This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2021.3081918, IEEE Internet of Things Journal

Localization Algorithm for Underwater Sensor Network: A Review

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***Abstract*—As a significant component of ocean exploration, underwater localization has attracted extensive attention in both military and civil fields. Due to its low cost and convenience, underwater wireless sensor networks (UWSNs) is favored by related fields. As an important part of Internet of Things (IoT), it can strengthen the trinity of land, sea and air. The location of the underwater sensor node is the foundation of the UWSNs application and is one of the research hotspots today. Many relevant research scholars have optimized the localization algorithm or introduced new methods to better locate the target nodes, thus promoting the development of related fields. In this paper, the challenges of underwater acoustic communication and underwater positioning, the comparison between UWSNs and terrestrial wireless sensor networks (WSNs), the network structure, routing technology, and localization evaluation criteria are all introduced in detail. Moreover, we survey many cutting-edge underwater localization algorithms based on a new taxonomy (i.e. distance measurement, network scale, and anchor utilization). Moreover, these localization algorithms are compared and analyzed from various aspects. Meanwhile, localization discussion and research prospects are illustrated in this paper.**

***Index Terms*—underwater localization, underwater sensor network, network architecture, distance measurement, network scale, survey**

I. INTRODUCTION

WITH the increasing maturity of terrestrial resource exploitation and other related technologies, humans gradually turn to more abundant marine resources. Moreover, the technology of the IOT has been developing rapidly on land. In order to realize the coordinated development of sea, land and air, the layout of marine monitoring must be an important matter in the past, present and future. However, the complex and varied underwater environment has caused great challenges for underwater resource exploration. Conventional terrestrial monitoring techniques are also not well suited for underwater. Against this background, the advancement in electronics and sensor miniaturization and low-power technologies enabled terrestrial WSNs to extend their reach to underwater applications [1]. Relevant researchers favor UWSNs due to its good underwater monitoring effect. Moreover, because of its high military and commercial value, the application of UWSNs has gradually become one of the hot research directions. At present, it is widely used in underwater environment monitoring, military application, oceanographic data collection, underwater pipeline leak detection, prediction of natural disasters, and other water-related fields [2-5]. The location of sensor nodes is the basis of the wide application of UWSNs. The research of the localization algorithm based on UWSNs is also a hot issue. In general, relevant underwater target positioning or tracking algorithms need to use the location of sensor nodes and the data collected by the nodes to detect, locate, or track underwater targets. The localization accuracy of sensor nodes greatly influences the performance of underwater target positioning or tracking algorithms. Therefore, research on the underwater localization algorithm based on UWSNs is of great importance. The innovation and optimization of a localization algorithm based on UWSNs promote the progress and development of related fields.

UWSN consists of several autonomous and individual sensor nodes, which are spatially distributed in the monitoring waters to capture and transmit relevant information [6]. Then, the monitoring system selects the appropriate localization algorithm and makes full use of the captured information to estimate or predict the coordinates of the underwater target or node. On land, nodes in WSNs usually use global positioning system (GPS) signals [7] and electromagnetic waves (such as Radio Frequency, Optical Waves, etc.) for terrestrial positioning. Unlike terrestrial WSNs, however, the high-frequency GPS signals do not propagate well in water. The attenuation of RF signal propagation underwater is large. Moreover, the radio signals in conductive seawater travel long distances only at low frequencies (30-300Hz) [5]. Besides, the requirements for the size of antenna and transmission power are relatively high. Furthermore, the optical signal is affected by scattering underwater, which makes it impossible to transmit over long distances underwater. Hence, communication waves for terrestrial WSNs are not well suitable for long-distance propagation in an underwater environment. After a lot of experiments and explorations, the relevant research scholars found that acoustic signals provide appropriate conditions for long-distance underwater propagation. Its frequency is low lying between 10 Hz and 1 MHz [6], which can offer bandwidth but have long wavelengths. The above several types of wireless communication waves are compared, as shown in TABLE I.

This work was supported in part by the Scientific and Technological Innovation and Entrepreneurship Talents and Seedling Engineering Projects in Science & Technology Department of Sichuan Province under Grant 2020JDRC0007.

TABLE I
COMPARISON OF UNDERWATER WIRELESS COMMUNICATION WAVES [8]

Parameters	Acoustic Waves	Optical Waves	EM Waves
Communication Distance	Up to 20 Km	10-100m	100m
Transmit Power	10–100 W	Few Watts	Few mW to Hundreds of Watts
Data Rate	In Kbps	Up to Gbps	Up to 100 Mbps
Cost	High	Low	High

There are many difficulties in this field, but many relevant researchers optimize and explore the localization method based on UWSNs from different directions and angles. With the continuous emergence of research results of UWSNs based localization algorithm, therefore, it is necessary to summarize the existing related outstanding literature. The contributions of this paper include: 1) the relevant knowledge of UWSNs is clarified in detail, which makes it easier for the readers to understand the field of underwater localization; 2) the underwater localization algorithm is classified from three main aspects: distance measurement, network scale, and anchor utilization; 3) the comprehensive comparison of localization algorithms enables readers to quickly find a suitable method to improve the localization performance of the target sensor nodes; 4) the future research prospects of underwater sensor node localization based on UWSNs are described in detail.

This paper concentrates on a comprehensive survey of underwater localization algorithms for UWSNs and is organized as follows: Some relevant review papers and our contributions are presented in Section II. In Section III, we introduce the basics of UWSNs, including a comparison of UWSNs and terrestrial WSNs, network architecture and scale, routing techniques, evaluation criteria and underwater acoustic communication and node localization challenges. Subsequently, the underwater localization algorithm classification is presented in Section IV. Moreover, in Section V, the discussion, challenges, and open issues are described in detail. Finally, we conclude and provide the future work of underwater localization in Section VI.

II. RELATED SURVEYS AND CONTRIBUTIONS

Up to now, some review papers have been conducted on underwater localization methods for UWSNs. The proposed survey paper is broadly compared to the other review papers presented in the literature and shown in TABLE II. In TABLE II, we used "common", "detailed", "brief" to describe whether the content of the evaluation criteria and related knowledge in the previous reviews are detailed. Among them, "brief" represents the relevant content more concise, "detailed" means that the relevant content is more detailed, and "common" indicates that the content descripted is less than "detailed". The papers [13-15] classified positioning algorithms based on distributed and centralized, estimation and prediction. The paper [14] described the underwater acoustic sensor network localization in more detail than [13] [15] and collected more than 20 algorithms. However, in the past, the innovation and number of localization algorithm papers are relatively small. Relevant reviews need to be updated and the latest relevant literature should be added. Additionally, although these reviews summarized the proposed literature from the aspects of range method, anchor type, communication type, synchronization, etc., there is no corresponding evaluation analysis. The papers [12] [16] [17-19] classified localization algorithm based on range-based and range-free. In [16], the authors summarized some existing underwater localization algorithms at that time. However, the overall references were insufficient and the evaluation criteria were relatively simple. Compared with other review kinds of literature, the authors [17] gave statistics of simulation experiments for some cited literature but failed to have an overall summary of all introduced literature. In [19], the authors also classified the localization algorithm from the network structure and location scheme. However, the collected algorithms and comparative analysis are inadequate. New cutting-edge algorithms need to be added. Then, in [20], the authors classified localization algorithms according to the state of sensor nodes. Moreover, the authors evaluated some cited literature from the aspects of localization coverage, computational complexity, accuracy, etc., but the number of references that have been introduced is still insufficient and the classification direction is single. Additionally, only the papers published before 2012 are collected. Therefore, to meet the needs of readers, we need new reviews to supplement some new localization algorithms. In [21], based on the classification of static and mobile sensor node states, the author subdivided the mobile positioning into two subgroups of non-propulsion anchors and propulsion anchors. However, it only classifies mobile localization algorithms, which does not comprehensively introduce the relevant underwater localization algorithm. In [22], the authors classified some of the underwater localization algorithms that existed at that time, namely, Stationary localization algorithms, Mobile localization algorithms, and Hybrid localization algorithms. But the algorithm evaluation criteria and summary points of this review are relatively simple. In [23], the authors mainly introduced the relevant knowledge of enabling technology, localization protocols, and underwater Internet of Things. There are many references in the review, but relatively few descriptions about the localization algorithm based on UWSNs. Therefore, it is necessary to do a new comprehensive survey about the underwater localization algorithms based on UWSNs.

In this paper, we survey numerous underwater localization papers ranging from innovative papers to the state-of-the-art in this field. Not only the related knowledge of underwater localization based on UWSNs is clarified in detail, but also a novel taxonomy method is proposed. Underwater localization algorithms are classified from three main aspects: 1) Distance measurement; 2) Network scale; 3) Anchor utilization. The new taxonomy will make the localization algorithm classification in this field more comprehensive. Different from previous reviews, those mentioned localization algorithms are compared and analyzed from various aspects in this review, which is more abundant and comprehensive. This review can help interested readers and related scholars to quickly find and learn what types of localization algorithms based on UWSNs are and the advantage and disadvantage of various algorithms. Moreover, related localization challenges in this field, localization algorithm performance evaluation criteria, and future research prospects are summarized in this paper in detail.

