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HASL: High-Speed AUV-Based Silent Localization for Underwater Sensor Networks

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Abstract. The existing solutions that have been proposed to address the localization problem for mobile Underwater Sensor Networks (UWSNs) exhibit performance challenges, such as, high message overhead, localization error, and cost. Few Autonomous Underwater Vehicle (AUV) based methods were introduced to utilize the flexibility of movement of an AUV. In this paper, we propose a distributed, 3-dimensional, energy-efficient localization scheme, named High-Speed AUV-Based Silent Localization (HASL), for large-scale mobile UWSNs. Three AUVs are used to provide beacon messages to localize the mobile sensor nodes 'silently'. Therefore, with the use of high-speed AUV and 'silent' listening, we design an efficient scheme capable of addressing some of the above mentioned challenges with the existing solutions. We evaluated our proposed scheme in NS-3. Simulation results show that HASL achieves more than 90% localization coverage with localization error in the order of 2-7 *meters*.

Key words: AUV based localization, Underwater Acoustic Sensor Networks, Silent Localization

1 Introduction

In event-driven networks, such as, UWSNs, tagging of sensed data with location information is fundamentally important specifically for target tracking, and environmental monitoring applications. Moreover, the performance of medium access and routing protocols can be significantly increased by providing location-aware information. However, UWSNs have some unique challenges, e.g., passive node mobility, acoustic communication, high energy consumption and limited bandwidth [1], [2], [3]. Due to passive node mobility, sensor nodes do not remain in the same position over time, and, thus, it is difficult to deploy fixed anchor nodes underwater. Therefore, the localization schemes, which consider sensor nodes and anchor nodes to be static inside water, do not work efficiently in mobile UWSN. Acoustic communication consumes more energy than radio frequency modems, and transmission of signal consumes at least 10 times more power than reception. For example, the acoustic modem proposed by [4] consumes 0.203 *watts*, 0.024 *watts* and 3×10^{-6} *watts* for transmit, receive, and sleep, respectively. Hence, it is not energy-efficient to use frequent message exchange schemes in underwater localization. Also, the limited bandwidth can be saved if the communication overhead is reduced.

Few localization protocols are proposed for 3D, mobile UWSNs in [5], [6], [7], [8]. However, these methods either introduce communication overhead, and implementation cost in the network, or require direct communication between the surface sinks and the underwater anchor nodes. AUV-based methods [9], [10], [11], [12] use AUVs instead of anchor nodes, as the beacon provider. Some of these methods introduce communication overhead, high localization delay (for example, [9], [12]), and assumes sensor nodes to be static or cabled with anchors and buoys.

These above mentioned challenges motivate us to propose an energy-efficient localization scheme, specifically for large-scale mobile UWSNs. To utilize the flexibility of movement of an AUV inside water, we use three high-speed AUVs as the location beacon provider. At the same time, the sensor nodes employ 'silent' listening of beacon messages, which reduces the communication overhead, and energy consumption significantly. Initially, the AUVs remains at the water surface, and receive GPS coordinates while floating. Subsequently, they descend below the water surface, and follow a predefined trajectory to cover the whole deployment area. Each underwater node silently localizes itself after receiving beacon messages from three different AUV.

The rest of the paper is organized as follows. In Section 2, we briefly present the related works, and in Section 3, we describe the proposed localization scheme, HASL, in detail. We evaluate HASL and present the simulation results in Section 4. Finally, we conclude the paper with suggestions for few future research directions in Section 5.

2 Related Works

Lot of research works exist in the literature for UWSN localization. Few excellent survey papers [13], [14] also exist summarizing the existing work done on this problem. The early works on UWSN localization [15], [16], [17] concentrated mainly on small scale network localization, and are impaired by huge communication cost, and low convergence.

