A Survey of Architectures and Localization Techniques for Underwater Acoustic Sensor Networks

Melike Erol-Kantarci, Hussein T. Mouftah, and Sema Oktug

***Abstract*—The widespread adoption of the Wireless Sensor Networks (WSNs) in various applications in the terrestrial environment and the rapid advancement of the WSN technology have motivated the development of Underwater Acoustic Sensor Networks (UASNs). UASNs and terrestrial WSNs have several common properties while there are several challenges particular to UASNs that are mostly due to acoustic communications, and inherent mobility. These challenges call for novel architectures and protocols to ensure successful operation of the UASN. Localization is one of the fundamental tasks for UASNs which is required for data tagging, node tracking, target detection, and it can be used for improving the performance of medium access and network protocols. Recently, various UASN architectures and a large number of localization techniques have been proposed. In this paper, we present a comprehensive survey of these architectures and localization methods. To familiarize the reader with the UASNs and localization concepts, we start our paper by providing background information on localization, state-of-the-art oceanographic systems, and the challenges of underwater communications. We then present our detailed survey, followed by a discussion on the performance of the localization techniques and open research issues.**

***Index Terms*—Localization, underwater acoustic sensor networks**

I. Introduction

UASN technology provides new opportunities to explore the oceans, and consequently it improves our understanding of the environmental issues, such as the climate change, the life of ocean animals and the variations in the population of coral reefs. Additionally, UASNs can enhance the underwater warfare capabilities of the naval forces since they can be used for surveillance, submarine detection, mine countermeasure missions and unmanned operations in the enemy fields. Researchers from the Office of Naval Research (ONR) have recently emphasized that the US Navy has an increasing interest in UASN technology [1]. Furthermore, monitoring the oil rigs with UASNs can help taking preventive actions for the disasters such as the rig explosion that took place in the Gulf of Mexico in 2010. Last but not least, earthquake and tsunami forewarning systems can also benefit from the UASN technology.

Ocean monitoring systems have been used for the past several decades where these traditional oceanographic data collection systems utilize individual and disconnected underwater equipments. Generally, these equipments collect data from their surroundings and send these data to an on-shore station or a vessel by means of satellite communications or underwater cables. In UASNs, these equipments are replaced by relatively small and less expensive underwater sensor nodes that house various sensors on board, e.g. salinity, temperature, pressure, current speed sensors. The underwater sensor nodes are networked unlike the traditional equipments, and they communicate underwater via acoustics.

In underwater, radio signals attenuate rapidly, hence they can only travel to short distances while optical signals scatter and cannot travel far in adverse conditions, as well [2]. On the other hand, acoustic signals attenuate less, and they are able to travel further distances than radio signals and optical signals. Consequently, acoustic communication emerges as a convenient choice for underwater communications. However it has several challenges. The bandwidth of the acoustic channel is low, hence the data rates are lower than they are in terrestrial WSNs. Data rates can be increased by using short range communications which means more sensor nodes will be required to attain a certain level of connectivity and coverage. In this case, the large-scale UASN bares additional challenges for communication and networking protocols. Moreover, the acoustic channel has low link quality [3] which is mostly due to the multi-path propagation and the time-variability of the medium. Furthermore, the speed of sound is slow (approximately 1500 m/s) yielding large propagation delay. In addition to those, in mobile UASNs, the relative motion of the transmitter or the receiver may create the Doppler effect. Besides these communication channel related challenges, UASNs are also energy limited similar to other WSNs.

Due to the above challenges, UASNs call for novel medium access, network, transport, localization, synchronization protocols and architectures some of which have been addressed in various studies [4]–[9]. The design of network and management protocols is closely related with the network architecture, and various UASN architectures have been proposed in the literature. Moreover, localization has been addressed widely since it is a fundamental task used in tagging the collected data, tracking underwater nodes, detecting the location of an underwater target and coordinating the motion of a group of nodes. Furthermore, location information can be used to optimize the medium access and the routing protocols.

In [10], the authors have surveyed several terrestrial localization methods and discussed their applicability for UASNs.

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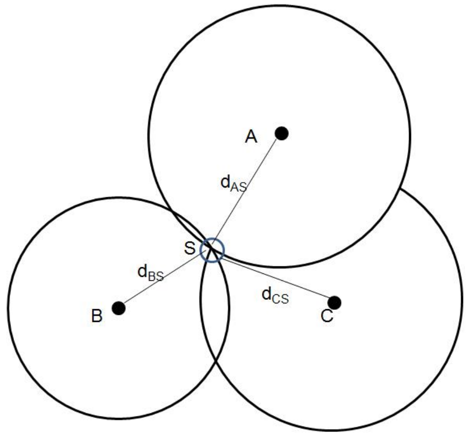

Fig. 1. Localization in two dimensional space using lateration.

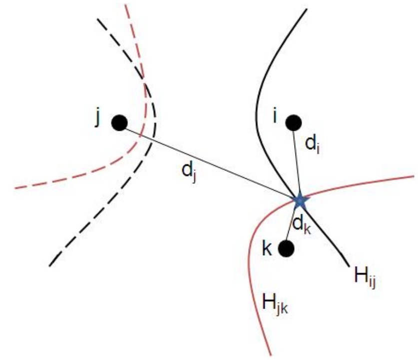

Fig. 2. The hyperbola based localization in two-dimensional space.

In [11], we presented a survey of the well-known localization techniques. However, due to space limitations, we did not include the UASN architectures and several localization techniques in our previous work. This paper is different than the previous survey papers, as it presents a recent, comprehensive survey of the UASN architectures and the localization techniques for UASNs proposed since the beginning of 2000s, together with an introduction on the basics of localization, summary of the state-of-the-art oceanographic research, and a discussion on the challenges of UASNs and underwater communications. Following the survey sections, we summarize the fundamental properties of the localization techniques in one table, discuss the performance of these techniques and point out the open issues in the field.

The rest of the paper is organized as follows. In Section II, we give background information on the basics of localization, the state-of-the-art oceanographic systems and the challenges of UASNs. In Section III and Section IV, we survey the UASN architectures and the localization schemes for UASNs, respectively. We summarize the fundamentals of the surveyed protocols, discuss their performances and point out the open issues in Section V. Finally, in Section VI we conclude our paper.

II. Background

In this section, we aim to familiarize the reader with the fundamental concepts of localization and UASNs.

A. Localization Basics

Localization generally requires several objects with known locations (anchors) and distance or angle measurements between these anchors and the object to be localized (unknown node). There are various methods to provide location information for the anchors. Anchors may be placed at fixed locations and their coordinates may have been pre-configured, or they may have special hardware to learn their locations from a location server, such as the Global Positioning System (GPS).

For estimating the location of an unknown node, traditional localization methods generally use distance or angle measurements between the anchor and the unknown node or a combination of the two measurements. For localization in WSNs, more advanced techniques have also been proposed, such as those using connectivity information. We limit our introduction to traditional techniques, for a detailed survey of the WSN localization techniques the reader is refered to [12].

Two well-known localization techniques are angulation and lateration. Angulation utilizes the bearing information and the geometric principles of triangles, whereas lateration uses the distance between two nodes, i.e. the range, and intersecting circles. Lateration is a widely used technique which is also employed by the GPS system. For simplicity, we show the principles of trilateration (three anchors) in Figure 1. Here, the location of a node is determined by computing the intersection of three circles. Multi-lateration is a generalization of the classical trilateration where n coordinates can be estimated by $n+1$ non-coplanar anchor coordinates. For instance, to estimate the coordinates of a node, denoted by (x, y, z), one can use the set of equations:

$$(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2 = d_i^2 \quad (1)$$

where(x_i, y_i, z_i) are the coordinates of the anchor and d_i is the measured distance between the anchor i and the node. Note that, underwater nodes are usually able to attain their depth by their pressure sensors, hence in UASN research generally the localization problem is simplified to estimating the (x, y) coordinates.

