A Three Dimensional Localization Algorithm for Underwater Acoustic Sensor Networks

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***Abstract*—Although many localization protocols have been proposed for terrestrial sensor networks in recent years, the unique characteristics of the underwater acoustic communication channel, such as high and variable propagation delay and the three dimensional volume of the environment make it necessary to design and develop new localization algorithms. In this paper, a localization algorithm called Three-Dimensional Underwater Localization (3DUL) is introduced. 3DUL achieves network-wide *robust* 3D localization by using a distributed and iterative algorithm. Most importantly, 3DUL exploits only three surface buoys for localization initially. The sensor nodes leverage the low speed of sound to accurately determine the inter-node distances. Performance evaluations show that 3DUL algorithm provides high accuracy in underwater localization, which does not degrade with network size.**

***Index Terms*—Underwater acoustic sensor networks, 3D localization, tracking, mobility, navigation.**

I. Introduction

UNDERWATER Acoustic Sensor Networks (UW-ASN) are emerging as the enabling technology for exploring and monitoring the world under the surface of the water in a timely and effective manner. They can enable a broad range of applications such as ocean sampling networks, environmental monitoring, disaster prevention, distributed tactical surveillance and mine reconnaissance.

In order to realize the potential gains of these applications, it is essential that the sensor nodes know their positions in a 3D topology. Associating the sampled data with the position information considerably increases the capability of the network. Moreover, position information can be used by geographical routing protocols which are promising with their scalability and limited required signaling features [1].

There are many localization techniques proposed for wireless sensor networks (WSN) [9], [11]. However, a fast and reliable communication channel, as assumed by these protocols, does not exist in UW-ASN.

Acoustic communication channel has unique characteristics such as limited capacity and high propagation delay. Another challenge is that the speed of sound depends on temperature, pressure and salinity which causes the propagation path to be curved. Moreover, the sensor nodes may move due to water currents. Hence, the existing localization protocols for WSN cannot be applied to UW-ASN. On the other hand, there exist very few proposals for underwater localization [2], [19]. However, none of them provides a scalable, fine-grained, dynamic, three-dimensional yet practical localization solution for UW-ASN.

In this paper, we introduce the *Three Dimensional Underwater Localization* (3DUL) algorithm that seeks to achieve 3D localization in large-scale UW-ASN in a dynamic, energy-efficient, simple and accurate way. It has been tailored to match the unique requirements of UW-ASN. 3DUL initially exploits only three anchor nodes like buoys at the surface that diffuse their global position information into all directions in a 3D dynamic underwater network topology. 3DUL does not assume the presence of designated anchor nodes deployed underwater. Importantly, 3DUL also does not require time synchronization.

3DUL follows a two-phase process. During the first phase, a sensor node with unknown location determines the distances to neighboring anchors. In the second phase, it uses these pairwise distances and depth information to project the anchors onto its horizontal level and forms a virtual geometric structure. If the structure is *robust*, the sensor node locates itself through dynamic trilateration and becomes an anchor. Then, it assists other nodes. This process dynamically iterates along all directions in 3D topology to localize as many nodes as possible. Performance evaluations reveal that 3DUL successfully spreads the global location of three surface anchors. Its simple algorithm allows the UW-ASN to adapt to the dynamic nature of the water world.

The remainder of the paper is organized as follows. In Section II, we present a review of related work on localization algorithms in UW-ASN. The operation of 3DUL is described in Section III. In Section IV, we characterize the possible sources of error and present a detailed analysis of 3DUL. Performance evaluation results of 3DUL are presented in Section V. Finally, the paper is concluded in Section VI.

II. Related Work

Classical methods of underwater positioning are Long Baseline (LBL) and Short Baseline (SBL) systems [6] which do not suit well to ad-hoc underwater networks. In LBL, transponders are deployed and localized which is a difficult, time-consuming and expensive process. In SBL, there is a need for a ship in the operation region which is not suitable for many applications and greatly increases the cost.

Underwater GPS [16] is proposed with surface buoys which broadcast satellite information underwater. In [1], multihop UW-ASN are envisioned which also use surface buoys. Therefore, GPS-inspired solutions are naturally suitable to the

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underwater positioning problem. However, they only serve a limited area. A sensor node should be within the range of at least three buoys to determine its position.

