Underwater Acoustic Sensor Network Localization Using Received Signals Power

Rahman Zandi *, Mahmoud Kamarei **, and Hadi Amiri ***

* School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran, r.zandi@ut.ac.ir
** School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran, kamarei@ut.ac.ir
*** Engineering Research Institute, Tehran, Iran, hamiri@eri.ac.ir

Abstract: This paper proposes a range-free localization scheme for Underwater Acoustic Sensor Networks (UW-ASNs) that uses an Autonomous Underwater Vehicle (AUV) equipped with a directional transceiver. In this scheme, AUV transmits its current position as it moves over sensors deployment area. Consequently each sensor node receives some signals. By measuring the received signals power and comparing them, the signal with maximum power can be found and its corresponding coordinate can be registered. Major advantage of this method is being robust against the loss of some signals as arrival time and exit time of AUV at communication range of the sensor nodes. Another feature of this localization method is being passive that results in energy-efficiency, and no need to time synchronization and distance estimation among the sensor nodes. Performance of the proposed localization method is evaluated by simulations using MATLAB. Simulation results show that the proposed method can localize more sensors with acceptable error than the other schemes.

Keywords: Underwater Acoustic Sensor Networks (UW-ASNs), Positioning.

1. Introduction

Underwater Acoustic Sensor Network (UW-ASN), consists of sensors equipped with acoustic modems for underwater wireless communications. UW-ASN due to its important usages for industrial and military aims has special popularity. UW-ASNs have many usages such as: Environmental monitoring, disaster prevention, assisted navigation, military surveillance, ocean sampling networks, etc. [1]-[4].

Each data of sensors could be interpreted with hinting 3D position of them [3], therefore one of important issues in UW-ASNs is sensor localization. Localization is used for data tagging and geographical routing [5].

So far, there are a few works in the field of underwater localization techniques [3, 6, 7], but many localization techniques are proposed for usages in terrestrial networks [8] and [9]. Due to some limitations, these methods could not be directly utilized for underwater localization.

In general, position estimation algorithms are classified into two categories: Range-based algorithms, and Range-free algorithms.

In range-based algorithms, initially, values of distance or angle among sensor nodes should be estimated, and then by utilizing these information, position of sensor nodes in the network will be estimated. Estimation of distance or angle among sensor nodes can be accomplished by one of the following information: Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival (AOA), and Received Signal Strength Indicator (RSSI) [6].

Range-free algorithms don’t need estimation of angle or distance among sensor nodes. In these algorithms sensor nodes use information that exist in the received messages and estimate themselves location.

Our motivated position estimation, Localization with Directional Beacons for sparse 3d underwater acoustic sensor networks (LDB) [10], uses an AUV that is equipped with a directional acoustic transceiver under it. Sensors passively receive AUV messages, then using first and last received messages (beacon points) information, localize themselves. In the calculation of y coordinate, each sensor node uses radius of communication range at its depth. Major drawback of LDB method is using communication range in the form of a whole circle while communication range is not a whole circle. In fact irregularity moreover transmission range of directional beams is in width of this type of beams. Therefore communication range of each sensor node at its depth has irregularity. Due to this irregularity, some transmitted messages may be lost when arrival or exit AUV into communication range of the sensor node. Due to loss of some messages, LDB will have severe position estimation error.

Proposed method has the following advantages:
(i) Don’t use any anchor node, therefore do not suffer from inaccurate distance estimation of anchors usage; (ii) In economical aspect, this method is energy-efficient because sensors are passive and don’t transmit any message for localization, therefore lifetime of the sensor
nodes is long; (iii) The proposed localization method is suitable for sparse and dense deploying of the sensor nodes; (iv) Because the proposed localization method is passive and don’t exchange message among the sensor nodes, the sensor nodes don’t need time synchronization; (v) Due to using vertical channel this method has less or no time dispersion while horizontal channel has multipath spread [4]; (vi) This method is a distributed algorithm, in which, each sensor node estimates its location. Most of the underwater applications use distributed localization since they are suitable for online monitoring systems than centralized protocols [6]; (vii) Has low computation overhead; (viii) And finally is robust against loss of some messages due to irregularity in communication range of the sensor nodes in experiment.

In this paper an AUV-aided power based underwater localization scheme is proposed, that is robust against loss of some messages due to irregularity in communication range of each sensor node in experiment. Measured received messages power are compared to find highest power in each received message sequences. These maximum powers are used to estimate the position of the sensor nodes. Performance evaluation of the proposed localization method is in terms of the localization successfully.