The difference between the arrival times of the acoustic signal at different nodes can be also used to form intersecting hyperbolas. The two dimensional hyperbola-based localization is shown in Figure 2. H_{ij} and H_{jk} are the hyperbolas whose foci are at the locations of the anchors i, j and j, k, respectively. Assuming that the anchor locations are given as (x_i, y_i), (x_j, y_j), (x_k, y_k), and the sensor (or event) is at (x, y). d_i denotes the distance of the i^{th} anchor from the unknown node and $t_{ij} = t_i - t_j$ where t_i and t_j are the arrival times of the signal at anchor i and anchor j, respectively. The speed of sound is denoted by c. The set of points satisfying (x, y) are given by the hyperbola equation:

$$\begin{aligned} d_i - d_j &= c.t_{ij} \\ &= \sqrt{(x-x_i)^2 + (y-y_i)^2} \\ &\quad - \sqrt{(x-x_k)^2 + (y-y_k)^2}. \end{aligned} \quad (2)$$

In a WSN, angle and distance measurements can be collected by one of the following methods: *i*) Received Signal

Strength Indicator (RSSI), *ii*) Angle-of-Arrival (AoA), *iii*) Time Difference of Arrival (TDoA), *iv*) Time of Arrival (ToA) [13]. RSSI is based on converting the propagation loss, which is the difference between the transmitted and the received signal power, into a distance estimate. RSSI assumes the propagation property of the medium is already known or it can be learned in time. AoA is the angle between the propagation path of the signal and a reference direction. TDoA uses the time difference between the arrival of two signals, usually Radio Frequency (RF) signals and acoustic signals. ToA method generally calculates the distance by using one-way ranging and the speed of the signal assuming the nodes are synchronized. One-way range is calculated by the difference between the arrival time of the signal and the sending time of the signal which is included as a timestamp field in the packet. When synchronization cannot be achieved, average of the two-way (round trip) ranging is also used as an estimate of the range. Two-way range is calculated by the time difference between sending a short packet and receiving a response. Two-way ranging does not require synchronization among nodes however, for asymmetric channels this method may give inaccurate range information.

In UASNs, ToA is preferred more than it is preferred in terrestrial systems since the ToA method using the radio signal in air acquires high resolution timers. For instance, it takes approximately 33 nanoseconds for a light pulse to travel 10m. However, the speed of sound in water is slow, hence ToA can be used in ranging for UASNs. On the other hand, RSSI is not convenient since predicting the propagation loss accurately is difficult due to time-varying properties of the underwater environment [14]. Using AoA for UASNs has been considered in [6] but it has not been widely employed due to the size and cost of the directional antennas. There are several schemes employing TDoA for UASNs, as well.

In WSN literature, range-free localization techniques have also been proposed, however it is not straightforward to apply them to UASNs. These techniques generally utilize connectivity information and they have been proposed for WSNs that can either afford fixed infrastructure or that can tolerate relatively high communication overhead [15]–[18].

In practice, distance measurements are not exact, therefore localization techniques apply an estimation method to eliminate the effects of the errors. In literature, the least-squares estimation method is used widely due to its simplicity. A list of other methods can be found in [12].

B. State-of-the-art Oceanographic Systems and Localization Techniques in Oceanography

For several decades, oceanographers have been using various equipments to explore the oceans. Stationary surface buoys, ocean floor units and floats are among the most common ocean monitoring devices. Surface buoys and ocean floor units collect data from the ocean surface and the ocean floor, respectively. They have fixed locations and they communicate with a central station using either satellite communications or cables. On the other hand, floats do not have fixed locations, they are dropped from vessels and they drift with the force of the ocean currents. Profiling floats which are special types of floats having the ability of moving vertically in the water column, i.e. descend and ascend, are able to collect data from a certain depth up to approximately 2km. Presently, the largest ocean monitoring system employing such profiling floats, is the Argo Project [19], [20]. Argo floats transmit their data via satellite when they are on the surface. Device-to-device communication is not available hence floats do not form a network. The location of an Argo float is determined as it surfaces.

To the best of our knowledge, Seaweb is the only example of a large-scale wireless underwater device network [21]. It is being developed by the US Navy since 1980s. It employs Autonomous Underwater Vehicles (AUVs), gliders, buoys, repeaters and ships where the devices communicate via telesonar, radio or satellite links (Figure 3). Telesonar links enable underwater communication, radio links are used only by the devices on the surface to communicate with the command center on the ship and the on-shore command center is accessed via satellite links.

Localization in the traditional oceanographic systems generally utilize one of the two acoustics-based approaches, namely Short Base-Line (SBL) or Long Base-Line (LBL) [22]. In the SBL system, a ship follows the underwater devices and uses a short-range acoustic emitter to enable localization. In the LBL system, acoustic transponders are deployed either on the seafloor or on moorings around the area of operation. Devices that are in the transmission ranges of several sound sources estimate their location by triangulation. LBL or SBL cannot be used for UASNs because LBL uses long range signals which create interference and disable the communication among the sensor nodes while SBL involves a ship in the operation area which is not feasible for the large-scale and mobile UASNs.

Alternatives to LBL and SBL systems have also been investigated. For instance, GPS Intelligent Buoy (GIB) [23], which is a commercial system, is designed to track individual units, such as AUVs, divers and other underwater equipments. In the GIB system, GIB buoys, which have GPS receivers and hydrophones, listen to the signals that are emitted by an underwater equipment and estimate its distance via ToA. GIB buoys periodically send these distance measurements and self coordinates to a central station where the location of the underwater equipment is determined. GIB is not convenient for localization of UASNs for several reasons. First, the underwater equipments emit signals to be tracked which means they consume high amount of energy especially when long-range communications are required to reach the GIB buoys. On the other hand, if short range communications are used, a large number of GIB buoys may be needed. Moreover, GIB is a centralized technique and it does not provide location information for the sensors, it provides tracking ability for the central station.

C. Challenges of UASNs and Underwater Communications

WSNs generally utilize the unlicensed ISM bands for communications which are located at several frequency ranges varying from tens of MHz to several GHz values. It is not straight forward to use such high frequency signals in underwater because they are rapidly absorbed. In [24], the

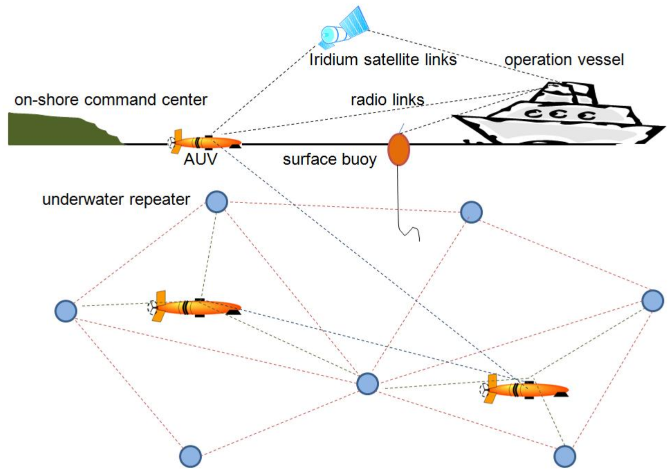

Fig. 3. Seaweb network in the Eastern Gulf of Mexico on February 2003, including three AUVs, six repeater nodes, and two gateway buoys [21].

authors refer to an experimental study at Robotic Embedded Systems Laboratory, University of California, where Mica2 motes have been reported to have a transmission range of 120cm at 433MHz in underwater environment. The use of RF signals is considered to be limited to the nodes that are close to the surface only [25], although a recent study provides a different perspective on the use of RF signals under water [26]. On the other hand, optical modems have been shown to achieve data rates reaching to Mbit/s with ranges up to 100m, only in very clear water conditions [2]. However, in practice it is hard to attain such conditions, and optical signals suffer from absorption and scattering at long ranges. For very short range underwater communications, i.e., 5m to 10m, optical modems have been utilized in [27].

