Localization Techniques for Underwater Acoustic Sensor Networks

Melike Erol-Kantarci and Hussein T. Mouftah, University of Ottawa
Sema Oktug, Istanbul Technical University

ABSTRACT

Underwater acoustic sensor networking is the enabling technology for a wide range of applications including naval surveillance, oil platform monitoring, earthquake and tsunami forewarning, climate and ocean observation, and water pollution tracking. Underwater sensor nodes with sensing and communication capabilities form the underwater acoustic sensor network. Localizing the underwater sensor nodes is one of the fundamental tasks for UASNs where the location information can be used in data tagging, routing, and node tracking. 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.

INTRODUCTION

During the past two decades, ocean monitoring systems have been using disconnected, individual units of equipment (e.g., surface buoys, floats, and ocean bottom units). Buoys can collect data from several meters below the ocean surface and transmit them to a vessel or an on-shore command center via satellite. Floats are underwater devices that can collect data from several hundreds of meters below the surface, and they surface to transmit their data. They generally stay underwater for several days or weeks, where accessing real-time data is not possible. Ocean-bottom units are mounted on the ocean floor, and they are either connected to the on-shore center via underwater cables, or they have cables to surface buoys.

Recently, advances in wireless sensor networks (WSNs) have motivated the deployment of wireless underwater sensor networks where sensors float underwater and use wireless communications to transmit and receive data. In underwater acoustic sensor networks (UASNs) conventional large, expensive, individual ocean monitoring equipment units are replaced by relatively small and less expensive underwater sensor nodes that are able to communicate with each other via acoustic signals.

Under water, acoustic signals propagate better than radio or optical signals; therefore, they are preferred for underwater communications. High-frequency radio signals attenuate fast, and optical signals generally scatter. On the other hand, acoustic communications have several handicaps. The acoustic channel has a low data rate which is only several tens of kilobits per second for ranges under 1 km, and it has even lower data rates at longer distances. For this reason, UASNs use short-range acoustic modems, and as a consequence they employ a large number of underwater nodes to cover a large oceanographic region. Another drawback of acoustic communication is the low link quality of the acoustic channel due to multipath signal propagation and time variability of the medium. The ocean surface and bottom are the major reasons for multipath propagation, while temperature and conductivity (salinity) differences form virtual layers with varying reflection and refraction properties, and contribute to multipath propagation. In addition, surface waves increase the time variability of the acoustic channel. The acoustic channel also has long propagation delay due to the slow speed of sound, which is approximately 1500 m/s. Moreover, in mobile UASNs, free-floating sensors drift with the ocean currents where the relative motion of the transmitter or receiver may create the Doppler effect. Since the speed of sound in water is slower than the speed of electromagnetic waves, the Doppler effect can be more significant in acoustic communications. Besides these physical-channel-related challenges, UASNs are energy-limited. Underwater sensor nodes may need to be left in the ocean for several days or weeks without battery replacement because deployment, maintenance, and mission termination tasks may require vessels which are costly to operate. In summary, protocols designed for UASNs need to address the adverse physical channel conditions while being energy-efficient.

In a sensor network, sensor nodes generally tag their measurements with time and location information because applications associate sampled values with when and from where they have been collected. Furthermore, location information can be used for optimizing the medium access and routing protocols. It is also necessary for tracking nodes and coordinating motion of a

 0163-6804/10/$25.00

group of nodes. Therefore, localization for UASNs has been one of the major research topics since UASNs started to draw the attention of the networking community in the early 2000s.

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.

Localization has also been studied in the context of terrestrial WSNs. Among the proposed solutions, GPS-based localization schemes are not suitable for UASNs since the high-frequency GPS signals do not propagate well in water, whereas GPS-less schemes are generally not convenient since they require large amounts of messaging between sensor nodes.

In the literature, a large number of studies focus on improving medium access, network, and transport protocols for UASNs. In this article we focus on localization, which is an active research topic, and a large number of protocols have been proposed recently. An early survey paper in 2006 [2] surveyed several terrestrial localization methods and discussed their suitability for UASNs. Our work is different than the previous survey paper, as we focus on recent localization techniques specifically designed for UASNs.

This article is organized as follows. In the next section we survey the localization techniques for UASNs. We then discuss the performance of these protocols and point out the open issues. We conclude our article in the final section.

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 neighbors, 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.

Estimation-based methods use the most recent information to compute the current location of a node where the prediction-based schemes aim to predict the location of a node at the next time instant, using previous and current location information.

