Review on Localization Algorithms in Underwater Sensor Networks

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Abstract: This review paper provides a comprehensive examination of localization algorithms in underwater sensor networks (UWSNs), addressing the unique challenges posed by the aquatic environment, such as severe signal attenuation, multipath propagation, node mobility due to water currents, and significant energy constraints. It categorizes the localization algorithms into time-of-arrival (TOA), time-difference-of-arrival (TDOA), received signal strength indicator (RSSI), angle-of-arrival (AOA), and hybrid and collaborative approaches, highlighting their operational mechanisms, advantages, and limitations. Furthermore, the paper discusses the current trends and future directions in UWSNs localization, including the integration of machine learning techniques and the potential for enhancing localization accuracy through the use of auxiliary information like ocean current models. Through an analysis of existing literature and a discussion on the environmental challenges and technical limitations of underwater communication technologies, this paper aims to provide insights into the advancements and remaining hurdles in the field of UWSN localization, contributing to a deeper understanding of its critical role in enhancing the capabilities and applications of underwater sensor networks.

1 INTRODUCTION

Underwater Sensor Networks (UWSNs) represent a pivotal advancement in the domain of underwater exploration and monitoring, facilitating a wide array of applications from oceanographic data collection, pollution monitoring, underwater pipeline monitoring to surveillance and reconnaissance missions [1]. These networks comprise a multitude of sensor nodes and vehicles deployed underwater, tasked with collecting and transmitting data back to surface stations or underwater bases. Unlike their terrestrial counterparts, UWSNs operate in a uniquely challenging environment that significantly impacts communication, localization, and network management [2].

Localization, the process of determining the geographical positions of nodes within a network, is crucial for the operational efficacy of UWSNs. It underpins tasks such as data tagging with spatial information, network routing, and the deployment and retrieval of sensor nodes. However, the underwater environment introduces a set of formidable challenges not present in terrestrial settings, including severe signal attenuation, multipath propagation due to reflection from the surface and seabed, and node mobility induced by water currents. These factors necessitate specialized localization algorithms tailored to the underwater environment.

The primary communication medium in UWSNs is acoustic signaling, chosen over radio or optical means due to its better propagation characteristics underwater[19]. However, acoustic communication is fraught with challenges, such as limited bandwidth, high latency, and significant signal attenuation with distance and due to
absorption by the water body, all of which complicate the localization process[8]. Moreover, the speed of sound in water varies with temperature, salinity, and pressure, adding another layer of complexity to accurate distance estimation based on signal propagation time.

In addition to communication challenges, the underwater environment itself poses significant hurdles. The variability in environmental conditions affects sensor operations and acoustic signal propagation, necessitating adaptive and robust localization methods. Furthermore, the energy constraints of underwater sensors, compounded by the difficulty of battery replacement or recharging, demand highly

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energy-efficient localization algorithms to ensure the longevity and sustainability of UWSN deployments[3].

Given these challenges, a variety of localization algorithms have been proposed, each attempting to address the intricacies of underwater environments. These algorithms can be broadly classified into range-based and range-free methods. Range-based methods, which include Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA), rely on the measurement of distances or angles between nodes to estimate positions. These methods often require additional hardware and can be affected by the aforementioned issues of acoustic communication . On the other hand, range-free methods, which infer location based on network connectivity and proximity, offer a less hardware-intensive solution but typically with lower accuracy .

Emerging trends in UWSN localization focus on overcoming the limitations of existing algorithms through the integration of machine learning techniques, the use of auxiliary information such as ocean current models, and the development of hybrid methods combining the strengths of range-based and range-free approaches Moreover, the potential for integrating UWSNs with other types of networks, such as terrestrial and satellite networks, presents opportunities for creating a more interconnected and comprehensive monitoring and data collection system.

This review paper aims to provide a thorough examination of the state-of-the-art in localization algorithms for underwater sensor networks. By navigating through the complexities of underwater communication, addressing the environmental challenges, and exploring innovative solutions, this paper seeks to offer insights into the advancements and remaining hurdles in the field of UWSN localization. Through a comprehensive analysis of existing literature and current research trends, this review will contribute to a deeper understanding of the critical role of localization in enhancing the capabilities and applications of underwater sensor networks..