Acoustic communications, despite having several drawbacks, are preferred to radio communications and optical communications because the acoustic signals attenuate less than the RF and the optical signals. Attenuation in an underwater acoustic channel for a signal with frequency f over a distance l is given as [28]:

$$A(l,f) = A_{norm} l^k a(f)^l \tag{3}$$

where A_{norm} is a normalization constant, $a(f)$ is the absorption coefficient, k is the spreading factor that is used to describe the geometry of propagation, and $k = 1.5$ is assumed to be the practical spreading value. The absorption coefficient is expressed empirically for frequency values above a few hundred Hz as [28]:

$$10\log a(f) = 0.003 + 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75.10^{-4} f^2 \tag{4}$$

where f is given in kHz and $a(f)$ is given in dB/km. Eq. 4 is simplified into the following expression for lower frequencies:

$$10\log a(f) = 0.002 + 0.11\frac{f^2}{1+f^2} + 0.011 f^2 \tag{5}$$

For long range underwater communications (10-100km), the bandwidth is limited to few kHz. For shorter ranges (1-10km), the available bandwidth becomes in the order of 10kHz, and for ranges below 100m available bandwidth is only over a few hundred kHz [29]. Due to the low bandwidth of the acoustic channel, data rates are low, as well. The maximum attainable data rate and range of the acoustic channel is limited approximately by 40 km.kbps range-rate product [30]. Recently, short-range acoustic modems and advanced modulation techniques [31]–[34] have been proposed to increase the data rates of UASNs.

Acoustic channel also suffers from the multi-path propagation and the time-variability of the underwater medium. The major reason for multi-path propagation is the reflections from the ocean surface and the ocean floor. Additionally, temperature and conductivity (salinity) differences form virtual layers which have varying reflection and refraction properties and they contribute to the multi-path propagation. Time-variability is mainly due to the surface waves where the place of the reflection point changes with the waves [35]. Consequently, low link quality causes high Bit Error Rate (BER). [7] reports a BER of 10^{-2} although less BERs can be attained in the new acoustic modems. Additionally, link quality of the acoustic channel depends on the direction of the communication (vertical or horizontal) and the deployment environment of the system (deep water or shallow water). For the former, the vertical channel has less multi-path spread than the horizontal channel, and for the latter, in shallow waters multi-path is more pronounced due to ocean floor and surface bounces [29].

The propagation speed of the acoustic signal is slow, introducing a large propagation delay which is almost five orders of magnitude higher than radio communications. In addition, temperature and salinity variations in different parts of the ocean affect the speed of sound and cause high delay variance [3].

In a mobile UASN, motion of the sensor nodes may create the Doppler effect which is due to the relative motion of the transmitter or the receiver. In underwater applications, mobile platforms such as AUVs can move with a speed of several knots, while untethered, free-floating equipments can drift with the ocean currents which are generally slower than 1 knot. Doppler effect is related with the ratio of the relative transmitter-receiver velocity and the speed of the signal. Since the speed of sound in water is slower than speed of the electromagnetic waves in the air, Doppler effect can be more significant in UASNs than in WSNs. Mobility also mandates that the localization process is repeated at certain intervals so that the node locations do not become obsolete. Therefore, mobility introduces another challenge from the view point of communications overhead and energy-efficiency. Energy-efficiency is required since underwater equipments are expected to be left in the ocean for several weeks or months before they are collected and recharged for their next mission. Each mission cycle will possibly involve vessels to collect the sensors and due to the high cost of vessel operation, longer mission cycles are desired. It may be also possible to have energy harvesting UASNs in the future. Underwater sensor nodes may benefit from the force of currents or solar radiation or wind power to generate their own energy, however those energy sources are intermittent and energy-efficiency is again essential for UASNs. Currently, energy harvesting underwater sensor nodes are not available because of size and cost limitations.

Briefly, in UASN research, application, transport, network, medium access, synchronization and localization studies aim to provide successful operation of the UASN under the adverse channel conditions and the additional challenges due to mobility and energy limitations [36].

III. UASN Architectures

UASN architectures can be classified based on two criteria, one is the motion capability of the sensor nodes, such as stationary, mobile or hybrid UASNs, and the other is the spatial coverage of the UASN such as two-dimensional or three-dimensional UASNs.

In the stationary UASNs, sensor nodes are attached to surface buoys or ocean floor units which have fixed locations. Stationary UASNs are utilized for monitoring a certain region, e.g. the harbor entrances. In the mobile UASNs, mobility of the nodes may have different characteristics. In a UASN with unpropelled and untethered sensor nodes, the nodes float freely underwater and drift with the currents. In a UASN with propelled sensor nodes, the motion of the nodes can be controlled by inertial navigation devices. Examples of such propelled equipments are AUVs and Unmanned Underwater Vehicles (UUVs) while examples of unpropelled mobile equipments are drifters, floats, profiling floats and gliders. These equipments have been used in oceanography for collecting measurements from the various layers of the ocean. Drifters operate on the surface and drift with the winds and the surface waves while floats move with the subsurface currents and they are able to operate at several hundreds of meters below the surface. Profiling floats also drift with the subsurface currents however they have the capability of moving up and down by using buoyancy properties. They have been utilized for collecting measurements from the depths of the oceans and delivering those information to the on-shore command centers via satellite [19]. Gliders are buoyancy-driven devices, i.e., they can move vertically similar to profiling floats. In addition to that, they can also move horizontally by the help of their body and wing design. In hybrid UASN architectures, stationary and mobile nodes coexist. In [37], [38], a hybrid architecture has been employed where a mobile sink node traverses the network and collects data from the underwater sensor nodes.

The latter classification of UASN architectures is based on spatial coverage property. In the two-dimensional UASNs, all of the sensor nodes are assumed to be at the same depth, e.g. they may be deployed on the ocean surface or the ocean floor, or they may be floating at a certain depth. In the three-dimensional UASNs, each sensor node may be floating at an arbitrary depth [39]. In general, stationary sensor networks are considered to be two-dimensional since the sensor nodes are placed on the surface buoys or ocean floor anchors. However in [40], the authors have used stationary surface buoys with tethered sensor nodes where the length of the tether is modified to increase the coverage of the network, forming a three-dimensional UASN.

The richness of UASN architectures is partly due to lack of a standard UASN description and partly due to the large number of applications and their specific design requirements. A more detailed survey of UASN architectures is given in [41]. Here, we briefly summarized the architectures as there are several localization techniques that are tailored for specific architectures, and there are architectures where localization might be simpler than the others. For example, for a two-dimensional stationary UASN with nodes deployed on the sea surface, GPS can be used for localization, or for a similar UASN with ocean floor units, the nodes may be deployed in predefined locations so that localization is trivial. Moreover, stationary UASNs do not require periodic localization as the mobile UASNs do, which means localization protocols with relatively high communication overhead may still be used since they will only run at the setup time. As obvious from these examples, the choice of the localization protocol may depend on the architecture. However there are also architecture-independent localization techniques.

IV. Localization Techniques for UASNs

Localization for UASNs has been one of the major research tracks since UASNs started to draw the attention of the networking community in the early 2000s. Localization has also been widely studied in the WSN context and detailed surveys of these techniques have been presented in [12] and [42]. Briefly, for outdoor terrestrial WSNs, GPS-based localization schemes have been proposed which cannot be directly applied to UASNs because the high frequency GPS signals attenuate in water and cannot reach to the nodes at several meters below the surface. On the other hand, GPS-less localization schemes generally introduce high communication overhead [43], [44].

Since WSN localization techniques cannot be applied to UASNs, novel localization protocols have been proposed in the literature. We group these techniques under two categories as centralized and distributed techniques. Centralized techniques calculate the location of each sensor node in a command center or sink, and the sensor nodes do not know their locations unless the sink node explicitly sends this information. These techniques may localize nodes at the end of the mission, i.e. in post-processing stage, or they may periodically collect information to track sensor nodes. Distributed localization techniques allow each sensor node to do localization individually. We divide the centralized and distributed techniques into two subcategories as estimation-based and prediction-based schemes. In estimation-based methods, the current location of the sensor node is of interest and it is calculated with the most recent information available. On the other hand, in the prediction-based schemes, the location of a node at the next time instant is predicted using distance measurements, previous node locations and anchor locations. Prediction-based schemes can be applied to mobile or hybrid UASNs.

A. Centralized Localization Techniques

In this section, we will summarize six centralized localization schemes where five of them are estimation-based and one of them is prediction-based.

