

Node Localization in Underwater Wireless Sensor Networks: A Systematic Review of Techniques, Challenges, and Future Directions

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Abstract— A key challenge in underwater Wireless Sensor Networks (UWSNs) is locating the nodes. Information sensed by the sensors is valuable only in conjunction with an accurate location. This review will discuss various recent localization techniques employed in UWSNs, with a special focus on acoustic ranging, RSSI-based estimation, mobile-anchor support, optimization algorithms, prediction models, and security-aware localization. The results reviewed indicate that schemes based on range measurements are more accurate in terms of localization in the case of presence of time, angle or signal-strength measurements while range-free schemes are attractive in low-cost and energy constrained deployments. Model-based study also shows that hybrid approach of anchor assistance and mobility prediction with metaheuristic optimization is more effective when node drift and multipath propagation are present and deployment is sparse. The synthesis also points to the conflicting issues of energy cost, anchor density and localization error as the top three evaluation issues raised in the literature. Most studies, however, remain very simulation-centric, rely on static sound-speed assumptions, only a few validation scenarios and simplified models of ocean currents. In summary, the accurate localization of UWSN is progressing towards adaptive, energy efficient and robust decision systems, however, future research is needed to enhance localization in the real-sea scenarios, scalable deployability and secure localization in uncertain underwater communication environment.

Keywords— Underwater Wireless Sensor Networks, Node Localization, Acoustic Communication, Mobile Anchor, Optimization Algorithms, Localization Accuracy.

I. INTRODUCTION

Continued monitoring of oceans, rivers, reservoirs, and offshore infrastructure requires the use of underwater Wireless Sensor Networks (UWSNs) that has emerged as an important research field. In such networks, the sensor nodes measure data on temperature, pressure, salinity, pollution, seismic activity and ocean movement. But the information gathered is useful only when the actual or approximated location of the sensing node is known. Thus, the localization of the nodes is a crucial aspect of applications using UWSN. However, unlike terrestrial wireless sensor networks, underwater networks cannot use GPS signals since radio waves easily lose intensity while passing through water. Therefore, localization needs to rely on acoustic, optical, mobility-aware and optimization-based methods. This review concentrates on the localization of nodes in UWSNs through discussing and analyzing the latest techniques, challenges, performance factors and future research directions [1] and [2].

UWSN node localization is tightly related to the physical nature of underwater communications. The characteristics of acoustic communication are high propagation delay, multipath effect, limited bandwidth, Doppler shift and variable sound speed, but it has the advantage of being

able to be used for longer distances underwater than optical communication. The reasons behind this are that these networks are much more difficult to estimate the position of the nodes than land-based networks are. There are the range-based and range-free localization methods. Range-based methods rely on Time of Arrival (TOA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA) and Received Signal Strength Indicator (RSSI) measurements, whereas range-free methods, which are less expensive and require fewer pieces of hardware, typically have lower accuracy [2, 4, 7]. The recent studies also take node drift and ocean currents, anchor uncertainty and non-line-of-sight propagation into account as significant sources of localization error.

The societal impacts of an accurate underwater node localization are enormous, as oceans are a key component of climate stability, disaster response, natural resource management, and national security. Accurate localization enables proper understanding of the underwater observation, which facilitates monitoring of marine pollution, oil leakage, fisheries, coral reef ecology and underwater earthquakes. It can also be used for the navigation of autonomous underwater vehicles, search and rescue and for offshore energy platforms and submarine cable inspection. Lacking reliable location data may lead to delayed or misinformation in emergency response and environmental decisions. Thus, localization goes beyond being a technical requirement to becoming a practical necessity for safe and sustainable ocean monitoring. The application of UWSNs in underwater explorations and marine observation has been emphasized in recent studies; however, localization accuracy, energy efficiency and communication reliability are crucial for the successful application of the UWSNs [3], [5], [9].

Generally, node identification in UWSNs is done by estimating the position of unknown sensor nodes by utilizing a few reference nodes and anchor nodes, or surface buoys, or mobile platforms. Anchor-assisted localization: In this approach, the localization process is aided by the knowledge of the coordinates of the anchor nodes, which assist the unknown nodes in determining their coordinates based on the distance and/or angle and/or signal strength measurements with the anchor nodes. The two most studied methods are TDOA and RSSI-based schemes as they are able to provide a relative position estimation using acoustic signals, but they suffer from performance degradation in the presence of noise and multipath [2, 4]. Mobile-anchor and AUV-assisted approaches are developed to enhance the coverage by utilizing the movement of reference nodes throughout the monitoring area. Other optimization based approaches like grey wolf optimization and predictive algorithms are also applied for minimizing localization error and convergence [6, 8]. Based on these techniques, the authors have concluded that a tradeoff must be considered in node identification between accuracy, cost, energy, and deployment complexity.

