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Error control and adjustment method for underwater wireless sensor network localization

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ABSTRACT

Underwater sensor position information is very important in Underwater Wireless Sensor Networks (UWSNs). The sensor collected information is only meaningful with the correct positions. While current method only processes underwater nodes individually, which causes the localization precision for each nodes varying severely. This problem is very common in both centralized network and distributed network. The varying localization precision causes real trouble especially in data fusion, aided navigation, and signal processing. To solve this problem and achieve a consistent localization precision in the network, we propose an error control and adjustment method to make all the sensor localization precision refined. We use the distance information between nodes to establish a network error adjustment model, which can improve the localization precision and make the network localization error consistent. The simulation and actual experiment proves that this method can make all the node positioning more precise, the localization precision can be lower than decimetres. This method can be widely used in UWSNs and show a favourable potential in ocean engineering applications.

1. Introduction

Underwater wireless sensor networks (UWSNs) attract increasing interests in ocean exploration and underwater applications, such as environmental monitoring, offshore exploration, disaster prevention, and military surveillance [5,22,8,17,1,21]. Underwater sensors equipped with wireless communication systems provide a cost-effective means to meet stringent requirements in those applications, and to measure infrastructure parameters, collect environmental data, and transmit information in real time between each nodes or to base stations.

In many UWSN applications, it is desirable to have the location information of each sensor node, but accurate node localization is one of the most challenging tasks for UWSNs due to several challenges [10,7]. First, underwater nodes are often unstable and they can drift/float around even if they are physically anchored. Second, Global Positioning System (GPS) signals are severely attenuated underwater, therefore it is expensive to equip sensor nodes at deep water with GPS receivers[3,9,20]. Furthermore, It is also difficult to provide accurate timing/clock reference for low-cost sensor nodes because atomic clocks are expensive and high-quality ovenized crystal oscillators are power hungry. Apart from a few high-end reference nodes whose locations may be measured with high accuracy and precision with high-end instrumentation [14,13], ordinary nodes have to rely on communication signals in the network to localize themselves [17,1,8,4]. Thus make the reference node localization precision different with ordinary nodes. The ordinary node localization precision also differs with each other because of using different reference node information.

In UWSN, especially large-scale UWSNs, the nodes cannot be localized by one-hop because of the limitation of communication distance. In this situation, the recursive localization methods are proposed. The method divides the nodes into two kinds, reference nodes and ordinary nodes. The reference nodes are moored underwater by a fixed structure, which can be localized by surface to achieve a high accuracy. The ordinary nodes use the reference nodes as known positions, measuring the distances to references and achieving positions. After being localized, the ordinary nodes can upgrade to reference nodes to help other unlocalized nodes positioning. In this process, the underwater nodes will result in different localization precision because of using different reference nodes. The inconsistent localization precision in UWSN will bring huge trouble in data fusion and post-process.

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The information collected by the sensor should be used for fusion with the position data after underwater node data information obtained [11]. No matter centralized systems or distributed systems, the underwater positions with Geodetic coordinates can only be obtained by surface GPS and the measured distance to GPS. This process can deliver GPS information to underwater. While the Geodetic coordinates are always uncertain due to the time-varying or space varying changes in sound speed, flows, tides, etc. Because of the limited underwater characteristic, such as long propagation delay, severe multi-path inference and limited signal bandwidth, the underwater node can be only localized individually to achieve high precision. In this way, the large-scale network with multiple nodes will be result in different precision because of time or spatial varying.

To solve the problem that the sensor nodes in UWSN have inconsistent localization error, we propose an error control and adjustment method. This method using the distance information between nodes to establish the math model, which uses the time-delay measurements combining with actual sound speed profile. After processing, the localization precision of each node can be improved with a same level network localization precision.

This paper is organized as follows. Section 1 gives the background of UWSN and the purpose of data post-processing. Section 2 gives the related works of UWSN localization method. Section 3 gives the mathematical models of the proposed data post-processing method and simulation analysis are listed in Section 4. Section 5 gives the experiment results to prove the method and conclusion is listed in Section 6.