Localization algorithms developed for WSN that achieve fine-grained localization [10], [13], [11] are generally based on ranging, the most popular methods of which are received signal strength indicator (RSSI), angle-of-arrival (AoA) and time-based techniques (ToA, TDoA). RSSI is sensitive to multipath and fading whereas AoA systems are expensive and obtaining precise estimates is often difficult. Besides, UW-ASN cannot leverage TDoA due to the strong attenuation of RF signals. On the other hand, the low speed of sound permits accurate timing of signals. In [5], range resolution of 5 meters has been reported.

One of the few efforts of localization in UW-ASN [19] distributes anchor nodes throughout the network which use long-range acoustic links to talk to the surface buoys. Localization is divided into two sub-processes: anchor node and ordinary node localization. For anchor node localization, the anchors and the surface buoys exchange messages which can also be received by the ordinary nodes. Then, they can estimate the distances to the surface buoys too and thus localize themselves just like the anchors. This makes ordinary node localization unnecessary. In addition, [19] assumes the presence of a large number of static anchor nodes deployed underwater. Moreover, the nodes achieve ranging with one-way message exchange implying time synchronization which is difficult to achieve and to maintain in UW-ASN.

[2] employs predetermined number of iterations. First, localized nodes broadcast their positions. Then, nodes calculate their positions with projection and bilateration. However, a set of candidate positions is kept the average size of which increases up to 200 for a network of node degree 10. Besides, ranging is achieved using ToA without time synchronization using the work in [3]. However, this work requires three base-stations periodically broadcasting to the whole network, which turns the localization problem into a trivial message exchange scheduling between each unlocalized node and these high capable anchors. Additionally, location error is measured to be approximately a quarter of communication range when node degree is around 10, which translates to an error larger than $100m$ for typical UW-ASN. Hence, there is a need for a localization algorithm in UW-ASN that gives particular importance to low-complexity, accuracy and scalability.

To achieve these objectives, in this paper we introduce the Three Dimensional Underwater Localization (3DUL) which enables fine-grained, scalable localization with minimum energy expenditure.

III. Three Dimensional Underwater Localization Algorithm (3DUL)

The primary objective is to dynamically achieve network-wide 3D localization accurately, timely and efficiently. A possible deployment of a UW-ASN is shown in Fig. 1. Three buoys float at the surface referred to as *anchor* nodes which are equipped with GPS, RF and acoustic transceivers.

A large number of underwater sensor nodes are deployed at different depths. These might be anchored to the ocean bottom and equipped with a floating buoy. Therefore, these sensor nodes have limited moving capability and are referred to as *semi-stationary* sensor nodes. In addition, the network can have propelled and freely floating autonomous robots (e.g., AUV, drogue). We refer to these nodes and robots as *unknown* nodes because their positions are not known a priori. The goal is to accurately estimate the positions of as many *unknown* nodes as possible in a simple, accurate, and more importantly scalable fashion.

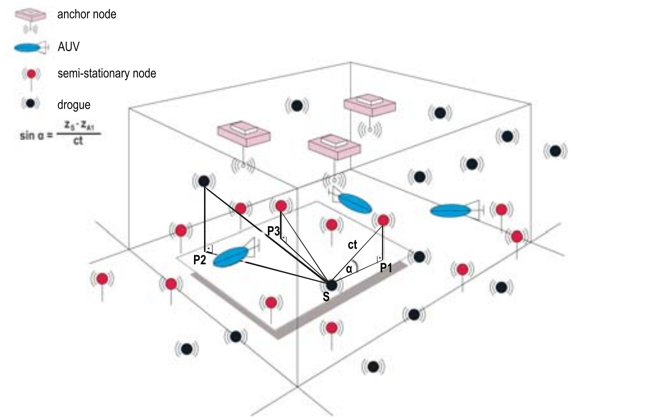

Fig. 1. A possible architecture for Underwater Acoustic Sensor Networks and Projection: P_1, P_2, P_3 are the projection points of the three anchors, A_1, A_2, A_3, respectively.

A. Overview

3DUL is a two phase protocol. During the first phase, a sensor node estimates the distances to its neighboring anchors and acquires their depth. We call this phase of the algorithm as *Ranging*.

Once the distances to at least three anchors are estimated, the second phase of the algorithm, *Projection and Dynamic Trilateration*, is initiated. During this phase, the sensor node projects three anchors onto its horizontal level and checks whether it forms a *robust virtual anchors plane* (see Section III-C) with the three anchors. If so, it locates itself through trilateration and becomes an anchor.

When an *unknown* node becomes an *anchor*, it advertises its new status and assists in spreading the location information across the network. This process repeats iteratively to dynamically achieve network-wide localization. Therefore, 3DUL does not require extra anchor nodes deployed throughout the network.