Distributed Localization Techniques

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

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-coordinates 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 over-

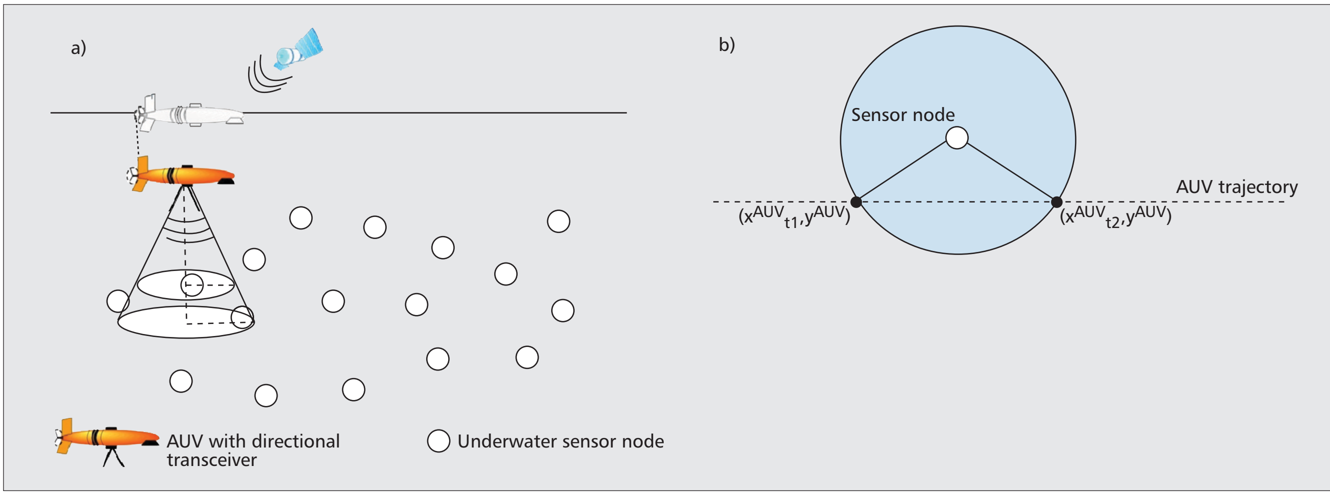

Figure 1. *a) AUV with directional beam for the LDB scheme; b) sensor localization in LDB.*

head 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 one-way 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, then dives to a certain depth above the UASN, and travels over the area of operation as shown in Fig. 1a. 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 its x-coordinate as the average of the coordinates of the AUV at two points, which are shown in Fig. 1b. x^{AUV}_{t1} is the projection 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, x^{AUV}_{t2}, 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 neighbors 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 [9] the authors propose the Underwater Positioning Scheme (UPS) for stationary UASNs. UPS is a time difference of arrival (TDoA)-based localization scheme, using beacon signals from four anchors sent in sequential time slots. A master anchor (anchor A in Fig. 2) initiates the localization process by sending a beacon signal. Anchor B and the sensor node hear this beacon signal, and anchor B replies to anchor A by sending the time difference between the received time of A's beacon signal and the transmission time of its beacon signal. The sensor node hears anchor B's beacons as well. Anchors C and D repeat the same process. Then the TDoAs measured by the sensor node are converted to range differences by using the speed of sound. Range differences are used in trilateration equations to estimate the location of the sensor node. UPS does not require synchronization, and the underwater nodes do not send localization messages. Therefore, UPS is silent and energy-efficient. The drawback of UPS is that it can localize nodes that reside in an area enclosed by four anchor nodes, which means UPS demands long-range anchors for localizing a large-scale UASN. Moreover, the anchor locations need to be fixed and known by the sensor nodes, which may not be possible or may be hard to obtain in practice.

