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A Survey of Localization Techniques for Underwater Wireless Sensor Networks

Wangyutong Pu

Key Laboratory of Electronic and Information Engineering (Southwest Minzu University), State Ethnic Affairs Commission, College of Electronic and Information, Southwest Minzu University, Chengdu, China

Abstract: With the continuous development of marine resources, the position of Underwater Wireless Sensor Network (UWSN) is becoming more and more important, and UWSN needs to know the location of sensor nodes when completing tasks such as marine data collection, environmental monitoring, and aiding navigation, etc. Accurate sensor node location information is the key to effective acquisition of underwater data. The key to effective underwater data acquisition is accurate sensor node location information. Due to the influence of the environment, global positioning system (GPS) signals cannot be propagated underwater, so hydroacoustic communication becomes the best choice for node positioning. However, the unstable underwater environment brings a series of challenges to hydroacoustic communication, such as high channel bit error rate, low bandwidth, large propagation delay, and obvious multipath effect. According to the characteristics and challenges of hydroacoustic communication, this paper classifies the localization algorithms of underwater wireless sensor networks into (i) distance-based and distance-free localization algorithms, (ii) single-hop and multi-hop localization algorithms, and (iii) distributed and centralized localization algorithms.

Keywords: Underwater wireless sensor networks; Localization algorithm; AR model; Network connectivity.

1. Introduction

The ocean accounts for about 70% of the global area and is rich in resources, such as marine biological resources, mineral resources, chemical resources, marine energy and maritime shipping, etc. In the face of ocean exploration, utilization and development, USWN has an indispensable position [1]. UWSN is an important part of Wireless Sensor Network (WSN). Underwater wireless sensor networks inherit the characteristics of small size of terrestrial sensor nodes, relatively low cost, and easy node deployment, which make them have great advantages in the underwater environment [2]. UWSN mainly collects information through sensor nodes deployed underwater and transmits, processes, and fuses the collected data [3]. However, for underwater wireless sensor network monitoring systems, the underwater sensor nodes collect information in the ocean and only subsequently transmit it to a control center such as a land-based base station, which indicates that the collected information must be combined with the location information of the sensor nodes to be of practical significance [4]. Therefore, underwater node localization is a fundamental and key technology for underwater sensor networks to realize numerous fields such as ocean data collection, environmental monitoring, offshore exploration, aided navigation, distributed tactical surveillance, and other applications [5]. Among them, the location information of sensor nodes is crucial, and the effective implementation of underwater data collection and analysis can be facilitated by obtaining accurate location data [6].

Compared to terrestrial nodes that use Global Positioning System (GPS) to obtain their own node coordinates, underwater nodes cannot achieve large-scale node affiliation and wide-area localization underwater because of their difficulty in recoverability leading to the cost of using GPS hardware [7]. In addition, underwater wireless sensor networks cannot use electromagnetic waves for underwater communication like terrestrial wireless sensor networks due to the severe attenuation of electromagnetic waves underwater. Therefore, acoustic signals can be an ideal medium for UWSN to solve the problems of storage, communication or data exchange between nodes [8], thus making hydroacoustic communication the main communication method for underwater wireless sensor networks. However, on the other hand, hydroacoustic communication is much more convenient than radio communication in terms of transmission delay, and environmental factors such as underwater pressure, water temperature, and salinity can have an impact on hydroacoustic communication, which makes some problems in underwater sensor networks such as clock synchronization and ranging techniques more complex compared to land, and the positioning accuracy can be directly affected [9].

2. Underwater Wireless Sensor Network Architecture

UWSN usually consists of anchor nodes (beacon nodes), unknown nodes, sink nodes, surface buoys, neighbor nodes, AUV or ROV, and infrastructure (For example, satellite base stations, GPS, and other fixed devices.) The architecture of a UWSN is shown in Figure 1.

3. Underwater Wireless Sensor Network Positioning Technology

3.1. Challenges in locating underwater wireless sensor networks

The characteristics of the marine environment pose great difficulties and challenges to the UWSN node localization algorithm, and only a reasonable analysis of the characteristics of the marine environment can lead to an effective solution. The main challenges faced by the UWSN node localization algorithm are as follows [11]:

3.1.1. Limited communication bandwidth

Since electromagnetic waves in the water transmission attenuation is too large, the transmission distance is short, so usually use the frequency between 20 ~ 20000Hz sound waves for communication.