TABLE II.
COMPARISON OF REVIEW PAPERS FOR THE UNDERWATER LOCALIZATION ALGORITHMS

Ref.	Taxonomy Method	The Number of References	The Newest Reference	Evaluation criteria	The Related Knowledge
[13]	1.Distributed localization techniques 2.Centralized localization techniques	15	2011	Common	Brief
[14]	1.Centralized localization techniques 2.Distributed localization techniques	81	2010	Common	Detailed
[15]	1.Centralized localization techniques 2.Distributed localization techniques	15	2010	Common	Brief
[16]	1.Range-based schemes 2.Range-free schemes	31	2006	Common	Brief
[17]	1.Range-based underwater localization 2.Range-free underwater localization schemes	55	2011	Detailed	Detailed
[12]	1.Range-based localization schemes 2.Range-free localization schemes	19	2011	Common	Brief
[18]	1.Range-based scheme 2.Range-free localization schemes	29	2014	Common	Brief
[19]	1.Ranging algorithms in UASNs 2.UASN architecture and localization schemes	70	2015	Common	Detailed
[20]	1.Stationary localization algorithm 2.Mobile localization algorithm 3.Hybrid localization algorithm	72	2011	Detailed	Detailed
[21]	1.Non propelled anchor-based localization 2.Propelled anchor-based localization	23	2014	Common	Brief
[22]	1.Stationary localization algorithms 2.Mobile localization algorithms 3.Hybrid localization algorithms	118	2017	Common	Detailed
[23]	1.Acoustic communications 2.Magneto-inductive communications	147	2019	Common	Brief
Ours	1.Distance measurement 2.Network scale 3. Anchor utilization	88	2020	Detailed	Detailed

III. RELATED KNOWLEDGE

A. *UWSNs Vs terrestrial WSNs*

Compared with terrestrial WSNs, UWSNs are in a more challenging environment. The height of the deployment area of the terrestrial WSNs is much smaller than the length and width of the area. Generally, its localization problem can be regarded as the localization problem of a two-dimensional (2D) plane. For UWSNs, the water depth cannot be ignored. Therefore, underwater localization is generally 2-D positioning of a certain depth plane or three- dimensional (3-D) positioning of certain water space. Moreover, the location of the node of the WSNs deployed on the ground is relatively fixed. The topology of the network has no dynamic evolution and it is not necessary to consider the node's movement under external forces. But underwater nodes are susceptible to drift due to ocean current activity and other natural factors. Besides, sensor nodes use electromagnetic waves for communication on land, and their performance characteristics such as communication bandwidth, propagation speed and delay are much better than those between underwater network nodes. Due to the complex and variable underwater environment, the noise and interference, energy consumption, and cost of underwater sensor nodes are much higher than those of terrestrial sensor nodes. As shown in TABLE III, moreover, terrestrial WSNs and UWSNs were summarized and compared.

TABLE III.
COMPARISON BETWEEN UWSNS AND TERRESTRIAL WSNS

Sensor Networks Performance Index	UWSNs	terrestrial WSNs
Communication	Acoustic	Electromagnetic
Propagation Speed	Slow	Fast
Propagation Delay	High	Low
Bandwidth	Low	High
Data Rates	Slow	Fast
Noise and Interference	High	Low
Bit Error Rate	High	Low
Mobility	High	Low
Reliability	Low	High
Power	High	Low
Energy Consumption	High	Low

B. *Network Architecture and Scale*

UWSNs consists of many sensor nodes and motion carriers and collaborative monitoring of the region of interest. The composition and basic knowledge of UWSNs are summarized as follows:

1. ***Anchor node:*** Also known as a beacon node, which can obtain the position information of the anchor node through a built-in GPS or manual setting. It's mainly used to estimate the coordinates of unknown nodes.
2. ***Unknown node:*** This type of node is a normal sensor node, and the position information is not available directly. Its function is to collect relevant information

about the monitoring area;

3. ***Sink node:*** It is mainly responsible for the connection between the underwater sensor network and the satellite or the outer network, which can be regarded as the gateway node;
4. ***Surface buoys:*** Surface buoys can get their absolute locations from the equipped GPS. Each buoy uses an acoustic transceiver to communicate periodically with beacon nodes and then sends a message package including the information of its location [24].
5. ***Neighbor nodes:*** Other nodes in the communication radius of the sensor node are called neighbors of the node;
6. ***AUV or ROV:*** Unmanned underwater vehicle (UUV) can be classified as a remotely operated vehicle (ROV) or autonomous underwater vehicles (AUV). UUV can carry sensor nodes to adjust the depth and horizontal coordinates of sensor nodes to achieve movement of the sensor node;
7. ***Hop Distance:*** The sum of each hop distance between two sensor nodes;
8. ***Hop Count:*** The total number of hops between two sensor nodes;
9. ***Connectivity:*** The number of neighbor nodes owned by the sensor node is referred as the connectivity of the node;
10. ***Infrastructure:*** Fixed equipment, such as satellite base station, GPS, etc., can help sensor node locate and know its position.

Sensor nodes are regarded as the basic component of the whole UWSNs. It is necessary to understand the internal architecture of the node. The node consists of five main units, namely, the central processing unit, communication unit, sensing unit, depth measuring unit, and energy management unit [25]. These units are responsible for the processing of all data information, communication receiving and transmission, energy supply, information sensing, and depth control among sensor nodes. Generally, the network architecture is one of the important key factors to determine network capacity, energy consumption [26]. Energy consumption directly affects the life cycle of the whole localization system. Therefore, the network architecture is an indispensable aspect, which needs to be carefully designed to improve network performance. The existing architecture of UWSNs is shown in Fig. 1. The network architecture is divided into 2D-UWSNs and 3D-UWSNs.

In general, the 2D-UWSNS architecture can be regarded as a network structure deployed in the seabed plane and composed of numerous clusters. Each cluster includes an anchor node (cluster head) and some ordinary sensor nodes. The underwater information collected by each ordinary sensor node of the cluster can be transmitted to the cluster head, and then aggregated and transmitted by the anchor node to the surface buoyancy node [9]. Moreover, the 2D-UWSNs communication link includes a vertical link and a horizontal link. The communication link between the cluster head in the cluster and the ordinary node is horizontal. Besides, the communication link between the cluster head and the surface buoyant node is vertical. Unlike 2D architecture, the architecture of 3D-UWSNs is no longer limited to observation of a certain underwater plane. Therefore, sensor nodes are deployed at different depths in the 3D network. Moreover, each sensor node can convey the local information of the underwater plane. There are three types of 3D-UWSNs communication, respectively, inter-cluster communication at different depths, sensor-cluster head communication, and buoyant-cluster head communication.

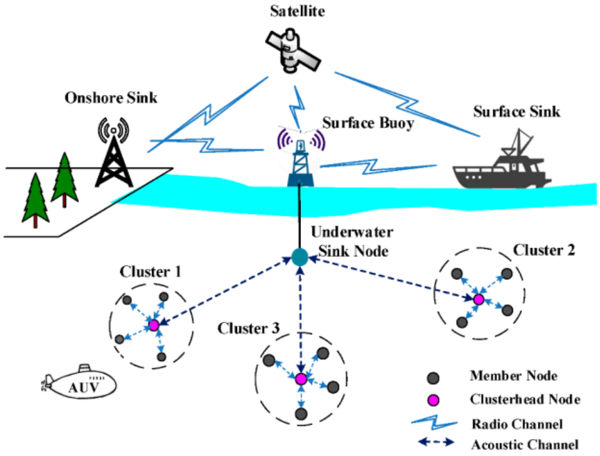

Fig. 1. UWSNs Architecture [27]

The network scale can be divided into small-scale UWSNs and larger-scale UWSNs. The size of the network scale depends on the number of sensor nodes and the scope of a deployment. However, different localization algorithms are required for different network scales. Generally, the localization method of small-scale UWSNs is a single-stage localization method, and the sensor nodes that have been positioned do not participate in the positioning of other sensor nodes. The localization algorithm of large-scale UWSNs is a two-stage localization method, and the sensor nodes located in Phase I will be used to locate other sensor nodes in Phase II.

C. *Routing Technique*

As a guarantee of efficient and reliable communication between sensor nodes of UWSNs, the importance of routing technology is self-evident. Compared to terrestrial WSNs, the design of the routing protocol in an underwater environment is more complicated. Additionally, the long propagation delay of acoustic communication may decrease effectiveness. Due to the continuous movement of water, the static topology is not suitable for the underwater environment [28]. Although dynamic topology design is applicable, it also faces many challenges. Hence, many valuable techniques of terrestrial WSNs cannot be directly applied in UWSNs. In recent decades, a lot of routing techniques for UWSNs have been proposed [29-32]. Those efficient routing techniques improve network reliability and reduce energy consumption. Some review articles summarized the existing routing technology in this field [33-37]. In [33], the authors classified the protocols based on the energy-efficiency and reliability and considered the protocols devoted to ameliorating energy-efficiency and reliability. The authors described routing protocol from two aspects: cross-layer design routing and non-cross-layer design routing in [34]. Unlike the classification of [34], in [35], the authors classified the routes of UWSNs from localization, routing, and reliability. The authors classified routing-based location, clustering scheme, and hierarchical in [36]. Additionally, the authors focus on the problems of those routing protocols which are based on data forwarding [37]. The above five review articles have collected many cutting-edge pieces of literature on UWSNs routing technology and classified them from different aspects. Hence, we will not repeat the knowledge of routing technology from the above five survey papers in this paper.

D. *Evaluation criteria*

When an underwater localization algorithm based on UWSNs is proposed, how to effectively evaluate its performance is worth considering. In this paper, therefore, we summarize the evaluation criteria of underwater localization algorithm:

1. **Localization accuracy:** The fundamental of the localization system is to have good accuracy. Generally, the localization accuracy is reflected in the error between the predicted or estimated coordinates and the source coordinates. The smaller the error, the higher the localization accuracy.
2. **Energy consumption:** Energy consumption directly affects the life cycle and cost of the whole positioning system, which is often reflected in the communication reception and transmission of sensor nodes, processing of perception data, motion adjustment, and other aspects. Hence, the high energy consumption of the underwater localization method is often not feasible.
3. **Area coverage:** Under the same infrastructure, maximize the positioning system sensing area. Under the same monitoring area, the number of sensor nodes used is minimized [38].
4. **Localization time:** The time of the entire underwater node or target location process should be fast. Otherwise, when the target moves, the acquired coordinates have a large error with the actual position.
5. **Computational complexity:** The complexity of the algorithm directly affects the localization process and part of the energy consumption. Reducing the complexity of the algorithm is also one of the hot research directions.
6. **Network lifetime:** The network life cycle of a localization system is generally related to the energy consumption of nodes and the number of nodes that can work efficiently. A longer life cycle is beneficial to the stability of the monitoring.
7. **Sensor density:** The main problem is how many sensor nodes can be placed in a certain sea area to achieve a better monitoring effect. Under the same monitoring effect, the lower the density, the lower the localization cost. The density of a sensor node is generally defined as the number of neighbors of the sensor node.
8. **Anchor density:** The anchor node with a known position is helpful to locate the unknown position of another ordinary node. It is worth exploring to maximize its functions by reasonably distributing anchor nodes. The location information of the anchor node is directly available for the coordinates of unknown nodes. Besides, underwater node localization methods also exist based on anchor-free [39].
9. **Communication overhead:** The evaluation of communication overhead is mainly based on the average number of broadcasts required by each sensor node. Within the range of reasonable localization requirements, the communication overhead can be reduced as far as possible by optimizing the communication path or localization protocol.