1) Estimation-based Schemes:

a) Motion-Aware Self Localization (MASL) Technique: In [45], the authors propose the MASL scheme for a mobile UASN. The main idea of the study comes from the observation that in a mobile network, distance estimates between nodes may become obsolete when one of the nodes move. In the underwater environment, due to long propagation delays, collecting the number of distance estimates required for localization may take relatively long time which increases the possibility of obsolete information. MASL aims to address the inaccuracies in the distance estimates and provide accurate localization. It targets applications where the relation between data and location is resolved at the post processing stage by a central station. In MASL, an underwater node collects distance estimates between itself and its neighbors. The distance estimates are fed into an iterative estimation algorithm when the UASN mission ends. At each iteration, the algorithm refines position distributions by diving the area of operation into smaller grids, selecting the area in which the node resides in with high probability and using it in the next iteration. In [45], the authors model the ocean currents as layers with equal thickness and varying speeds, and assume that the sensor nodes move with those currents. The advantages of MASL are reducing the computational burden of the underwater nodes and being anchor-free. On the other hand, the major drawback of the scheme is its inconvenience for the applications that involve online monitoring, coordinated motion or actuators that use real-time location information. Other drawbacks are the need for synchronization and frequent messaging for distance estimation. Although synchronization may be established by relatively inexpensive high precision clock modules for relatively short-term underwater missions, a synchronization protocol may be necessary for long-term underwater missions [7].

Authors tackle the synchronization problem in [46] and propose the Sufficient Distance Map Estimation (SDME) scheme. SDME establishes post-mission synchronization in order to calculate accurate post-mission distances. Accurate distance estimation has been studied in [47], as well. In the underwater medium, the propagation speed of the acoustic signal may be different along the multiple paths where in some cases the direct path between two nodes may not be the first arrival. This property may lead to inaccurate distance estimates. In [47], multiple range measurements are fed into the weighted Gerchberg-Saxton algorithm (WGSA) to identify the direct path and improve the accuracy of distance measurement.

b) Hyperbola-based Localization (HL): HL adapts the conventional sound source localization problem in oceanography to localization of stationary, two-dimensional UASNs [48], [49]. In the traditional oceanographic systems, the location of a sound source, e.g. a see mammal, can be detected by a set of hydrophones (sensors) with known locations [50] using the hyperbola-based localization approach. In [48], [49], the authors apply source localization to sensor localization by replacing the sensors/hydrophones with anchors and the event with an unknown sensor. In HL, the sensor node (event in the traditional oceanographic systems) sends long-range signals (around 1km) to the anchor nodes (sensors or hydrophones in the traditional systems), and its location is estimated by a centralized node. HL has several architectural constraints, i.e. the anchor nodes need to be placed at the corners of the UASN and hence it is not extendable to three-dimensional mobile UASNs. Moreover, underwater sensor nodes consume excessive energy for sending long-range signals.

c) Area-based Localization Scheme (ALS): ALS has been initially proposed for terrestrial WSNs in [51], and it is employed to stationary, two-dimensional UASNs in [52]. ALS is a coarse-grained localization technique which gives an estimate of the area where the sensor node resides in, rather than the exact 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 measurement at the sensor node. An underwater node passively listens to the anchor messages, keeps a list of the 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 when the anchors are able to modify their transmission power. The advantages of ALS are being range-free, computationally light, having no synchronization requirement and having no need for measuring the received signal strength. On the other hand, it is not suitable for applications that require online location estimates. It is also coarse-grained, hence it is not convenient for applications that require accurate localization. Nevertheless, its accuracy may be improved by increasing the number of anchors or by using specialized hardware to generate smaller steps in power levels. Furthermore, ALS incurs high communication overhead and high energy consumption due to sending localization related messages to the sink node.

d) Three Dimensional Multi-power Area Localization Scheme (3D-MALS): In [53], the authors propose 3D-MALS which extends ALS to three dimensional UASNs. 3D-MALS combines the idea of anchors with variable transmission power levels of [52] and the idea of anchors with vertical mobility of [54]. The vertical mobility is implemented as follows. Surface buoys of [53] house a mechanical unit that works like an elevator for the underwater transceivers, which are called Detachable Elevator Transceivers (DETs). In 3D-MALS, DETs broadcast their set of GPS-driven coordinates at varying power levels as they descend underwater. Unlocalized nodes collect mobile anchor positions and their respective lowest power levels and send these to the sink node. Sink node uses the power level values and anchor locations to determine the area at which the node resides in. 3D-MALS may introduce additional overhead by sending anchor locations and power levels to the sink node where sensor nodes can already estimate self location using the anchor messages.

e) Silent Localization using Magnetometers (SLM): SLM is proposed in [55] where the authors target surveillance applications. In SLM, the sensor nodes are not allowed to use acoustic communications to be completely hidden. They are assumed to send data via wired communications. The term "silent" is generally used in the literature to refer to the localization techniques that do not require sensor nodes to send packets for localization, and the sensors are localized by listening to the messages of the anchor nodes. SLM assumes that the underwater nodes are equipped with triaxial magnetometers, accelerometers and pressure sensors, and a friendly vessel with known static magnetic signature is assumed to be helping localization. The magnetic signature of a vessel is a result of its construction materials such as iron. SLM reverses the well-known Simultaneous Localization and Mapping (SLAM) problem of robotics. In SLAM, the position of the landmarks and the vehicle/robot trajectory are estimated simultaneously. In SLM, sensors are assumed to be observing the vessel from the landmark positions. SLM assumes that the sensors estimate their depth via pressure sensors and the accelerometer gives the orientation of the sensor nodes which is used to estimate the trajectory of the vessel. The trajectory of the vessel and the locations of the sensors are estimated simultaneously using an extended Kalman filter. The results of the Kalman filter is translated into global locations when one sensor with known global location is available. SLM is a costly localization method where sensors are equipped with additional hardware and a vessel is involved in localization. Since it targets shallow water military applications, in [55], the major objective of the study has been silent localization. For civilian applications, SLM can be favored for its energy-efficiency since underwater sensors do not spend energy for localization. Although SLM has been initially proposed for wired underwater networks it can be extended to UASNs. However, the cost of operating a ship and the cost of the additional hardware is the drawback of SLM.

2) Prediction-based Scheme:

a) Collaborative Localization (CL): CL scheme is proposed in [56] considering a mobile UASN application where underwater sensor nodes are responsible for collecting data from the depths of the oceans and carrying them to the surface. The architecture employs two types of underwater nodes that are "profilers" and "followers." Both type of nodes descend underwater however profilers descend ahead (deeper) of the others. The distances between the profiler and the followers are periodically measured using the ToA technique (Figure 4) in order to position the profilers with respect to the followers. The nodes descend with the same speed and they move in the same reference frame. The location of the profiler gives a prediction of the future locations of the followers since the followers will be drifting horizontally with the currents similar to the profiler. The authors assume the network descends with a constant velocity (v_z), and hence the differential depth (α) between nodes do not change. One of the drawbacks of CL is the synchronization requirement. Another drawback of CL is its architectural dependence, i.e., for a sparse or non-homogenous network, the performance of CL could degrade significantly.

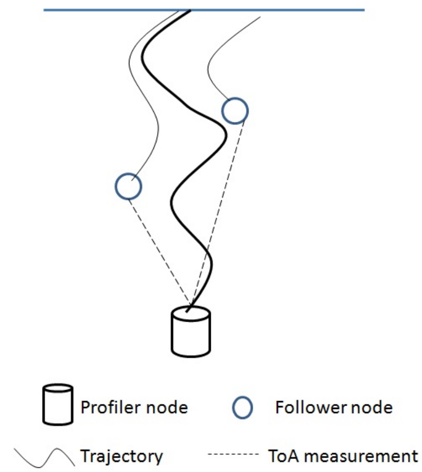

Fig. 4. Profiler and follower nodes of the CL scheme.

B. Distributed Localization Techniques

In distributed localization techniques, each underwater sensor node collects localization related information; such as anchor positions, distance to anchors or neighbors, or connectivity information and then, runs a location estimation algorithm individually.

