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A Survey on Underwater Sensor Networks Localization Techniques

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Abstract:–This Proposed Mechanism is characterized by long propagation times and frequency-dependent attenuation that is highly affected by the distance between nodes as well as by the link orientation. Some of other issues in which UWSNs differ from terrestrial are limited bandwidth, constrained battery power, more failure of sensors because of fouling and corrosion, etc. Localization for UASNs is an active research topic where a large number of techniques have been proposed recently. This article provides an up-to-date survey of these techniques while pointing out the open issues.

I. INTRODUCTION

Ocean bottom sensor nodes are deemed to enable applications for oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. Multiple Unmanned or Autonomous Underwater Vehicles (UUVs, AUVs), equipped with underwater sensors, will also find application in exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. To make these applications viable, there is a need to enable underwater communications among underwater devices. Underwater sensor nodes and vehicles must possess self-configuration capabilities, i.e., they must be able to coordinate their operation by exchanging configuration, location and movement information, and to relay monitored data to an onshore station. Wireless underwater acoustic networking is the enabling technology for these applications. Under Water Acoustic Sensor Networks (UW-ASN) consist of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area. To achieve this objective, sensors and vehicles self-organize in an autonomous network which can adapt to the characteristics of the ocean environment.

Underwater networking is a rather unexplored area although underwater communications have been experimented since World War II, when, in 1945, an underwater telephone was developed in the United States to communicate with submarines. Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate at long distances through conductive sea water only at extra low frequencies (30-300 Hz), which require large antennae and high transmission power. Optical waves do not suffer from such high attenuation but are affected by scattering. Moreover, transmission of optical signals requires high precision in pointing the narrow laser beams. Thus, links in underwater networks are based on acoustic wireless communications.

The traditional approach for ocean-bottom or ocean column monitoring is to deploy underwater sensors that record data during the monitoring mission, and then recover the instruments. This approach has the following disadvantages.

- **Real time monitoring is not possible**. This is critical especially in surveillance or in environmental monitoring applications such as seismic monitoring. The recorded data cannot be accessed until the instruments are recovered, which may happen several months after the beginning of the monitoring mission.
- **No interaction is possible between onshore control systems and the monitoring instruments.** This impedes any adaptive tuning of the instruments, nor is it possible to reconfigure the system after particular events occur.
- **If *failures* or *misconfigurations* occur**, **it may not be possible to detect them** before the instruments are recovered. This can easily lead to the complete failure of a monitoring mission.
- **The amount of data that can be recorded during the monitoring mission by every sensor is limited** by the capacity of the onboard storage devices (memories, hard disks, etc.).

Therefore, there is a need to deploy underwater networks that will enable real time monitoring of selected ocean areas, remote configuration and interaction with onshore human operators. This can be obtained by connecting underwater instruments by means of wireless links based on acoustic communication. Many researchers are currently engaged in developing networking solutions for terrestrial wireless ad hoc and sensor networks. Although there exist many recently developed network protocols for wireless sensor networks, the unique characteristics of the underwater acoustic communication channel, such as limited bandwidth capacity and variable delays, require for very efficient and reliable new data communication protocols. Major challenges in the design of underwater acoustic networks are:

- Battery power is limited and usually batteries cannot be recharged, also because solar energy cannot be exploited.
- The available bandwidth is severely limited.
- Channel characteristics, including long and variable propagation delays, multi-path and fading problems.
- High bit error rates.
- Underwater sensors are prone to failures because of fouling, corrosion, etc.

Many challenges arise with such an architecture, that need to be solved in order to enable 3D monitoring, including:

- Sensing coverage. Sensors should collaboratively regulate their depth in order to achieve 3D coverage of the ocean column, according to their sensing ranges. Hence, it must be possible to obtain sampling of the desired phenomenon at all depths.
- Communication coverage. Since in 3D underwater networks there may be no notion of uw-sink, sensors should be able to relay information to the surface station via multi-hop paths. Thus, network devices should coordinate their depths in such a way that the network topology is always connected, i.e., at least one path from every sensor to the surface station always exists.

