AUV-Aided Localization for Underwater Sensor Networks

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Abstract

We propose a localization scheme for underwater acoustic sensor networks (UWSN) that does not require a priori infras-structure or synchronization between nodes. An Autonomous Underwater Vehicle (AUV) aids in localiz-ing the sensor nodes while roaming across the underwater sensor field. The objectives of this paper are to describe how to localize nodes using AUV and to describe the trade-offs involved, i.e. ratio of localized nodes and localization accuracy. We show that localization success improves as the duration of the AUV localization process increases. In addition, we investigated localization using two methods, bounding-box and triangulation. The former achieves a higher localization ratio but with a higher error. In certain scenarios, we achieved 100% nodes localized with 3% error.

1 Introduction

Underwater Sensor Networks (UWSNs) consist of relatively low-cost, mobile sensors that can be used for monitoring daily ocean life, emergency events in military purposes, environmental research or etc.

Localization is a major issue and a challenging task for UWSNs. It is essential for data tagging and geographical routing. Localization schemes designed for UWSNs should tackle: i) lack of GPS, ii) 3-D space, iii) mobility, iv) minimal message exchange, v) and try to be robust under sleep/wake-up cycles. In essence, the major challenges of localization arise from physical layer constraints. Unlike terrestrial networks, underwater networks use acoustic communications. Acoustic channels have low bandwidth, high propagation delay and high bit error rate. The speed of sound is approximately 1500 m/s, but it varies with temperature, pressure and salinity [8]. Although energy limitation is faced in the terrestrial wireless sensor networks, we also have to reconsider this problem.

In this paper, we propose a simple underwater GPS system using one AUV. AUVs can be used to construct an UWSN as well, however due to high cost and physical inability to diffuse into small areas, they are not always handy: e.g. for environmental monitoring around rocks or reefs. In this work, we employ an architecture that is midway between performance and cost: we consider using a large number of sensors and one AUV. AUV is used for localization and jointly, once it is submerged, it can be used to carry messages of disconnected nodes or time-critical information. The underwater sensors are freely suspended in ocean (e.g. dropped into the ocean from a ship or plane) and they have no surface or ocean bottom connection. This kind of ad hoc deployment forces least infrastructure where the nodes are scattered freely on the 3-D space. Localization is a challenging issue for such networks. The nodes cannot rely on GPS to determine their positions because GPS signal does not propagate well in the water [11]. This complicates the tasks of determining where an event happened or employing position-based routing.

In our scheme, AUV receives GPS signals while floating. Then it dives to a fixed depth and follows a predefined trajectory, moving among sensor nodes. While the AUV is patrolling the whole field of sensors, it broadcasts messages. In this paper, we will refer to those messages as beacons. Beacons include coordinate information. Equally important, beacons are also used for distance estimation. By receiving several beacons, sensor nodes estimate their coordinates.

2 State-of-the-art in Localization Schemes

UWSNs are a recent research topic of significant interest. Various architectures related to application areas have been proposed. The UWSN architectures can be classified in the following groups: i) ocean floor embedded sensor networks, ii) UWSNs with sensors attached either to anchors on the ocean floor [1] or to surface buoys [5], iii) networks with freely suspending sensors (mobile underwater
sensor networks) [9], iv) hybrid architectures [8] v) AUV-aided UWSNs where AUVs are used for additional support in any of the above architectures [18].

Localization issue has different aspects in each of the above architectures. In the first type of UWSNs, localization is trivial. For the second type of tethered architectures, which include sensors wired to buoys, one can assume that the anchor positions are known via GPS and rough sensor localization can be established with little effort. Whereas for the third type of UWSNs, the sensors cannot rely on GPS. In this paper, we try to solve the localization problem of such freely deployed sensors. We use one AUV to aid localization. AUV gets its coordinates from GPS while floating. Then, it dives into a fixed depth and navigates through a predefined route using compass and dead-reckoning. Hence, it can calculate its coordinates with small error. AUV may also resurface periodically to correct its coordinates. Moreover, the sensor nodes are equipped with pressure sensors. For this reason, they know their depth (z-coordinate). Therefore, the localization method estimates the missing x-y coordinates from the beacon exchange between the nodes and the AUV.

