Localization of Large Scale Underwater Sensor Networks Based on Recursive Position Estimation

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***Abstract*—Large scale underwater wireless sensor networks (UWSNs) have great applications in ocean exploration. The basic localization scheme is the recursive position estimation with hierarchical steps. To achieve accurate localization for each node and a rather high localization coverage, the localized nodes to be chosen as reference nodes are one of the critical steps. This paper proposed a new method to define the confidence value of a reference node based on covariance law. With the measured distance between nodes, the estimated position is more accurate throughout the network and can give a comprehensive localization error. Localization coverage and localization error are used to evaluate the performance. Compared with the previous methods, the simulation results show that the proposed method have great advantage in controlling error accumulation, it is suitable for high precision large scale UWSNs.**

I. Introduction

Large scale Underwater Wireless Sensor Networks (UWSN) has great impact on ocean exploration and environmental monitoring. The intelligent sensor integrated with communication system, data collecting system and environmental monitoring can meet the stringent requirements in many challenging tasks. The data collected by underwater sensor becomes meaningful with the location information, but the accurate node localization of large scale UWSN is one of the most challenging tasks due to severe underwater environments [1]–[5].

Unlike terrestrial WSNs in air that node localization is often performed by GPS, UWSNs is often implemented by acoustic signals. Because the severe underwater environment, UWSNs have many challenges especially for localization. First, underwater node is mobile with water drift that is unable to fix like nodes in air. The absolute position of underwater node is unstable for most applications. Second, global positioning system (GPS) signals attenuates dramatically underwater, how to extend equal precision from inland to underwater is one of the great challenges. Furthermore, sound speed is nearly 1500 m/s which is far slow compared to light speed, the carrier characteristics determine the long propagation delay, low frequency resolution and difficult to achieve accurate time [6]–[8].

The localization methods can be categorised into range-based method, range-free method and other methods. Among these methods, the range-based method have the best localization accuracy. Distance measurements are the bases of the range-based methods. Terrestrial WSNs in air always use received signal strength indicator (RSSI) for range measurement, while this method is unsuitable for underwater because of the multi-path, reverberation and interference. Therefore, UWSNs always use time difference of arrival (TDoA) or time of arrival (ToA) instead of RSSI. For each nodes, after measuring the distances to several anchor nodes, the location can be estimated by triangulation or trilateration. For a large scale network with a small number of anchor nodes, it is another challenge of how to improve localization accuracy with small localization error and low communication cost [2], [4].

The recursive position estimation scheme is first proposed in large scale WSN [9]. There are two types in the whole networks, ordinary nodes and anchor nodes. The anchor nodes are the references to be used for ordinary node localization. The ordinary nodes first use the near several anchor nodes to estimate their locations, and under some specified accuracy condition, these newly localized ordinary nodes can become reference nodes for other ordinary nodes localization. The procedure repeats iteratively to increase the coverage of localization. It has good performance with small distance estimation errors. Recently, large scale localization (LSL) [2] extends this localization schemes to UWSNs and modifies the original algorithm to a hierarchical approach that allows multi hop links to perform distance measurement. The new approach have high localization coverage and low communication cost.

This paper proposes a new metrics for ordinary nodes to become references in recursive localization schemes. It uses error propagation theory based on the hypothesis of distance measurement error obeyed normal distribution. The method is more related to the actual application environment. Localization coverage and localization error are used as performance metrics compared with the previous works. The related works in UWSNs are listed in Section II. The recursive schemes are introduced in Section III. The comparison of different reference selection methods and the method we proposed are listed in Section IV. The simulation results are shown in Section V and conclusions are given in Section VI.

II. Related works

The recursive position estimation algorithm is designed for large scale RF WSN [9]. This algorithm can estimate their locations from a small set of anchor nodes using only local information. System coverage increases iteratively with newly estimated positions join the anchor nodes. Large-scale localization (LSL) extends it to UWSN and modifies the algorithm to hierarchical approach that allows multi hop links

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in distance measurement [2]. They integrate the 3-dimensional Euclidean distance estimation method with the recursive location method for distributed scheme. The results achieve high localization coverage with relatively small localization error and communication cost. But this scheme has the problem of the convergence property tightly linked with the message limit. Beyond the value of critical message, the communication costs increase significantly without any corresponding improvement in localization coverage. Underwater positioning system (UPS) using TDoA techniques by multiple beacon intervals which has the advantage of not requiring time synchronization [10]. Ordinary nodes listen to the broadcasts of anchor nodes to localize itself. They use Saleh-Valenzuela model for underwater acoustic channel, the results perform low localization error and utilize very few anchor nodes while this scheme has limitations in harsh and dynamic underwater acoustic channels.

Wide coverage positioning system (WPS) [11], GPS-less localization protocol (GPS-less) [12], motion-aware sensor localization (MASL) [13], underwater sparse positioning (USP) [14] and 3D underwater localization (3DUL) [15] can be used for different application environments with ToA techniques. They analyse the measurement errors due to sound speed variation, NLOS signals, time non-synchronization and node mobility with the assumption that the direct path signal has the strongest signal, which is not always the case in reality.