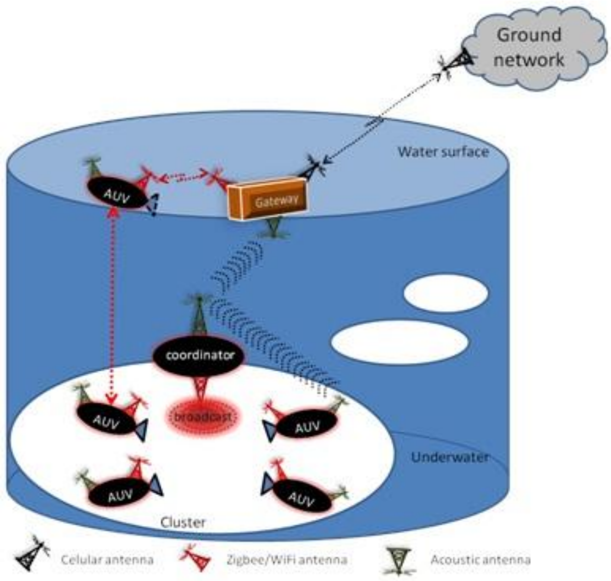

Fig1

A. Differences with terrestrial sensor networks

The main differences between terrestrial and underwater sensor networks are as follows:

• Cost. While terrestrial sensor nodes are expected to become increasingly inexpensive, underwater sensors are expensive devices. This is especially due to the more complex underwater transceivers and to the hardware protection needed in the extreme underwater environment.

• Deployment. While terrestrial sensor networks are densely deployed, in underwater, the deployment is deemed to be more sparse, due to the cost involved and to the challenges associated to the deployment itself.

• Power. The power needed for acoustic underwater communications is higher than in terrestrial radio communications due to higher distances and to more complex signal processing at the receivers to compensate for the impairments of the channel.

• Memory. While terrestrial sensor nodes have very limited storage capacity, uw-sensors may need to be able to do some data caching as the underwater channel may be intermittent.

• Spatial correlation. While the readings from terrestrial sensors are often correlated, this is more unlikely to happen in underwater networks due to the higher distance among sensors.

Localization of underwater equipment has also been an essential part of the traditional oceanographic systems where it has been established by one of two techniques: short base line (SBL) or long base line (LBL). In the SBL technique, a ship follows the underwater equipment and uses a short-range emitter to enable localization. In the LBL technique acoustic transponders are deployed on either the seafloor or the moorings around the area of operation. Equipment units in the transmission ranges of several sound sources are able to estimate their location. A recent work combines SBL and LBL by using short-range Global Positioning System (GPS)-enabled stationary buoys for autonomous underwater vehicle (AUV) tracking applications.[1] Although SBL and LBL can be utilized for localization of disconnected individual underwater equipment, they are not convenient for UASNs. SBL requires the operation of a ship which is costly and unscalable for UASNs, whereas the long-range signals of LBL have the possibility of interfering with the communication among UASN nodes.[2]

B. Positioning and Communication in Underwater Systems

In the underwater environment there is additionally the possibility to use acoustic beacon systems for positioning purposes. The beacons are also used as base stations which further can be used to forward the collected information to a central station. The positioning is computed generally by measuring the time-of-flight of the acoustic signals and by multilateration. The advantage of this approach is that requires few communication resources. However the main problem of this approach is that first tries to optimize the positioning functionality and second the communication process. A disadvantage is that both the scalability and the accuracy which can be achieved in long distances are relatively low. We argue that the integration of the positioning functionality and the communication process in a common scheme is an important issue to be integrated within the framework of providing positioning facilities to underwater acoustic sensor networks. This consideration should lead to a more efficient and scalable developed system.

II. LOCALIZATION TECHNIQUES FOR UASNS

In the literature, UASN studies generally assume one of the following architectures: a stationary UASN, where the nodes are fixed at a certain location, or a mobile UASN, where the nodes are able to move. In a mobile UASN, the motion of the nodes may be controlled or the nodes may be drifting. Controlled motion may be available by propelled underwater vehicles such as AUVs, or there may be buoyancy-driven equipment that can move vertically (e.g., profiling float) or those that can also move horizontally with the help of their wings (e.g., glider). In hybrid architectures several nodes may have the capability of motion while other nodes may be stationary. In this article, although some of the surveyed localization protocols can be grouped based on the architectures for which they are proposed, there are architecture-independent protocols as well. Therefore, we group the localization protocols for UASNs in two categories, distributed and centralized, based on where the location of a sensor node is determined. In distributed localization techniques, each underwater sensor node collects localization related information, such as anchor positions or distance to anchors or distance to neighbours, and then runs a location estimation algorithm individually. In centralized protocols, the location of each sensor node is estimated by a node at the command center or a sink node in the network.