The basic building block of localization is range measurement. Without reliable range measurement, localization schemes will suffer from inaccuracy. There are four basic range measurement techniques [14]: Received Signal Strength Indicator (RSSI), Angle-of-Arrival (AoA), Time of Arrival (ToA) and Time Difference of Arrival (TDoA). For UWSNs, a ToA-like technique using the round trip time of an acoustic beacon seems the most promising approach [11]. There are also several range-free schemes [13, 7] which estimates the distance via hop count and average hop distance, nevertheless hop count requires at least one flooding and average hop distance has to be updated for mobile networks which brings in high message overhead.

Either range-based or range-free methods used for distance estimation, the coordinates of the anchors/beacons should be known and fed into the localization algorithm. There are various localization techniques proposed for terrestrial sensor networks, however they cannot be directly applied to UWSNs. We can group these algorithms as: i) infrastructured (with anchors/buoys) and ii) infrastructure-less (without anchors/buoys). For indoor applications [2] propose an infrastructured GPS-free method where the anchor nodes (nodes that send beacons) are placed in the corners of a grid and the sensor nodes receive location information from the anchors and use the range estimations to calculate their location. A similar approach may be considered for UWSNs where surface buoys cover the whole range of the sensor network in x-y plane but it is far from realistic when we take mobility and cost into account. A more relaxed infrastructure is considered in [19] with hierarchical deployment. The authors assume surface buoys and two types of underwater nodes: anchor nodes and ordinary sensor nodes. At first anchor nodes are localized by the help of surface buoys. Then the ordinary sensors are localized using the coordinates of anchor nodes that are spread out randomly among the ordinary sensor nodes. Another localization scheme uses “mobile beacons” where a mobile device distributes its coordinates. Sonardyne [17] is such a commercial product that uses a vessel to scan the area of underwater sensors in shallow waters. On the other hand, infrastructure-less, GPS-free techniques such as [3, 4] need intense messaging. However UWSNs use acoustic channel that has low bandwidth, high propagation delay, high bit error rate and also sensors have energy constraints, extra message should be avoided. Infrastructure-less techniques include an initial range-measurement phase, location estimation phase and a refinement phase [6]. The refinement phase is a must and it is unaffordable for UWSNs in the sense of communication cost and energy.

There are only a few recent works on localization for UWSNs. In [12], the authors propose an anchor-free localization method for UWSNs however before localization they utilize a node discovery protocol which includes high message exchange. The previously discussed hierarchical node deployment [19] and Sonardyne [17] are localization efforts for UWSNs, as well. [19] assumes surface buoys to aid in localization but this infrastructure does not consider urgent deployment. Our scheme answers the need for node localization in emergency cases as well as long term deployed sensor networks. [17] is similar to our work in considering a mobile beacon however using a vessel is expensive and unpractical for short communication ranges. AUV is more flexible where it can dive into several levels to aid localization in 3D. In the next section, we explain our AUV-aided localization scheme.

3 AUV-Aided Localization

In this section, we describe the AUV-aided localization technique. When there is need for a popup UWSN, e.g., emergency cases, the sensor nodes can be dropped to the ocean and left there for several days. Since the nodes are not tied to fixed objects and they will be moving with currents, a periodic localization update may be established by sending the AUV among sensors. We don’t assume any a priori infra-structure or synchronization.

AUV-aided localization scheme uses three messages: wakeup, request and response messages. AUV sends a wakeup beacon to declare its presence to the sensors in its communication range. We assume the nodes are not synchronized, therefore we use a request/response message pair to measure the Round Trip Propagation Delay (RTPD). The sensors that receive wakeup message start range measurement by sending a location request packet.
The AUV replies with a response packet that includes its coordinates. Assuming uniform bidirectional links and homogenous speed of sound, we estimate the distance from (speed of sound*RTPD/2). Response message includes the coordinates of the AUV. The number of necessary responses differs with the localization algorithm used. There are several algorithms and we utilize the two well known ones: triangulation and bounding box [15]. These algorithms use the range measurements and the received AUV coordinates to estimate the coordinates of the sensor nodes.

Triangulation uses \( n + 1 \) equations for \( n \) dimensions and relies on solving linear independent equations. AUV-aided localization with triangulation needs three messages for 2D. The sensor nodes learn their z-coordinate (depth) via pressure sensors. We solve the independent set of equations for messages sent from different, nonaligned locations:

\[
(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = d_i^2
\]  

(1)

Here, \( x, y \) are the desired coordinates. As stated before, \( z \) is known via pressure sensors. For each beacon message, \( x_i, y_i \) and \( z_i \) (for 2D \( i = \{1,2,3\} \)) are the AUV coordinates at the time the AUV sent the messages. \( d_i^2 \) is the square of the range measured.