The excellent literature on underwater positioning algorithms introduced in this paper will be summarized and evaluated from some of the above evaluation criteria.

E. *Challenges of underwater acoustic communication*

In the introduction of this review, we have explained the reasons why UWSNs use acoustic communication. Although the underwater area of interest can be effectively monitored through underwater acoustic communication, it still has many challenges. The specific summary is as follows:

1. ***Low data transfer:*** The typical bandwidths and data rates of underwater channels in different ranges are summarized [9], as shown in TABLE IV. Underwater acoustic communication has severe bandwidth restrictions, which is less than 100 kHz [3]. Therefore, the data transfer of acoustic signals is also low.
2. ***Long propagation delay:*** It is obvious that the speed of sound propagates in seawater at a rate of 1497 m/s (25 $^{\circ}$C). Moreover, the acoustic signals channel is five orders of magnitude lower than the propagation rate of the radio channel [10]. When the temperature, depth, density, and other factors of seawater change, the propagation speed also changes. However, the slower propagation speed leads to long propagation delay and higher end-to-end time [11].
3. ***High dynamic topology:*** The sensor nodes in the network are not static due to the interference of natural factors such as ocean current movement. Therefore, the topology of UWSNs will change over time.
4. ***Low-quality link:*** since the multipath signal propagation and the time variation of the medium, the link quality of the underwater acoustic channel is lower.
5. ***High noise and interference:*** Compared with the land, the underwater environment is more changeable and complex. Marine life, the flow of water, and reflections touch the sea floor will bring interference. It makes the received underwater acoustic communication inevitably carrying noise.
6. ***High energy consumption:*** In TABLE III, it can be seen that the transmission power of the underwater node is higher than that of the terrestrial sensor node. Moreover, the motion resistance and environmental interference also increase the energy consumption of underwater sensor nodes.

TABLE IV.
DATA RATES AND BANDWIDTH FOR UNDERWATER CHANNEL WITH VARIOUS RANGES [9]

Span	Range(Km)	Data Rate	Bandwidth(KHz)
Short range	<1	~20kbps	20-50
Medium range	1-10	~10kbps	~10
Long range	10-100	~1kbps	2-5
Basin scale	3000	~10bps	<1

F. Challenges of node localization based on UWSNs

As we know, underwater flow velocity, temperature, depth, the water density of different sea areas, and other factors all affect the propagation of the underwater acoustic signals and the process of UWSNs localization. Therefore, in the complex and varied underwater environment, in addition to the shortcomings of underwater acoustic communication, the process of target or node localization based on UWSNs also has many challenges that require relevant researchers to overcome and optimize:

1. ***Energy restriction.*** The energy of the underwater sensor node to receive and transmit the captured information comes from the battery it carries. Moreover, the motion of mobile sensor nodes, data preprocessing, and selection of location computation algorithm (distributed or centralized) all have different degrees of energy consumption. The energy of the battery is limited, and when the battery energy is exhausted, the battery cannot be recharged or replaced in time due to the complicated underwater environment and node deployment. Hence, good control of the energy consumption of the target or node localization process, on the one hand, can make the target positioning system provide longer service, thereby improving the life cycle of the system. On the other hand, reducing energy consumption is equivalent to saving the cost of UWSNs.
2. ***Accuracy of localization.*** Estimating or predicting the precise position of the sensor node is the significance of the entire localization system. However, the distance of the localization target from the positioning infrastructure and the changes in the underwater environment affect the accuracy of the positioning. Also, when the energy of many underwater sensor nodes is exhausted, they need to be replaced in time to avoid loopholes in monitoring. There are conflicts between response speed and localization accuracy, so the relationship between them needs to be balanced according to the actual scene. Besides, the localization algorithm is difficult to balance between localization precision and energy consumption. Therefore, how to balance the relationship between various aspects of the entire localization system to improve the accuracy of localization or minimize the distance between the estimated position and the actual position is also one of the challenges.
3. ***The life cycle of the positioning system.*** The effective service time of the positioning system is its life cycle. the complexity of the real underwater monitoring environment and the energy consumption rate of the system may directly or indirectly affect the life cycle of the positioning system. Prolonging the life cycle of the positioning system can reduce the system cost. Therefore, prolonging the life cycle of the positioning system is one of the research hotspots in this field.
4. ***Complex underwater environment and network deployment.*** UWSNs are influenced by many natural factors that are often unpredictable. Such as ocean current activity, water pressure at different depths, the temperature of the water, interference by underwater organisms, and uneven depth of the seabed. Therefore, the network architecture deployment and design of UWSNs are intricate. In constrained communication, the currently tethered technology can be used but with additional cost [3]. Besides, how to reasonably design and deploy the network structure according to the actual conditions of the underwater environment is also one of the challenges at present.
5. ***Physical damage to equipment.*** As we all known, physical damage of equipment is inevitable due to seawater corrosion and other external factors. The accumulation of algae and salts may make sensor nodes less efficient [3]. Moreover, due to the fouling and corrosion of seawater, underwater sensors are also prone to malfunction, which may bring trouble to the localization process and increases costs.
6. ***Deployment and mobility of node.*** The sensor node drift with natural factors such as water flow [12]. As the underwater environment changes with time and is unpredictable, the location estimation of mobile nodes may produce some errors in distance.
7. ***Time synchronization.*** Time synchronization plays an important role in some localization schemes. The surface nodes can be time-synchronized via GPS. However, GPS devices do not work under water. underwater acoustic signal propagation delay is long. Therefore, time synchronization between underwater sensors is difficult to achieve. Besides, many scholars like to use the TOA algorithm to measure the distance between nodes, which also fails time synchronization between sensor nodes.

IV. UNDERWATER LOCALIZATION ALGORITHM CLASSIFICATION

The localization problem of UWSNs is more complicated than that of terrestrial WSNs. Some localization algorithms of terrestrial WSNs are not suitable to be used in UWSNs directly. Since the many challenges of underwater localization, in recent years, many researchers in related fields have continuously proposed novel optimization schemes or innovative methods to overcome these challenges. Therefore, it is necessary to classify, summarize, and compare the relevant frontier literature. To better compare these papers, we classify them into three aspects, namely, distance measurement, network scale, and anchor utilization. The taxonomy figure is shown in Fig. 2.

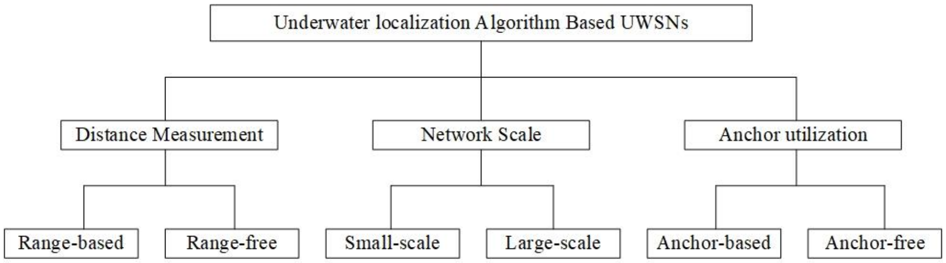

Fig. 2. Underwater localization algorithm based UWSNs

A. Distance measurement

According to the difference of distance measurement, the localization algorithms is divided into two classes, respectively, range-based scheme and range-free scheme. We introduce the ideas of its classic and recent frontier underwater localization algorithms of two subclasses. Additionally, we point out the advantages and disadvantages of some algorithms, and also summarize and compare all the introduced algorithms.

1) Range-based

In [40], the authors presented a source localization algorithm for UWSNs, which can applly both to 2-D or 3-D networks. Firstly, each sensor node takes the hydrophone sensor array to measure the directional of arrival (DOA) of the target signal. Then, the MUSIC method [41] is used to estimate the DOA. Finally, the sensor node is located by using the maximum likelihood (ML) method based on multiple DOAs. Simulation results show that the proposed algorithm is superior to the linear least square (LLS) and nonlinear least square (NLS) algorithms.

In the underwater acoustic wave propagation process, the geometric spreading and absorption of acoustic energy by the propagation medium itself lead to the partial loss of wave signal intensity, which may affect the accuracy of localization. For such cases, the authors proposed a novel underwater acoustic localization method based on energy (EB) [42]. The idea of the algorithm can be divided into two phases. One is to measure the signal intensity of the target and compute energy. The other is to estimate the optimal location of the target by establishing a signal transmission model and defining the topology of the UWSNs. The numerical simulation results show that this algorithm has a certain reference value for energy-based underwater node localization.

For heterogeneous underwater propagation medium, in [43], an asynchronous target location algorithm based on time difference of arrival (TDOA) is proposed, which is implemented by the iterative algorithm. Moreover, the algorithm can converge well to the Cramer-Rao Lower Bound (CRLB) with smaller location errors. The contribution of this paper was to consider that the speed of the wave is not constant, so it propagates through a curvature. Its limitation is that it is more suitable to locate sensor nodes asynchronously with anchors.