Centralized protocols may localize nodes at the end of a mission (i.e., in a post-processing stage) or periodically collect information to track sensor nodes. These two categories can also be divided into subcategories of estimation-based and prediction-based schemes. Estimation-based methods use the most recent information to compute the current location of a node, while prediction-based schemes aim to predict the location of a node at the next time instant, using previous and current location information.

III. DISTRIBUTED LOCALIZATION TECHNIQUES

In this section we survey the distributed localization techniques under two subcategories: estimation- based and prediction-based schemes.

A. Estimation-Based Schemes

The Dive and Rise Localization (DNRL) protocol [3] is a distributed estimation-based protocol that can be used for mobile UASNs. DNRL utilizes mobile anchors that are able to descend and ascend in the water column, similar to profiling floats. Mobile anchors carry GPS receivers and attain their coordinates from GPS while they are floating on the surface. Then they descend to announce these coordinates. Mobile anchors periodically broadcast self-coordinate while descending and ascending. After one cycle underwater, when the mobile anchor reaches the surface, it recalculates coordinates via GPS and descends again. In [3] the mobile anchor nodes are called Dive'N'Rise (DNR) beacons. Underwater sensor nodes passively listen to the time-stamped DNR messages and use a time of arrival (ToA) technique to calculate their distances to the DNR beacons. DNRL uses one-way ranging where the time difference between the message origination and arrival is multiplied by the speed of the signal assuming that the nodes are synchronized. In DNRL an underwater node estimates its location by lateration, using the coordinates of three non-coplanar anchors and its distance estimates to the anchors. Lateration is a widely used localization technique that is also employed by GPS. Note that underwater nodes are usually able to attain their depth by their pressure sensors; hence, they only need to estimate their (x, y) coordinates. One of the major advantages of DNRL is being silent, which means the underwater nodes do not send messages. This results in low communication overhead and energy efficiency. Furthermore, DNRL has high coverage and provides accurate estimates because the mobile anchors descend to the vicinity of the underwater nodes, and they update their locations periodically. On the other hand, DNRL requires a large number of DNR beacons for high localization success and high accuracy, where the DNR beacons are expected to be more expensive than the other underwater nodes due to their motion capability. Moreover, DNRL requires synchronization since it uses one-way ranging in ToA calculations. Although synchronization may be established by relatively inexpensive high-precision clock modules, for long-term underwater missions, a synchronization protocol may be necessary.

In [4] DNRL is extended to the Multi-Stage Localization (MSL) scheme by including an iterative phase. Since DNR beacons are not propelled, they are not able to move fast. This means nodes that float deeper receive DNR messages later than nodes closer to the surface, and localization information diffuses non-homogeneously. To overcome this problem, in [4] the authors propose using successfully localized nodes as beacons. These new beacons are not able to descend or ascend, but are allowed to send self-coordinates. This iterative localization approach increases the coverage and decreases the delay of DNRL. However, in MSL localized underwater nodes provide their estimated locations, which already include estimation errors. Error accumulates at the nodes that use the coordinates of localized underwater nodes instead of the coordinates of the anchor nodes. Moreover, since localized underwater nodes also send localization messages, overall energy consumption and overhead of MSL is higher than DNRL. MSL uses the ToA method with oneway ranging; therefore, it requires synchronization similar to DNRL.

In [5] the authors propose a localization scheme that uses an AUV. In the AUV-Aided Localization (AAL) scheme, underwater sensor nodes are stationary, and an AUV travels underwater to localize the sensor nodes. The AUV periodically surfaces to receive GPS coordinates, and does dead-reckoning for tracking self-location while submerged. The AUV broadcasts wake-up messages from different places on its route, and the underwater sensor nodes start the localization process upon hearing these messages.