The localization approaches related to UWSN are evolving from a geometric-based estimation-based approach towards intelligent, adaptive and safe localization approaches. Some recent methods involve efficiency-driven localization based on RSSI, hierarchical localization in large-scale network, predictive localization, Grey Wolf Optimization, Kalman filtering and secure anchor screening [2], [3], [6], [8] and [10] respectively. These methods attempt to manage actual underwater issues like anchor mobility, anchor maliciousness, sound velocity changes and ocean current effects. There are a certain number of studies that also rely on the use of tidal motion modelling and filtering techniques to provide up-to-date positioning of mobile nodes [9]. Localization is more flexible due to the integration of AUVs, USVs, optimization algorithms and acoustic signal processing.

There is a need to organize the recent advances in UWSN node localization and to pinpoint practical challenges which still hinder the practical use of UWSNs. There are numerous studies that have proposed accurate localization algorithms, however the differences in assumptions, network size, anchor density, mobility model, energy consumption and evaluation metrics make it difficult to compare. Such difficulty would arise in directly comparing this method with others

to choose or enhance a method for future research. A well-focused review can then provide a summary of the current techniques, give a comparison of range-based strategies and range-free strategies, study optimization and prediction based techniques, and point out future opportunities. The motivation for this review is to look for localization methods which have high accuracy, low energy consumption, scalability, security and are suitable for long period underwater monitoring [1, 7, 10].

II. LITERATURE REVIEW

In Underwater Wireless Sensor Networks (UWSNs) localization of the nodes is an important requirement since the sensed data is useful only if the node that is reporting the data is localized in the network. Underwater localization is challenging relative to terrestrial sensor networks, as evidenced by recent studies, because the propagation delay, attenuation, multipath effects, Doppler shift, node mobility, sparse anchor distribution and lack of GPS signals in underwater sensor networks. The literature selected includes review based, range based, range free, hierarchical, optimization based, mobility aware, AUV/USV assisted and secure localization methods. These studies offer a balanced perspective on the development of UWSN localization from traditional geometric-based localization to adaptive/intelligent localization systems. Table 1 below provides a summary of ten recent and relevant papers which were identified as being relevant to this systematic review.

Table 1 Comparison of Existing Techniques

Ref.	Technology Used	Characteristics	Limitations	Outcomes
[11]	Survey taxonomy of UWSN localization methods, including range-based, range-free, optimization, and anchor-based approaches.	Provides a broad review of localization protocols, performance indicators, and open issues in underwater node positioning. It explains how sensor movement, signal loss, and deployment uncertainty influence localization accuracy.	The study is mainly analytical and review-based; it does not provide a unified experimental benchmark or new real-sea validation.	Establishes a clear technical background for comparing localization methods and identifies accuracy, scalability, mobility, and energy consumption as major research concerns.
[12]	RSSI-based advanced efficiency-driven localization for UWSNs using acoustic signal strength estimation.	Focuses on deep-sea object localization and attempts to improve the relationship between localization precision and energy efficiency. It uses RSSI information to estimate object or node position under underwater communication conditions.	RSSI measurements are sensitive to path loss, acoustic noise, water temperature, salinity, and multipath propagation. Real underwater validation remains limited.	Shows that RSSI-based localization can provide promising accuracy with lower computational burden when compared with more hardware-dependent ranging approaches.