3.1.2. Node deployment problem

The deployment of nodes will directly affect the positioning effect. Underwater sensor nodes are randomly broadcasted by aircraft and ships or manually deployed in the monitoring area, and sensor nodes will be deployed at two levels: surface and underwater. Sensor nodes on the surface do not require much complex processing, but sensor nodes deployed underwater require air pressure devices to ensure that they can float in the water. In addition, some nodes need to be deployed on the seabed at a depth of several thousand meters, and the complex submarine environment can make deployment extremely difficult.

3.1.3. Difficult time synchronization between nodes

In the terrestrial environment, the radio wave signal transmission speed is fast, which can reach 3×108 m/s, so it can be used to realize the time synchronization between nodes. However, in the marine environment, acoustic signals are usually used to realize the communication between nodes, and the acoustic signals are much lower than the transmission speed of electromagnetic wave signals, which cannot compensate the difference between the current time and the absolute time, so it is difficult to realize the consistency between the local time and the absolute time, and cannot guarantee the time synchronization between nodes when positioning.

3.1.4. Mobility of nodes

Given the complex underwater environment, underwater nodes can be affected by ocean currents and even human activities and move. Therefore, if the nodes are displaced during the positioning process, it will lead to changes in the measured distance between the nodes, thus affecting the positioning accuracy. Therefore, static network localization algorithms on land are not applicable to underwater, and we need to study the special characteristics of the underwater environment.

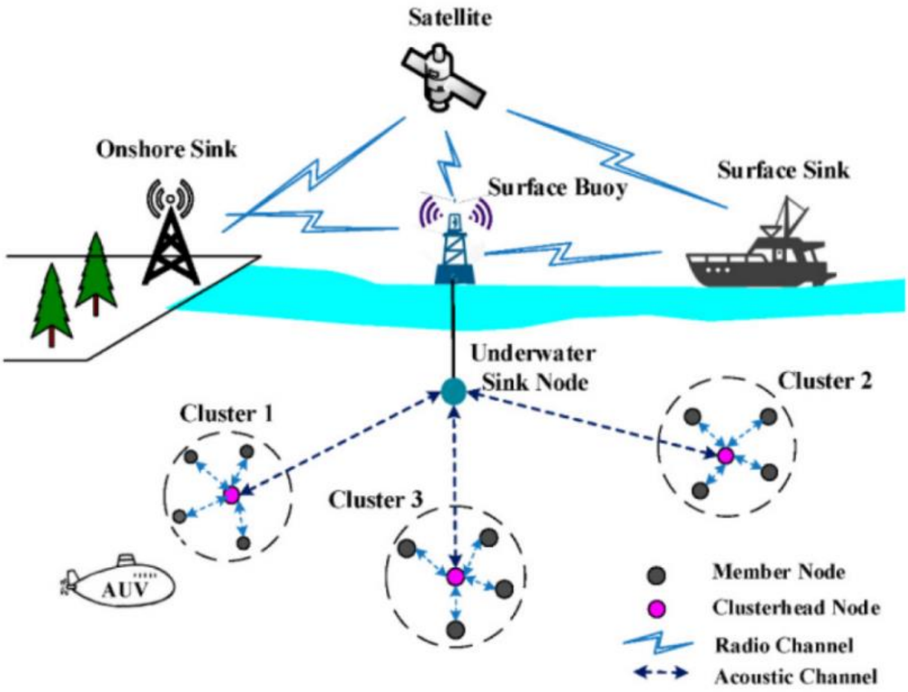

Figure 1. UWSN architecture [10]

3.2. Classification of underwater wireless sensor networks for positioning

In response to the challenges faced above, researchers have designed a variety of localization algorithms applicable to underwater sensor networks. These localization algorithms can be classified in different ways according to the data acquisition and processing methods, and the common classification methods are as follows:

3.2.1. The localization algorithms are classified into range-based and range-free localization algorithms [12] [13] based on whether the distance between the nodes is measured during localization. In the ranging-based algorithm, the distance between the nodes is measured by an underwater ranging instrument and then the unknown nodes are located [14].