Bounding box method draws a rectangular region with the intersection of the distance estimates (see Figure 1). In that Figure, positions A and C represent the position of the AUV at two different time slots and B is the position of the sensor node. The intersection of the diagonals give the coordinates of the node. This method needs two messages sent from nonaligned positions. The performance of bounding box is highly dependent on anchor node positions. A node is better localized if the beacons are sent from opposite sides of the box.

4 Simulation Results

We implement AUV-aided localization in Qualnet [16] simulator. We test our method for static nodes assuming that there are no currents. The sensor nodes are randomly deployed in 1000m x 1000m x 120m volume in 3D space. AUV is the mobile beacon. It follows a given trajectory at a constant speed and depth, covering the whole plane within the given simulation time. We consider two different trajectories for AUV, i.e. lattice and spiral trajectories. We assume that AUV can follow a given trajectory with relatively small error \( \delta \), where \( \delta \epsilon (-1m, 1m) \).

The AUV and sensor nodes have a communication range of 60m and the corresponding data rate is 500 kbit/s [10]. We employ CSMA for medium access and an acoustic channel at the physical layer.

We evaluate the performance of AUV-aided localization with three parameters; i) localization success, defined as the ratio between the number of localized nodes and the total number of nodes ii) localization error iii) communication overhead: ratio of the messages to the total number of nodes. The amount of energy consumed is directly related with the number of messages sent.

We vary the number of sensor nodes from 100 to 200 by increments of 10. The AUV speed varied proportionally to the localization duration, which varied from 1hr to 2hrs, increased by 10mins. We present the results for localization durations at 1 hr and 2hrs. For the localization durations between 1 hr and 2hrs, the results are observed to be between these two cases. In addition, the beacon interval varies from 1s to 10s.

4.1 Lattice Trajectory

In this set of simulations, AUV dives into the mid-depth of the 3D space and moves in a lattice-like trajectory, covering the whole x-y sensor field plane. Though this is not the optimal path, it is implemented for its simplicity. The AUV is assumed to follow this simple trajectory within small error bounds.

We test our scheme for varying AUV speeds. Given a fixed trajectory length, low speed values make the localization process longer. It can last even 2 hours. This may be acceptable for long lasting and static UWSNs but is unpractical for mobile scenarios. For comparison we include the results of both durations.

In Figure 2 and Figure 3, we show the ratio of the localized nodes for 1hr (AUV speed is 6.67 m/s (\( \approx 12 \) knot)) and 2hrs (AUV speed is 3.34m/s (\( \approx 6 \) knots)). We first present the results for bounding box algorithm.

For 1hr duration, the ratio of the localized nodes are always above 70%. This is the case even for large message intervals, such as 10 seconds. For 2hr of localization process,
nearly at all beacon intervals, successfully localized nodes are more than 90%. Here, we observe the impact of the speed of the AUV. By increasing the duration of localization process and hence reducing the speed of AUV, we increase the number of nodes that can correctly exchange message with the AUV which increases the localization success. The trade-off involves the time to finish localizing nodes, it takes longer but present more localized nodes. It is also worth mentioning that, for the 2hrs-case, frequency of beacons loses its significance and more than 90% of nodes are localized for even 10 seconds.

Error evaluation is given in Figure 4 and Figure 5. The mean error is between 25-30 meters for 1hr duration and it is slightly higher for 2hrs.

As shown by Figure 6-7, reducing the interval time increases the localized nodes and at the same time, increases the number of messages per node. Especially at high AUV speeds, the more often the AUV transmits beacons, more nodes will be able to receive the message. On the other hand, more nodes will reply and it will increase the access to the congestion medium. This trade-off can be fully exploited by choosing the appropriate interval value for the given application.

Next, we repeat the same set of experiments with triangulation algorithm. In Figure 8-9, we show the ratio of the localized nodes for 1hr and 2hrs. The AUV speed is the same as the above experiments since the duration and the trajectory is the same.

The ratio of the localized nodes are significantly lower than the bounding box results for both cases. For the worst case, in 1hr with 10 seconds of beacon interval and 200 sensor nodes, localization success is only 35% which is quite low. In 2hrs, the algorithm performs better but still not as successful as bounding box. The trade-off comes from the error bounds.

Mean error is shown in Figure 10 and Figure 11. The mean error is below 10 meters for most of the cases. These results reveal the trade-off between the number of localized nodes and the accuracy. Communication overhead given in Figure 12-13 and the tradeoff between beacon intervals and the number of messages per node persists for triangulation.

