{true}(i) \right\| \right) / (n \times r) \quad (17)$$

where n is the total number of network nodes, r is the communication radius of the node.

Simulation area is a rectangular area of 1000m X 1000m, random uniform deployment of 100 nodes, the node communication radius of 200m, average connectivity of network is 9.44, taking the ranging error of 5%. The simulation results show that under the same conditions, MDS-MAP (C, E) algorithm has the average location error of 14%, while the MDS-MAP (P) algorithm has the positioning error of 19%. MDS-MAP (P) algorithm uses the shortest path to calculate the distance between nodes, while MDS-MAP (C, E) algorithm uses Euclidean algorithm to calculate the distance between nodes, which has smaller positioning error. Figure 4 shows in different ranging error, the positioning error of the improved MDS-MAP(C,E) and MDS-MAP(P) which both based on distance information. The ranging error increases, the positioning error of both algorithms trend to increase. Because MDS-MAP uses the shortest path distance instead of the actual distance between nodes, positioning error still exists when ranging error is zero.

Figure 5 the average positioning error of two algorithms in different connectivity when the range error is 5%. To increase the network connectivity during simulation by increasing communication distance between nodes. With the increase of network connectivity, the average location error is showing a downward trend, the network connectivity is lower, MDS-MAP (C, E) shows a better performance.

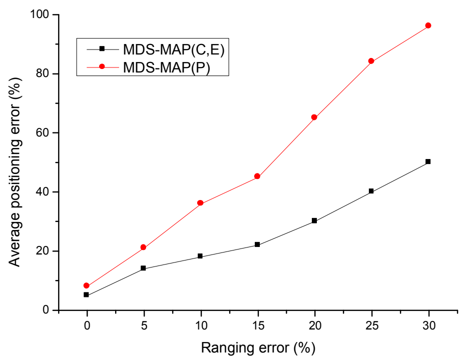

Figure 4: : Relation between ranging error and average positioning error

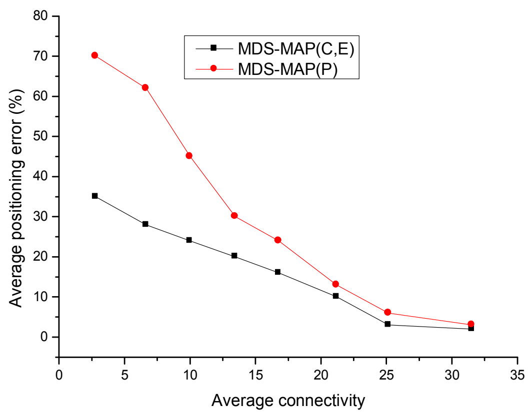

Figure 5: : Relation between Connectivity and positioning error

VI. SUMMARY

In underwater wireless sensor networks, underwater anchor nodes are sparse, ranging error is large. When applying multidimensional scaling techniques, the error comes mainly from the distance matrix estimation. The larger the network, the greater the error, and also increases the complexity of the algorithm. The algorithm proposed in the article uses the idea of clustering to implement distributed positioning, calculate Euclidean distance between nodes in the cluster by Euclidean algorithm, calculate the location of each cluster node by MDS algorithm, and then merge into a global map and get the global node distribution. Compared with MDS-MAP (P), this algorithm has lower complexity, and higher average location accuracy.

ACKNOWLEDGMENT

This work was supported by the Fundamental Research Funds for the Central Universities (2011121050, 2012121028), the National Natural Science Foundation of China (61001142, 61071150) and the Science Technology Project of Xiamen Government (3502z20123011).

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