1) Estimation-based Schemes:

a) AUV-Aided Localization (AAL): In [57], the authors propose the AAL scheme for a hybrid, three dimensional UASN where the underwater sensor nodes are stationary and an AUV travels in the UASN region. An illustration of the network is given in Figure 5. AUV is a propelled underwater vehicle which is able to attain its location in underwater by a technique called dead-reckoning. Dead-reckoning is possible with the expensive inertial navigation tools and the location has to be calibrated periodically. For this reason, the AUV surfaces to receive GPS coordinates at certain intervals. During one cycle of operation in underwater, it broadcasts "wake-up messages" from different places on its route. When an underwater sensor node hears this message, it starts the localization process by sending a request packet to the AUV, and the AUV replies with a response packet. This request/reply packet pair enables two-way ranging and the reply packet of the AUV contains its coordinates, therefore after the message exchange from three different non-coplanar AUV locations, the underwater node executes lateration to estimate self location. AAL utilizes two-way ranging which alleviates the need for synchronization but on the other hand, nodes spend more energy than they do in silent schemes and the communication overhead of the protocol increases. Another drawback of AAL is that its accuracy is affected by the frequency of the location calibration of the AUV.

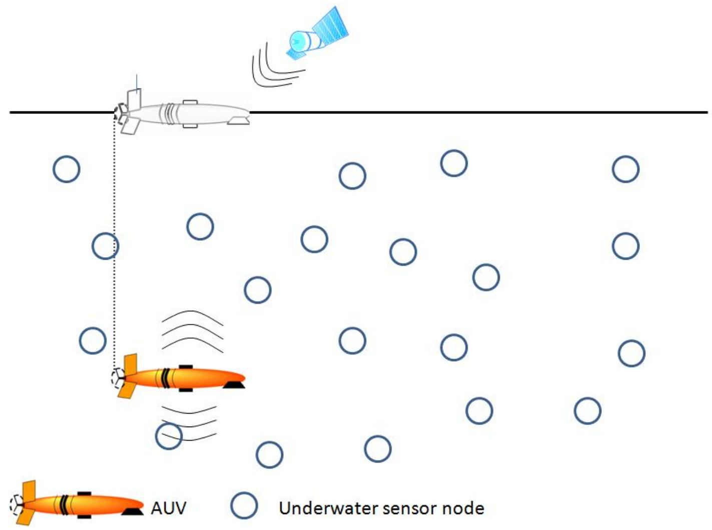

Fig. 5. Localization with AAL.

The accuracy of AAL improves when the AUV frequently surfaces for location calibration, however this may drain the battery of the AUV fast. In literature, various techniques have been proposed for charging the batteries of the AUVs such as using photovoltaic panels [58] or recharging their batteries under water using ocean floor docking stations [59]. Yet, these techniques are not mature enough. Another drawback of AAL is its high localization delay due to the slow speed of the AUV (around 2-3 knots). Providing localization information for the three dimensional UASN using a single AUV may take long time whereas using multiple AUVs would certainly increase the cost.

b) Localization with Directional Beacons (LDB): LDB is proposed for a hybrid, three dimensioanl UASN where stationary underwater nodes are localized by an AUV similar to the AAL scheme [60], [61]. AUV receives its coordinates from the GPS while floating on the surface, then it dives to a certain depth and does dead-reckoning for self localization in underwater. The difference of LDB from AAL is that the AUV travels above the area of operation as shown in Figure 6a, and it uses a directional acoustic transceiver to broadcast its coordinates and the angle of its transceiver's beam. The angle information is used by the sensor node to map the AUV coordinates to the same horizontal plane with itself. The sensor node calculates its x-coordinate as the average of the x-coordinates of the AUV at two points on the circle as shown in Figure 6b. The circle is the communication range of the sensor node. Ideally, the node should be able to attain the coordinates of the AUV when the AUV enters and exists its communication range. In Figure 6b, $x_{t_1}^{AUV}$ is the projection of the x-coordinate of the AUV at time t_1, when the AUV enters in the communication range of the sensor node, and $x_{t_2}^{AUV}$ is at time t_2 when the AUV exits the communication range. y-coordinate is estimated by using the range, r, x and y^{AUV}:

$$y = y^{AUV} + \sqrt{r^2 - \left(\frac{x_{t_1}^{AUV} - x_{t_2}^{AUV}}{2}\right)^2} \qquad (6)$$

Since LDB is a range-free, silent localization technique, it is more energy-efficient than the AAL technique. One of the drawbacks of LDB is that the AUV is restricted to travel above the UASN region which may not be possible in practice. Furthermore, the frequency of the AUV messages impacts the accuracy of localization. In some cases, if the AUV sends beacons with too long intervals, underwater nodes may not be able to obtain their locations or two nodes may estimate the same location.

c) Dive and Rise Localization (DNRL) Protocol: DNRL is a distributed, estimation-based localization protocol [54]. It utilizes mobile anchor nodes to help localization of the underwater nodes and these anchors are named as "Dive'N'Rise (DNR) beacons." DNR beacons are able to descend and ascend by using the hydraulic principles similar to the profiling floats. They carry GPS receivers and attain their coordinates from the GPS while they are floating on the surface. Then, they descend until a pre-calibrated depth, and while descending they announce their coordinates at several intervals. In one round of localization, mobile anchors ascend to the surface to receive the updated GPS coordinates. Afterwards, they periodically descend and ascend until the end of the UASN mission. Underwater sensor nodes listen to the time-stamped DNR messages and use ToA technique with one-way ranging to calculate their distances to the DNR beacons. The distance estimates and the coordinates of the anchors are used in lateration. One of the advantages of DNRL is being silent which yields low communication overhead and high 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 by surfacing periodically. On the other hand, DNRL requires a large number of DNR beacons for high localization success while the DNR beacons are expected to be more expensive than the other underwater nodes due to their motion capability. Moreover, DNR beacons are not able to descend fast because they are not propelled. This leads to non-homogenous diffusion of the location information where the nodes that float deeper receive DNR messages later than the

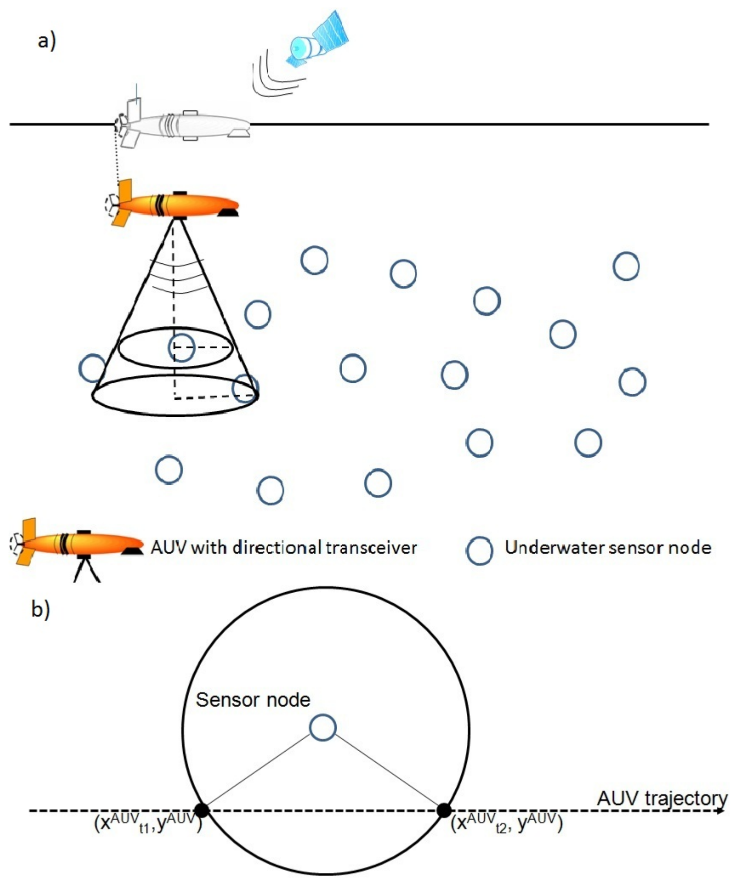

Fig. 6. a) AUV with directional beam in the LDB scheme b) sensor localization in LDB.

nodes closer to the surface and it also increases the localization delay. Note that, DNRL protocol also requires synchronization due to one-way ranging in ToA calculations.

d) Multi-Stage Localization (MSL): In [62], the authors propose the MSL scheme which addresses the coverage and delay concerns of DNRL by adding an iterative localization phase and using successfully localized underwater nodes as anchors. An unlocalized node uses the coordinates and distance measurements from three non-coplanar nodes which may be DNR beacons or a localized underwater node. One of the major drawbacks of MSL is its high communication overhead due to iterative localization. For this reason, it is less energy-efficient than DNRL. Moreover, in MSL, localized underwater nodes provide their estimated locations, which already include estimation errors. Error accumulates at the nodes that use the coordinates of the localized underwater nodes instead of the coordinates of the anchor nodes. MSL also requires synchronization due to one-way ranging ToA method, similar to DNRL.