AAL uses the ToA method with two-way ranging where an underwater node sends a request packet to the AUV and the AUV replies back with a message containing its coordinates. This request/respond type communication enables sensor nodes to measure the round-trip time by which the nodes estimate their distance to the AUV. The distance estimates and AUV coordinates are used in lateration. In AAL underwater nodes are no longer silent; they send messages in the two-way ranging process. This alleviates the need for synchronization, but on the other hand, the nodes spend more energy, and the communication overhead of the protocol increases. Another drawback of AAL is its high localization delay due to the slow speed of the AUV (approximately 2–3 knots). Moreover, the accuracy of AAL is affected by the frequency of the location updates of the AUV, which are attained as the vehicle surfaces for location calibration.

Localization with Directional Beacons (LDB) [6] utilizes an AUV to localize a stationary UASN, similar to AAL. The AUV receives its coordinates from GPS while floating on the surface, and then dives to a certain depth above the UASN, and travels over the area of operation as shown in Fig1. In LDB the AUV uses a directional acoustic transceiver to broadcast self coordinates and the angle of its transceiver's beam. A sensor node uses the angle information to map the AUV coordinates to the horizontal plane on which it resides. It calculates it's *x*-coordinate as the average of the coordinates of the AUV at two points, which are shown in Fig1. *Xt1 AUV* is the projections of the x coordinate of the AUV at time *t*1, when the AUV enters into the circle defined by the communication range of the sensor node. The second point, *xt*2 *AUV*, is at time *t*2, when the AUV exits this range. The *y* coordinate is driven from the Euclidian relation. Since LDB is a range-free technique, unlike DNRL, MSL, and AAL, it does not require synchronization. In LDB underwater nodes passively listen to AUV messages; hence, it is energy efficient.

One of the drawbacks of LDB is that the AUV is restricted to travel above the UASN, which may not be possible in practice. Moreover, its accuracy depends on the frequency of the AUV messages. When the AUV sends beacons with long intervals, underwater nodes may not be able to obtain their locations, or two nodes may estimate the same location. In [7] the authors propose a distributed hierarchical localization scheme for stationary UASNs. The hierarchical architecture of Large- Scale Localization (LSL) employs three types of nodes: *surface buoys*, *anchor nodes*, and *ordinary sensor nodes*. Surface buoys float on the surface and learn their coordinates through GPS. Anchor nodes and ordinary sensor nodes float underwater. Anchor nodes are assumed to be localized by the surface buoys at an earlier deployment stage, and LSL considers only the localization of ordinary sensor nodes. In the ordinary sensor localization process, anchor nodes periodically broadcast their coordinates, while ordinary nodes send short messages periodically to measure distances to their neighbours via ToA. If an ordinary node gathers enough localization messages (i.e., three messages from non-coplanar anchors), it performs lateration and estimates its location. For each localized node, a confidence value is calculated to determine its eligibility to become a reference node. A reference node is a localized underwater node that is able to send localization messages. If an ordinary node is unable to collect the necessary number of messages to localize itself, it broadcasts the received localization messages along with the distance measurements to the anchors and other neighboring nodes. LSL has a hierarchical structure, which means this scheme can be used in large-scale UASNs. Its main drawback is having high energy consumption and overhead due to beacon exchanges, localization messages, and the messages forwarded by unlocalized nodes. In [8] the authors show that LSL has the highest energy consumption and the highest overhead compared to DNRL and MSL. Moreover, LSL requires synchronization similar to DNRL and MSL.