Erol *et al.* proposed a localization method, named Dive'n'Rise Localization (DNRL) [5], with "Dive'n'Rise" (DNR) mobile anchor nodes, which dive and rise along the water column. The anchor nodes get their coordinates using the GPS receiver affixed with them, and then they dive into water to announce their coordinate through beacon messages. Ordinary nodes listen to the beacon messages and localize themselves 'silently'. The advantages of DNRL are that it is 'silent' and energy-efficient. The disadvantage of this method is, the requirement of large number of DNR beacons for localization coverage. Also, the implementation cost increases with the use of large number of DNR beacons. The nodes placed deep inside water are localized later than the nodes placed near the surface. Moreover, nodes should be time synchronized to estimate range from

Time-of-Arrival (ToA) measurements. However, as these DNR beacons are slow, the position estimation of the sensor nodes are greatly affected by node mobility. In [9], AUVs were used instead of DNR beacons. The method in this work does not require any fixed network infrastructure, and the nodes do not require to be time-synchronized. However, this method is not energy-efficient, as, the nodes do 'active' message exchange between themselves, and the localization delay in this method is about 2 *hours*.

DNRL was extended in Multi Stage Localization (MSL) [7], where the nodes once localized are used as reference nodes for the rest of the nodes. The use of iterative localization increases the overall communication cost, and, thus, additional energy gets consumed. Also, the position estimation error in the first iteration propagates to rest of the nodes, while they are localized using those estimated coordinates. This method also needs time synchronization between nodes. Another multi-stage iterative localization method was proposed in [12], where unlocalized nodes are initially localized with the help of an AUV. Thereafter, the rest of the nodes localize themselves iteratively. However, this scheme is limited only to 2D static UWSNs.

Mirza *et al.* proposed a localization scheme [6], where the effect of propagation delay, and node mobility in distance estimation were considered. The centralized algorithm iteratively estimates the distance throughout the execution of the application. Therefore, this method does not require anchor nodes. However, the method was criticized for the lack of time synchronization algorithm [13]. Another centralized prediction based localization scheme, called Collaborative Localization, was proposed in [18]. In this method, a specific application scenario was considered, where two types of nodes, 'profilers' and 'followers', descend under the water. The 'profilers' descend faster, and they predict the future locations of the 'followers' by measuring the distance from 'followers' using ToA technique. However, lack of synchronization between the nodes may disrupt the performance of the algorithm. Moreover, the algorithm specifically suits limited applications.

Using Directional Beacons for Localization (UDB) [10], used a directional antenna powered AUV as the location beacon provider. It was extended for 3D UWSNs in Localization with Directional Beacons (LDB) [11]. Both of these methods are energy-efficient as they use 'silent' localization. However, the authors assumed that the nodes cannot move freely, as they are restricted to move by the elastic anchor chain's pull force, and buoy's floating force. Moreover, to cover the whole network, an AUV needs to traverse the network more than once, as it is able to send beacon to one direction only.

3 High-Speed AUV-Based Silent Localization

3.1 Assumptions

We consider a 3-dimensional UWSN deployed in a large area, which is affected by passive node mobility. The sensor nodes are equipped with pressure sensors, by which they are able to calculate their depth. We also consider that three AUVs move along the middle of the network maintaining their trajectory using dead-reckoning [19], [20]. The scenario model is shown in Figure 1. We also assume that the AUVs are time synchronized and move together maintaining the same speed. Therefore, the AUVs broadcast beacons together and the sensor nodes receive three beacons from three different AUVs at nearly the same time. Also, the displacement of a sensor node between the time interval of the reception of three beacons is negligible. The deployment area may be along an ocean coast, which is bounded by large value of area length with comparatively less breadth and depth.