3DUL requires that the sensor nodes be equipped with CTD (Conductivity, Temperature, Depth) sensors [15] to estimate the sound speed. The depth information is also used for the projection of the anchor nodes.

Note that 3DUL employs two-way message exchange to estimate the propagation delay and uses estimated sound speed to find the inter-node distances. Therefore, 3DUL does not require time synchronization.

B. Ranging Phase

When the network is deployed, the three anchor nodes at the surface broadcast an *anchor_ranging* packet. If an *unknown* sensor node receives at least three *anchor_ranging* packets from different anchors, it initiates the *Ranging phase* by broadcasting a *ranging* packet. 3DUL estimates the propagation delay between the unknown node and the anchor nodes by using the two-way message exchange technique. Then, it multiplies the propagation delay with the estimated speed of sound to obtain the range information.

Consider the two-way message exchange between an *anchor* and an *unknown node*. At $t = T1$, the *unknown node* sends a *ranging packet*. The anchor receives this packet at $t = T2$ and at $t = T3$ sends back an *acknowledgment packet* to the *unknown node* which contains the values of $T2$, $T3$, its coordinates and depth z. The *unknown node* receives the packet at $T4$. $T1$ and $T4$ are measured by the local clock of the *unknown node*, whereas $T2$ and $T3$ are measured by the local clock of the *anchor*, i.e., $T2 = T1 + \delta + t_{prop}$ and $T4 = T3 - \delta + t_{prop}$, where δ is the clock drift between an *unknown* node and the anchor, t_{prop} is propagation delay. Then, the *unknown* node can estimate the propagation delay as

$$t_{prop} = [(T2 - T1) + (T4 - T3)]/2 \quad (1)$$

When c is the estimated speed of sound, distance between the anchor and an *unknown node* is $d = t_{prop}c$.

If a sensor node determines the distances to three anchors, i.e., if it gets *acknowledgment* packets from three anchors, it initiates the *Projection and Dynamic Trilateration* phase as explained in Section III-C.

C. Projection and Dynamic Trilateration Phase

In this phase, a sensor node performs 3D localization by using the distance and depth information obtained during the ranging phase. Each sensor node projects three neighboring anchors onto its horizontal level as in Fig. 1 and checks if it forms a *robust virtual anchors plane* with them.

A *robust virtual anchors plane* exploits the notion of *robust quadrilateral* defined for localization [9]. Therein, *robust quadrilaterals* are proposed to avoid the incorrect realizations of flip ambiguities. Here, we combine the *robust quadrilateral* with projection to achieve robust 3D localization. A *robust virtual anchors plane* consists of three virtual *anchors* and one *unknown* node which are unambiguously localized.

Consider the plane shown in Fig. 1 which can be decomposed into four triangles: $\Delta P_1P_2P_3$, ΔSP_1P_2, ΔSP_1P_3 and ΔSP_2P_3. A triangle is regarded as *robust* if it satisfies $a \sin^2\theta > d_{min}$ where a is the length of the shortest side, θ is the smallest angle and d_{min} is a threshold that depends on measurement noise [9]. Then, a *robust virtual anchors plane* is defined as a quadrilateral whose four sub-triangles are robust.

After projection, the plane is tested for robustness. If correct, the *unknown node* becomes an *anchor* and broadcasts an *anchor_ranging* packet to assist its neighboring *unknown nodes*. This process repeats itself iteratively to achieve network-wide localization. Hence, 3DUL can dynamically perform localization by diffusing the location information from the surface anchors to the network without employing designated anchors deployed underwater and without requiring time synchronization. The new anchor remains as anchor only for a finite duration of time which mainly depends on its movement characteristics.

Algorithm 1: Algorithm of the 3DUL protocol operation. n is the number of received anchor_ranging packets, m is the number of received acknowledgment packets. IsRobust(d_1, d_2, d_3) tests the triangle with sides d_1, d_2, d_3 for robustness. a, b, c are the pairwise distances between the anchors, z_S is the depth of the unknown node S and z_{A1}, z_{A2}, z_{A3} are the depths of the anchors.