The authors proposed a novel node localization algorithm in UWSNs using received signal strength (RSS) measurements [44]. In a 2D underwater environment, the authors assumed that there are N anchor nodes with known coordinates and one target sensor node with unknown locations. The link between the target node and the *i*-th anchor node is shown in Fig. 3, where $d_i = \|x - s_i\|$ is the Euclidean distance and P_0 is the reference power at the reference distance $d_0 (d_0 \le d_i)$.

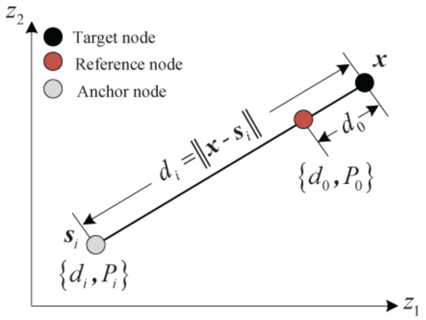

Fig. 3. The *i*-th sensoring link in the UWSNs model [44].

The algorithm first formulates the target node location problem by using the ML criterion. Due to fact that the obtained ML estimator function is non-convex, it is difficult to find a globally optimal solution. The ML estimator is then transformed into a generalized trust-region subproblem (GTRS) by an approximation technique, and the further expression of the location distance is obtained. Finally, the performance of the proposed algorithm is compared by using the CRLB of the node localization in UWSNs. Simulation results show that this algorithm outperforms a semi-definite programming (SDP) algorithm [45]. However, the limitation of this algorithm is that the positions of the anchor nodes and the target nodes need to remain unchanged during the observation period. In an actual underwater environment, the positions of the anchor nodes or target nodes may change. In the case of mobile nodes in UWSNs, therefore, whether the algorithm is applicable or not is yet to be studied. Unlike the [44], the authors proposed a novel RSS-based underwater localization method based on the convex relaxation technique in UWSNs to improve the location accuracy of the target [46]. For the case of known target transmit power, the authors first derive a weighted least squares (WLS) estimator by using an approximation to the RSS expressions. Then, the originally non-convex problem is transformed into a mixed semi-definite (SD)/second-order cone programming (SOCP) problem for reaching an effective solution. For the case of unknown target transmit power, on the other hand, iterative ML and mixed SD/SOCP algorithms are adopted to solve the WLS problem. Finally, the performance of the proposed algorithm is evaluated by deriving the CRLB on the root mean square error (RMSE). The simulation results

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2021.3081918, IEEE Internet of Things Journal

show that the algorithm has good localization accuracy in 2D or 3D underwater space. However, since the localization coverage area of the algorithm simulation is small, whether it is suitable for the actual large-scale underwater monitoring area remains to be further explored.

In[[47], the authors considered the difficulty of time synchronization of sensor nodes and the unknown sound velocity in the real underwater environment. A distance-based (DB) and an angle-based underwater localization algorithm are proposed. The distance-based localization algorithm selects four anchor nodes and many mobile nodes. The anchor node is placed at four vertices of the 120m x 120m region, and a beacon node is connected to a relative antenna to estimate a distance between a normal or mobile node and the beacon node. Then, the average estimation error between the mobile sensor node and the estimated position is estimated to verify the relevant properties of the algorithm. Simulation results show that the algorithm has a low average estimation error and good positioning accuracy, but the positioning accuracy of the proposed algorithm is directly related to the number of anchor nodes deployed in the sensor network. Furthermore, the algorithm is based on 2D-network, whether it is suitable for 3D space remains to be explored.

Many ordinary sensor nodes must pass multi-hop links to reach an anchor node in large-scale sparse UWSNs. In [48], the algorithm proposed by the authors firstly estimates the distance between the anchor node and the multi-hop node by using the assistance angle of arrival (AOA). Then, the location of the target node is estimated by using trilateration based on WLS. AOA measurement errors and the number of hops are two major factors that affect the localization error. The proposed algorithm has a lower distance error than DV-distance, DV-hop and the Distance-based method and is suitable for 2D and 3D space.

2) Range-free

Lots of node localization algorithms based on range-free has been proposed for terrestrial WSNs [49-51]. In [7], the author classified the rang-free localization algorithms of terrestrial WSNs into two categories, namely, centralized and distributed. It introduces in detail approximate point in a triangle (APIT), DV-hop, multi-hop, centroid, and gradient, which are range-free localization methods in terrestrial WSNs. Due to the complex underwater environment, some methods may not be suitable for underwater positioning or need to be improved. In this subsection, some underwater sensor node localization methods using range-free measurements are introduced. In [52], the authors proposed a localization with a mobile beacon (LoMoB) method based on range-free. The LoMoB is an improvement of localization with directional beacons (LDB). The mobile beacon that knows its location broadcasts a beacon message containing its location information. And sensor nodes are individually located by passively receiving the beacon messages without the need for inter-node communication. The LoMoB algorithm obtains a set of potential locations of the target node and then carries out a weighted mean of these potential locations to locate the target node. The simulation results show that the algorithm has a lower location error than LDB.

Due to the limited bandwidth of the acoustic signal, the impaired propagation channel, and the expensive underwater equipment, it is very difficult for the UWSNs to accurately locate the target node in the deep-sea environment. For non-ideal channel propagation conditions, a range-free localization based on mobile detachable elevator transceiver (DET) and 3D multi-power area localization scheme (3D-MALS) is presented in [53]. The DET can rise or dive vertically in the underwater environment, through realizing the communication between the transceiver and ordinary nodes. They assumed that the z-coordinates of all underwater nodes are available from the configured underwater pressure sensor (UPS), and the 3D space is converted into a 2D spatial localization problem. Therefore, as shown in Fig. 4, the algorithm calculates the maximum distance (external round) from each ordinary node to a DET in the 2D coordinate space. After that, calculate the shortest distance between an ordinary node and a DET. Finally, calculate the intersection area of all the rectangles associated with the circle of DET. Simulation results show that the average distance errors of the method are lower than the 2-D area localization scheme (ALS) [54]. Moreover, the authors also proposed a range-free localization method for ideal channel propagation conditions in [55]. Compared with [53], this algorithm is relatively ideal.

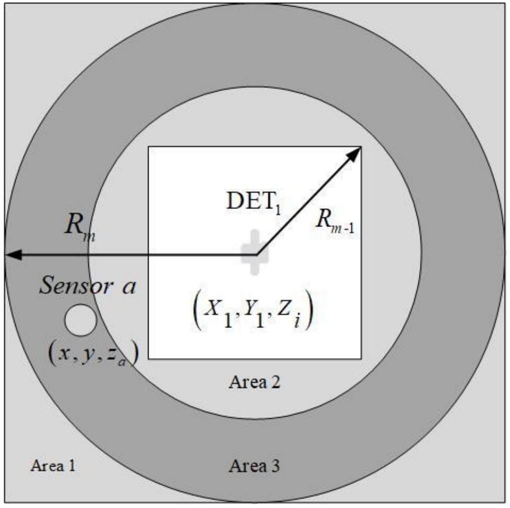

Fig. 4. 3D-MALS [53]

In the above localization algorithm, the range measurement algorithm based on TOA and TDOA needs to assume the time synchronization, and the costs are high [44]. However, time synchronization between sensor nodes is difficult to achieve. Moreover, the estimation error of the localization algorithm based on RSS is relatively large due to the propagation loss of the underwater acoustic signal. Additionally, the range-free localization algorithm does not need to measure the distance and azimuth information. Moreover, this type of algorithm is less affected by the underwater environment and location costs than the range-based algorithm. However, this scheme can only obtain a coarser position. In other words, the precision is lower than the range-based scheme.

In this paper, some localization methods based on distance measurement are summarized as shown in TABLE V. In TABLE V, each algorithm has a low, medium, and high rating in different evaluation criteria. The depend, high, middle, and low values of an evaluation criterion are determined by the simulation results of the algorithm. "Depend" means that the relevant narrative is missing and depends on the simulation environment. For example, the size of the simulation coverage of each algorithm may be different, and it will be graded according to the specific value. The same is true for subsequent related lists. We use the abbreviations to express some aspects, namely, range-based or range-free (Rb or Rf) and synchronous or asynchronous (Sy or As). Moreover, we mainly compare the accuracy, energy consumption, computational complexity, time, coverage, communication overhead, sensor density, and anchor density. In addition, a comparison of the localization algorithms mentioned in this section with those described in other sections is shown in Table VIII.

TABLE V.
COMPARISON OF LOCALIZATION ALGORITHMS BASED ON DISTANCE MEASUREMENTS

Ref.	Distance measurement	Method	Accuracy	Energy consumption	Computational complexity	Localization time	Simulation coverage	Communication overhead	Sensor density	Anchor density
[40]	Rb and Sy	DOA	Medium	Depend	Medium	Depend	Large	Medium	—	Low
[42]	Rb and Sy	EB	Medium	Low	Low	Medium	Large	Low	Low	Low
[43]	Rb and Sy	TDOA	High	Large	High	Depend	Small	Large	—	Medium
[44]	Rb and Not	RSS	Medium	Large	Low	Short	Small	Large	—	High
[46].	Rb and Not	RSS	High	Large	Medium	Depend	Small	Large	—	High
[47]	Rb and As	DB/AOA	Depend	Medium	Low	Medium	Small	Medium	High	High
[48]	Rb and Not	AOA	High	Large	Medium	Depend	Small	Large	High	High
[52]	Rf and As	LoMoB	Depend	Large	Low	Depend	Large	Large	Medium	Low
[53]	Rf and As	MALS	Medium	Medium	Low	Medium	Large	Medium	Medium	Low
[54]	Rf and As	ALS	Low	Large	Low	Average	Medium	Larger	High	Medium
[55]	Rf and As	MALS	Medium	Large	Low	Medium	Large	Large	Medium	Low

B. *Network scale*

According to the network scale, the localization algorithms are divided into two categories: small-scale localization schemes and large-scale localization schemes respectively. We introduced the ideas of its classic and recent frontier underwater localization algorithms of two subclasses. All the introduced algorithms are summarized and compared.