III. THE RECURSIVE LOCALIZATION ALGORITHM

The recursive localization algorithm is first used in large scale RF WSNs [9] to iteratively estimate node positions from a few anchor nodes. Figure 1 shows the recursive localization scheme, where anchor nodes are illustrated by black squares and ordinary nodes are illustrated by gray circles.

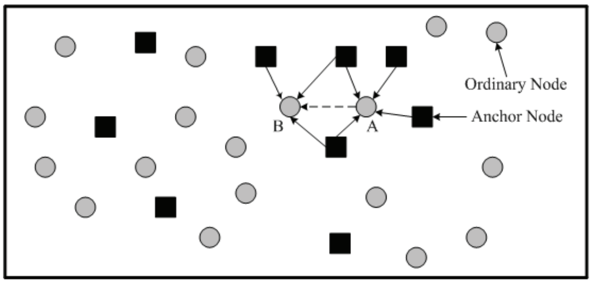

Fig. 1. Recursive localization scheme

Localization of an ordinary node is achieved in four steps: 1) Anchor node will broadcast its location and beacon message for other nodes to use; 2) Node A measures the distances between itself and four or more near anchor nodes, and estimates its own location; 3) It will broadcast its own location information for other nodes to use. If the location error is small enough, Node A can be regarded as a new reference node. 4) Ordinary node B receives locations of reference Node A and other anchor nodes or other newly-localized reference nodes. Node B selects reference nodes based on their confidence levels and calculate its own location using the measured distances between these reference nodes and Node B.

From the above scheme we can see the positioning error of each node is depends on the selection of reference nodes. For the first step, we assume the anchor nodes have the accurate position, and the localized ordinary nodes have the rather high accuracy compared to the later steps. With the iterative steps moving on, the error will accumulate because of the inaccurate references that changed from localized ordinary nodes. To control the network average localization error, the evaluation metrics of confidence value are really important. The next section will give the former works of the confidence value and the one we propose based on error propagation theory.

IV. CONFIDENCE VALUE FOR REFERENCE SELECTION

The recursive localization scheme uses the error between observations and estimated results to evaluate the localized nodes whether can be reference nodes [9]. It uses the anchor node positions and distance measurements between anchor nodes and ordinary node. When the ordinary node gets its estimated position, the residuals of estimated distances between anchor node and ordinary nodes and the observations are regarded as the confidence value. If the residuals are small enough, the new localized ordinary nodes can be regarded references for other ordinary nodes to localize. The residuals are defined in 1.

$$R(u,v,w) = \sum_i (\sqrt{(u-x_i)^2 + (v-y_i)^2 + (w-z_i)^2} - l_i)^2 \tag{1}$$

Where (u, v, w) is the estimated coordinates of the ordinary node, (x_i, y_i, z_i) are the coordinates of anchor node i, and l_i is the measured distance between the ordinary node and anchor node i.

LSL extends 1 with the percentage error of the new localized nodes [2]. It assumes the anchor nodes are accurate with no error, so it defines the confidence value of anchor nodes to 1. For a new localized node, it uses 2 to define the confidence value. The bigger the confidence value is, the high accuracy it assumes to be.

$$\eta = \begin{cases} 1, & \text{if anchor node,} \\ 1 - \frac{\sum_i |\delta_i^2 - l_i^2|}{\sum_i \delta_i^2}, & \text{if ordinary node,} \end{cases} \tag{2}$$

where

$$\delta_i^2 = (u-x_i)^2 + (v-y_i)^2 + (w-z_i)^2, \tag{3}$$

and (u, v, w) is the estimated coordinates of the ordinary node, (x_i, y_i, z_i) are the coordinates of anchor node i, and l_i is the measured distance between the ordinary node and anchor node i. For initial anchor nodes, η is the largest. For a newly-localized node, η is associated with its mean localization error. The normalized localization error has to be bigger than a specified error threshold for a node to be considered as being localized. For the ordinary node to become a reference node, a different threshold may be used.

We propose a method using error propagation theory to define the confidence value. We assume the distance measurement uncertainties obey normal distribution. The 4 to 6 gives the general principles of error propagation theory [6], [16].

Given the general equation

$$y = g(\mathbf{z}) \tag{4}$$

that relates the parameters y to the parameters $\mathbf{z}$, the uncertainties in the vector $\mathbf{z}$, given in terms of the covariance matrix Σ_z are traced into y and characterized by Σ_y. This is referred to as covariance law and is given by

$$\Sigma_y = \mathbf{G}\Sigma_z\mathbf{G}^t \tag{5}$$

where $\mathbf{G}$ are the partial derivatives

$$\mathbf{G} = (\frac{\delta g}{\delta z})_z. \tag{6}$$

For the ordinary node, it can obtain N distance measurement equations if it can reach N anchor nodes to form observation equations. The observation equation is shown in 7.

$$f_i = \sqrt{(u-x_i)^2 + (v-y_i)^2 + (w-z_i)^2} - l_i = 0 \tag{7}$$

where (u, v, w) is the estimated coordinates of the ordinary node, (x_i, y_i, z_i) are the coordinates of anchor node i, and l_i is the measured distance between the ordinary node and anchor node i.