2 CLASSIFICATION OF LOCALIZATION ALGORITHMS

Localization algorithms in underwater sensor networks (UWSNs) can be classified based on their methodologies, which encompass a variety of techniques for determining the sensor nodes locations in the underwater environment. Depending on the method for estimating position, localization strategies belong to the category of range-based or range-free schemes. The method of range-based localization's position estimate consists of two steps. First, measure the angle or separation between the nodes in the range phase of localization. The sensor node's approximate location is ascertained using the measured values during the localization phase, which follows the range phase. Methods listed below is used to measure range .These algorithms leverage different principles and measurements such as time-of-arrival TOA, TDOA, AOA, received signal strength indicator (RSSI) to infer the sensor nodes' spatial coordinates . This section presents an overview of each category and a classification of localization algorithms in UWSNs.

2.1 Time-of-Arrival Based Algorithms

TOA algorithms measure the time it takes for acoustic signals to travel between the sensor nodes to ascertain their distances. By employing synchronized clocks and pre cise timing measurements, these algorithms determine the time-of-arrival of signals at different nodes and use this information to calculate the distances. Sequential methods iteratively refine the position estimate based on sequential distance measuments.MLE approaches estimate node positions by maximizing the likelihood function based on observed TOA measurements and assumed statistical models[25].

2.2 Time-Difference-of-Arrival Based Algorithms

TDOA based algorithms estimate the differences in arrival times of signals between
pairs of sensor nodes. By comparing the time differences at multiple reference nodes, these algorithms infer the difference in distances between nodes and triangulate the target node's location. Common TDOA based algorithms include two-way ranging (TWR), multilateration, and non-linear least squares (NLLS). TWR involves bidirectional communication between nodes in order to gauge the round-trip time of acoustic signals. Multilateration methods determine the location of the target node by utilizing TDOA data from several reference nodes. NLLS methods iteratively refine position estimates by minimizing the difference between observed and predicted TDOA values[25] .

2.3 Received Signal Strength Indicator Based Algorithms

RSSI-based algorithms use the received signal intensity of acoustic broadcasts to determine the distances between sensor nodes. By correlating signal strength measurements with distance attenuation models, these algorithms infer the distances between nodes. Examples of RSSI based algorithms include trilateration, fingerprinting, and machine learning approaches. Based on established reference node locations and distance estimates from RSSI data, trilateration determines node positions. Fingerprinting methods create a database of signal strength patterns at known locations and match observed RSSI measurements to determine node positions. Machine learning algorithms utilize RSSI data to train models for predicting node positions based on observed signal characteristics [25].

2.4 Angle-of-Arrival Based Algorithms

AOA based algorithms estimate the angles at which acoustic signals arrive at sensor nodes relative to known reference directions. By measuring the arrival angles from multiple reference nodes, these algorithms triangulate where the target node is located. AOA based algorithms include techniques such as Acoustic Doppler Shift (ADS) and Angle-of-Arrival estimation. ADS methods exploit the Doppler effect induced by the motion of the target node to estimate arrival angles. Using array processing algorithms, AOA estimation methods determine the angles of arrival using spatial beamforming and signal processing [25].

2.5 Hybrid and Collaborative Localization Approaches

Hybrid and collaborative localization approaches combine multiple localization techniques to improve accuracy, robustness, and scalability. These approaches leverage complementary strengths of different techniques for localization to get around the restrictions of individual techniques. Examples of hybrid and collaborative localization approaches include sensor fusion, cooperative localization, adaptive algorithms. Sensor fusion integrates measurements from multiple sources, like TOA, TDOA, RSSI, and AOA, to increase the precision of localization. Cooperative localization schemes involve collaboration between sensing nodes to exchange data and enhance localization performance. Adaptive algorithms dynamically select and combine localization methods based on environmental conditions, network dynamics, and application requirements [27][16].

3 CHALLENGES IN UNDERWATER LOCALIZATION

Underwater localization faces a unique set of difficulties that are mostly caused by the characteristics of the aquatic environment and the technical limitations of underwater communication technologies. Underwater localization faces a unique set of difficulties that are largely caused by the characteristics of the aquatic environment and the technical limitations of underwater communication technologies. Underwater communication systems have several difficulties, including restricted bandwidth, increased energy consumption, longer propagation delay times, End-End Delays (E-ED), three-dimensional topology, media access control, routing, resource optimization, and power limitations[26]. Since There exist certain differences between sensor environments on land and underwater, we have opted for acoustic waves over radio signals:

Implementation: Although sensor networks on land are widely dispersed, those underwater are thought to be deployed less frequently because of the related costs and difficulties.