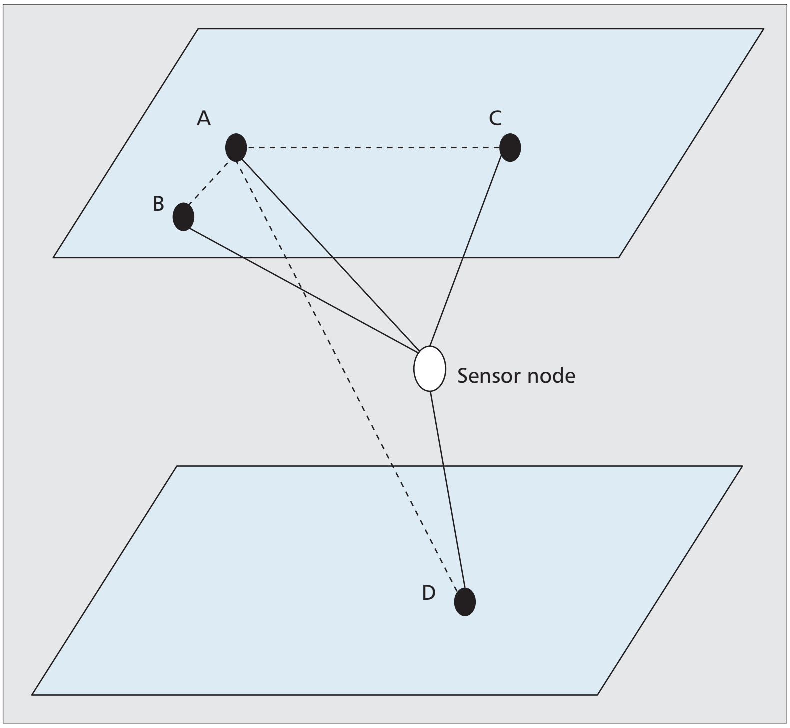

Figure 2. *The UPS scheme using TDoAs of beacon signals from four anchors.*

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 sur-

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.

veyed 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.

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.

Centralized Localization Techniques

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

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 neighbors. 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.

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
UPS [9]	Distributed	Estimation	Stationary anchors	TDoA	Silent	No
LSLS [10]	Distributed	Estimation	Stationary anchors and reference nodes	TDoA	Iterative	No
USP [11]	Distributed	Estimation	Stationary anchors	Not specified	Active	No
SLMP [12]	Distributed	Prediction	Surface buoys, underwater anchors, and reference nodes	ToA (one-way ranging)	Iterative	Yes
MASL [13]	Centralized	Estimation	No anchors	ToA (one-way ranging)	Active	Yes
ALS [14]	Centralized	Estimation	Anchors with variable power levels	Range-free	Active	No
CL [15]	Centralized	Prediction	No anchors	ToA (one-way ranging)	Active	Yes

Table 1. *Properties of localization protocols for UASNs.*

On the other hand, in MASL and CL nodes make distance measurements, and in ALS nodes send messages to the sink node for localization. We denote the communication behavior of these protocols *active*.

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

For future research, accurate mobility models and their interaction with localization schemes need to be explored. Furthermore, cross layer approaches, which may be employed for improving the efficiency of the localization protocols, are still open issues.

other networking activities, may be considered to reduce overhead and increase energy efficiency of the localization protocols. However, they are still unexplored.

Conclusion

Localization has been one of the fundamental challenges of UASNs, and in recent years a large number of studies have been tackling this problem. In this survey we present the state of the art in localization techniques for UASNs. 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).

Most of the underwater applications in the literature demand distributed localization since it is more convenient for online monitoring systems than centralized protocols are. For mobile UASNs, prediction is also a desired property since it may reduce the repetitions of the localization process. For future research, accurate mobility models and their interaction with localization schemes need to be explored. Furthermore, cross-layer approaches, which may be employed for improving the efficiency of the localization protocols, are still open issues.

References

[1] D. Green, "Underwater Acoustic Communication and Modem-Based Navigation Aids," *Lecture Notes in Comp. Sci.*, Springer, vol. 4809, 2007, pp. 474–81.

[2] V. Chandrasekhar et al., "Localization in Underwater Sensor Networks: Survey and Challenges," *Proc. 1st ACM Wksp. Underwater Net.*, Los Angeles, CA, 2006, pp. 33–40.

[3] M. Erol, L. Vieira, and M. Gerla, "Localization with Dive'N'Rise (DNR) Beacons for Underwater Acoustic Sensor Networks," *Proc. 2nd ACM Wksp. Underwater Net.*, Montreal, Canada, 2007, pp. 97–100.

[4] M. Erol *et al.*, "Multi Stage Underwater Sensor Localization using Mobile Beacons," *Proc. 2nd Int'l. Conf. Sen. Tech. Apps.*, Cap Esterel, France, Aug. 25–31, 2008, pp. 710–14.

[5] M. Erol, L. Vieira, and M. Gerla, "AUV-Aided Localization for Underwater Sensor Networks," *Proc. Int'l. Conf. Wireless Algorithms, Sys., Apps.*, Chicago, IL, 2007, pp. 44–54.