According to the error propagation theory, the estimated error of the localized node is shown in 8.

$$R(u, v, w) = \sqrt{\sum diag\{(\mathbf{B}^T\mathbf{B})^{-1}\}} \tag{8}$$

where $\mathbf{B}$ is defined as

$$\mathbf{B} = (\frac{\partial f_i}{\partial(u, v, w)})_{(u,v,w)} \tag{9}$$

and $diag$ represents the diagonal elements of a matrix, the other symbols have the same definition with 1 and 2.

V. Impact of Confidence Values Set on Node Localization

We use simulation to evaluate the impact of confidence value set on the iterative localization algorithm under the realistic error assumptions for UWSNs. We consider the performance metrics of localization coverage and localization error. Localization coverage is defined as the ratio of localized nodes compared to the total ordinary nodes. Localization error is the network error, that is the average deviation between the estimated positions we calculated and the true positions we simulated of the whole localized noes. All the errors are normalized with the node communication range and the whole nodes in the network.

In our simulation, 500 sensor nodes are randomly deployed in a 100 m $\times$ 100 m $\times$ 100 m cubic region. Twenty percent of the nodes in the whole network are anchor nodes and the rest of the nodes are regarded as ordinary nodes. We define the node density as the number of nodes in the neighbourhood of an ordinary node, which is controlled by changing the communication range of the node. The relationship between node density and communication distance is shown in Figure 2.

In our simulation, we add 1% real distance as random errors in distance measurements and the errors follow a normal distribution. The localization coverage and localization error with the three different confidence values are shown in Figure 3 and 4.

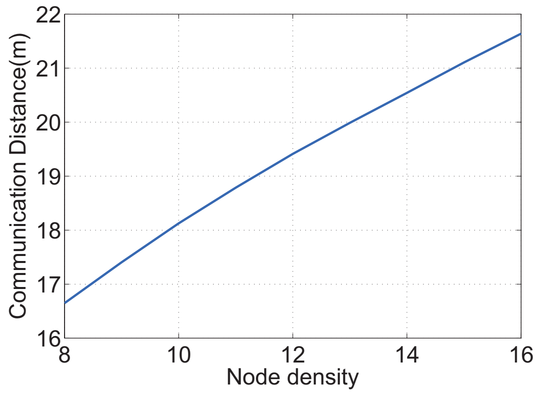

Fig. 2. Node density vs. communication distance

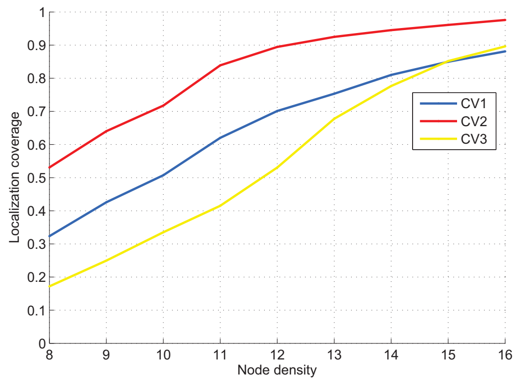

Fig. 3. Localization coverage.

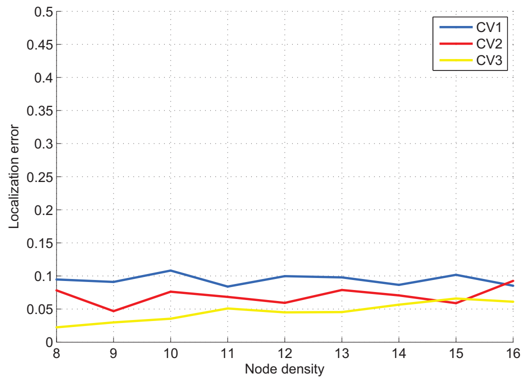

Fig. 4. Localization error.

Blue, red and yellow lines represent the confidence values defined in 1, 2 and 8 respectively. To achieve rather equal errors for these confidence values, we set the residuals of 1 the error of confidence value we propose to 0.1 communication distance, the confidence value of 2 to 0.99. From the results we can see the confidence value we propose have the smallest localization error while a drawback of a rather small localization coverage. This is because we focus on the control error accumulation, which will lead to a rather small localization error but reduce the localization coverage. But with the increase of node density, the localization will raise and have the equal performance with the other two. So the confidence value we proposed for large scale UWSNs is suitable for large communication distance with high node density.

VI. Conclusion and Future Work

Large scale UWSNs have great challenges in localization especially for recursive localization schemes. To achieve accurate localization for each node and a rather high localization coverage, we propose a method to set the confidence value based on error propagation theory. This paper first introduces the recursive localization method and the critical metrics of confidence value, then give a comparison of the previous method of definition. We use simulation results to verify the advantage in controlling the error accumulation in large scale UWSNs, especially for high node density. ecision large scale UWSNs. The results can give the suggestions for the reference node selections.

VII. Acknowledgement

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