In [10] the authors extend [9] to include iterative localization in order to cover a larger area by four initial anchors. This technique is called the Large-Scale Localization Scheme (LSLS). LSLS has three phases: surface anchor localization, iterative localization, and complementary. In the surface anchor localization phase, UPS is used to localize the underwater nodes that can communicate with the initial group of anchors. In the iterative localization phase, certain nodes are selected as reference nodes. They help in localizing the other underwater nodes by using UPS. LSLS employs a third phase, the complementary phase, where the nodes that are not localized in the first two phases initiate a localization request. This request results in selecting a different set of reference nodes. LSLS inherits the advantages of UPS, and it can additionally localize a large-scale UASN with short-range acoustic communications. However, LSLS has higher overhead and energy consumption than UPS. In [11] the authors propose a projection based localization technique, Underwater Sensor Positioning (USP). In USP an underwater node is assumed to know its depth and, using this information, maps the available anchors on the horizontal plane on which it resides. The projection transforms localization in 3D to localization in 2D, which allows the use of bilateration (i.e., localization using two anchor nodes). USP has lower localization success than the other surveyed localization techniques, even under moderate degrees of connectivity, as shown in [11]. However, its performance may be improved by increasing the number of anchor nodes.

B. Prediction-Based Schemes

In [12] the authors utilize the same hierarchical architecture of [7] and propose Scalable Localization with Mobility Prediction (SLMP) for mobile UASNs. Anchor nodes and ordinary nodes estimate their locations by using their previous coordinates and their mobility patterns. In a mobile UASN, mobility patterns may become obsolete in time; therefore, anchor nodes periodically check the validity of their mobility pattern and trigger an update when necessary. An anchor node, after predicting its location, uses surface buoy coordinates and distance measurements to buoys to estimate its location. If the Euclidean difference between the predicted and estimated locations is less than a threshold, the anchor node assumes its mobility model is accurate. Otherwise, the anchor node runs its mobility prediction algorithm, determines the new mobility pattern, and broadcasts its coordinates along with the updated pattern. When ordinary nodes hear messages from anchors, they run their mobility prediction algorithm and update their patterns, as well as their location estimates. In SLMP, communication overhead may be low when the mobility pattern does not change frequently. In UASNs prediction-based schemes are expected to perform well due to the correlated motion of the ocean currents; however, the relation between localization protocols and mobility patterns is still unexplored.

IV. CENTRALIZED LOCALIZATION TECHNIQUES

In this section we survey the centralized localization techniques, once more under two subcategories: estimation-based and prediction-based schemes.

A. Estimation-Based Schemes

Motion-Aware Self Localization (MASL) [13] aims to provide accurate localization by addressing inaccurate distance estimates in mobile UASNs. In a mobile network, distance estimates may become obsolete in time. Especially underwater, gathering a number of distance estimates may require relatively long time intervals, which increases the possibility of obsolete information. In MASL an underwater node collects distance estimates between itself and its neighbours. These estimates are processed offline when the UASN mission ends. Distance estimates are fed into an iterative estimation algorithm. At each iteration, the algorithm refines position distributions by dividing the area of operation into smaller grids and selecting the area in which the node resides with the highest probability, and uses it in the next iteration. MASL is centralized, hence alleviating the computational burden of localization from underwater nodes, and it does not require anchors. MASL is targeted for applications where data is collected and delivered to a central station, and the relation between data and location is resolved at the post-processing stage. The major drawback of MASL is its unsuitability for UASN applications that aim online monitoring or require coordinated motion where real time location information is necessary. Other drawbacks are that MASL requires synchronization and has high overhead due to frequent messaging. Another centralized localization scheme, the Area-Based Localization Scheme (ALS), is proposed in [14]. ALS is a range-free coarse-grained localization technique that gives an estimate of the area where the sensor node resides rather than its set of coordinates. In ALS anchor nodes partition the region into non-overlapping areas by sending messages at varying power levels. These messages carry an indicator of the transmit power level which helps to eliminate the uncertainties that might occur due to inaccurate power measurements at the receiver side. An underwater sensor passively listens to anchor messages, keeps a list of anchors and their corresponding power levels, and sends this information to a sink node. The sink knows the coordinates of the anchors; therefore, it can determine the location of the sensor node. ALS is appropriate when precise location information is not necessary, and the anchors are able to modify their transmission power. The advantages of ALS are being computationally light, having no synchronization requirement, and having no need to measure the received signal strength. On the other hand, it has the same drawback as MASL due to being centralized (i.e., it is not suitable for applications that require online location estimates). Furthermore, it has high communication overhead and is less energy-efficient than the silent localization protocols as the sensor nodes send localization related messages to the sink node.