To the best of our knowledge, MSL is one of the first localization studies that use a realistic underwater mobility model. Conventional mobility models such as, random way point mobility and group mobility that have been used for Mobile Ad Hoc Networks (MANETs), do not fully capture the motion of the underwater nodes. Accurate underwater mobility modeling is closely related with the ocean currents which have been studied for a long time in oceanography. A simple model using a kinematic approach has been introduced in [63], [64]. This kinematic approach is employed to UASNs to represent the mobility of the underwater sensors drifting with subsurface currents in [65] and it was called as the Meandering Current Mobility (MCM) model. MSL uses an extended version of MCM that includes the sensor mobility close to the ocean surface.

e) Large-Scale Hierarchical Localization (LSHL) Protocol: In [66], the authors propose a hierarchical localization scheme for a stationary UASN. LSHL employs three types of nodes: "surface buoys", "anchor nodes" and "ordinary sensor nodes". Surface buoys are equipped with GPS receivers and they float on the surface, hence they are able to attain their coordinates via line of sight communication with the satellites. "Anchor nodes" float underwater and they are assumed to be localized by the surface buoys at an earlier deployment stage. LSHL considers only the localization of the ordinary sensor nodes. In the "ordinary sensor localization process", anchor nodes periodically broadcast their coordinates. Ordinary nodes exchange beacons with their peers. Beacons are short messages sent periodically to measure distance to the neighbors. The distance is measured with one-way ranging ToA method. If an ordinary node gathers the coordinates of three non-coplanar anchors, and the distance in between, it performs lateration to estimate its location. A localized underwater node may become a "reference node" if its confidence value is above a certain threshold. A reference node broadcasts its coordinates while an unlocalized node broadcasts the received localization messages along with the distance measurements

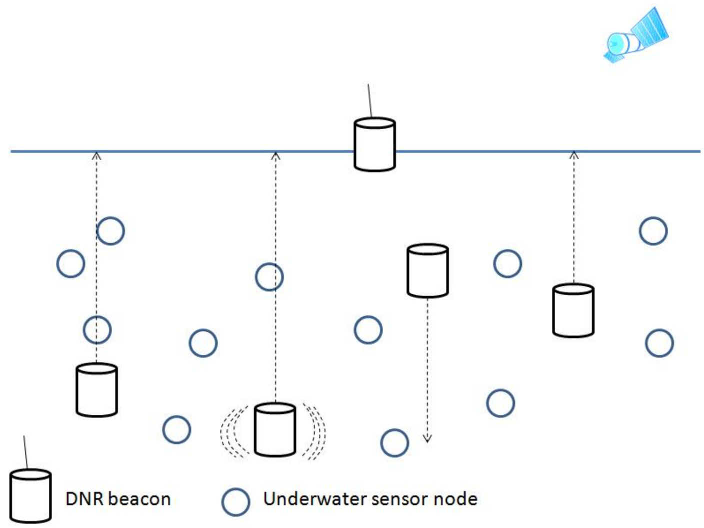

Fig. 7. DNRL technique with mobile DNR beacons.

to the anchors and other neighboring nodes. Another non-localized node may use this information in the extended Euclidean distance estimation algorithm which has been introduced in [66].

The extended Euclidean distance estimation determines the distance to an anchor node that is two-hops away. Figure 9 shows an example topology. For example, say node E hears the coordinates of node A from its neighbors but it needs the distance in between to use in lateration. In this case, node E needs to have at least three neighbors (B, C and D) which have distance estimates to A. Moreover, E should have the length information of EB, BA, EC, CA, ED, DA, DB, DC, and BC edges. Note that, in the Euclidean distance estimation method, nodes A, B, C and D should not be coplanar and any three nodes out of A, B, C, D and E should not be collinear. Here, node E uses the edges BA, CA, BC to construct the basic localization plane. Since the lengths of edges DB, DA and DC are already known, the relative position of D is estimated by lateration. Then, E estimates its relative location by lateration. After that, based on the relative locations of node E and A, node E calculates the Euclidean distance to node A.

LSHL is an hierarchical protocol which provides the opportunity to be used in large-scale UASNs. Its main drawback is having high energy consumption and communication overhead due to beacon exchanges, localization messages and the messages forwarded by unlocalized nodes. In [67], the authors show that LSHL has the highest energy consumption and the highest overhead when compared to DNRL and MSL. Another significant drawback of LSHL is the assumption of establishing anchor localization separately, and omitting its impacts on the ordinary sensor localization process. Moreover, LSHL requires synchronization similar to the other techniques that use one-way ToA method.

f) Detachable Elevator Transceiver Localization (DETL) Protocol: In [68], the authors use the DET units that are also employed in [53] and they utilize the same architecture of LSHL. DET eliminates the need for long-range communication between surface buoys and anchors and solves the anchor localization problem of LSHL. Surface buoys learn their coordinates from GPS, DET units descend and ascend, and broadcast surface buoy coordinates at several depths, similar to DNRL beacons but this time they are attached to cables. Anchor nodes are localized using the coordinates of the DETs and the distance estimates to those units. Ordinary sensor nodes are localized similar to LSHL. DETL may be a practical solution for anchor localization for deep and narrow UASNs where DETs can descend until a certain depth and broadcast coordinates with short-range acoustic links. However, for a horizontally wide UASN, either the number of DETs needs to be increased or DETs would use long-range communication.

g) Three-Dimensional Underwater Localization (3DUL): In [69], the authors propose an iterative localization scheme for hybrid UASNs. Localization starts with a ranging phase where the surface anchors broadcast their GPS-driven coordinates. Underwater sensor nodes, that are in one hop distance, receive the anchor packets and send a response back to the anchors to measure the distance using two-way ranging ToA technique. When distance measurements to three anchors are completed, the sensor node projects the location of the anchors on its plane and estimates self location via lateration. Following localization phase, the underwater node becomes an anchor, and the above process continues iteratively similar to MSL and LSHL. The drawback of 3DUL is the long localization delay. In underwater acoustic propagation is already slow, using two-way ranging and a limited number of initial anchors at the surface may increase the localization delay. In mobile UASNs localization delay is a significant factor affecting the localization accuracy.

h) Anchor-Free Localization (AFL): In [70], [71], the authors propose the AFL method for stationary UASNs. Similar to terrestrial anchor-free methods [43], AFL is based on sharing distance estimates among neighbor nodes. Since underwater environment is bandwidth limited, the authors propose to use "seed" nodes to control the communication overhead and avoid contentions during localization epochs. In AFL, localization starts with a "node discovery" process

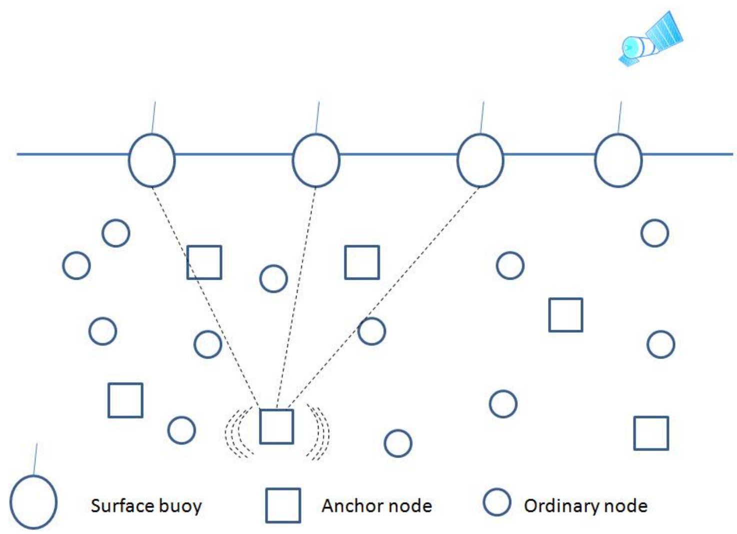

Fig. 8. The hierarchical LSHL architecture.