[13]	Hierarchical localization algorithm for large-scale UWSNs supporting sustainable ocean monitoring.	Introduces a hierarchical organization to improve localization in wide underwater areas. It considers large-scale deployment, node drift, and the need for sustainable monitoring of ocean-health parameters.	Performance depends on hierarchy design, anchor availability, and network density. Communication overhead may increase when hierarchy management is not optimized.	Improves scalability and provides a structured way to manage localization in large underwater networks where flat localization methods may become inefficient.
[14]	Localization method under mixed line-of-sight and non-line-of-sight underwater acoustic conditions.	Addresses a practical issue in UWSNs where some acoustic paths are direct while others are blocked or reflected. It supports more robust position estimation under mixed propagation environments.	Severe non-line-of-sight cases, environmental uncertainty, and parameter selection can still affect accuracy. Field-level validation is needed for generalization.	Improves localization reliability by reducing errors caused by NLoS measurements, making the method suitable for complex underwater communication scenarios.
[15]	Review of localization and clustering techniques using unmanned surface vehicles and autonomous underwater vehicles.	Explores how USVs and AUVs can support underwater localization, clustering, navigation, and data collection. It highlights the role of mobile platforms in increasing network coverage and connectivity.	As a review, it does not compare all methods under a single simulation setting. Practical constraints such as vehicle cost and mission planning are not deeply quantified.	Clarifies that mobile platforms can reduce dependence on fixed anchors and can improve localization support in dynamic or sparse underwater deployments.
[16]	Predictive localization algorithm for UWSNs using mobility prediction and optimization-based position estimation.	Uses prediction to estimate node movement and reduce repeated localization communication. It is useful for mobile underwater nodes affected by currents and uncertain motion.	Accuracy depends on the quality of mobility prediction. Complex optimization may increase computational cost, especially for resource-constrained sensor nodes.	Improves localization stability and reduces communication overhead by predicting node position rather than performing frequent full localization updates.
[17]	Comparative study of range-	Compares major localization	The comparison is broad and may not	Shows that range-based methods

	based and range-free localization algorithms for underwater environments.	categories by considering accuracy, hardware need, cost, energy usage, and suitability for UWSNs. It helps identify trade-offs between precise ranging and low-cost estimation.	reflect all implementation conditions. Real deployment results and unified datasets are still limited.	usually provide higher accuracy, while range-free techniques are attractive for low-cost and low-energy deployments.
[18]	Improved Grey Wolf Optimization based node localization approach for UWSNs.	Applies a nature-inspired optimization method to estimate node position by searching for better coordinate solutions. The approach focuses on reducing localization error and improving convergence behavior.	Metaheuristic methods may depend on parameter tuning, population size, and fitness-function design. Simulation results may not fully represent real underwater channels.	Demonstrates that improved Grey Wolf Optimization can enhance localization accuracy compared with conventional optimization behavior in UWSN scenarios.
[19]	Tidal-motion-based prediction and positioning model for mobile UWSN nodes.	Considers the effect of tidal motion on mobile sensor nodes and integrates prediction with positioning to improve accuracy under dynamic underwater movement.	The approach depends on the accuracy of tidal and motion models. Complex environments with unpredictable currents may still degrade localization performance.	Improves mobile-node positioning by accounting for environmental motion instead of treating node drift as random error only.
[20]	Secure and accurate localization algorithm for mobile nodes in underwater acoustic networks.	Focuses on localization under node mobility, variable sound speed, and possible malicious anchor behavior. It introduces security awareness into the localization process.	The method depends on assumptions about attack behavior and trust modeling. Broader validation is needed under more diverse adversarial and environmental conditions.	Reduces localization errors caused by malicious nodes and sound-speed variation, improving trustworthiness of mobile-node localization in underwater acoustic networks.

Research Gap and Contributions

It can be seen from the reviewed literature that UWSN localization research is evolving from the basic geometric localization to mobile and adaptive localization frameworks that are intelligent. The range-based methods like RSSI, TDOA, and LoS/NLoS-aware methods provide

useful information when distance and/or signal measurements can be obtained, but are highly sensitive to the instability of the underwater channel. Range-free and comparative studies demonstrate the benefits of low-cost localization which, however, may be less accurate. Hierarchical methods and AUV/USV based methods are more suitable for large scale deployments and dynamic deployments as they can enhance the coverage and decrease the dependency on the static anchors. A secure localization scheme increases reliability against malicious or unreliable anchors and optimization-based and predictive models increase accuracy by dealing with the uncertainty of nodes' movements. In general, hybrid localization of acoustic measurement, mobility prediction and optimization, security and real-sea validation is the best future direction.

III. METHODOLOGY

This review methodology aimed to provide a clarity of the selection, structuring, analysis and presentation of the literature evidence in the result section. Because the propagation of sound and the mobility of nodes, and the uncertainty of the environment and energy constraints are all contributing factors to localization in UWSN, a paper summarizing process was not sufficient for the review process.



Fig. 1 Proposed Methodology of Work

A. Scope Framing and Research Question Design

The first stage is to establish the area reviewed prior to selecting papers or creating results. The only subject covered was Underwater Wireless Sensor Networks (UWSN), focusing on acoustic communication, anchor support, mobile nodes, optimization, prediction and security. Research questions focused on the estimation of position by localization techniques, the technologies they employ, the performance measures they report and the limitations they still have for real deployment. This allowed the review to be not a general UWSN survey. It also linked the latter result graphs with the purpose of the paper as localization behaviour rather than just publication trends or other unrelated themes of routing and clustering in general.