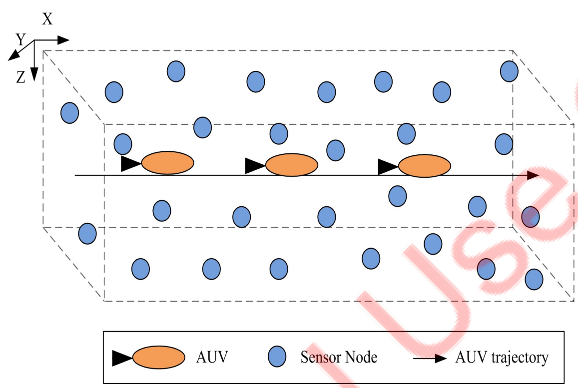


Fig. 1. Deployment of sensor nodes and the AUVs

3.2 Features

In this Section, we summarize the salient features of HASL, which differentiates it from the existing localization protocols.

a. *It is applicable to large-scale mobile UWSNs.* HASL protocol can localize nodes deployed over a vast area. We consider that the nodes are displaced with the effect of passive node mobility. The effect of passive node mobility does not affect the performance of the protocol.
b. *It is energy-efficient.* We make use of the 'silent' beacon message receiving method, and thus, the nodes consume energy only for beacon listening.
c. *Time synchronization between sensor nodes is not needed.* In HASL, the sensor nodes passively listen to the AUVs. Thus, there is no additional requirement of time synchronization between the sensor nodes. However, the AUVs are time synchronized.
d. *No anchor nodes required.* There is no need of deploying any static anchor node inside or above the water surface. Therefore, HASL is free from the complexity of deploying static anchor node inside water.

e. *Protocol overhead is very low.* Only three beacon messages are required for localizing an unlocalized sensor node.
f. *Localization time is low.* The time required to localize the sensor nodes $t \propto \frac{l}{v}$, where l is the length of the network, and v is the velocity of the AUVs.

3.3 Procedure

Beacon Sending. The AUVs are the only location beacon providers in the proposed HASL scheme. Initially, the AUVs collect their coordinates from the GPS receiver attached with them. Then they descend till the middle of the deployment region's depth. This is the starting position of the AUV's trajectory. It maintains its predefined trajectory along the middle of the network. Each AUV broadcasts beacon messages starting from the first position, with constant time interval between two beacon messages. Each beacon message sent from the AUV contains the AUV id, and the present location of that AUV with current time-stamp. One set of 'effective beacon messages' is formed with beacon messages from three different AUVs, with the same time-stamp value. Using the time-stamp value, the sensor nodes differentiate between two different set of beacon messages. The beacon message format is shown in Figure 2.

AUV id	X_{AUV}	Y_{AUV}	Z_{AUV}	time

Fig. 2. A beacon message format

Sensor Node Localization. Each sensor node 'silently' listens to beacon messages, and measures its distance (d_i) from the corresponding AUV using Received Signal Strength Intensity (RSSI). The sensor nodes are able to calculate their depth using the pressure sensor equipped with them. Therefore, a sensor node needs to calculate its x, and y coordinate values only. Let, at t_1 time, the position of the three AUVs at those time be (x_1, y_1, z_1), (x_2, y_2, z_2), and (x_3, y_3, z_3), respectively. This is one set of 'effective beacon messages'.

For each of the three beacon messages,

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = d_i^2, \text{where, } i = 1, 2, 3 \tag{1}$$

$$\text{or, } (x - x_i)^2 + (y - y_i)^2 = d_i^2 - h^2, \text{where, } h = z - z_i$$

Here, $i = 1, 2, 3$ is the three beacon messages from the three AUVs. From these three beacon messages, a sensor node can successfully localize itself using Equation 1.

4 Performance Evaluation

4.1 Simulation Settings

We evaluated the performance of HASL by simulations in NS-3 simulator [21]. The simulation area considered was 1000 m × 200 m × 200 m, and in each of these simulation regions, we deployed 100, 200, 300, 400 and 500 nodes. In two different scenarios, the transmission range of the AUVs, as well as the sensors, are taken to be 100 m, and 150 m. Each AUV moves with constant velocity of 15 *Knots* (7.7166 m/s), maintaining its trajectory, as shown in Figure 1. This type of high-speed AUV, called *VT High Speed AUV (VT HSAUV)* designed by Virginia Tech Autonomous Systems and Controls Laboratory, the specifications can be found at [23]. Other simulation parameters are shown in Table 1.