In section 2, network model used in proposed localization method is explained. In section 3, proposed localization technique will be described. In section 4, effective factors on underwater signal propagation such as attenuation and noise will be discussed. In section 5, results of simulations are discussed and finally conclusion is presented in section 6.

2. Network Model

In this paper, a 3D UW-ASN is assumed, as shown in Fig. 1, that consists of mobile portion and anchored nodes. Mobile portion is an AUV, and anchored nodes are sensor nodes which are fixed in different depths. An AUV is equipped with a unidirectional acoustic transceiver under it, GPS receiver, digital compass, and cheap pressure sensors. The sensor nodes have been equipped with omnidirectional acoustic receiver and cheap pressure sensors. Moreover, the sensor nodes can measure the received signals power. These sensors are battery powered, consequently constraint power, and also they have low memory. This unidirectional acoustic transceiver has beam pattern conical shape as shown in Fig. 1. In this figure radius of maximum communication range of the sensor $S_i$ is $r_{\text{max},S_i}$. AUV patrols on the predefined path, as shown in Fig. 2, over the sensor nodes area, to localize the sensor nodes. It has not energy limitation and rise up surface to receive GPS coordinates at certain intervals [6]. In this work, this interval is chosen between start and end point of each horizontal section of AUV path, because between each of these two points the path is straight and AUV can use digital compass to have less error in these sections of path. AUV and all of the sensor nodes can use cheap pressure sensors to determine the depths therefore 3D localization is transformed into 2D. AUV has low speed about several knots.

3. Localization Technique

Each sensor node may place in range of directional beam of AUV and after some time exit from this range. We define messages that can be detected by the sensor node during this time as a message sequence.

In this localization method, initially AUV patrol on the predefined path over the sensors deployment area and broadcast messages periodically that contain AUVs current position, timestamp, depth and the maximum angle of directional beam. Duration of each period is $T$ second and AUV has speed of $v$ in $m/s$, hence AUV traverses $d = vT$ meter in each period.

The AUV path is shown in Fig. 2. In this figure AUV broadcast messages only in horizontal sections of its path. When moving from a horizontal section of its path to next horizontal section there is no need to transmit message. In Fig. 2, $DX \times DY$ is the dimension of sensors deployment area, and $L$ is the distance between two successive horizontal sections of AUV path. AUV will move in the direction of arrows.

Let us consider a sensor node that will receive $n$ message sequence. Initially the sensor node finds message in each message sequence that has maximum power. To find maximum of received messages power
there is no need the sensor node records all of the
received messages and corresponding measured powers.
It can upon receiving message, compare its measured
power with measured power of previous message
(message with less timestamp), then records greater
power and corresponding message in localization list and
drop message with lower power. Therefore a sensor does
not need much memory. By this method sensor will
record $n_1$ maximum power and their corresponding
coordinate, that $n_1 < n_{\text{max}}$, and $n_{\text{max}} = \left\lfloor \frac{2r_{\text{max}}}{L} \right\rfloor$. In this equation $r_{\text{max}}$ is the maximum communication range of
the considered sensor node, $L$ is the distance between
two successive horizontal sections of AUV path and $\left\lfloor x \right\rfloor$
denotes the largest integer smaller than the real variable $x$. Each of these maximum powers is in different
received message sequence. A sensor node can obtain
radius of its maximum communication range by using the
following equation:

$$ r_{\text{max}} = (h_i - h_a) \times \tan \left( \frac{\alpha}{2} \right) $$

(1)

which in this equation $h_i$ is the sensor depth and $h_a$ is
the AUV depth both measured by the pressure sensors,
and $\alpha$ is the maximum directional beam angle, that $h_i$
and $\alpha$ is transmitted for the sensors by AUV. The sensor
uses $x$ coordinate of the recorded messages with maximum power in each sequence and calculate their
mean to estimate its $x$ coordinate. The sensor needs to
know has been placed between which two successive
horizontal sections of AUV path to estimate its $y$ coordinate. For this purpose it must sort recorded maximum power of all received sequences. Then it uses four or three maximum powers of four or three different message sequences respectively, to determine it has been
placed between which two horizontal sections of AUV
path. And also determine it is closer to which of these
two sections. If a sensor has received $n_i = 0$ message
sequence, this sensor cannot localize itself. If $n_i = 1$, it
can assume its location same as the position of a recorded
maximum power message. If $n_i = 2$, it can calculate
mean of $y$ coordinate of two recorded messages with maximum power to estimate its $y$ coordinate. When
$n_i = 2$, it can calculate mean of $x$ coordinate of two
recorded messages with maximum power to estimate $x$
coordinate of its position. If $n_i > 2$ in order to localize
itself with less error, two cases are considered. In first case, sensor $S$ has been placed between $L_i$ and $L_{i+1}$
horizontal sections of AUV path and is near the middle of
them, as shown in Fig. 3a. In this figure, the sensor $S$
has been placed at center of its maximum communication
range circle. The found maximum power of each sequence
by the sensor are named as follows: $P_{\text{max, i-1}}$, $P_{\text{max, i+1}}$, $P_{\text{max, i+2}}$. To simplify, after sorting these maximum powers, we have shown them by: $P_1 > P_2 > P_3 > P_4$.