The commonly used technical parameters for ranging include Time of Arrival (TOA) [15] [16], Time Difference of Arrva1 (TDOA) [17], Received Signal Strength Indication (RSSI) [18] and Angle of Arrival (AOA) [19] [20] based on the signal arrival angle.

1)TOA algorithm: TOA is based on the transmission time of the signal as well as the transmission speed to find out the distance between nodes, so the localization algorithm based on TOA ranging requires time synchronization in the network [21]. TOA is used in underwater localization algorithms better than in land-based localization algorithms because in underwater sensor node localization, the propagation rate of wireless acoustic signals is higher than that of hydroacoustic signals high, and the error of ranging is relatively high when the distance between nodes is the same.

2)TDOA algorithm: the TDOA mainly uses the difference in arrival times of two signals and their velocities to calculate the distance between nodes. Compared with the TOA algorithm, TDOA only measures the consumption of time during propagation, reducing the prediction distance error due to time asynchrony [22]. Although TDOA has relatively high measurement accuracy, this distance measurement technique requires high hardware requirements of the nodes, as it requires sensor nodes to be able to send two different signals simultaneously.

3)RSSI algorithm: since signals show attenuation with increasing transmission distance during transmission, RSSI then converts the loss during signal transmission into distance according to an empirical model [23]. RSSI ranging is widely used in wireless sensor networks because it is less expensive and does not require time synchronization between nodes. However, changes in the environment can affect the accuracy of RSSI measurements, so it is suitable for some positioning techniques that do not require high accuracy.

4)AOA algorithm: It needs to rely on sensor nodes to install antennas for ranging. The unknown node needs to measure the angle of arrival of the received signal using a set of antenna arrays and then calculate the coordinates of the unknown node using triangulation based on the angular information and the relationship between the nodes. The AOA algorithm, although simple in structure, has directional transmission/reception equipment, which can incur extremely high additional costs and is difficult to use on a large scale [24].

The localization algorithm without ranging does not rely on the ranging hardware to measure the actual distance information between the nodes, but mainly uses the information about the number of hops between the anchor node and the sought node as well as the direction, and converts the data such as the number of hops into distance to estimate the position of the sought node [25]. However, algorithms that do not require ranging do not have high localization accuracy and provide only the rough location of the node [26]. The commonly used non-ranging localization algorithms are DV-Hop localization [27], Centroid Algorithm [28], APIT localization (Approximate Point In Triangulation Test) [29], etc. Compared with the ranging localization algorithms, the positioning algorithms without ranging require less costly sensor nodes and can satisfy most of the localization accuracy requirements.

1)DV-Hop localization algorithm: DV-Hop calculates the distance between nodes by obtaining the number of hops between nodes and using the number of hops. The unknown node first calculates the minimum number of hops with the anchor node, then estimates the average distance per hop, and uses the minimum number of hops multiplied by the average distance per hop to estimate the distance between the unknown node and the anchor node, and finally estimates the coordinates of the unknown node. The DV-Hop algorithm is widely used because of its low hardware requirement and high localization coverage.

2)Center-of-mass localization algorithm: In the center-of-mass algorithm, the unknown node needs to select multiple anchor nodes within the communication radius and receive their information. When the information exceeds a set threshold, the coordinates of the vertices of the polygon region formed by these anchor nodes are summed and averaged, and then the average value, i.e., the center-of-mass coordinates, is used as the final estimated position of the unknown node. The center-of-mass localization algorithm is relatively easy to implement without additional equipment, but the localization accuracy is low.

3)APIT localization algorithm [30]: the APIT algorithm is a localization algorithm derived from the center-of-mass algorithm. Like the center-of-mass algorithm, the unknown node needs to select multiple anchor nodes within its communication radius. Firstly, the unknown node determines whether it is in the triangle overlap region surrounded by three anchor nodes, if it is not in the region, it is not processed; if it is in the region, it records the range of the region and reselects three anchor nodes to perform the above judgment process again, then the overlap region of two triangles is used as the region of its own position, after that, the above judgment process is repeated until all triangle combinations of anchor nodes are obtained The APIT algorithm can reduce the range of its own location to a certain extent and improve the accuracy of localization, but it needs to be carried out in a network with dense node distribution.