Table 1. Simulation Parameters

Parameter	Value
Inter AUV distance	10-30 m
Node mobility	0.5 - 2 m/s
Node mobility model	Meandering Current Mobility model [22]
Transmission power	0.203 *watts* [4]
Receive & Idle power	0.024 *watts* [4]
Sleep power	3×10^{-6} *watts* [4]
Initial energy of a node	150 J

4.2 Performance Metrics

We evaluated the performance of our algorithm using the following metrics:

- *Localization Error:* Localization error is the euclidean distance between the sensor node's estimated location, and the original location.
- *Localization Coverage:* It is defined as the number of localized nodes to the total number of nodes. A node is considered to be localized if the localization error is less than the error threshold.

4.3 Benchmark

We compare the performance of the proposed protocol, HASL, with LDB [11]. LDB is an localization algorithm for 3D static UWSNs. In LDB, an AUV equipped with directional antenna is the location beacon provider for the sensor nodes. The sensor nodes localize themselves using *the first-heard beacon point*, and *the last-heard beacon point* of beacon message from the AUV.

LDB uses 'silent' localization, which provides an energy-efficient localization scheme. Also, it is free from range estimation. Therefore, we choose LDB to compare the performance HASL.

4.4 Results and Analysis

Effect of Node Mobility. In Figure 3, we plot the localization error for the localized sensor nodes. The transmission range of both AUVs, and the nodes are set to 100 m. The error threshold value is set to be 10 m. The inter-AUV-distance for this experiment was set to 20 m. We plot the results for node mobility value of 0.5 m/s, 1.0 m/s, and 2.0 m/s. The localization error increases with higher node mobility. However, LDB results in more localization error than HASL. In LDB, nodes estimate their position by the first-heard, and the last-heard beacon positions. However, LDB does not include the displacement of sensor nodes, during this time period, in the estimation.

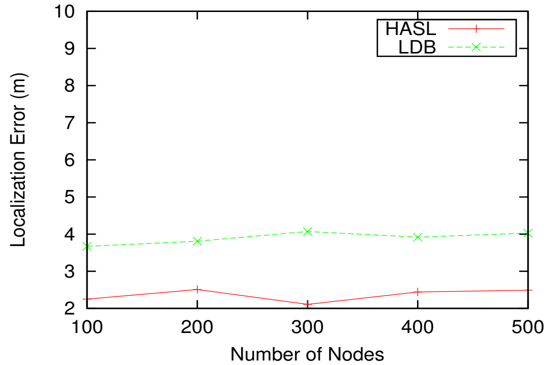
In Figure 4, we plot the localization error for HASL, and LDB. Here, the transmission range of both AUVs, and the nodes are set to 150 m. With the increase of transmission range, the farthest nodes are also localized. However, the transmission delay of beacon messages let the nodes displace more from their original position. With this amount of added delay, LDB results in more localization error.

Effect of Transmission Range. We simulated HASL by changing the transmission range of the sensor nodes and the AUVs. Increasing the transmission range allows more number of nodes to be present in the communication zone of the AUVs. Therefore, more number of sensor nodes can receive beacon messages, which results in better localization coverage. We show the results of this experiment in Figure 5.

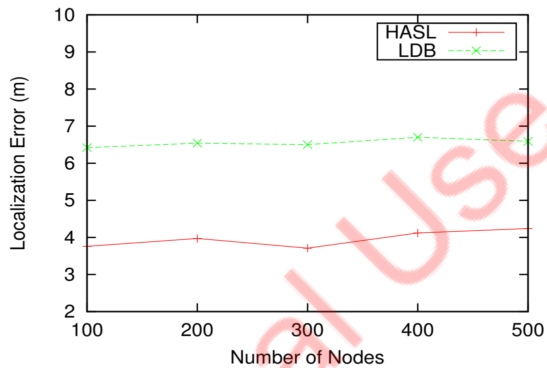
LDB also exhibited the same type of performance characteristics for localization coverage in both the scenarios. However, the time required to localize the sensor nodes is double in case of LDB compared to HASL. This is because of the directional antenna used in LDB, the AUV need to traverse the deployment area twice.