Figure 3. The cases for placing sensor between two successive horizontal path: a) First case. b) Second case.

Figure 4. Coverage condition of all deployed sensors.

In order to differentiate between two cases, the sensor
must calculate values of these differences: $P_1 - P_2$, $P_1 - P_3$, $P_2 - P_3$, $P_2 - P_4$. If first case occurs, by
comparing these differences the sensor will obtain the
following results:

$$ \text{First Case} = \begin{cases} P_1 - P_2 < P_2 - P_3, \\ P_1 - P_2 < P_2 - P_4, \end{cases} $$

(2)

With these results, sensor can deduce that has been
placed between sequences contain measured powers of
$P_1$ and $P_2$, and has been placed approximately middle
of them.

In the second case, the sensor $S$ has been placed between $L_i$ and $L_{i+1}$ horizontal sections of AUV path, and it is near the $L_{i+1}$ section, as shown in Fig. 3b.

In this case maximum power of the sequences are:

- $P_{\text{max, i-1}}$, $P_{\text{max, i-1}}$, $P_{\text{max, i+1}}$, $P_{\text{max, i+2}}$.
- $P_{\text{max, i+2}}$, $P_{\text{max, i+3}}$.

After sorting maximum powers, the sensor obtains:

$P_1 > P_2 > P_3 > P_4 > P_5$. 

If the second case occurs, then the sensor by comparing mentioned differences will obtain the following results:

**Second Case** = \[
\begin{aligned}
P_1 - P_3 > P_2 - P_3 \\
P_1 - P_2 > P_2 - P_3
\end{aligned}
\] (3)

With these results, the sensor can deduce that has been placed between sequences contain \( P_1 \) and \( P_2 \), and it has been placed near the sequence contain \( P_3 \). As shown, the sensor depending on its case, uses four or three maximum received power for several purposes. First, to differentiate between two cases, second to know it has been placed between which two horizontal sections of AUV path, and third if second case has occurred determine it is closer to which horizontal section. It can use two maximum received powers to only deduce that has been placed between which two successive horizontal sections.

In order to the proposed localization method cover the entire deployed sensor nodes in expose of directional beam, optimum value of \( L \) must be calculated. For this purpose consider Fig. 4. In this figure AUV moves along arrows and broadcast messages at \( t_1 \) and \( t_2 \) instants. If a sensor has been placed in DBEC area this means that it has not placed in expose of directional beam hence it cannot receive any message and cannot localize itself. This problem can be solved by limiting value of \( L \), and choosing optimum value for it. We show deployment sensors surface depth with \( h_s \). In Fig. 4, distance \( AB \) obtains as follows:

\[
AB = \sqrt{r_{\text{max},S}^2 - d^2} \quad \text{(4)}
\]

where,

\[
r_{\text{max},S} = (h_s - h_{sr}) \times \tan\left(\frac{\alpha}{2}\right) \quad \text{(5)}
\]

Therefore if it is wanted to all sensors place out of DBEC area, mean all of them be placed in expose of directional beam, AUV must move on the predefined path with value of \( L \) less than AB distance,

\[
L < \sqrt{r_{\text{max},S}^2 - d^2} \quad \text{per} \quad \text{(6)}
\]

For trade off between localization time and coverage of all sensor nodes, value of \( L \) should not be very less than AB distance. BC distance is calculated by the following equation:

\[
BC = r_{\text{max},S} - \sqrt{r_{\text{max},S}^2 - d^2} \quad \text{(7)}
\]

As it can be seen in Equation (7), when \( d \) increase, value of BC distance and consequent DBEC area increase. This means that when \( d \) increase due to increasing DBEC area, probability of placing more sensors in this area increase, consequently more sensors do not receive any signal and cannot localize themselves. Therefore AUV should not choose very large value of \( d \) which results some sensors could not localize themselves.