1) *Small-scale UWSNs*

In the case of mobile UWSNs, the need to periodically track nodes, and the pseudo-random mobility of nodes leads to network partitioning, which makes the localization problem of target nodes more challenging. In [56], the authors proposed a two-stage technique to efficiently locate nodes in a partitioned network. Divided the sensor nodes in the network into two types, namely, two or more GPS-enabled nodes and ordinary sensor nodes. Moreover, if the primary GPS node fails, a backup GPS node is responsible. Otherwise, the backup GPS node will be regarded as an ordinary node. Assume that the ordinary node is X and the localized node is Y (GPS or a localized node). Node X can estimate its absolute coordinates, and only two pieces of information are needed, respectively, the absolute position of node Y and the relative position of node X to node Y. When an ordinary node is located, its absolute location information is broadcasted by a beacon node. The whole localization process can be divided into two phases: the reactive stage and the proactive stage respectively. Estimate the relative locations of all one-hop and multi-hop neighbors of the GPS node in the first stage. In stage two, which occurs iteratively, partitioned nodes cluster up into one or more clusters according to their communication distance. The cluster header represents the cluster that sent the localization request. The simulation results show that this method has lower energy consumption and overhead.

For the stratification effect of the water medium, in [57], the authors proposed a unified framework for joint synchronization and localization scheme based on the Gauss-Newton method (GN-JSL). Firstly, the ray-tracing method is applied to model the stratification effect. Then, the stratification effect, clock imperfections, and the position of ordinary nodes are represented as a unified framework. The corresponding ML estimation is given, which is highly nonlinear and non-convex. Finally, the Gauss-Newton iterative algorithm is used to solve the problem. In [58], the scheme proposed by the authors uses the hyperbola event localization algorithm and normal distribution for estimation error to model and calibration. There are some differences between the common circle-based and hyperbola-based method. Generally, the two hyperbolas have a point of intersection, whereas the circle-based algorithm does not.

2) *Large-scale UWSNs*

In general, the underwater area under surveillance for many military or civilian applications is large. Therefore, large-scale UWSNs are needed to effectively monitor it. In a large-scale UWSNs, however, most sensor nodes cannot realize self-localization because they cannot directly communicate with multiple anchor nodes or neighbour node [48]. Furthermore, node deployment, communication between nodes, and mobility of nodes in large-scale UWSNs are also relatively more challenging. Therefore, localization algorithms for large UWSNs networks have been proposed one after another.

In [59], a distributed localization scheme is proposed, which integrates the 3D Euclidean distance algorithm with a recursive position estimation algorithm. Sensor nodes are divided into

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2021.3081918, IEEE Internet of Things Journal

three categories, namely, anchor nodes, ordinary nodes and surface buoys. Surface buoys can obtain accurate position information from the equipped GPS. Anchor nodes can compute their positions by obtaining the position message of surface buoys. In the process of ordinary node localization, the sensor nodes are divided into reference nodes and non-localized nodes. And the communication messages are divided into localization messages and beacon messages. Firstly, all anchor nodes are marked as reference nodes and set their confidence values to 1. The non-localized sensor node selects four non-collinear reference nodes with the highest confidence values for position estimation. If the estimation error of the non-localized node is small, then it can become a new reference node. Otherwise, it cannot be regarded as a reference node and will not broadcast its position information. Simulation results show that this localization scheme has smaller localization errors and larger localization coverage.

For the deep ocean environment, unlike [59], the authors proposed a hierarchical localization method [60]. This paper divides sensor nodes into four types, a DETs category is added on the basis of [59]. The DET can broadcast its location message by going up and down. The location of the anchor node can be independently calculated after receiving the location information of more than 3 DETs. It is assumed that there are n anchor nodes. (x, y): The coordinates of the target node. (x_i, y_i) : the coordinates of the ith anchor node. d_i : the estimated distance between the target node and the ith anchor node. Simultaneous equations are shown below.

$$\begin{cases} (x_1 - x)^2 + (y_1 - y)^2 = d_1^2 \\ (x_2 - x)^2 + (y_2 - y)^2 = d_2^2 \\ \vdots \\ (x_n - x)^2 + (y_n - y)^2 = d_n^2 \end{cases} \tag{1}$$

By subtracting the last equation from the first $n-1$ equation, the equation can be linearized and expressed as $Ax = b$. The standard least square method is used to solve the equation: $\hat{x} = (A^T A)^{-1} A^T b$.

$$A = \begin{bmatrix} 2(x_1 - x_n) & 2(y_1 - y_n) \\ 2(x_2 - x_n) & 2(y_2 - y_n) \\ \vdots & \vdots \\ 2(x_{n-1} - x_n) & 2(y_{n-1} - y_n) \end{bmatrix} \tag{2}$$

$$b = \begin{bmatrix} x_1^2 - x_n^2 + y_1^2 - y_n^2 + d_n^2 - d_1^2 \\ x_2^2 - x_n^2 + y_2^2 - y_n^2 + d_n^2 - d_2^2 \\ \vdots \\ x_{n-1}^2 - x_n^2 + y_{n-1}^2 - y_n^2 + d_n^2 - d_{n-1}^2 \end{bmatrix} \tag{3}$$

UWSNs use acoustic signals for data transmission. Due to the introduction of high transmission delay, the phenomenon of conflicting data loss is prominent. In [61], therefore, considered the impact of the medium access control (MAC) protocol on the localization algorithm, the authors proposed the variable interval ALOHA (VI-ALOHA) protocol based on the Poisson distribution. Firstly, the authors design a multi-layer localization framework, as shown in Fig. 5. The physical layer realizes the basic data communication. The data link layer needs to ensure the collision of multiple nodes is avoided. The Non-Synchronous Localization Scheme is used in the application layer of the multi-layer localization network.

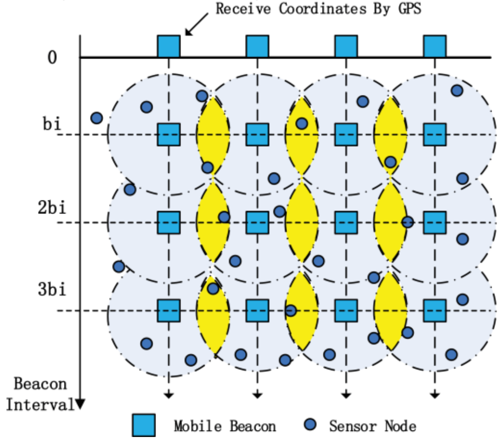

Fig. 5. Underwater localization collision scenario [61]

The broadcast interval between moving anchor nodes in the original localization scheme is uniform. Beacon node realized the rise and down by using UUV. However, when a common sensor node is within the communication range of the intersection of two anchor nodes, it may not accept two messages from different anchor nodes. Therefore, the authors analyze the collision effect of the beacon packet. The VI-ALOHA protocol reduces the collision by adding random space-time. Simulation results show that the VI-ALOHA protocol is outperformed than the equal interval ALOHA (EI-ALOHA).

In [62], the authors presented an asymmetrical round-trip based localization (ARTL) method. The localization method has excellent scalability, low computational complexity and time synchronization-free. There is only one pair of message exchange and the other passively listen to the beacons. This algorithm does not require time synchronization, and the purpose of the ARTL protocol is to find which beacon node needs to collect what data while minimizing negotiation between beacons and ordinary nodes. Since the z-coordinate of the sensor node is obtained by the USP. The node localization converts the 3D space into the 2D space localization problem by using the LS method. Simulation results show that the algorithm has good localization accuracy. Based on this algorithm, the influence of ordinary node mobility and the uncertainty of the beacon node position on localization accuracy can be considered to better adapt to the realistic underwater environment.

In [63], the problems of the node self-positioning scheme based on nonlinear LS are analyzed. The authors pointed out the bias distribution of multi-hop distance estimation error and

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2021.3081918, IEEE Internet of Things Journal

solved the normal node localization problem in the case of anchor position error by using orthogonal regression method. In addition, the two sources of distance estimation error in multi-hop scenarios are discussed, and the multi-hop distance estimation error in 3D network is analyzed empirically.

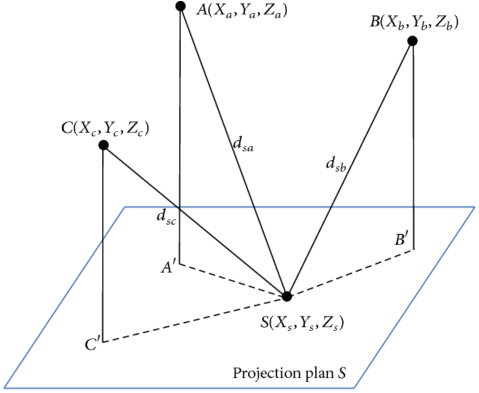

Fig. 6. An example of the projection technique.

In [64], as shown in Fig. 6, the localization algorithm used projection method to transform the 3D problem into the 2D problem. The localization scheme includes three phases: (1) sea surface anchor localization; (2) iterative localization; (3) complementary phase. In the case of only three surface anchor nodes, in the first phase, the surface nodes would send message block in the order described in basic time synchronization-free localization (BSFL) [65]. Then, their locations would be evaluated independently by the ordinary nodes that received all three beacons. In the secondary stage, after the unknown node is located, it can be used as a new reference node to assist the location of other unknown nodes after . If the unknown node failed to locate in the previous stage, a localization request is sent in the third stage, and then a new set of anchors is selected to locate the unknown node.