if $n \geq 3$ **then**
    Broadcast $ranging$ packet
end
foreach $received\ acknowledgment\ packet$ **do**
    $t_{prop} = \frac{(T2-T1)+(T4-T3)}{2}$
    $d_A = t_{prop}c$ /*Distance to the anchor*/
    $m = m + 1$
end
if $m \geq 3$ **then**
    repeat
        Pick three neighbor anchors (A_1, A_2, A_3) and project them:
        $d_{P1} = \sqrt{d_{A1}^2 - (z_S - z_{A1})^2}$
        $d_{P2} = \sqrt{d_{A2}^2 - (z_S - z_{A2})^2}$
        $d_{P3} = \sqrt{d_{A3}^2 - (z_S - z_{A3})^2}$
        if *IsRobust(a, b, c) AND IsRobust(d_{P1}, d_{P2}, a) AND IsRobust(d_{P1}, d_{P3}, b) AND IsRobust(d_{P2}, d_{P3}, c)* **then**
            P_S=TRILATERATE(P_{P1}, d_{P1}, P_{P2}, d_{P2}, P_{P3}, d_{P3})
        end
    until *(S is robustly localized) OR (all combinations of triplets of neighbor anchors are used)*
end

As soon as three *acknowledgment* packets arrive, 3DUL initiates the *Projection and Dynamic Trilateration* phase. If the plane formed with the selected three anchors fails to be robust then all the possible combinations of triplets of anchors are tried until a robust plane is found. Otherwise, the node is not localized. Note also that 3DUL does not incorporate a smart anchor selection algorithm, which would increase its complexity, and also decrease the performance given the dynamic environment it operates in and the low speed of communication due to the acoustic signals.

D. Diffusion of Location Information

The three surface anchors initiate localization. The location information of the surface anchors is first spread to the *unknown* nodes that are within the range of the three surface anchors. Then, those sensor nodes that are *robustly* localized assist in dynamically diffusing the location information across the network.

3DUL does not restrict the orientation of the anchors with respect to the *unknown* node. As long as the unknown node forms a robust virtual anchors plane, the anchors can reside anywhere within the communication sphere of the *unknown* node. This flexibility for the anchors endows 3DUL with the capability of 3D diffusion of location information. 3DUL protocol operation is outlined in Algorithm 1.

IV. ERROR ANALYSIS OF 3DUL

In this section, we analyze 3DUL in detail and point out the sources of error which affect its accuracy.

A. Projection Accuracy

Each sensor node employs the following simple geometric relationship to project an anchor node:

$$r = \sqrt{d^2 - (z_S - z_A)^2} = \sqrt{c^2t^2 - (z_S - z_A)^2}$$

where r and d are the distances to the virtual anchor and actual anchor, respectively. c is the sound speed, t is the propagation delay, z_S is the depth of the sensor node and z_A is the depth of the anchor node.

The error on r can be estimated by the error propagation formula and is bounded by:

$$\begin{aligned} \Delta r &\leq \tfrac{\partial r}{\partial c}\Delta c + \tfrac{\partial r}{\partial t}\Delta t + \tfrac{\partial r}{\partial z_S}\Delta z_S + \tfrac{\partial r}{\partial z_A}\Delta z_A \\ &= \frac{t\Delta c + c\Delta t + 2(\frac{z_S - z_A}{ct})\Delta z}{\sqrt{1-(\frac{z_S-z_A}{ct})^2}} \end{aligned} \quad (2)$$

where Δr, Δc, Δt, $\Delta z_S = \Delta z_A = \Delta z$ are the errors in r, c, t, z_S and z_A, respectively.

1) Error in Propagation Delay: Consider the model for the clocks of the sensor *S* and the anchor *A*,

$$f_S(t) = at + b \qquad f_A(t) = t$$

where a is the skew, b is the offset, and t is the global reference time. When the sensor node *S* and the anchor node *A* exchange timestamps, with $T_1 = f_S(t_1)$, $T_2 = f_A(t_1 + t_{prop})$, $T_3 = f_A(t_3)$, $T_4 = f_S(t_3 + t_{prop})$, the corresponding error in propagation delay can be calculated as

$$\begin{aligned} \Delta t_{prop} &= t_{prop} - \frac{(T2-T1)+(T4-T3)}{2} \\ &= \frac{(1-a)(t_3 - t_1 + d/c_{av})}{2} \end{aligned} \quad (3)$$

For Berkeley motes, the upper bound for skew given in the datasheet [14] is 40ppm. The average sound speed is $c_{av} =$ 1500m/s. Even when $d = 1500$m and $t_3 - t_1 = 1$s, the error in t_{prop} is $\Delta t = 40\mu$s.