### 4. Underwater Channel

In this subsection, effect of underwater channel on transmitted acoustic signal will be studied. Source Level (\( SL \)) is defined as follows:

\[
SL = 10.\log(P) + 170.8 + DI_t \quad \text{(8)}
\]

Where \( SL \) is the source level, \( P \) is the total transmitted acoustic signal power, \( DI_t \) is transmit directivity index that when projector uses directional beam, this parameter has value in \( dB \), and when using omnidirectional projector value of this parameter is zero [11].

In passive sonar \( SNR \) calculation, one-way transmission is used, as follows:

\[
SL - TL = NL - DI_t + SNR \quad \text{(9)}
\]

where all of these parameters are in \( dB \). Therefore for computing \( SNR \), value of Transmission Loss (\( TL \)) and ambient noise level (\( NL \)) must be calculated [11].

Transmitted acoustic signal power between transmitter and receiver reduces due to absorption and geometric spreading. Power reduction by absorption is due to converting acoustic energy to thermal energy. We use a simple model for describing acoustic absorption in underwater here, named Thorp model [6].

Total loss of acoustic path for given distance \( r \) and signal with frequency \( f \), obtains by using the following equation:

\[
TL(r, f) = 10.\log\left(\frac{A(r, f)}{A_{\text{norm}}}\right) = 10.k.\log(r) + \alpha.r \quad \text{(10)}
\]

where \( \alpha \) in (10), for frequencies above several hundred \( kHz \), is as follows:

\[
\alpha = 10.\log(a(f)) = 0.11.f^2 + 44.f^2 \frac{4100 + f^2}{1 + f^2} + 2.75.10^{-4}f^2 + 0.003 \quad \text{(11)}
\]

In Equation (10), the first term is spreading loss and the second is absorption loss. \( k \) is spreading coefficient that describes geometric of spreading and it can take values of 1 (for cylindrical spreading), 2 (for spherical spreading) and 1.5 for practical usages. \( a(f) \) is absorption coefficient in \( dB/\text{km} \), and frequency \( f \) is in \( kHz \) [6] and [12].

We obtain value of noise level 33 \( dB \) re \( \mu Pa \) by diagram from reference [11] at operating frequency 50 \( kHz \), and due to being approximately shallow water we add 5 \( dB \) to this noise level [11], which means that total noise level is 38 \( dB \) in this work.
5. Simulations

In this section proposed localization method is evaluated using simulations by MATLAB. Simulation uses 200 sensor nodes that randomly distributed in an area with $1000m \times 1000m \times 100m$ dimensions. Each sensor node is equipped with an omnidirectional transceiver to receive transmitted messages by AUV. AUV uses a directional transceiver to transmit messages. Width of this directional beam is assumed 60 degree. AUV moves at constant depth 10 meter underwater, with speed of $1 \text{ m/s}$, along predefined path as shown in Fig. 2, and periodically broadcast messages every $T$ second. Threshold $SNR$ for detection by each sensor is 10 $dB$. The parameters that their effect has been considered on performance of the proposed localization method are: transmission interval, number of the sensor nodes and distance between two successive horizontal sections of AUV path. To ensure the reliability of the results, simulations have been performed for each simulation conditions, with a different random deployment of the sensor nodes in every case. The distance between AUV and the sensors deployment area surface, $h_A - h_s$, is 20 meter, and operating frequency is 50 $kHz$, hence attenuation and noise level is calculated for this frequency. For spreading coefficient we use its practical value mean that $k = 1.5$. Error threshold to evaluate each sensor position estimation error is 6 meter. Maximum angle of directional beam is 60 degree and minimum is 50 degree, therefore messages that place between these two angles may have not been received by the sensor nodes due to irregularity with probability of 60 percent. In this simulation, this phenomenon has been modeled by Gaussian distribution. The transmission range of directional beam is equal to distance between AUV and seabed mean 120 meter. Sea state has been considered 2. Source level due to omnidirectional transmitted acoustic power is 90 $dB re \mu Pa$, and directivity index value is 10 $dB$ mean that the total source level is 100 $dB$. Observation duration of signal is 0.1 $ms$ and its sampling frequency 800 $kHz$ have been considered.