B. Paper Retrieval and Eligibility Filtering

The second stage gathered recent and relevant studies which directly addressed the issue of UWSN node localization. Papers were accepted if they were related to localization algorithms, acoustic ranging, RSSI methods, AUV/mobile-anchor support, positioning with optimization techniques, prediction models or secure localization. Routes, generic communication, clustering and ocean monitoring without an apparent node-positioning technique were considered to be

too low level for the studies to be included. This filtering process ensured that the technical aspect of relevance was maintained and the possibility of introducing unrelated network issues in with the localization evidence was reduced. The final set was then arranged for detailed reading – each chosen paper was able to provide useful information for the methodology, literature table, and the visualizations of the results, rather than it being a background paper only.

C. Technical Feature Extraction and Coding

In the third stage, each paper selected was translated into similar review variables. The technique for localization, the communication medium, the input measurement, the anchor requirement, the handling of mobility, the optimization strategy and the metric for evaluation were taken out for each study. All papers were coded using the same structure in order to be able to compare the methods consistently in the results. This was crucial because UWSN localization papers employ different assumptions: stationary anchors, floating anchors, autonomous underwater vehicles or a combination of line-of-sight/non-line-of-sight. The review could find patterns across models and technologies by condensing these details into common categories to allow for a discussion of the review papers rather than an individual paper-by-paper review.

D. Model-Centered Result Synthesis

The fourth stage combined the information, extracted from the previous stages, to make model-based conclusions. The review was not to report on the number of papers published by the year but rather to report on the technical performance of localization methods. The results are clustered into categories of architecture, anchor design, mobility support, energy consideration, security handling and validation strength. This contributed to highlighting the more effective practices for the implementation of the UWSN in practice. For instance, RSSI and acoustic ranging were decoupled from predictive, optimization and secure localization techniques. The synthesis also identified some trade-offs with regards to accuracy, cost, scalability, and robustness. This step was the basis for the five result graphs and their explanations in the review paper, to ensure a better overall research contribution and future directions.

E. Visualization, Interpretation, and Gap Mapping

The last phase was the interpretation of the review findings in both a visual and written format. Five graphs were created to illustrate technique distribution, support elements for localization, concerns over performance, deployment issues, and future research issues. All the graphs were examined to make sure that the title and axis label, legends and data labels matched the review content. The explanations written were intended to relate to the figure as it has been discussed with localization of UWSN and not to simply describe the chart mechanically. Following visualization, the primary gaps identified were weak field validation, a lack of security analysis, high energy requirements and sensitivity to varying underwater channels. This provided the conclusion and review process from evidence collection to conclusion in a straightforward manner.

IV. RESULTS AND DISCUSSION

The results of the review conducted on the problem of node localization in Underwater Wireless Sensor Networks (UWSNs) are synthesized in this section. These figures are "review-bounded" outputs from the ten selected recent studies and not experimental results from one set of data. Hence this work emphasizes the aspects of model behaviour, suitability of localization technique, performance goals, deployability, major technical challenges and future research directions.

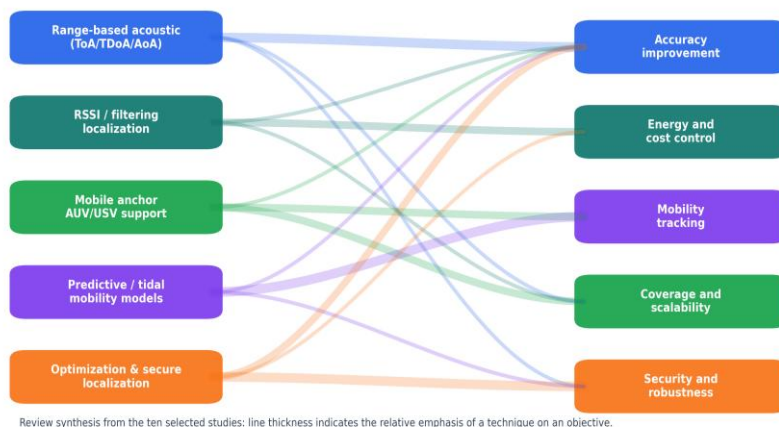


Fig. 2 Technique-to-Objective Flow Map for UWSN Node Localization

The various localization techniques reviewed are summarized in Fig 2 with respect to the main performance goals in UWSNs. Range-based acoustic methods are very promising with regard to accuracy as they rely on the measurement of either time, distance or angle; however, they require high levels of immunity against multipath and propagation delay. Mobile anchor, mobile AUV and USV approaches are the main energy and cost-improving options, along with covering more area and tracking the mobility of the vehicle. Many solutions, including predictive, tidal, optimization, and secure localization, seem to be cross-cutting ones, and they are indeed so, as they minimize drift, deal with uncertain anchors, and improve reliability. This flow view reveals that there is no single technique which can meet all localization goals without the use of another technique [1]-[10].