2) Error in Sound Speed: The sound speed depends on temperature, pressure and salinity and can change between 1450m/s and 1550m/s [7]. For its estimation 3DUL employs the following equation [8] which has an accuracy of about $0.1m/s$ [4]. It models the underwater acoustic propagation speed as

$$\begin{aligned} c(T,S,z) = A + BT + CT^2 + DT^3 + E(S-35) + \\ + Fz + Gz^2 + HT(S-35) + JTz^3 \end{aligned} \quad (4)$$

where $c(T,S,z)$ is in m/s, T is the temperature in °C, S is the salinity in *ppt* (parts per thousand), and z is the depth in m. The error on the sound speed is then bounded by the following formula [12]:

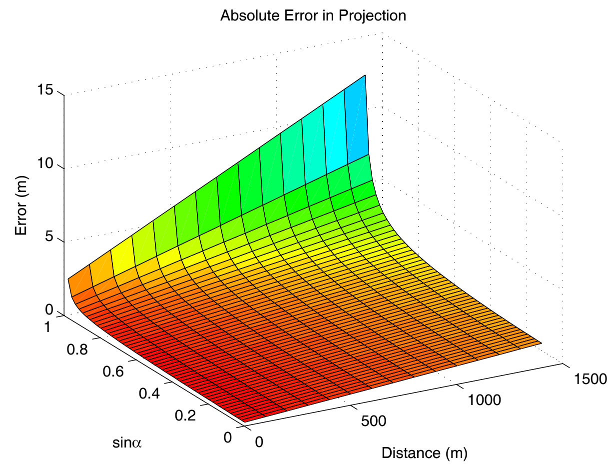

Fig. 2. Absolute error in projection.

$$\begin{aligned} \Delta c &\leq \tfrac{\partial c}{\partial T}\Delta T + \tfrac{\partial c}{\partial S}\Delta S + \tfrac{\partial c}{\partial z}\Delta z \\ &= (B + 2CT + 3DT^2 + H(S-35) + Jz^3)\Delta T + \\ &\quad +(E + HT)\Delta S + (F + 2Gz + 3JTz^2)\Delta z \end{aligned}$$

When $\Delta T = 0.1\,°$C and $\Delta S = 0.75$ [15], in the ranges of $5 - 30\,°$C and $34 - 39$, the maximum error is less than 1.5 m/s. Underwater sensor nodes can estimate the speed of sound using CTD sensors.

3) Overall Error: To see the overall error of projection, we use (2). We assume $\Delta c = 1.5$m/s, $\Delta t = 100\mu$s, $c = 1500$m/s and $\Delta z = 0.1$m. The results are shown in Fig. 2 where we plot Δr versus d and $sin\alpha = \frac{z_S - z_A}{ct}$. As long as $sin\alpha \leq 0.9$, Δr is comfortably less than $5m$. As $sin\alpha$ approaches towards 1, the error increases. However, it is less than $15m$ even when $sin\alpha = 0.99$ and $d = 1500$m. A better insight can be gained by inspecting the relative error, $\frac{\Delta r}{r}$. When d is less than $100m$, the relative error increases rapidly as $sin\alpha$ gets beyond 0.9. These results dictate that the anchor selection should be made carefully. Specifically, the anchors which are less than $100m$ away should be used only when $sin\alpha \leq 0.9$.

Note that the first part of the error analysis performed here considers the projection accuracy, which depends on the errors in propagation delay and sound speed, whereas the second part discusses the errors resulting from the trilateration process. These processes are independent of the transmission loss. Hence, unlike the simulation experiments in Section V, which require investigation of two distinct cases, i.e., deep and shallow waters with different channel and transmission loss characteristics, the numerical error analysis here applies to both deep and shallow water environments.

B. Virtual Anchors Plane

Once a sensor node determines its separation to three anchors, it checks the *virtual anchors plane* for robustness. The virtual anchors plane is regarded as *robust* if the four triangles constituting it (see Fig. 1) are *robust*. A triangle is regarded as *robust* if $a\sin^2\theta > d_{min}$. By choosing a suitable

d_{min} depending on σ, the standard deviation of measurement noise, the probability of error is bounded. For example, if d_{min} is 3σ, for Gaussian noise, the probability of error for a given virtual anchors plane is less than $\%1$ [9].