initiated by a seed node (S_1). S_1 broadcasts a message to its neighbors and collects replies from the neighbors which contain their distance estimates to S_1. Then, it selects the second seed node (S_2) among its neighbors as the furthest node and broadcasts the ID of S_2. Second seed node repeats the same procedure to select a third seed node, S_3. After each new seed selection, the distance of the new seeds are broadcasted by the other seeds. In this way, the sensor nodes that reside in the intersection area of three seeds can determine their positions by trilateration (Figure 10). For positioning the nodes in the unshaded parts of Figure 10, new seed nodes are selected in the same way as described before. AFL forms a local coordinate system in the node discovery phase without the need of an anchor (the location of S_1 can be assumed as (0,0)). Local coordinates can be translated into global location when the global coordinates of seeds are known. The major drawback of AFL is its high energy consumption and communication overhead. Moreover, node discovery process may take long time due to the long propagation delay in underwater.

i) Underwater Positioning Scheme (UPS): In [72], [73], the authors propose UPS which is an extension of the terrestrial WSN localization scheme that has been introduced in [74]. UPS is a TDoA-based localization scheme for stationary UASNs. It employs four anchors which sequentially send beacon signals. One of the anchors is selected as a master anchor and it initiates the localization process. An illustration of the UPS scheme is given in Figure 11. Assume that the master anchor is selected to be Anchor A of Figure 11. When it sends the beacon signal, Anchor B and Sensor node S hear this signal. Anchor B replies to Anchor A by sending the time difference between the arrival time of the Anchor A's beacon signal and the transmission time of its beacon signal. Following Anchor B, Anchor C and D repeats the same process sequentially. Node S hears these anchor beacons and calculates the TDoA between the beacons. Then, it converts TDoA values to range differences by multiplying them with the speed of sound. Node S is assumed to know the locations of the anchors and it estimates self location using anchor

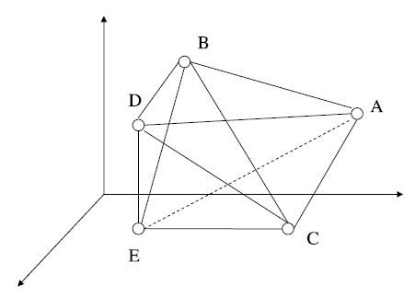

Fig. 9. Extended Euclidean distance estimation.

locations and the range differences in trilateration equations. Since UPS uses TDoA it does not require synchronization. Additionally, the underwater nodes do not send localization messages hence UPS is silent. Its communication overhead and energy consumption are low. On the other hand, the drawback of UPS is that it cannot localize the nodes that reside outside the enclosed area by four anchor nodes [72]. To increase its coverage, long-range anchors may be used which causes a similar problem with the LBL method, i.e., localization messages may interfere with the communication of the underwater sensor nodes. Moreover, the anchor locations need to be fixed and their locations need to be known by the sensor nodes which may not be possible or hard to obtain in practice.

j) Wide Coverage Positioning (WPS): In [75], the authors show that the UPS technique may not be able to uniquely localize all of the sensor nodes in the enclosed area of four anchor nodes. They show that the sensor nodes that reside close to the anchor nodes require five anchors and the authors propose WSP in [75] to overcome this problem. WPS uses four anchors whenever unique localization is attainable by using four anchors (called as UPS(4)), otherwise WPS uses five anchors (UPS(5)). UPS(4) and UPS(5) are used together to reduce the communication overhead for the nodes that are already localizable with four anchors. These nodes spend the same amount of energy as in the original scheme proposed in [72]. The nodes that reside close to the initial set of anchor

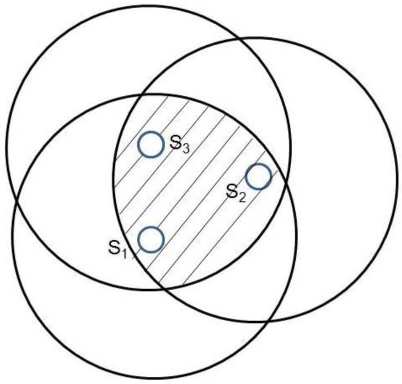

Fig. 10. AFL with three selected seeds at the node discovery phase.

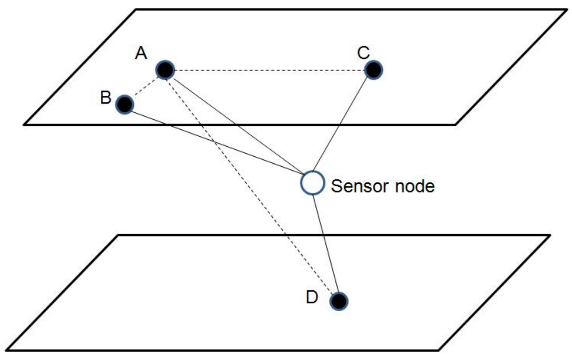

Fig. 11. UPS scheme using TDoA from four anchors.

nodes, require an additional anchor to ensure a unique location estimate. WPS also includes a time-out value for the maximum waiting time of the anchor node messages. UPS with timeout has been initially proposed in [76] to design an underwater positioning system for deep-water installations. In WPS, if a message is lost due to adverse acoustic channel conditions, the sensor node waits for a timeout period and then, re-initiates the localization procedure. WPS is claimed to provide higher unique localization success than UPS however its localization delay and communication cost is higher than UPS.

k) Large-Scale Localization Scheme (LSLS): In [77], the authors propose the LSLS scheme which increases the coverage of UPS by adding an iterative localization phase and a complementary phase. Initially, LSLS uses UPS to localize the underwater nodes that can communicate with the anchors. In the iterative localization phase, certain localized nodes are selected as reference nodes. They act as the anchors of UPS and help in localizing the other underwater nodes. In the complementary phase, unlocalized nodes initiate a localization request which results in selecting a different set of reference nodes and repeating the UPS scheme. LSLS inherits the advantages of UPS, and it can additionally localize a large-scale UASN with short-range acoustic communications. Iterative phase increases coverage while the complimentary phase can address the unique localization concerns raised in [75]. On the other hand, LSLS has higher communication overhead and energy consumption than UPS since in the iterative and complementary phases underwater nodes send messages.

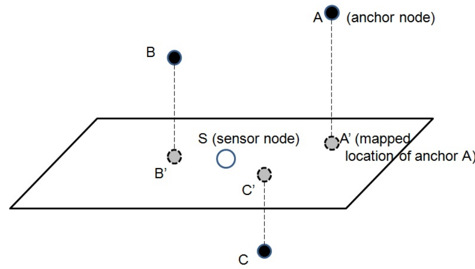

Fig. 12. The projection technique of USP scheme.

l) Underwater Sensor Positioning (USP): In [78]–[80], the authors propose the USP scheme for three dimensional UASNs as illustrated in Figure 12. In USP, underwater nodes are assumed to be equipped with pressure sensors by which they learn their depth. An underwater node uses the depth information to map the available anchors on the horizontal plane it resides on. While mapping from three dimensions to two dimensions, some anchors may have overlapping locations. In such cases, the underwater node selects another set of anchors. At each iteration of USP, localized underwater nodes broadcast their location and refine their location estimates using the messages of their neighbors. The unlocalized nodes try to establish localization using two anchors which is called as bilateration. If a unique location cannot be computed with two anchors, the node waits until it hears from other localized neighbors. This localization procedure is re-initiated after a sleep period which is pre-configured. As a drawback of USP, to comply with such timing requirements, the nodes need to be synchronized. Note that, the ranging method has not been specified by the authors. If ToA is used synchronization may be also required for distance estimation. Another drawback of USP is its high communication overhead and energy consumption due to distance estimation process and each node broadcasting self coordinates. Moreover, USP has lower localization success than the other surveyed localization techniques, even under moderate degree of connectivity according to [78]. However, its performance may be improved by increasing the initial number of anchor nodes where in [78] three anchors are selected to bootstrap the localization procedure.