[6] H. Luo *et al.*, "LDB: Localization with Directional Beacons for Sparse 3D Underwater Acoustic Sensor Networks," *J. Net.*, vol. 5, no. 1, Jan. 2010, pp. 28–38.

[7] Z. Zhou, J. Cui, and S. Zhou, "Efficient Localization for Large-Scale Underwater Sensor Networks," *Ad Hoc Net.*, vol. 8, no. 3, May 2010, pp. 267–79.

[8] M. Erol-Kantarci *et al.*, "Performance Evaluation of Distributed Localization Techniques for Mobile Underwater Acoustic Sensor Networks," *Ad Hoc Net.*, vol. 9, no. 1, Jan. 2011, pp. 61–72.

[9] X. Cheng *et al.*, "Silent Positioning in Underwater Acoustic Sensor Networks," *IEEE Trans. Vehic. Tech.*, vol. 57, no. 3, 2008, pp. 1756–66.

[10] W. Cheng *et al.*, "Time-Synchronization Free Localization in Large Scale Underwater Acoustic Sensor Networks," *Proc. 29th IEEE ICDCS*, Montreal, Canada, June 2009, pp. 80–87.

[11] A. Y. Teymorian *et al.*, "3D Underwater Sensor Network Localization," *IEEE Trans. Mobile Comp.*, vol. 8, no. 12, 2009, pp. 1610–21.

[12] J. H. Cui, Z. Zhou, and A. Bagtzoglou, "Scalable Localization with Mobility Prediction for Underwater Sensor Networks," *Proc. 2nd ACM Wksp. Underwater Net.*, Montreal, Canada, 2007, pp. 2198–2206.

[13] D. Mirza and C. Schurgers, "Motion-Aware Self-Localization for Underwater Networks," *Proc. 3rd ACM Wksp. Underwater Net.*, San Francisco, CA, 2008, pp. 51–58.

[14] V. Chandrasekhar and W. Seah, "An Area Localization Scheme for Underwater Sensor Networks," *IEEE OCEANS Asia Pacific Conf.*, May 2006, pp. 1–8.

[15] D. Mirza and C. Schurgers, "Collaborative Localization for Fleets of Underwater Drifters," *Proc. IEEE OCEANS*, Vancouver, Canada, 2007, pp. 1–6.

Biographies

MELIKE EROL-KANTARCI [M'08] (melike.erolkantarci@uottawa.ca) is a postdoctoral fellow at the School of Information Technology and Engineering, University of Ottawa, Canada, since October 2009. She received her B.S. (2001), M.Sc. (2004), and Ph.D. (2009) degrees from the Computer Engineering Department, Istanbul Technical University, Turkey. She worked as a Fulbright visiting researcher at the Computer Science Department, University of California at Los Angeles, from September 2006 to August 2007. Her main research interests are localization protocols, underwater sensor networks, and wireless sensor networks.

HUSSEIN MOUFTAH [F] (mouftah@uottawa.ca) joined the School of Information Technology and Engineering, University of Ottawa in September 2002 as a Canada Research Chair Professor. He was with the ECE Department at Queen's University (1979–2002) prior to his departure as a full professor and associate department head. He has three years of industrial experience mainly at BNR of Ottawa, now Nortel Networks (1977–1979). He served as Editor-in-Chief of *IEEE Communications Magazine* and IEEE Communications Society Director of Magazines, Chair of the Awards Committee, and Director of Education. He has been a Distinguished Speaker of the IEEE Communications Society (2000–2007). He is the author or coauthor of six books, 40 book chapters, and more than 1000 technical papers and 10 patents in this area. He is a Fellow of the Canadian Academy of Engineering, the Engineering Institute of Canada, and the Royal Society of Canada RSC: The Academy of Science.

SEMA F. OKTUG [M'91] (oktug@itu.edu.tr) received her B.Sc., M.Sc., and Ph.D. degrees in computer engineering from Bogazici University, Istanbul, Turkey, in 1987, 1989, and 1996, respectively. Currently, she is a professor with the Department of Computer Engineering, Istanbul Technical University. She is the coordinator of the Computer Networks Research Laboratory in the department. She has been serving as vice dean at the Faculty of Electrical Electronics Engineering, Istanbul Technical University since November 2007. She serves on the editorial board of the *Computer Networks* journal. Her research interests are in communication protocols, modeling and analysis of communication networks, optical WDM networks, and wireless networks.