Strength: Because acoustic underwater communications operate over longer distances and require more sophisticated signal processing at the receivers to account for channel imperfections, compared to radio communications on land, they use more energy.

Recollection: While the storage capacity of terrestrial sensor nodes is quite restricted, under-water sensors may require the ability to perform some data caching due to the possibility of intermittent underwater channel connectivity.

Correlation in Space: Although there is often correlation between the results from terrestrial sensors, underwater networks are less likely to experience this because of the greater distances between the sensors [2].

Table 1: Comparison of Electromagnetic(EM), Acoustic, and Optical Waves in Underwater Environment.

Properties	EM	Acoustic Waves	Optical Waves
Frequency	kHz	MHz	10^{14} –10^{15} Hz
Bandwidth	kHz	MHz	10-15 MHz
Effective range	1 m	10 m	10-100 m
Nominal speed(m/s)	1,500	33,333,333	33,333,333
Antenna size	0.1 m	0.5 m	0.1 m

Acoustic communication, the predominant method for underwater sensors due to its better propagation characteristics in water compared to electromagnetic and optical signals1, introduces significant challenges including signal attenuation, multi-path propagation, and delay variances. Signal attenuation occurs as the acoustic signal loses its energy over distance and due to absorption by the water, which limits the range and reliability of communication. Multi-path propagation, where the ocean's surface and bottom reflect signals, leads to multiple replicas of the signal that will arrive at the receiver at different times, causing signal distortion and making it difficult to accurately determine the TOA and, consequently, the distance between nodes. Furthermore, the process of localization is made more difficult by the water currents that cause the mobility of sensor nodes, which constantly change the topology of the sensor network. If not sufficiently considered,this mobility can result in large localization mistakes, necessitating techniques that can adjust to changes in the node positions over time. These difficulties are made worse by the energy limitations of underwater sensors. Given the difficulty and expense of replacing or recharging batteries in underwater environments, energy efficiency becomes a critical consideration in the design of localization algorithms, necessitating methods that minimize communication and computational overheads. The harsh underwater environment itself—characterized by varying temperature, pressure, and salinity—can affect sensor operation and signal propagation. These surrounding conditions may change the speed of sound through water, influencing how accurate distance readings are based on acoustic signal propagation time. Innovative strategies are needed to address these issues to localization that can cope with the dynamic and harsh conditions of underwater environments, including robust signal processing techniques, adaptive algorithms capable of responding to changes in network topology and environmental conditions, and energy-efficient designs that extend the operational lifespan of the sensor nodes[28].

4 LITERATURE SURVEY ON LOCALIZATION ALGORITHM OF UWSNS

This section provides a brief explanation of the relevant survey on localization algorithms, which offers a wide range of strategies to address the difficulties of localization in dynamic and heterogeneous environments. These strategies take into account variables like mobility, time synchronization, localization accuracy, and the particulars of the underwater medium.

4.1 Localization Based on Mobility Constraints Beacon

[11] The two-dimensional localization method, MCB-2D, and the three-dimensional localization algorithm, MCB-3D, are two of the node location algorithms that the author suggested depending on mobile restricted beacons. The technique is not required to know the beacon node's precise location; instead, through the geometric relationship between the anchor's position and the moving radius of the beacon node, the unknown node can be located. According to the experiments result , the method improves localization accuracy and decreases the rate of network node placement errors.

4.2 Mobility Prediction and Particle Swarm Optimization Algorithms

To solve the problems of longer localization times, higher energy consumption, and lower beacon node distribution density in UWSNs, the author [32] proposed a PSO method based on range to find beacon nodes and predict unknown node locations depends on the mobility of an underwater object's spatial correlation. The algorithm takes node mobility patterns into account. Through simulation findings, it was able to achieve better coverage rate and higher localization accuracy in comparison to additional widely used localization methods applied in practice. Since the mobility prediction-based approach, large localization errors could result from these predictions being inaccurate. Predicting underwater sensor node movement accurately can be difficult because of a number of variables, including turbulence, currents, and the erratic behavior of marine life.