B. Prediction-Based Schemes

Collaborative Localization (CL) is proposed in [15] for a “fleet of underwater drifters.” A fleet of underwater drifters refers to a mobile UASN with sensor nodes equipped with the ability to descend and ascend in the water column. The authors assume that the UASN is designed for a specific application scenario where underwater sensor nodes are responsible for collecting data from the depths of the oceans and carrying them to the surface. The architecture employs profilers, which move ahead of the follower nodes and provide an estimate of future locations to them. A follower node predicts its location by using its previous location and the displacement of the profiler. The displacement of the profiler can be attained by periodically measuring distances in between via ToA. CL requires synchronization like the other ToA-based techniques. Another drawback of CL is its architectural dependence: for a sparse or non-homogenous network, the performance of CL could degrade significantly. We summarize the fundamental properties of the surveyed localization techniques in Table 1. Several protocols do not employ a specific ranging method; we mention those as not specified. In iterative protocols localized underwater sensor nodes help the localization process by broadcasting self-coordinates, whereas in silent localization protocols underwater sensor nodes are not allowed to send messages. Therefore, they are called iterative and silent, respectively.

	Distributed/ Centralized	Estimation/ Prediction	Anchor type	Ranging method	Communication	Synchronization
DNRL [3]	Distributed	Estimation	Non-propelled mobile anchors	ToA (one-way ranging)	Silent	Yes
MSL [4]	Distributed	Estimation	Non-propelled mobile anchors and reference nodes	ToA (one-way ranging)	Iterative	Yes
AAL [5]	Distributed	Estimation	Propelled mobile anchor (AUV)	ToA (two-way ranging)	Silent	No
LDB [6]	Distributed	Estimation	Propelled mobile anchor (AUV)	Range-free	Silent	No
LSL [7]	Distributed	Estimation	Surface buoys, underwater anchors, and reference nodes	ToA (one-way ranging)	Iterative	Yes

Table1

C. Discussion and Open Research Issues

Performance of the localization protocols can be mainly evaluated in terms of their localization success and accuracy. Additionally, for sensor networks, energy efficiency becomes a significant metric. An energy-efficient localization protocol means that the protocol spends the least possible energy on localization. Moreover, the number of localization messages is important, not only because it causes the sensor nodes to spend energy, but also because it uses the limited bandwidth of the acoustic links in UASNs. Localization success and accuracy are generally related to the number of anchors and the frequency of the localization messages. For most of the surveyed protocols, as the number of anchors increase, the localization success increases. In mobile UASNs more accurate location estimates can be available with frequent location updates from the anchors. Furthermore, the speed of the anchors and the freshness of anchor locations affect the accuracy in mobile UASNs. For instance, AAL and LDB use an AUV, which has slow speed, and they suffer from slow propagation of anchor locations. From the energy consumption and communication overhead view, range-free techniques such as LDB and ALS consume more energy and have higher communication overhead than the other schemes. Furthermore, range-based schemes that employ two-way ranging spend more energy than the techniques that use one way ranging. However, one-way ranging may face synchronization problems, especially in long-term missions.

As for a general comparison among the categories, centralized schemes may not be as flexible as distributed schemes. For instance, they are not suitable for online monitoring applications or applications that require coordinated motion of the UASN. When estimation-based and prediction- based schemes are compared, prediction based schemes are expected to have better performance since mobility in UASNs can be spatio-temporally correlated. In correlated motion, prediction could provide localization with less overhead and less energy consumption. However, evaluation of the prediction-based schemes demands realistic mobility models that can reflect the actual merits and handicaps of the schemes. Mobility modeling and analyzing the performance of prediction-based localization schemes on accurate models are still open issues. Furthermore, cross-layer approaches, such as extracting localization related information from other networking activities, may be considered to reduce overhead and increase energy efficiency of the localization protocols. However, they are still unexplored.

V. CONCLUSION

In this paper we discussed about the challenges of underwater acoustic networks. In this we present localization techniques, we compare the protocols by discussing their design principles, architectural dependencies, advantages, and disadvantages. We group them under two categories, distributed and centralized localization schemes, based on where the location of a sensor node is determined, and then we divide these into two subcategories based on how the localization is established (i.e., estimation-based or prediction-based schemes).

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