It is obvious that lattice trajectory takes long time and there may be better methods to cover the space of the sensor nodes. In the next section, we use a spiral trajectory.

4.2 Spiral Trajectory

In this section, we evaluate the impact of trajectory. We assume AUV travels in mid-depth but this time following an Archimedean spiral. This spiral is defined by:

\[ x(t) = at \cos(t), \quad y(t) = at \sin(t) \]

(2)
where $t$ is the time and $a$ is constant. Spiral trajectory allows the AUV to communicate with sensor nodes in the whole area, while minimizing the speed and time needed to visit all the nodes. As a result localization may finish in a shorter time producing less messaging and energy conservation for AUV. First we show the results of bounding box method.

In Figure 14-15, we show the localization success for 1hr (AUV speed is 0.536 m/s ($\approx 1.03$ knots)) and 2hr duration (AUV speed is 0.484 ($\approx 0.939$ knots)) for bounding box method. As in the lattice trajectory, the spiral trajectory also improves the ratio of localized nodes with longer duration. The ratio of the localized nodes is above 50% for 1hr and above 60% for 2hrs. However, the ratio of localized nodes are less when compared to lattice trajectory even though AUV speed is lower. This is a result of our effort to keep some simulation settings fixed. We keep the distance between the spiral cycles equal to the distance between lattice edges, to make the results comparable. A more condensed spiral would give better localization by broadcasting from closer points thus achieving better localization.

The mean error results are given in Figure 16 and Figure 17. The mean error is higher here than lattice trajectory for both durations. The number of messages are the same because the duration and the interval are the same.

The triangulation method had worse localization success even for the lattice trajectory. For the spiral trajectory, the localization success of triangulation drops to 30% for the worst case as given in Figures 18 and 19. However, the mean error range is similar to the results of the previous section (see Figures 20-21).

Spiral trajectory performs worse than the lattice because it has a sparse path, i.e. the distance between the arms of the spiral is large. A longer spiral trajectory (but less than lattice trajectory) might result in better performance.
Figure 9. Ratio of localized nodes for lattice trajectory for simulation duration=2hrs (triangulation)

Figure 10. Mean error for lattice trajectory for simulation duration=1hr (triangulation)

Figure 11. Mean error for lattice trajectory for simulation duration=2hrs (triangulation)

Figure 12. Ratio of messages for lattice trajectory, duration=1hr (triangulation)

Figure 13. Ratio of messages for lattice trajectory, duration=2hrs (triangulation)

Figure 14. Ratio of localized nodes for spiral trajectory for simulation duration=1hr (bounding box)
Figure 15. Ratio of localized nodes for spiral trajectory for simulation duration=2hrs (bounding box)

Figure 16. Mean error for spiral trajectory for simulation duration=1hr (bounding box)

Figure 17. Mean error for spiral trajectory for simulation duration=2hrs (bounding box)

Figure 18. Ratio of localized nodes for spiral trajectory for simulation duration=1hr (triangulation)

Figure 19. Ratio of localized nodes for spiral trajectory for simulation duration=2hrs (triangulation)

Figure 20. Mean error for spiral trajectory for simulation duration=1hr (triangulation)
5 Conclusion

We proposed an AUV-aided localization system that enables localization of sensor nodes in a UWSN. The method exploits the mobility of the AUV to overcome the lack of GPS and to communicate with sensor nodes in disconnected parts of the network.

We observed a trade-off between the time to finish the localization process and the number of successfully localized nodes. We showed that the ratio of the localized nodes improves as the duration of the localization process increases. This is mainly due to slower AUV movement yielding more successful message delivery. In addition, we showed that mean error in localization and communication overhead are not significantly affected by this duration. Furthermore, we verified the trade-off in communication overhead increasing proportional to the number of nodes. We also observed a trade-off between bounding box and triangulation regarding to localization success and accuracy. Bounding box yields a higher ratio of localized nodes, while triangulation a smaller mean error.

For future work, we plan to study the performance of AUV-aided localization under mobility. We also consider extending our work to cooperate with sleep/wakeup schemes. If a node does not receive the localization beacons as a result of a sleep cycle, it can reactively ask for coordinates for the localized nodes around. In addition, we plan to evaluate the performance of AUV-aided localization over geographic routing and perform cross-layer optimizations.

References


Figure 21. Mean error for spiral trajectory for simulation duration=2hr (triangulation)