2. Related works

A recursive position estimation algorithm is designed for large scale RF WSN [2]. 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 in distance measurement [22]. 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) uses TDoA techniques by multiple beacon intervals which has the advantage of not requiring time synchronization [6]. 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) [18], GPS-less localization protocol (GPS-less) [16], motion-aware sensor localization (MASL) [15], underwater sparse positioning (USP) [19] and 3D underwater localization (3DUL) [12] 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.

3. Mathematical models

With the positions of sensor nodes obtained previously being the initial values, the UWSN can achieve optimization of the global error after the accurate range measurement information is obtained. While the direct observation is time-delay measurement (measured by time of arrival between nodes), we use the actual sound speed profile and ray-tracing model to calculate the accurate distance. We establish the error equation based on distance measurement information. We assume that there are N nodes in UWSN, and the number of range measurements within the communication distance range is L. Based on the calculated distance, the distance error equation established is as follows:

$$v_{ij} = -\frac{\Delta x_{ij}}{r_{ij}}\widehat{x}_i - \frac{\Delta y_{ij}}{r_{ij}}\widehat{y}_i + \frac{\Delta x_{ij}}{r_{ij}}\widehat{x}_j + \frac{\Delta y_{ij}}{r_{ij}}\widehat{y}_j - \Delta_{ij} \tag{1}$$

where $(\widehat{x}_i, \widehat{y}_i)$ and $(\widehat{x}_j, \widehat{y}_j)$ are the corrected coordinate values of the initial node positions (x_i, y_i) and (x_j, y_j)respectively. r_{ij} is the measured distance between two nodes; l_{ij} is the calculated distance between two nodes using initial positions; $\Delta x_{ij} = x_i - x_j$ and $\Delta y_{ij} = y_i - y_j$ are the coordinate difference between the two nodes in x direction and y direction; $\Delta_{ij} = r_{ij} - l_{ij}$ is the difference between the measured value and the calculated value.

Therefore, L error equations can be established for L range measurements.

$$\mathbf{V} = \mathbf{B}\widehat{\mathbf{x}} - \Delta \tag{2}$$

where $\mathbf{V}$ is the coefficient of the error equation (vector dimension is $L \times 1$); $\mathbf{B}$ is the coefficient matrix constituted by various corrections (matrix dimension is $L \times 2N$); $\widehat{\mathbf{x}}$ is the vector constituted by various coordinate corrections (vector dimension is $2N \times 1$); Δ is the vector constituted by the calculated value and the measurement differences (dimension is $L \times 1$). We assume that the range measurement error is a random error of the same precision conforming to the Gaussian distribution. The position optimization is solved under the $\mathbf{V}^T\mathbf{V} = min$ criterion.

As L, the number of the range measurements obtained during calculation, is determined by the node density, there are two cases: (1) The number of equations is larger than the number of unknown numbers ($L > 2N$). The corrected coordinate value is

$$\widehat{\mathbf{x}} = (\mathbf{B}^T\mathbf{B})^{-1}\mathbf{B}^T\Delta \tag{3}$$

The coordinate of each node after correction is

$$\widehat{\mathbf{X}} = \mathbf{x}_0 + \widehat{\mathbf{x}} \tag{4}$$

(2) The number of equations is smaller than the number of unknown numbers ($L < 2N$). We obtain a problem of underdetermined equation solving with the number of unknown numbers larger than the number of equations. For this purpose, constraint conditions should be added to the model to constitute the solution conditions. We use a weighted benchmark constraint condition added to the model:

$$\mathbf{S}^T\mathbf{P}_x\widehat{x} = 0 \tag{5}$$

It is assumed that the following relationship is true:

$$\begin{cases} rank[\mathbf{B}\ \mathbf{S}^T]^T = rank(\mathbf{B}) \\ \mathbf{BS} = 0 \end{cases} \tag{6}$$

where $\mathbf{S}^T$ is a non-singular matrix. Meanwhile, various equations are not correlated. According to the principle of least squares, the function is

$$\varphi = \mathbf{V}^T\mathbf{V} + 2\mathbf{K}^T(\mathbf{S}^T\mathbf{P}_x\widehat{x}) = min \tag{7}$$

The normal equation is:

$$\begin{cases} \mathbf{N}\widehat{x} + \mathbf{P}_x\mathbf{SK} = \Delta \\ \mathbf{S}^T\mathbf{P}_x\widehat{x} = 0 \end{cases} \tag{8}$$