A novel virtual node assistance-based localization algorithm is proposed in [66]. The algorithm can be separated into two parts, namely, virtual node assisted static (VAS) localization algorithm and virtual node assisted dynamic (VAD) localization algorithm. There are three types of sensor nodes in the network, namely, the mobile beacon node, the auxiliary nodes, and the unlocated nodes. For these sensor nodes, the ship on the surface of the water is a mobile beacon node, and the precise location can be obtained through the configured GPS. The location of the auxiliary node is known and does not directly participate in the localization of the unlocated node. In a static underwater environment, the VAS localization algorithm can be used to solve the problem of unlocated nodes' location. The process of the VAS method is shown in Fig. 7(a). However, in a dynamic marine environment, the sensor node usually moves with water flow. Therefore, the VAD method can be used to solve the case, as shown in Fig. 7(b). The simulation results show that the algorithm has high localization coverage and small localization error and communication overhead. However, this method has higher energy requirements. How to deal with unlocated nodes that are not in the communication range is still to be explored.

In this section, we discuss the localization method of UWSNs based on a network scale and the difference between small-scale and large-scale methods. Generally, the localization method of small-scale UWSNs is a single-stage localization method, and the sensor nodes that have been positioned do not participate in the positioning of other sensor nodes. The positioning algorithm of large-scale UWSNs is a two-stage localization method, and the sensor nodes located in Phase I will be used to locate other sensor nodes in Phase II. As shown in TABLE VI, we have summarized and compared the introduced algorithms from many aspects. A comparison of the localization algorithms mentioned in this section with those described in other sections is shown in Table VIII.

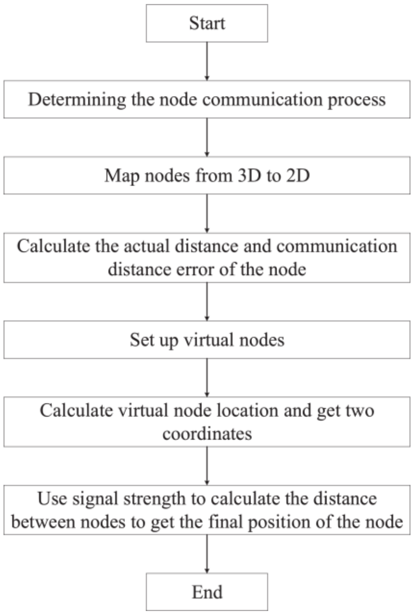

Fig. 7(a). VAS localization [66]

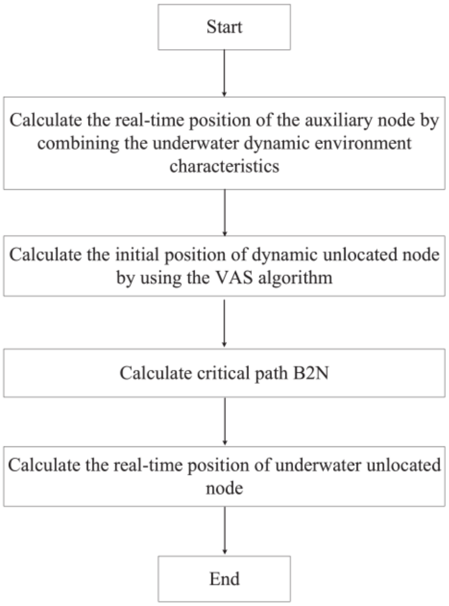

Fig. 7(b). VAD localization [66]

TABLE VI.
COMPARISON OF LOCALIZATION ALGORITHMS BASED ON NETWORK SCALE

Ref.	Network Scale	Network architecture	Accuracy	Energy consumption	Computation complexity	Localization time	Simulation coverage	Communication overhead	Sensor density	Anchor density
[56]	Small-scale	3D	Medium	Medium	Medium	Average	Large	Low	Low	Low
[57]	Small-large	3D	High	Medium	High	Short	Large	Medium	Low	Low
[58]	Small-large	2D	High	High	Low	Average	Small	Medium	Low	Medium
[59]	Large-scale	3D	High	Large	Medium	Medium	Small	Medium	High	High
[60]	Large-scale	3D	Medium	Large	Low	Medium	Large	Low	High	Medium
[61]	Large-scale	3D	Average	Medium	Medium	Short	Large	Medium	Low	Low
[62]	Large-scale	3D	High	Large	Low	Long	Large	Low	High	Low
[63]	Large-scale	3D	Average	Medium	Medium	Medium	Large	Medium	Medium	Medium
[64]	Large-scale	3D	Average	Medium	Medium	Medium	Medium	Medium	High	Low
[66]	Large-scale	3D	High	High	Medium	Average	Small	Low	High	Low

C. Anchor utilization

According to the presence or absence of anchor nodes in the localization scheme, the localization algorithms are divided into two classes, namely, an anchor-based localization scheme and an anchor-free localization scheme. We will introduce its two subclasses of classic and up-to-date frontier underwater localization algorithms. Moreover, we also summarize and compare all the introduced algorithms.

1) Anchor-based

In [67], the authors proposed a joint time synchronization and localization algorithm for UWSNs, which can be divided into two phases. In the first phase, the location of its target sensor is estimated through the method based on TOA measurement. The relative clock skew is ignored because of its small size, and the nonlinear equation is transformed into a linear equation, and the coarse time synchronization and positioning results are obtained by using the LS method. In the second phase, the coarse time estimate is refined by another LS estimator. AUV, as a moving beacon node, moves in a fixed direction and speed in every K + 1 time slots, and then turns to a randomly selected direction. Moreover, the target sensor only passively receives the AUV's periodic broadcast beacon signal, which contains the AUV's location information and the transmission time of the packet. The simulation results show that the localization and time synchronization error of the algorithm approximates CRLB.

A compressive sensing-based node self-localization algorithm is proposed in [68]. Firstly, the 3D cubic underwater monitoring area is divided into smaller cubic modules, and the unknown sensor node is randomly distributed in this area. The anchor node moves at a constant speed and the movement path of the mobile anchor node follows the random waypoint (RWP) path and the layered-scan path. Then, to effectively solve the range measurement error due to the delay of underwater acoustic transmission, the energy-based range algorithm is adopted in the localization method. The anchor node sends the collected signal strength value of the unknown node to the fusion center. Finally, the localization algorithm based on compressed sensing and centroid algorithm is used to locate all unknown target nodes. The idea of compressed sensing is to know the entire network by acquiring information about a small number of nodes in the network. The experimental results show that the QR-decomposition algorithm has a better localization effect under the layered-scan path conditions than the RWP path model. Although the localization method utilizes the layered-scan path to make the target node positioning error small, it also loses the timeliness of the target node positioning.

An energy optimized distributed location (EODL) method based on mobile beacon water is proposed in [69]. It’s an efficient technique for the distributed sensor network localization. An AUV as a mobile beacon, which is equipped with a transceiver with a beam width of 180° to broadcast the semispherical beacon signal and select a rectangular path motion to save energy consumption. When the target node receives four beacon signals with special significance from the AUV. Its location can be estimated by calculating the innermost intersection body. The localization method has the advantages of not requiring time synchronization, range-free, and energy saving. However, its localization accuracy is slightly lower than that of the range-based method. Moreover, the localization method lacks the timeliness of node localization.

UWSNs are typically deployed in larger sea areas, and nodes are typically floating. The range error caused by the mobility and uncertainty of sound velocity brings great challenges to the location of mobile nodes. For mobile node positioning, in [70], the authors proposed a localization method based on a mobility prediction and a particle swarm optimization algorithm (MP-PSO). The idea of this algorithm is to use the PSO algorithm and the known position of buoy nodes to locate beacon nodes and calculate the speed of beacon nodes. Then the velocity of the unknown node is calculated by using the spatial correlation of underwater target motion, and the position of the unknown node is predicted. However, the application of this method in the actual environment remains to be explored.

Also, for mobile node positioning in UWSNS, in [71], the authors believe that the localization error of the mobile node mainly comes from two aspects: the different positions where the mobile node receives the timestamps from different anchor nodes in the same positioning period, and the ray bending. Therefore, a novel localization algorithm (TA-PCCP-RT) is proposed, which incorporates time alignment and range bending compensation to overcome the challenges of mobile node localization. In this scheme, TA represents time alignment; PCCP represents the penalty convex-concave procedure, and RT represents ray tracing. This method allocates the distance between different adjacent nodes and moving nodes through the Kalman filter to estimate the exact time delay. Then, acoustic ray tracing is used to determine the exact distance between the adjacent anchor node and the moving node. Finally, the localization problem with unknown sound velocity change is transformed into a non-convex localization optimization problem, which is solved by the penalty convex-concave method. The simulation results show that the proposed algorithm is effective for mobile node localization.

A range-based scheme of localization is proposed in [72], namely, ProLo. The scheme firstly constructs a beacon plane through three non-collinear beacons and projects the edges of non-beacon sensor nodes onto the plane and then converts 3D positioning to 2D planar positioning. By applying the global stiffness theory, the nodes in mobile UWSNs maintain global stiffness in the process of moving. Finally, the position error of the whole unknown node is obtained. In this localization scheme, however, the nodes in the mobile UWSNs are moved. Furthermore, the scheme cannot handle the distance measurement errors well.

In [73], the authors proposed a localization algorithm called the two-phase time synchronization-free localization algorithm (TP-TSFLA). The localization algorithm can be divided into two phases, namely, the range-based evaluation phase and the range-free evaluation phase. It is assumed that all sensor nodes are configured with a UPS to obtain the depth of the node. In Phase I, all mobile beacons can dive and rise (DNR) vertical direction with the aid of extra weight and broadcast messages at fixed intervals. The unknown node accepts the information transmitted by the mobile anchor node for range measurement. Then, the PSO algorithm is used to solve the positioning optimization problem. In Phase II, the ordinary node that was in the first phase is used as a new reference node for nodes that are not located in the first phase. However, the algorithm can only guarantee that the selected anchor node has a high probability and its positioning result is optimal. Therefore, the application of this method in actual scenarios remains to be explored. In [74], a mobility-assisted underwater localization scheme (MALS-TSF) for large-scale 3D-UWSNs is proposed. Unlike [73], the two-TOA algorithm was used in Phase II. Also, the deployment scheme of anchor nodes in the monitoring area is designed. The simulation results show that the algorithm has a better localization ratio. However, the localization ratio of edge nodes in the monitoring area can be improved in the future. In summary, the localization schemes in [73] [74] can all use large-scale UWSNs. In [74], the authors used ranging-based localization algorithms in Phase I and Phase II. In [73], the localization algorithm of range-free is used in Phase II. In terms of localization accuracy and localization ratio, the localization scheme of [74] is higher than that in [73]. However, compared to the literature [74], the energy consumption of the localization scheme in the literature [73] is lower. Related readers can choose a suitable localization scheme according to the needs of the real scene.