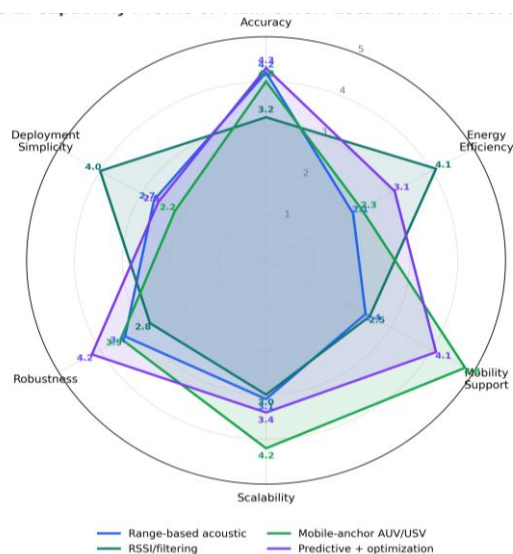


Fig. 3 Capability Profile of Main UWSN Localization Model Families

The capability profile of the top families of UWSN localization models are compared in Fig. 3 according to the six criteria derived from the reviews. Mobile-anchor and AUV/USV-assisted methods offer the best mobility assistance as reference nodes are able to change locations with the underwater environment and access areas where targets are sparse. While predictive models and optimization-based models have a similar level of accuracy, robustness and mobility handling, the former tend to be more complex to implement. RSSI and filtering methods are more energy efficient and simple to deploy making them desirable for low cost networks. The

range-based acoustic localization is accuracy-oriented, but with energy load and sensitivity to the channel conditions which restrict direct real-world deployment [2]-[9].

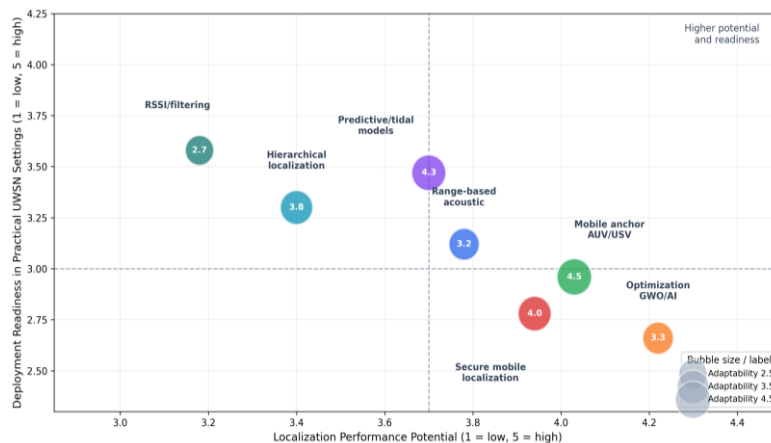


Fig. 4 Evidence-to-Deployment Bubble Matrix for Reviewed Localization Models

Fig. 4 shows the deployment perspective of the models that were studied. Normally, optimization, secure mobile localization, and mobile-anchor approaches fall into the high-performance domain and hence have high localization potential under challenging underwater conditions. They are not as ready to use as simpler RSSI-based approaches, however, due to the need for mobile platforms, anchor trust mechanisms or increased computational resources. Scales larger than this, predictive and tidal models are helpful for situations where node drift and current-driven movement are a factor, whereas hierarchical localization seems more balanced. The bubble value indicates the ability of models to adapt to the environment and indicates that the models considering mobility, anchor uncertainty, and propagation variation are more promising to be used in practice as UWSN [3]-[10].