V. Performance Evaluation of 3DUL

We present results evaluating the performance of 3DUL algorithm. We created an evaluation environment in ns-2 [17]. The signal propagation speed is set to $1500m/s$. In addition, the underwater nodes estimate their depths and the speed of sound with inaccuracies of $\pm 1m$ and $\pm 1.5m/s$, respectively. The data rate is set to 15kbps and the operating frequency is $50kHz$. We are interested in how both node degree and propagation models for different kinds of channels of common occurrence in the sea affect the performance. Node degree was varied by modifying the transmission power. We implemented two propagation models:

- The *shallow water sound channel* models the communication in waters with depth lower than $100m$, where sound propagates by repeated reflections from both surface and bottom. For the ranges of interest to UW-ASN, the transmission loss in the shallow-water sound channel is

$$TL = 20logr + \alpha r + 60 - k_L \quad (5)$$

  where r is the range in meters, α is the absorption coefficient in dB/m and k_L is a near-field anomaly dependent on the sea state and bottom type [18].
- The *deep water sound channel* is used to model the communication in deep oceans. The deep water sound channel has remarkable transmission characteristics. However, for typical ranges targeted for UW-ASN, the transmission loss in deep water sound channel is generally higher:

$$TL = 10logr_0 + 10logr + \alpha r \quad (6)$$

  where r is the range in meters and α is the absorption coefficient in dB/m. r_0 is the transition range between spherical and cylindrical spreading [18]. Its magnitude is between 1450m and 3650m [18].

A. Evaluation Criteria

The first evaluation metric is the mean-square error in Euclidean 3D space. This error is expressed as

$$\sigma_p^2 = \sum_{i=1}^{N} \left[(\hat{x}_i - x_i)^2 + (\hat{y}_i - y_i)^2 + (\hat{z}_i - z_i)^2 \right] / N \quad (7)$$

where N is the number of nodes, $\hat{x}_i$, $\hat{y}_i$ and $\hat{z}_i$ are the coordinates of node i determined by 3DUL, and x_i, y_i and z_i are the actual coordinates of node i. Second, we compare σ_p^2 to the mean-square error in distance measurements to see how well 3DUL determines the inter-node distances and how well it performs 3D localization using these noisy measurements. The mean-square error of the distance measurements is

$$\sigma_d^2 = \sum_{i=1}^{M} (\hat{d}_i - d_i)^2 / M \quad (8)$$

where M is the number of computed inter-node distances, $\hat{d}_i$ and d_i are the measured and actual values of distance i, respectively. Another useful metric is the ratio of nodes in the entire network that could be localized successfully. Let L be the number of underwater nodes that are successfully localized by the algorithm and N be the total number of nodes in the network. We define *localization coverage* as $R = \frac{L}{N}$.

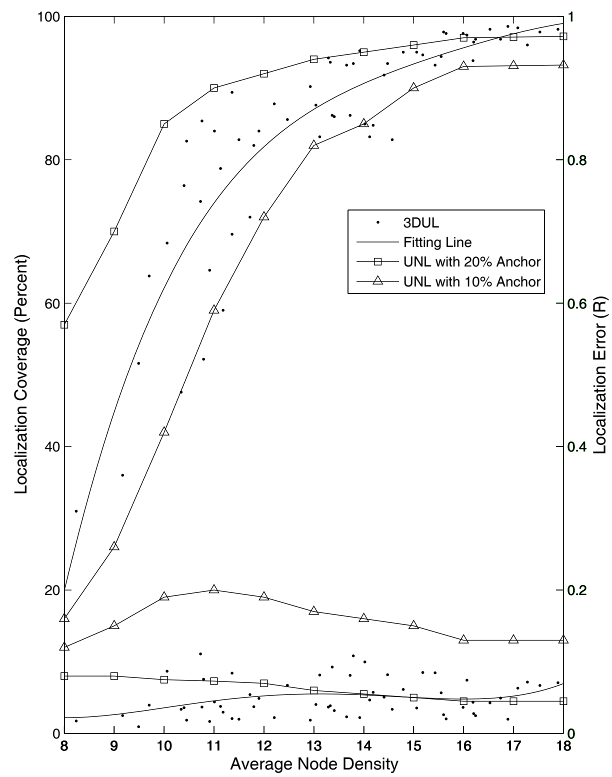

Fig. 3. The localization coverage and localization error vs. the average node density.

The *average communication cost* of the algorithm is also an important performance metric and is defined as $C = \frac{M}{L}$ where M is the number of messages sent by all the nodes in the network.

The time required for localization, t_{loc}, will also be given for each simulation. During the simulations, the surface anchors broadcast their positions only once and at the beginning.