4.3 A Predictive Localization Algorithm Based on Improved Backtracking Search Optimization and GWO

[29] Predictive localization algorithm (MGP), based on enhanced backtracking search optimization and gray wolf optimizer, is made available for UWSNs by the author. When compared to other existing algorithms, MGP produces better localization results. It suggested the usage of the predictive localization algorithm (MGP) to improve time of node convergence and position accuracy for enhanced node positioning and UWSNs by introducing a two-part localization procedure using the gray wolf optimizer (GWO) and modified backtracking search optimization (MBSA). Simulations result demonstrates that the MGP technique performs better relative to other algorithms in terms of localization outcomes such as SLMP, MCL-MP, and MP-PSO. But the study doesn't go into great detail about the possible difficulties or disadvantages of putting the suggested predictive localization method into practice.

4.4 Static Localization Using Nelder–Mead Algorithm for Smart Cities

In this paper the author[14] employs virtual nodes and the Nelder-Mead algorithm for static underwater sensor network localization in order to overcome obstacles such as communication constraints and water conditions, improving coverage without synchronization overhead. One shortcoming of this work is that it skips over how the properties of the underwater acoustic channel impact the performance of the localization techniques

4.5 A Computationally Efficient Target Localization Algorithm

Block principal pivoting-based localization (BPPL), a computationally effective technique that demonstrated competitive accurate location and computational complexity under a variety of conditions, was proposed by the author[20].The author's computationally efficient approach, BPPL, studied the localization problem in the ANCLS framework after this algorithm's linearization procedure and outperformed state-of-the-art techniques in numerous scenarios both with regard to competitive computational complexity and localization accuracy. After dividing potential solutions into two groups, it employed variable exchange to select the optimal choice given the constraints. It provided the target location method known as block principal pivoting-based localization (BPPL). Simulations show that BPPL provides competitive computing complexity and localization accuracy in comparison to cutting-edge techniques in a range of scenarios.

4.6 Silent Positioning in Underwater Acoustic Sensor Networks (UASNs)

The time difference between arrivals measured locally at the sensor and the four anchor nodes the author suggested as part of the UPS (Underwater Positioning System). [4] . The purpose of trilateration is to infer the 3-D sensor position by summing these range discrepancies over several beacon intervals. UPS offers location privacy for sensors and underwater vehicles whose whereabouts must be ascertained, and it doesn't require time synchronization. It use a modified ultrawide and Saleh-Valenzuela model to simulate the underwater acoustic channels in order to examine the UPS's performance. Each path cluster's arrival, as well as the paths inside it, have double Poisson distributions, the multipath channel gain, on the other hand, has a Rician distribution. The outcomes show that UPS is a successful underwater vehicle/sensor self-positioning technique.

Table 2: Localization Algorithms for UWSNs.

Algorithms	Method (Range based or Range free)	Technique	Time Sync	Mobility	Inferences
Asynchronous localization with Mobile Prediction [36]	Both	Hybrid	No	Yes	Enhanced Localization Accuracy, Reduction in Localization error, Time Compensation for Node Mobility
Energy Harvesting Hybrid Acoustic-Optical Underwater Wireless Sensor Networks Localization [23]	Both	Hybrid	No	No	Estimate the final sensor node locations accurately Energy harvesting capability within the nodes of sensors assist in solving the energy consumption issue.
Deep Sea TDOA Localization Method Based on Improved OMP Algorithm[13]	Range Based	TDOA	Yes	No	localization effectiveness in comparison to alternative techniques in a multipath interference environment and have higher accuracy and stability in time delay estimation
Two-Phase Time Synchronization Free Localization [18]	Both	TDOA	No	No	Provide Localization Accuracy Robust under various underwater conditions Challenges in this algorithm are acoustic interference and signal attenuation
Received signal strength based localization in inhomogeneous underwater medium[22]	Range Based No	RSSI	No	No	RSS can be influenced by propagation effects like absorption, scattering, refraction can lead to fluctuations in RSS measurements but improved Navigation Accuracy and RSS-based localization is cost-effective than GPS
Doppler shift and modified genetic algorithm [6]	Both	TOA ,TDOA	No	Yes	Provide accurate node localization ,Limited Range, Handle large-scale USWNs, Require precise the sensor node calibration and acoustic equipment
MANCl:A Multi Anchor Nodes collabarative Localization Algortihm [34]	Both	Hybrid	Yes	May or May not	Better localization covergae Better Energy Cosumption Reduce localization Error
AdaDelta Gradient Descent Algorithm[35]	Range Based	TDOA	Yes	Yes	Reduce Ranging Interference faster convergence and better optimization performance. Its adaptive learning rate mechanism helps in efficient convergence during optimization and it rely on initial parameter values for convergence