3.2.2. According to the network topology and the node connectivity, the localization algorithms are classified into single-hop and multi-hop localization algorithms. If the unknown node needs only one hop distance to communicate with the anchor node, it is called single-hop localization algorithm; if it needs to pass through multiple nodes on the way to communicate with the anchor node, it is called multi-hop localization algorithm. Single-hop localization algorithm requires high density of anchor nodes and the cost is too large, so multi-hop localization algorithm is often used in actual localization.

3.2.3. The localization algorithms are classified into centralized and distributed localization algorithms depending on how the node information is processed.

1)Centralized localization algorithm: In the centralized localization algorithm, the node sends all the information to the sink node for convergence and processing. Since the sink node can communicate with the surface buoy and has a strong computational capability, the position information of the unknown node is calculated at the sink node, and then the sink node sends the information after localization to the unknown node, so that the unknown node can know its position information. However, the centralized localization algorithm is only suitable for small-scale underwater sensor networks because a large number of computational processes need to be implemented at the sink node, which will generate huge energy consumption. The common centralized localization methods are ALS [31], CL [32], MASL [33], SLUM [34], etc.

ALS (Area-Based Localization Scheme) [31] is an algorithm for localization of two-dimensional stationary underwater sensor networks, mainly used to determine the area where the unknown nodes are located. The network consists of sink node, anchor node and unknown node; the anchor node sends signals with different powers to divide the water into several small areas; the unknown node is in a silent state, i.e., it only receives information without exchanging information with the anchor node, and then transmits the received anchor node identification number and the lowest power energy level to the sink node; the sink node can determine the unknown node based on the received information of the unknown node and the ALS is a distance-free localization method, which avoids the requirement of time synchronization, and the calculation process is carried out at the sink node, which reduces the computational energy consumption of the unknown node. However, ALS is only used as rough localization and is not applicable to networks with high accuracy requirements.

The CL (Collaborative Localization) [32] algorithm is a collaborative localization algorithm that consists of analysis nodes and following nodes. In the initial stage, all nodes in the network are deployed on the surface of the water and have access to the position information through GPS. Then the analysis node dives underwater and after a period of time the following node dives into the water at the same speed as the analysis node. Considering that the dive speed of both nodes is the same and their depth difference remains constant, the position of the following node can be obtained from the position prediction of the analysis node. The CL algorithm effectively reduces the amount of information exchanged between nodes, which in turn reduces the communication energy consumption. However, the node density has a large impact on the localization performance, so it is not suitable for networks with sparse or uneven node deployment.

The MASL (Motion-Aware Self-Localization) [33] algorithm is a motion-aware self-localization scheme based on sensor networks, which effectively reduces the ranging errors between nodes. During the localization process, the nodes measure the distance information with their neighbor nodes and send the distance information to the sink node at the end of the task, which uses an iterative algorithm for localization. In the iterative process, the localization area is divided into smaller grids and the grid with the highest probability of node appearance is selected as the localization area for the next iteration.

The SLUM (Silent Localization of Underwater Sensors Using Magnetometers) algorithm [34] uses a vessel with known static magnetization properties to perform silent localization of underwater sensors equipped with a three-axis magnetometer, each also equipped with a sensor for depth estimation and sensor orientation, respectively Each sensor is also equipped with a pressure sensor and an accelerometer for depth estimation and sensor orientation estimation, respectively. According to the proponents, this is the first application of magnetic dipole tracking to the field of sensor localization.

2)Distributed localization algorithm: In the distributed localization algorithm, each node processes its own information individually and then interacts with the information to achieve localization. Distributed localization algorithms are suitable for large-scale underwater sensor networks because unknown nodes can obtain their own position information in real time and spread out the computational effort. Common distributed localization algorithms include UPS [35], LSLS [36], USP [37], SLMP [38], MP-PSO [39], etc.