5.1 Metrics

The metric that has been used to evaluate performance of the proposed localization method is the ratio of localized sensor nodes same as LDB method, that is defined as follows:

$$R = 1 - \frac{N_{Unlocalized}}{N_{Total}}$$

(12)

where $N_{Total}$ is the total number of deployed sensors in deployment space, and $N_{Unlocalized}$ is the number of sensors that their position estimation error are greater than given threshold.

5.2 Simulation Results

1. Ratio of the localized sensor nodes vs. Transmission interval: Fig. 5, shows the ratio of localized sensor nodes versus transmission interval. In this figure, given constant $L$, transmission interval is varied from 3 to 15 second with a step size of 3 second. Using this setting, we find the number of sensor nodes that their position estimation error is less than 6 meter. As it is shown, in the proposed localization method given constant $L$, ratio of the localized sensor nodes decreases with increasing the transmission interval. This is due to with increasing the transmission interval, according to Equation $d = vT$, position distance between two corresponding successive transmitted messages increases, also. Increasing $d$ results in decreasing AB distance in Fig. 4. As $L$ is constant, with decreasing AB distance, inequality $L < AB$ do not be satisfied that it is caused some of the sensor nodes do not place in expose of directional beam of AUV, mean that they will place in DBEC area of Fig. 4, and consequently cannot localize themselves. With increase of the difference between AB distance and radius of maximum communication range, DBEC area of Fig. 4 is increased, consequently probability that more sensor nodes place in this area is increased. Therefore with satisfying Equation (6), more sensor nodes can localize themselves. Other factor is that due to longer distance between successive transmissions, mean error in the estimation of $x$ coordinate of each sensor node increases. As shown in Fig. 5, if Equation (6) can be satisfied, with choosing transmission interval less than 9 second, more than 98 percent of the sensor nodes despite value of the noise level obtained in 50 $kHz$, are localized, which means their error are less than 6 meter. As shown in Fig. 5, despite mentioned irregularity, the number of localized sensor nodes at $L = 30$ meter in the proposed localization method is greater than the number of localized sensor nodes at $L = 10$ meter in the LDB method. This means, for attaining approximate same performance, LDB method needs more time than proposed method to travel above all sensors deployment area, consequently in LDB method more messages will be transmitted and more powers will be consumed.

![Figure 5. Ratio of localized sensor nodes vs. Transmission interval for different values of distance between two successive horizontal sections of AUV path.](image-url)
2. Ratio of localized sensor nodes vs. Number of sensor nodes

Fig. 6, shows the ratio of localized sensor nodes versus the total number of them. With increasing the number of sensors from 40 to 200 with a step size of 40 sensor nodes, the number of localized sensors has little changes. This is due to that this method is passive, which means in this method the sensor nodes do not transmit any message and only receive messages to localize themselves. Therefore localization does not depend on the number of sensor nodes. As we can see in this figure, with satisfying coverage condition of all deployed sensor nodes, more than 98 percent of all deployed sensor nodes can localize themselves with acceptable error (error less than 6 meter here). But if values of \( L \) and \( T \) used in the proposed method be used in the LDB method, although due to being silent the number of localized nodes is approximately constant but only approximately 20 to 30 percent of all deployed sensor nodes can localize themselves. In this figure, difference between the numbers of localized sensor nodes of two localization methods is approximately 70 percent. This is due to that this simulation has used irregularity in communication range of each sensor node and the proposed localization method do not use radius of the communication range of the sensor nodes while LDB method uses this radius of each sensor node to localize them. Therefore due to using signals with highest measured power in each message sequence, the proposed localization method is robust against loss of some messages that occurs due to irregularity in communication range of each sensor node.

6. Conclusion

In this paper we have proposed a simple, distributed, energy-efficient, range-free, no need to time synchronization among sensor nodes, robust against loss of some messages, suitable for sparse and dense sensors deployment, and passive localization scheme. In the proposed method a directional transceiver has mounted under AUV and transmits messages when it moves over the sensors deployment area. As messages are received by the sensor nodes they measure these messages power and through comparing received messages power, based on advertised location of AUV, the sensor nodes can be localized. Performance of the proposed localization method is evaluated by using MATLAB. Simulation results show that the proposed localization method depends on transmission interval, and it is not affected by the number of deployed sensor nodes. Moreover, it has been shown by the simulation and theoretically that the proposed localization method outperforms LDB method in terms of localization successfully. It has been shown that the proposed localization method is robust against loss of some messages due to irregularity in communication range of sensors.

References