SEAL: Self Adaptive AUV based Localization [21]	Both	RSSI	No	Yes	Accuracy of localization is found using AUV and Sensor nodes are dispersed throughout a wide area with significant gaps
Joint localization and tracking for autonomous underwater vehicle[30]	Both	RSSI and TOA	Yes (When TOA used)	Yes	Use of AUV leads to safer operations, reduced risk of collisions, and enhanced success rates of sensor deployments
Virtual Node Assisted Localization Algorithm [17]	Range Based	Hybrid	No	Yes	Efficient UWSNs localization Reduce Communication Error High localization coverage error

4.7 Cluster Based Localization Scheme with Backup Node

[24] In order to increase energy on initial parameter values for convergence efficiency and extend network lifetime in an underwater environment, the author suggests a cluster-based localization technique. In addition, a clustering protocol comprising cluster heads, anchor nodes, and the purpose of adding backup nodes is to optimize energy consumption and promote information transfer. The objective of this plan is to increase network longevity in submerged situations and enhance energy efficiency. Over time, it might have difficulties preserving the dynamic character of cluster heads and related nodes, which could have an effect about the network's stability table.

4.8 Iterative Localization Technique for UWSNs

In order for Geo-routing to be executed successfully and produce meaningful location-aware data, medium access and routing protocols must be optimized. Localization plays a critical part in this process. This study [31] examines comparison between localization with and without reference nodes in UWSNs via the author's investigation. In order for Geo-routing to be executed successfully and produce meaningful location-aware data, medium access and routing protocols must be optimized.

Localization plays a critical part in this process. While multipath interference and water currents pose obstacles, the localization of non localized sensor nodes is essential for many underwater communication applications.

4.9 An Intelligent Agent-Based Localization System in UWSNs

The author [5] proposed an intelligent scan model technique for the localization system under UWSN. The information used in this procedure comes from unmanned floating vehicles (MULEs) that have enough storage capacity and rechargeable energy to determine the precise position of the sensor nodes for the purpose of properly identifying sense data through Data MULE (mobile ubiquitous LAN extensions).The suggested approach makes use of unmanned floating vehicles that are outfitted with energy, storage, and data transmission capabilities Information is gathered via underwater sensor nodes and locate them using sophisticated localization algorithms. This method increases the efficiency and accuracy of localization of UWSNs, allowing for more accurate sensed data identification and application.

The severe channel characteristics of UWSNs make precise localization difficult to achieve. Even though sound waves can be used for long-distance communication, accurate position estimations need the inclusion of systems that can detect changes in direction and velocity. Furthermore, large data rates across shorter distances are possible using optical waves. By lowering contention and increasing data rates, a hybrid approach using, for example, optical waves for intra-cluster communication and acoustic waves for inter-cluster communication can improve performance. Time synchronization is still difficult to achieve, though, as current methods need constant communication between nodes and may use a lot of energy. To create effective and energy-saving synchronization techniques for UWSNs, more study is required.

5 CONCLUSION AND FUTURE WORK

This review highlights the critical importance of localization algorithms in optimizing the functionality of UWSNs across diverse applications, from oceanic research to environmental monitoring. It outlines the numerous challenges inherent in UWSN localization, stemming from underwater environmental factors and technical constraints of acoustic communication. Despite these hurdles, advancements in localization techniques, including range based and innovative range-free methods, signify significant progress in addressing these obstacles. The integration of machine learning and environmental data promises enhanced precision, robustness, and energy efficiency in localization solutions. The review not only underscores current challenges but also paves the way for future research directions, advocating for adaptive, scalable, and sustainable solutions tailored to the complexities of underwater environments. It calls for extensive real-world experimental validations and advocates for the exploration of hybrid approaches to further enhance accuracy, robustness, and scalability. Ultimately, interdisciplinary collaboration and technological advancements are driving forward the possibilities in underwater sensing, facilitating exploration, monitoring, and sustainable management of aquatic ecosystems. Localization in UWSNs faces challenges due to harsh channel conditions we can use hybrid approach combining acoustic and optical waves can enhance performance. However, achieving efficient time synchronization remains a challenge it is necessitating to further research for energy-conserving methods.

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