Due to the joint influence of communication delay and node mobility, the localization error of the sensor node has relatively large errors. In [75], therefore, a motion-aware self-localization scheme for underwater networks is proposed. The authors assumed that the motion model of nodes is Markovian and a small number of surface beacons exist. The network platform can learn the correlation of node movement process in space and time. The simulation results of the localization scheme show that localization performance is improved significantly in the case of message delay and node movement. Combined with realistic underwater scenes, in [76], the authors proposed a new sequential algorithm for joint time-synchronization and positioning. The simulation results show that the positioning algorithm has high positioning accuracy. Also, when knowledge of node synchronization and propagation speed is not available, precise positioning can be achieved using only two anchor nodes.

In [77], a low-cost distributed networked localization and time synchronization framework is proposed. The authors assumed that all anchor nodes are time synchronized. Firstly, each ordinary sensor node sends a message packet to the anchor node to request time synchronization and location services. When the anchor node has received the packet sent from the nearby nodes, it fuses the information into a new data packet and then broadcasts it back with the location message. Finally, the ordinary sensor node can estimate its position. The simulation results show that this localization scheme can achieve high-precision node localization under a limited energy budget.

2) *Anchor-free*

Because GPS is not effective in an underwater environment, the anchor nodes contained in the anchor node-based positioning algorithm generally float on the water surface or use special equipment nodes such as AUV as anchor nodes. However, this kind of localization algorithm increases the cost of node localization. It is different from most anchor node-based localization algorithms. It is different from the anchor node-based localization algorithm. Some anchor-free based localization algorithms have been proposed.

In [78], the authors presented an anchor-free localization algorithm (AFLA), which is suitable for the active-restricted UWSNs. This method does not need anchor nodes because it makes use of the relationship between neighbour nodes. In this localization scheme, as shown in Fig. 8, the active-restricted nodes mean that when they are anchored on the seafloor, they can float in a hemisphere region. The anchor and the cable length (L) are the center and radius of the hemisphere, respectively. The depth (H) of the sensor node can be obtained by the pressure sensor. The sensor node with the unknown position broadcasts the ccoordinates of its spherical center, depth, and cable length. When the sensor node receives two messages, it can calculate the position independently.

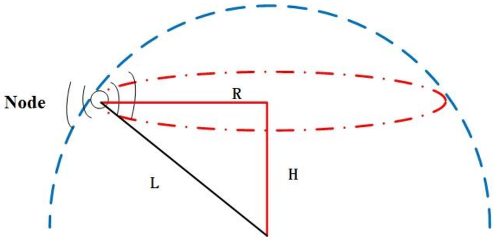

Fig. 8. Model of an active-restricted sensor node [78].

In [79], the authors proposed an underwater signal reflection-enabled acoustic-based localization (UREAL) scheme. It uses multimodal directional underwater piezoelectric transducers to generate omnidirectional or directional beams. Thus, this scheme can utilize both line-of-sight (LOS) and surface-reflected non-line-of-sight (NLOS) links of surface reflection to realize sensor node localization. Moreover, UREAL uses RSS message for LOS/NLOS link classification, while the AOA ranging is used for location estimation.

In this subsection, we discuss Anchor-based localization schemes and Anchor-free localization schemes. In the traditional 3D underwater positioning algorithm, four anchor nodes are usually needed to locate the target node (X coordinate, Y coordinate, Z coordinate). Moreover, some underwater localization algorithms obtain the Z coordinates of each node by assuming that all sensor nodes are configured with USP [24]. Therefore, the 3D underwater node localization can be transformed into a 2D planar localization problem after projection, and the target node can be located by using three anchor nodes. Due to the application of an anchor node in UWSNs, it provides convenience for relevant researchers to locate the target node. Although an anchor-free based localization algorithm can reduce localization cost to some extent, the algorithm is still insufficient in localization accuracy of target nodes and adapting to large UWSNs.

In this paper, we summarize the relevant cited references in this section, as shown in TABLE VII. Moreover, based on the types of anchor nodes, the existing anchor node state can be categorized into two types: static (fixed anchor node) and mobile [66], which it is also summarized in TABLE VII for the reader's understanding. In TABLE VII, low indicates that one of the evaluation criteria of the algorithm is relatively small. Medium denotes the degree of being in a relative middle. High means relatively large. The high, middle and low values of an evaluation criterion are determined by the simulation results of the algorithm. Furthermore, we mainly compare accuracy, energy consumption, computational complexity, localization time, simulation coverage, communication overhead, sensor density, and anchor density. A comparison of the localization algorithms mentioned in this section with those described in other sections is shown in Table VIII.

TABLE VII.
COMPARISON OF LOCALIZATION ALGORITHMS FOR USING DISTANCE MEASUREMENTS

Ref.	Anchor node	Anchor state	Accuracy	Energy consumption	Computation complexity	Localization time	Simulation coverage	Communication overhead	Sensor density	Anchor density
[67]	Anchor-based	Mobile	Medium	Low	Low	Medium	—	Low	—	Low
[68]	Anchor-based	Mobile	High	Medium	Medium	Average	Small	Low	Medium	Low
[69]	Anchor-based	Mobile	Medium	Medium	Medium	Average	Large	Low	Medium	Low
[70]	Anchor-based	Static	High	Medium	Medium	Medium	Large	Medium	Medium	Medium
[71]	Anchor-based	Static	High	High	High	Short	Large	Medium	Low	Medium
[72]	Anchor-based	Mobile	Medium	High	Medium	Average	Small	Medium	High	Medium
[73]	Anchor-based	Mobile	Average	Medium	Medium	Average	Large	Medium	High	Medium
[74]	Anchor-based	Mobile	High	Medium	Medium	Average	Large	Medium	High	Low
[75]	Anchor-based	Mobile	High	—	Medium	Medium	Small	Low	Low	Low
[76]	Anchor-based	Mobile	High	Medium	Medium	Average	Small	Medium	Low	Low
[77]	Anchor-based	Static	High	Medium	Low	Average	Small	Medium	Low	Low
[78]	Anchor-free	—	Average	Medium	Medium	Medium	Large	Medium	Medium	—
[79]	Anchor-free	—	Medium	Medium	Medium	Medium	Large	Medium	Medium	—

V. DISCUSSION

We divide the underwater localization algorithm into three main aspects, namely, distance measurement, network scale, and anchor utilization. The corresponding summary table is given under each classification algorithm, in TABLEs V, VI, and VII. However, relevant readers should understand that the focus of the underwater localization algorithm proposed in the literature is different, such as the proposed localization algorithm by the authors is distributed or centralized, estimated or predicted, range-based or range-free, anchor-based or anchor-free, and the network is static or mobile. The above-mentioned factors will directly or indirectly affect the accuracy of the target location, overall energy consumption, and monitoring coverage. In general, centralized localization schemes may not be as flexible as distributed schemes, and range-based localization algorithms may be smaller than range-free localization errors. But on the other hand, centralized localization algorithms usually have high positioning accuracy. The energy consumption of the range-free algorithm is relatively low, which can extend the service life of the whole system. High precision positioning and low energy consumption are often contradictory. It is necessary for relevant scholars to continuously explore the relationship between the two to meet practical needs as much as possible. Under different underwater environments and requirements, therefore, it is meaningless to compare the underwater localization algorithms in different underwater application scenarios. Aiming at large sea areas, moreover, the localization algorithm of sensor nodes in large-scale networks is one of the hotspots of continuous research in the future. Improving the localization ratio of network nodes and the localization accuracy of edge nodes is worthy of continuous exploration. Each relevant researcher must make continuous efforts and explore the most appropriate algorithm according to the actual needs and optimize and improve on this basis. The purpose of this review is to summarize and analyze the cutting-edge algorithms in this field from multiple perspectives, so that relevant readers can clearly and quickly understand the corresponding algorithms from multiple aspects and select the appropriate algorithm according to the actual underwater environment requirements.

Moreover, for the main classification of this review, this section also summarizes the algorithm literature introduced from several different aspects. Such as Network Architecture (2D or 3D), Computation algorithm (Centralized or Distributed; Estimation or Predicted), Node State (Stationary or Mobile or Hybrid), the Communication between sensor nodes (Synchronization or Asynchronization; Silent or Active; Single-stage or Multi-stage) and so on. The node that has been located is used as a new reference node to locate the unknown node, which is called a multi-stage localization algorithm. Otherwise, it is a single-stage localization algorithm. In TABLE VIII, we use the abbreviations to express all aspects, namely, Reference (Ref.), Lager-Scare Network (L-SN), Centralized or Distributed (C or D), two dimensional or three dimensional (2D or 3D), Estimation-based or Prediction-based (E or P), Range-free or Range-based (Rf or Rb), Anchor-free or Anchor-based (Af or Ab), Stationary or Mobile or Hybrid (Sa or M or H), Synchronization or Asynchronization (Sy or As), Active or Silent (A or Si), and Single-stage or Multi-stage (Ss and Ms). The details are shown in Table VIII.