2) Prediction-based Scheme:

a) Scalable Localization with Mobility Prediction (SLMP): In [81], the authors propose SLMP for a mobile UASN. Following [66], surface buoys, anchor nodes and ordinary sensor nodes are used. Anchor nodes estimate their locations by using their previous coordinates and their mobility patterns. Since mobility patterns may become obsolete in time, anchor nodes periodically check the validity of the pattern. When the model is no longer valid, anchors trigger updates. The validity of the model is checked as follows. Surface buoys receive their coordinates from GPS and send these to anchor nodes. An anchor node, after predicting its location, uses surface buoy coordinates and distance measurements to buoys in lateration, and estimates its location. If the Euclidean difference between the predicted and the estimated locations is less than a threshold, then the anchor node assumes its mobility model is valid. 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 mobility patterns, as well as their locations. The ordinary nodes use the mobility pattern to predict their locations, and the pattern is assumed to be valid until an update from an anchor node is received. In SLMP, communication overhead and energy consumption depend on the mobility pattern. SLMP uses a temporally and spatially correlated mobility model which represents the tidal currents in shallow waters. Due to this correlated motion, SLMP requires low number of updates and consequently its communication overhead and energy consumption are low.

V. Discussion and Open Research Issues

We surveyed the UASN architectures and the localization protocols proposed for UASNs in the previous sections. In this section, we summarize the main properties of these localization techniques, compare their performances and point out the open research problems. The majority of the localization schemes for UASNs are distributed and estimation-based techniques. Distributed techniques are convenient for applications that require online location information while generally estimation is more practical since it requires less computation than prediction, and it can be employed to both stationary and mobile UASNs. On the other hand, prediction-based schemes inherently address localization of mobile UASNs.

Localization techniques employ various types of ‘nodes with known locations’. In Table I, we use ‘anchors’ to mention special nodes that know their locations without the need of a localization protocol. We use ‘reference nodes’ to mention the successfully localized nodes that act like an anchor and broadcast their coordinates. Among the surveyed techniques, there are also some studies that do not utilize anchor nodes such as MASL and CL. Anchors or references may be mobile where the mobility might be due to drifting with the currents or sinking with buoyancy alteration or the mobile device might be propelled such as an AUV. In these cases, the speed of the mobile node, the frequency of localization messages and the frequency of location calibration of the mobile node becomes significant factors affecting the accuracy of the localization protocol. Note that, in Table I, we do not include SLM technique since it has been originally proposed for wired underwater sensor networks.

Localization techniques also show differences in the ranging methods they employ. Generally, one-way or two-way ToA is employed. However there are several methods that employ TDoA or that do not use distance measurements which are called as range-free, such as ALS and LDB. For the localization studies that do not specify any ranging we mention those as “Not specified”. One-way ToA based schemes require synchronization and lack of synchronization may yield inaccurate estimates while two-way ToA, TDoA-based and range-free techniques have high communication overhead and energy consumption.

In Table I, we present the message exchange properties of the localization schemes, as well. Some methods only allow anchors to send localization messages and the underwater nodes do not send messages. These techniques are called as ‘silent’ while in some techniques underwater nodes also send messages for localization. These methods are called as ‘active’ methods since the underwater nodes participate in the localization procedure. Active localization have higher communication overhead and higher energy consumption than the silent localization. Additionally, silent localization techniques may preserve the anonymity of the sensor nodes. On the other hand, silent protocols generally require more number of anchor nodes or anchors with long-range communication capabilities.

In UASNs, correlated motion of the underwater nodes which is due to the spatio-temporally correlated ocean currents may provide localization with less overhead and less energy consumption for the prediction-based schemes. However, realistic underwater mobility models can be complex and they may show regional and seasonal variations. Among the surveyed localization protocols MSL, MASL and SLMP employ relatively realistic mobility models. MSL uses the MCM model that is based on a kinematic approach borrowed from oceanographic studies. MASL models the current streams as layers with equal thickness and varying speeds. SLMP uses a model of the tidal currents in shallow waters. Analyzing the performance of prediction-based localization schemes on accurate mobility models is still an open issue.

In UASNs, geographic routing protocols appear as promising alternatives however they generally require accurate location information. The impact of various localization techniques on the performance of the geographic routing algorithms have not been explored. Moreover, geographic clustering schemes may be impacted from the underlying localization technique, as well. The impact of localization on networking and other UASN applications is an open issue.

Furthermore, majority of the localization protocols assume that the localization task is performed independent of the other networking tasks. However, cross layer operation can improve the energy-efficiency of the localization in many of the proposed techniques. For instance, residual battery lifetime could be considered in reference node selection in the iterative schemes. Another example could be using link quality information in selecting anchor nodes or reference nodes which may improve the accuracy of the distance estimates and consequently improve the location estimates. Such cross layer approaches are still open issues.

VI. Conclusion

In UASNs, localization is a fundamental task where the location of a sensor can be used for data tagging, node tracking and target detection. Traditional oceanographic equipment localization techniques and WSN localization protocols do not meet the requirements of UASNs where the adverse conditions of the underwater medium call for novel techniques. Recently, a large number of localization techniques have been proposed for UASNs. The majority of these studies assume that the localization schemes are coupled with a specific UASN architecture. Therefore, in this paper, we give a comprehensive survey of the UASN architectures and the localization techniques for UASNs.

TABLE I
PROPERTIES OF LOCALIZATION PROTOCOLS FOR UASNS

		Technique	Architecture	Anchor Properties	Ranging Properties	Messaging Properties
Centralized	Estimation	**MASL**	3D Mobile	No anchors	ToA (one-way ranging)	Active
		HL	2D Stationary	Stationary anchors	TDoA	Active
		ALS	2D Stationary	Anchors with variable power levels	Range-free	Active
		3D-MALS	3D Mobile	Mobile anchors (Electro-mechanical motion)	ToA (one-way ranging)	Active
	Prediction	**CL**	3D Mobile	No anchors	ToA (one-way ranging)	Active
Distributed	Estimation	**AAL**	3D Hybrid	Propelled mobile anchor (AUV)	ToA (two-way ranging)	Silent
		LDB	3D Hybrid	Propelled mobile anchor (AUV)	Range-free	Silent
		DNRL	3D Mobile	Non-propelled mobile anchors	ToA (one-way ranging)	Silent
		MSL	3D Mobile	Non-propelled mobile anchors and reference nodes	ToA (one-way ranging)	Active
		LSHL	3D Stationary	Surface buoys, underwater anchors and reference nodes	ToA (one-way ranging)	Active
		DETL	3D Mobile	Surface buoys with DETs, underwater anchors and reference nodes	ToA (one-way ranging)	Active
		3DUL	3D Hybrid	Three initial anchors and reference nodes	ToA (two-way ranging)	Active
		AFL	3D Stationary	Anchor-free (one initial seed)	Not specified	Active
		UPS	3D Stationary	Four stationary anchors	TDoA	Silent
		WPS	3D Stationary	Four or five stationary anchors	TDoA	Silent
		LSLS	3D Stationary	Stationary anchors	TDoA	Active
		USP	3D Stationary	Stationary anchors	Not specified	Active
	Prediction	**SLMP**	3D Mobile	Surface buoys, underwater anchors and reference nodes	ToA (one-way ranging)	Active

We group the UASN architectures based on their motion ability and spatial coverage, such as stationary/mobile/hybrid or two/three dimensional UASNs, respectively. Furthermore, we group the localization techniques under two categories, i.e. centralized and distributed techniques. Most of the underwater applications in literature demand distributed localization since they are more convenient for online monitoring systems than centralized protocols. However, distributed schemes require processing on the sensor nodes. Centralized and distributed localization schemes can be further divided into two categories as estimation-based or prediction-based techniques. Prediction is applicable to mobile UASNs and its accuracy depends on the underlying mobility model. The performance of the localization techniques under various mobility models are still unexplored. Moreover, future research needs to address the impact of the localization protocols on location-based routing and clustering protocols. In addition, cross layer approaches such as the ones considering the link quality in the underwater medium or the energy indicators of the underwater nodes are among the open issues.

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