In Figure 6, we depict the effect of transmission range on the localization coverage. The more the number of nodes present in the transmission range of the AUVs, the more is the localization coverage. The solid circle represents the zone covered by transmission range r of the AUV, and the dotted circle represents the zone covered when the transmission range is R. The maximum coverage is attained for $R = d \times \sqrt{2}$, when d is the side of the square.

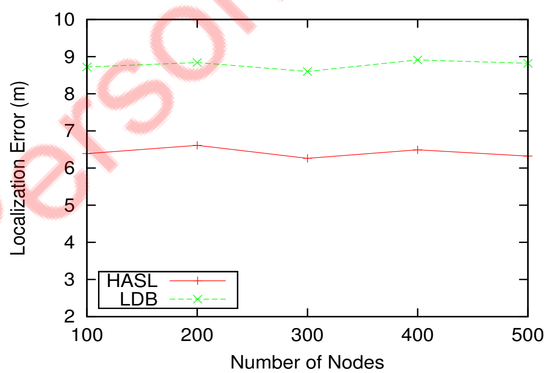
Effect of inter-AUV-distance. We study the effect of inter-AUV-distance (d_{aa}) on the localization error, and the results are plotted in Figure 7. In this experiment, we varied d_{aa} from 10-30 m with the transmission range of the AUVs, and the sensor nodes were set to 100 m. It is found that, when the AUVs are closely spaced, the localization estimation is coarse. However, increasing the d_{aa} parameter further exceeding $d_{aa} = 20$ m, the localization error again increases. This behavior can be explained with the help of propagation delay. For higher inter-AUV-distance, the three beacons take different time to reach a sensor node. During this time, the sensor nodes change their position, which introduce more error in localization.



(a) Node Mobility = 0.5 m/s

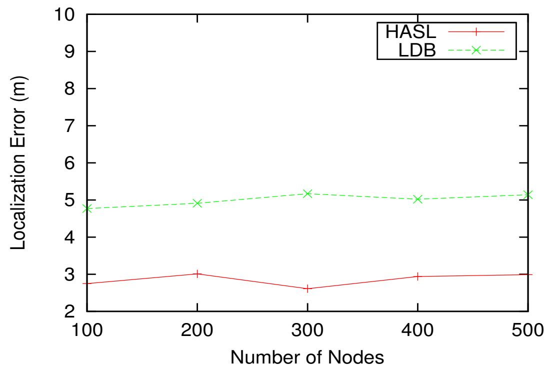


(b) Node Mobility = 1.0 m/s

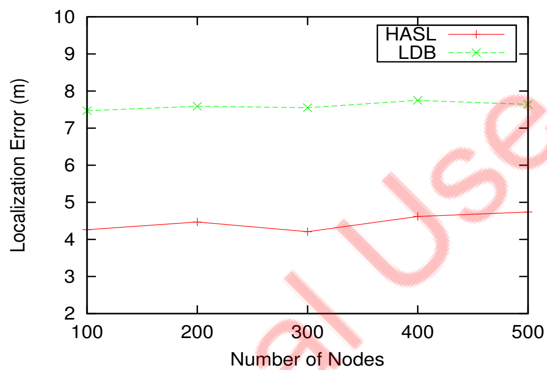


(c) Node Mobility = 2.0 m/s

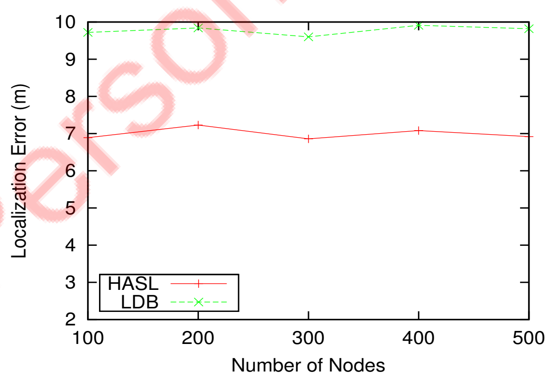
Fig. 3. The effect of node mobility on localization error (transmission range = 100 m)