TABLE VIII.
COMPARISON OF UNDERWATER POSITIONING ALGORITHMS

Ref.	**Method**	**L-SN**	**2D or 3D**	**C or D**	**E or P**	**Rf or Rb**	**Af or Ab**	**Sa or M or H**	**Sy or As**	**A or Si**	**Ss or Ms**
[40]	DOA	No	2D&3D	C	E	Rb	Ab	—	Sy	A	Ss
[42]	EB	No	3D	C	E	Rb	Ab	Sa	Sy	A	Ss
[43]	TDOA	No	3D	C	E	Rb	Ab	Sa	Sy	—	Ss
[44]	RSS	No	2D	C	E	Rb	Ab	Sa	—	A	Ss
[46]	RSS	No	2D&3D	C	E	Rb	Ab	Sa	—	A	Ss
[47]	DB/AOA	No	2D	D	E	Rb	Ab	H	As	A	Ss
[48]	AOA	Yes	2D&3D	D	E	Rb	Ab	Sa	—	A	Ms
[52]	LoMoB	No	3D	D	E	Rf	Ab	M	As	Si	Ss
[53]	MALS	Yes	3D	C	E	Rf	Ab	H	As	Si	Ss
[54]	ALS	Not	2D	C	E	Rf	Ab	Sa	As	A	Ms
[55]	MALS	Yes	3D	C	E	Rf	Ab	H	As	Si	Ss
[56]	2SC	No	3D	D	E	Rb	Ab	H	Sy	A	Ms
[57]	GN-JSL	No	3D	C	E	Rb	Ab	Sa	Sy	Si	Ss
[58]	HB	No	2D	C	E	Rb	Ab	Sa	Sy	A	Ms
[59]	HL	Yes	3D	D	E	Rb	Ab	Sa	—	A	Ms
[60]	HL	Yes	3D	C	E	Rb	Ab	H	—	Si	Ss
[61]	VI-ALOHA	Yes	3D	D	E	Rb	Ab	H	As	A	Ss
[62]	ARTL	Yes	3D	C	E	Rb	Ab	Sa	As	A	Ss
[63]	OR	Yes	3D	D	E	Rf	Ab	—	Sy	—	Ss
[64]	BSFL	Yes	3D	D	E	Rb	Ab	Sa	As	A	Ms
[66]	VAS, VAD	Yes	3D	D	E	Rb	Ab	H	As	A	Ms
[67]	TOA	No	3D	D	E	Rb	Ab	H	Sy	Si	Ss
[68]	SB	No	3D	C	E	Rb	Ab	H	—	A	Ss
[69]	EODL	No	3D	D	E	Rf	Ab	H	As	Si	Ss
[70]	MP-PSO	Yes	3D	D	P	Rb	Ab	H	Sy	A	Ms
[71]	TA-PCCP-RT	No	3D	D	E	Rb	Ab	H	Sy	Si	Ss
[72]	ProLo	No	3D	D	E	Rb	Ab	M	Sy	A	Ms
[73]	TP-TSFLA	Yes	3D	D	E	Rb	Ab	H	As	A	Ms
[74]	MALS-TSF	Yes	3D	D	E	Rb	Ab	H	As	A	Ms
[75]	MASL	No	3D	D	E	Rb	Ab	M	Sy	A	Ss
[76]	UWAL	No	3D	D	E	Rb	Ab	M	Sy	A	Ss
[77]	LCDNL	No	3D	D	E	Rb	Ab	Sa	Sy	A	Ss
[78]	AFLA	No	3D	D	E	Rb	Af	M	—	A	Ss
[79]	UREAL	No	3D	D	E	Rb	Af	M	As	A	Ss

VI. RESEARCH PROSPECT

As one of the research hotspots in many fields, underwater sensor node localization has been paid close attention and studied by relevant scholars. No matter the improvement of network topology or the optimization and innovation of location algorithms, modern scholars in related fields have made indelible contributions to the research and expansion of underwater sensor node localization. However, there are still many problems to be resolved to continue to explore and

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2021.3081918, IEEE Internet of Things Journal

optimize. Future research prospects are also summarized in this paper.

1. ***Large-scale UWSNs localization algorithm:*** With the increasing demand for underwater exploration in related fields, large-scale ocean areas inevitably need to be monitored. At present, however, most underwater localization algorithms are based on small-scale UWSNs. The localization algorithm for large-scale UWSNs is still far from enough and very challenging [80]. Therefore, considering the needs of the actual underwater monitoring environment, the research on the underwater localization method of large scale UWSNs still needs further exploration by relevant researchers.
2. ***Mobile node localization:*** The scope of the mobile node is much larger than that of the static node. Although the cost of a single mobile sensor is higher than the cost of a static node, the overall monitoring cost is relatively low. In a realistic underwater environment, furthermore, sensor nodes move with the influence of water flow and the like. In general, we can use AUV as a mobile beacon node, but configuring AUV for all mobile nodes is unrealistic because of the high cost [81]. Hence, in the complex and changeable underwater environment, how to effectively locate common motion sensor nodes and put forward a reasonable migration model of the mobile UWSNs [82] is one of the research hotspots.
3. ***Reliability, Security, and privacy:*** At present, most underwater localization algorithms are proposed to improve localization accuracy or reduce energy consumption. However, few articles consider the reliability, security, and privacy of location [27, 83]. There is no doubt that they are crucial in UWSNs. In [84], the authors have studied security attacks, privacy issues and corresponding countermeasures in underwater localization. Nodes need to disseminate message in order to achieve positioning, which may lead to privacy vulnerabilities.
4. ***Optimization, balance, and evaluation of underwater localization:*** In the relevant frontier literature introduced in this paper, some relevant researchers optimize the performance of underwater target positioning from different aspects. However, the optimization of the localization algorithm should be based on the complexity of the actual underwater environment and the actual requirements. How to better optimize and balance the localization accuracy of the target node, the life cycle of the overall positioning system and energy consumption, and other related issues still need to be explored.
5. ***Novel Routing protocols for UWSNs localization:*** Routing protocols aim to select the most convenient path to deliver data towards destination [33]. However, the acoustic channel has exclusive challenges regarding MAC [85, 23]. The MAC protocol inevitably introduces transmission delays and affects the accuracy of localization schemes that rely on two-way messaging. Thus, a new routing protocol is needed for UWSNs. Besides, UWSNs needs new routing protocols to ensure efficient communication between sensor nodes.
6. ***Sound speed variation**:* In most of the localization papers investigated, the velocity of sound propagation in the underwater environment is assumed to be a constant [86]. However, the speed of sound is closely connected with the density of the water, the temperature of the water, the multipath, and so on [87]. Thus, how to construct a common and accurate sound speed model is a research question that needs attention.
7. ***The path planning of the mobile anchor node:*** In general, path planning can be divided into two aspects, respectively, a static path planning algorithm and a dynamic path planning algorithm [88]. A mobile beacon node walks through a set path, and the mobile beacon stays on the path as a virtual beacon node. The unknown sensor node locates itself by receiving the location information propagated by the virtual beacon node. Therefore, it is also worthy of attention to optimize or propose a new path planning for mobile beacons to minimize the path under the same monitoring effect to achieve the purpose of reducing energy consumption.

VII. CONCLUSION

With the increasing interest in the exploration of abundant marine resources, underwater node localization based on UWSNs has attracted wide attention in related fields. Unlike terrestrial UWSNs, acoustic waves are utilized to enable communication between underwater sensor nodes due to the specificity and complexity of the underwater environment. In this review, we describe the acoustic communication and underwater localization challenges. UWSNs Vs terrestrial WSNs, network architecture, routing technique, and evaluation for underwater localization are also described in detail. Some professional-related acronyms are shown in TABLE IX. Different from other survey papers, furthermore, we survey many underwater localization algorithms based on a new taxonomy, namely, distance measurement, network scale, and anchor utilization. The algorithm paper cited by each class is summarized and compared from different aspects. In this paper, finally, future research prospects are summarized.

TABLE IX.
LIST OF ACRONYMS OF CORRESPONDING OF DEFINITIONS

Acronym	Definition
2D	Two-Dimensional
2SC	Two-Stage Communication
3D	Three-Dimensional
AFLA	Anchor-Free Localization Algorithm
AOA	Angle of arrival
ARTL	Asymmetrical Round-Trip based Localization
AUV	Autonomous underwater vehicle
BSFL	Basic Tine Synchronization-Free Localization
CRLBs	Cramer Rao Lower Bounds
DET	Detachable elevator transceiver
DNR	Dive-and-Rise
DOA	Directional of arrival
EB	Energy-based
EODL	Energy Optimized Distributed Location
GN-JSL	Joint synchronization and localization scheme based on Gauss-Newton
GTRS	Generalized trust region subproblem
HB	Hyperbola-based
HL	Hierarchical Localization
LCDNL	Low-cost Distributed Networked Localization
LLS	Linear least square
LOS	Line-of-sight
LS	Least squares
MAC	Medium access control
MALS-TSF	Mobility-assisted Localization Scheme with Time Synchronization-Free
MASL	Motion-Aware Self-Localization
ML	Maximum likelihood
MP-PSO	Mobility Prediction and a Particle Swarm Optimization algorithm
NLS	Nonlinear least square
OR	Orthogonal Regression
ProLo	Propose an adaptive localization scheme
PSO	Particle Swarm Optimization
RMSE	Root mean square error
RSS	Received signal strength
RWP	Random waypoint
SB	Sensing-based
SD	Semi-definite
SOCP	Second-order cone programming
TA-PCCP-RT	TA represents time alignment; PCCP represents the penalty convex-concave procedure, and RT represents ray tracing.
TDOA	Time difference of arrival
TOA	Time of arrival
TP-TSFLA	Two-Phase Time Synchronization-Free Localization Algorithm
UPS	Underwater pressure sensor
UREAL	Underwater Signal Reflection-enabled
UUV	Unmanned Underwater Vehicle
UWAL	Underwater acoustic localization
UWSNs	Underwater wireless sensor networks
VAD	Virtual node Assisted Dynamic
VAS	Virtual node Assisted Static
VI-ALOHA	Variable interval ALOHA
WLS	Weighted least squares
WSNs	Wireless sensor networks

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2021.3081918, IEEE Internet of Things Journal

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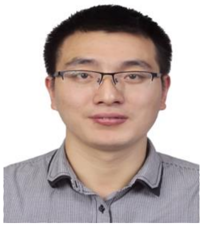

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