B. Evaluation Results

We compare 3DUL with [19], UNL (Underwater Node Localization), as it is the only network-wide algorithm achieving fine-grained localization in UW-ASN. 500 nodes are distributed in a topology of 100m x 100m x 100m as done for UNL. We also use the same metrics as UNL: *localization coverage*, *localization error* and *average communication cost*. The localization error is normalized to the communication range. During the simulation, the nodes stay at their initial positions. The results are shown in Fig. 3, 4. Each data point represents a single run. A line fitting the data points is overlaid on each plot.

1) Localization Coverage: 3DUL outperforms UNL in terms of localization coverage when UNL employs 10% of the nodes in the network as anchor. When UNL employs 20% of the nodes as anchor, 3DUL outperforms UNL when the average node density is high. It should be noted that UNL employs static anchor nodes deployed underwater which know their exact locations. In contrast, in 3DUL scheme, the only nodes that are assumed to know their exact locations are the three surface anchors.

2) Localization Error: The localization error is also shown in Fig. 3. 3DUL outperforms UNL even when UNL employs 20% of the nodes as static anchor. The error in 3DUL does not depend much on the node density. A node localizes itself whenever it forms a robust virtual anchors plane without differentiating between the anchors. On the other hand, UNL uses a scheme where the anchor nodes are associated with a confidence value. With a denser network, the nodes have more anchors to choose from.

3) Average Communication Cost: The communication cost incurred by 3DUL stays nearly constant as seen in Fig. 4. In contrast, the communication cost in UNL scheme decreases as the average node density increases. UNL outperforms 3DUL especially at high average node density. However, the messages required for time synchronization and anchor node localization are not counted in UNL. In contrast, 3DUL does not assume nor requires time synchronization. Besides, there is no designated static anchor node in water.

4) Deep Water: 100 static nodes are randomly distributed in a 1000m x 1000m x 1000m topology. $\alpha = 15.95dB/km$ and $r_0 = 10000m$. The surface anchors are placed near one of the edges: $(400, 40, 0)$, $(500, 150, 0)$, $(600, 40, 0)$. Error metrics of the simulation are given in Table I as an average of 50 simulation runs. Distances are accurately determined as demonstrated by the small value of σ_d. Moreover, 3DUL successfully localizes %82 of the nodes in less than 18s. On the other hand, σ_p is considerably larger than the measurement error in σ_d due to error propagation. Note that the surface anchors are placed near the edges. Nevertheless, 3DUL can successfully diffuse their global location information throughout the network.

5) Shallow Water: 150 static nodes are randomly distributed in a 1000m x 1000m x 100m topology. $\alpha = 15.95dB/km$ and $k_L = 3dB$. The surface anchors are again placed near one of the edges: $(400, 100, 0)$, $(500, 250, 0)$, $(600, 100, 0)$. The error metrics of the simulation are given in Table I. Accordingly, with a lower average node density as compared to deep water simulation, 3DUL is able to localize nearly $\%90$ of the nodes in $20s$. However, the localization error is larger. One reason is that there are more nodes in the network. Although 3DUL forces the underwater nodes to form robust structures with the anchors, its iterative nature generally causes an increase in error as more nodes are localized.

6) Effect of Virtual Anchors Plane: A potential drawback of the iterative nature of 3DUL is that it might experience the propagation of measurement and localization errors. To alleviate the effect of error propagation, 3DUL employs the *virtual anchors plane* to impose a robustness condition on becoming an anchor. Only those nodes that form a robust *virtual anchors plane* become an anchor. To show the importance of employing virtual anchors plane, in Table I we report the results of simulations of the UW-ASN with the same settings as in Section V-B4 except the virtual anchors planes are not constructed.

The results prove the importance of the virtual anchors plane to mitigate the effects of error propagation. According to Table I, localization errors as much as $119.18m$ in mean-square error are observed when the nodes do not construct the virtual anchors plane. Note that, 3DUL is still successful in determining the inter-node distances. However, the mean-square error dramatically increases due to the flip errors.

7) Effect of Mobility: We investigate the mobility factor. The nodes move towards a randomly determined position with a speed of $1m/s$. When a node is localized and becomes an anchor, it remains so for 5 seconds. The results are given in Table I. The nodes can still determine the inter-node distances very well and the localization success rate is $\%90$. On the other hand, the localization error is increased to $8.86m$ due to the passive movement.