(a) Node Mobility = 0.5 m/s



(b) Node Mobility = 1.0 m/s



(c) Node Mobility = 2.0 m/s

Fig. 4. The effect of node mobility on localization error (transmission range = 150 m)

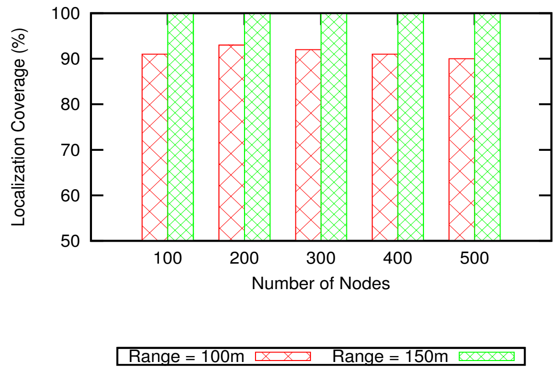


Fig. 5. Localization Coverage

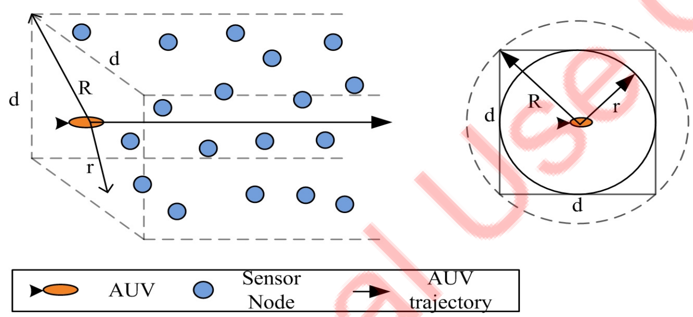


Fig. 6. Effect of Transmission Range on Localization Coverage

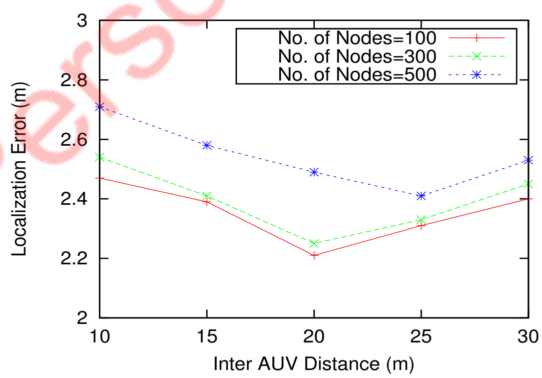


Fig. 7. Effect of Inter AUV distance on Localization Error (Node mobility = 0.5 m/s)

5 Conclusion

In this paper, we proposed HASL, an energy-efficient localization scheme for large-scale mobile UWSNs. Three high-speed AUVs are used as location beacon provider. As the mobile sensor nodes employ 'silent' beacon listening, nodes do not have any extra communication overhead. Therefore, HASL is, indeed, energy-efficient. Sensor nodes localize themselves in very less time, and it is equal to one trip travel time of the AUVs. The time required to localize the sensor nodes increases with increase of network dimension, and decreases with increase of AUV speed.

The simulation results show that with increasing effect of passive node mobility, HASL localizes nodes with less localization error than LDB. We showed how the communication range of an AUV affect the localization coverage.

In the future works, we would like to study: 1) different AUV trajectories to increase the localization coverage in different types of node deployment, and 2) the performance of the proposed protocol under the various underwater issues, such as, jamming [24], [25], wormhole attack [26], variable sound speed [27], and shadow zone.

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