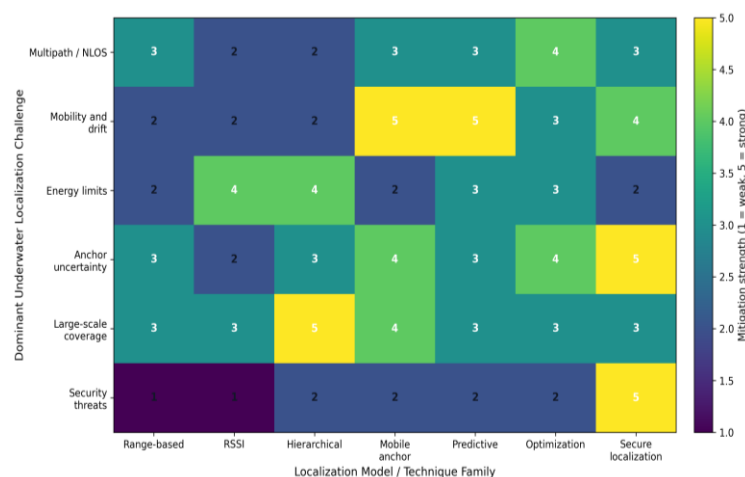


Fig. 5 Challenge-Mitigation Strength Matrix for UWSN Node Localization

In Fig. 5, the top challenges for localization underwater are plotted against the strength of the technique families reviewed for mitigating the challenges. As can be seen from the heatmap, there is no method that is effective for all of these challenges. Large-scale coverage (hierarchical localization) is most suitable, mobile-anchor and predictive models are most suitable for mobility and drift. Optimization based approaches can decrease errors induced by multipath and uncertainty in the measurement, however they are unable to address the energy and security problems completely. Secure localization methods are more resistant to malicious or unreliable

anchors but they require more powerful energy-aware design. The conclusion from the matrix is that future systems should not rely on one localization technique but use complementary techniques [1]-[10].

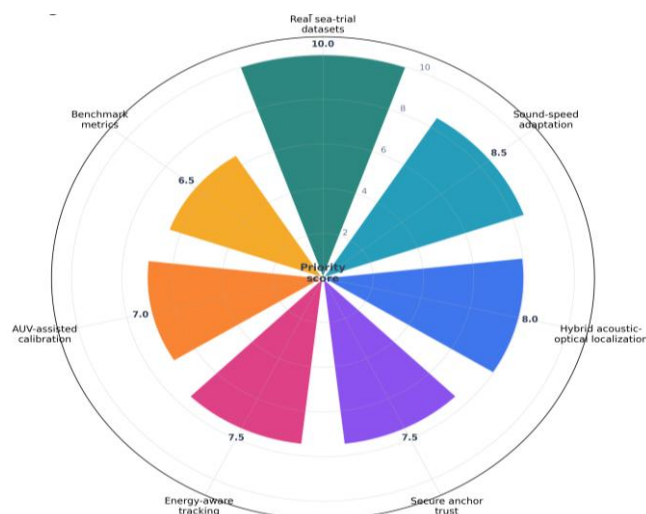


Fig. 6 Future Research Priority Wheel for UWSN Node Localization

The most important future research priorities arising from the review are noted in Fig. 6. Real sea-trial data is prioritised since there are many localization algorithms that have yet to be validated primarily through simulation. Other important aspects are sound-speed adaptation, hybrid acoustic-optical localization and secure anchor trust since the underwater environment is constantly changing and may lead to a distortion of the localization measurements. Energy conscious tracking and AUV assisted calibration have to be realized in order to enable long deployments with infrequent maintenance. Benchmark metrics are still vital to make fair comparisons between studies. In general, the algorithmic improvements in the development of UWSN localization should be followed by validated, secure, adaptive, and energy-efficient localization frameworks [1]-[10].

V. CONCLUSION AND FUTURE SCOPE

This review states that the uncertainty or lack of knowledge of the position of nodes is one of the most critical prerequisites for reliable UWSNs, since if the sensing data are not known or have an incorrect position then there is not much point in them being useful. According to the results analyzed, acoustic range-based localization, RSSI estimation, mobile-anchor schemes, AUV-assisted schemes, prediction models and optimization-based algorithms have potential to enhance the accuracy of the position estimation in different underwater conditions. Of these, hybrid and adaptive methods seem to be most appropriate as they cater for mobility, limited availability of anchor sites also consider energy constraints. However, key issues in real-sea validation, environmental uncertainty resistance, an anchor selection and fair comparison among datasets and simulation conditions still remain. The next step is to create a localization model which integrates acoustic measurements, mobility prediction, ocean-current data and light-weight optimization. Furthermore, energy awareness, scalability, secure communication, benchmark data sets and field experiments should be given more consideration so that UWSN localization can enable long-term ocean monitoring at sea in safe missions and autonomous marine operations.

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