UPS (Underwater Positioning Scheme) [35] is a distance-based distributed positioning algorithm that uses TDOA to achieve ranging. For unknown node positioning, three anchor nodes are placed on the surface and one anchor node is fixed on the seafloor. Firstly, anchor node A sends messages periodically, when anchor node B receives the signal from A and starts sending messages, anchor node C starts sending messages after receiving messages from A and B, and anchor node D sends messages after receiving messages from A, B and C. After that, the unknown node receives the information from all anchor nodes and calculates the distance to each anchor node using TDOA method, and then estimates the position coordinates according to the trilateral localization method. PS does not need to consider the time synchronization of nodes and has a small localization error.

To address the problem of limited UPS localization coverage, the literature [36] proposed LSLS (Large-Scale Localization Scheme), which consists of three processes: anchor node localization, iterative localization, and supplementary localization. In the anchor node localization phase, the unknown nodes are localized by the anchor node using the UPS method. In the iterative localization phase, some nodes whose position coordinates have been obtained are selected as reference nodes to assist other unknown nodes to localize. The purpose of supplementary localization is to localize the nodes that still have not obtained the position coordinates in the first two phases. The node to be positioned sends the positioning request information actively, and the positioned node is transformed into a reference node to assist the node in positioning based on the received information. Compared to UPS, LSLS localization coverage increases and can be applied to large-scale underwater sensor networks, but the iterative process and the supplementary process increase its communication overhead.

The USP (Underwater Sensor Positioning) [37] algorithm is used to achieve 3D underwater network localization, which is the first proposed method to convert 3D localization method into 2D localization method. The depth of the sensor node is measured by a pressure sensor, and then the unknown node and three non-collinear reference nodes are projected to the same plane simultaneously, and the trilateral localization method is used to localize the unknown node. Since this method reduces the localization in three-dimensional space to two-dimensional space, it reduces the storage and computation of nodes and enhances the robustness to channel errors. However, at least three non-coplanar reference nodes are required for the localization of unknown nodes, so when the reference node density is low, the localization will not be achieved.

The SLMP (Scalable Localization with Mobility Pattern) [38] algorithm is a predictive localization algorithm for large-scale underwater networks. The network structure in this algorithm consists of a surface buoy, an anchor node and an unknown node. The anchor node uses the AR model as the motion model, obtains the position information by communicating with the buoy node, and predicts the coefficients in the AR model based on the historical position information and velocity information, and then obtains the motion model to achieve velocity prediction. The common node estimates its own velocity by referring to the velocity information of the anchor node and achieves localization by combining the historical position information. the SLMP algorithm only requires a small number of updates to the motion model during localization, which reduces the communication energy consumption between nodes; however, the localization performance of the algorithm mainly depends on the motion model of the nodes, and the localization error and communication energy consumption can only be maintained within a certain range when the model accuracy is high.

The MP-PSO (Localization based on Mobility Prediction and Particle Swarm Optimization) [39] algorithm is also used for predictive localization of large-scale underwater sensor networks. Unlike the SLMP algorithm, the MP-PSO algorithm uses a particle swarm algorithm for anchor nodes to predict the position of nodes and thus obtain velocity information. In addition, a confidence formula is designed based on the signal strength received by the node and the number of iterations, so that a reference node with higher accuracy can be selected to participate in the localization. The introduction of the particle swarm algorithm improves the velocity accuracy of anchor node prediction in the MP-PSO algorithm, which in turn provides more accurate reference information for the unknown node and reduces the position error of the unknown node. However, it increases the energy consumption of the network due to the need to periodically update the particle swarm algorithm.

4. Summary

This paper focuses on node localization techniques for UWSN. The influence of underwater environment on node localization is analyzed, the existing localization algorithms are classified and compared, and the various types of localization algorithms are elaborated. It is one of the hot spots of current research to solve the problem of underwater communication signals being affected by environmental factors in the propagation process, resulting in changes of sound velocity, and at the same time to improve positioning accuracy and reduce positioning errors. Although UWSN-related technology still faces many problems and challenges, its role and status are self-evident. As the research progresses, UWSN will be more and more widely used in reality.

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