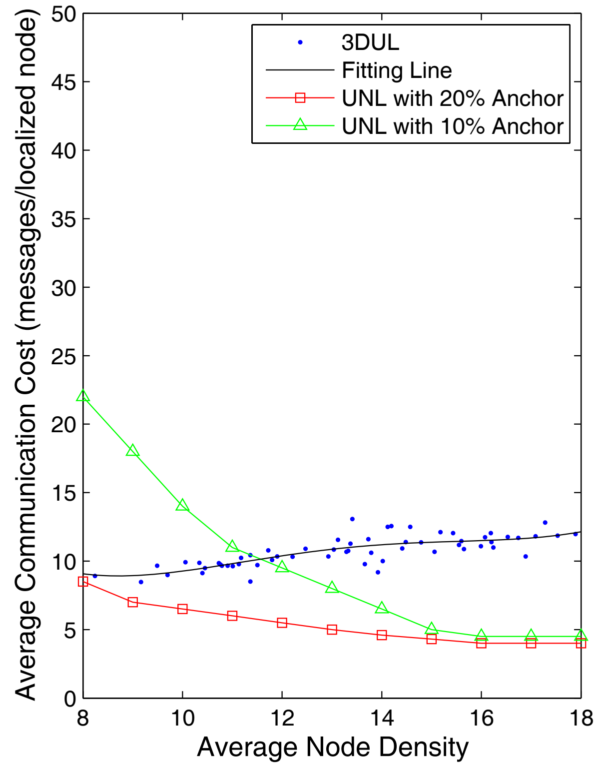

Fig. 4. The average communication cost vs. the average node density.

TABLE I

	Deep	Shallow	w/o VAP	Mobility
σ_d	0.16 m	0.17 m	0.14 m	0.33 m
σ_p	3.75 m	6.23 m	119.18 m	8.86 m
t_{loc}	17.57 s	20.01 s	11.43 s	18.61 s
Node Degree	12.63	10.97	13.03	11.56
R	82/100	132/150	82/100	135/150

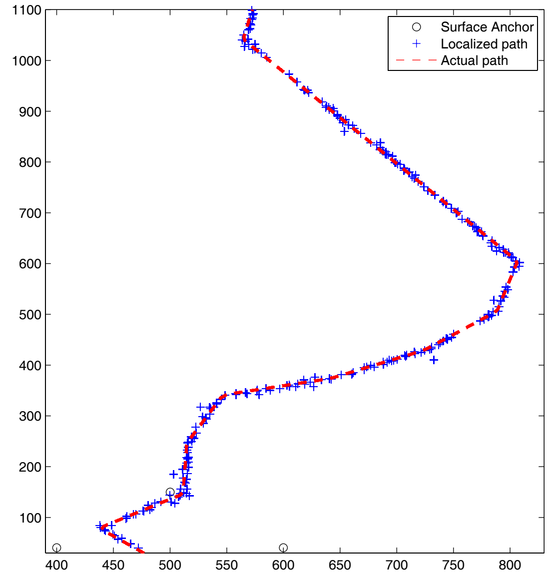

Fig. 5. The path determined by 3DUL compared to the actual path of the AUV at depth 500m. The surface anchors are shown with circles.

8) Localization of AUVs: We show that 3DUL can localize mobile underwater vehicles such as AUVs and drogues. The topology is the same as in Section V-B4. After $20s$, a mobile node enters the network at (475, 0, 500) with a $10m/s$ constant speed. The mobile node broadcasts *ranging* packets every other second. The results are shown in Fig. 5 where the actual path and the path as determined by 3DUL are plotted. At $200s$ the mean square error is $7.30m$.

VI. Conclusion

Localization is an indispensable part of many underwater sensor network applications. In this paper, Three-Dimensional Underwater Localization (3DUL), a 3D localization algorithm for underwater acoustic sensor networks, is presented. 3DUL is a distributed, iterative and dynamic solution to the underwater acoustic sensor network localization problem that exploits only three anchor nodes at the surface of the water. The algorithm starts at the anchor nodes and iterates along all directions in 3D topology. Through analysis and simulation we showed that 3DUL can localize the sensor nodes accurately by leveraging the low speed of sound. Moreover, by imposing a robustness condition, 3DUL mitigates the effects of error propagation phenomena and is a scalable protocol. We presented performance evaluation results of 3DUL in terms of localization coverage, localization error and communication cost. The behavior of 3DUL in deep and shallow waters is analyzed under specific channel models. The effects of passive node mobility on performance is also analyzed. Finally, we demonstrated that 3DUL can be used for AUV localization.

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