A Novel Technique for Underwater Object Detection Using 3D EM Sensor Network

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***Abstract*—Localization of objects in underwater environment using electromagnetic (EM) wave based underwater wireless sensor networks (UWSNs) provides the opportunity of faster object detection in comparison with acoustic wave based networks. For this purpose, we propose a novel technique using the law of reflection and spheres with different radii in three dimensional (3D) space. The overall system comprises of a source (transmitter), sensors in a sensor field, cluster heads and an onshore base station (BS). The system is divided in various zones with each zone having a number of spheres. If the object is in the propagation path of the transmitted EM wave, signal gets reflected and is received by one or multiple sensors. Information of location of these sensors is subsequently transferred to the onshore BS which then calculates the location of the object using the proposed algorithm. To assess the performance of the proposed system in a seawater environment, substantial simulations are carried out.**

***Index Terms*—localization; underwater environment; EM wave communication; UWSN.**

I. Introduction

Underwater sensor networks (UWSNs), utilized in underwater wireless communications is a widely used practical strategy for coastal surveillance, environmental research, oceanography and control of autonomous underwater vehicle (AUV), submarine and surface vessel [1]. In most cases UWSNs use acoustic as transmission medium due to relatively longer transmission capability compared with EM wave. However, slow propagation speed, very slow data rate, severe attenuation at the water-air boundary etc have raised serious concerns over the feasibility of underwater acoustic networks [2], [3]. In case of EM wave, though it suffers from having shorter transmission range due to severe attenuation, underwater EM wave communications provide some advantages, like higher bandwidth, faster data rates, lower propagation delays and robustness to channel [1]. Also, in case of optical wave, although higher data rates are achievable from optical wave transmission, it requires clear water with line-of-sight (LOS) propagation [3]. The overall advantages facilitate the use of EM wave over acoustic medium and optical wave in the underwater surroundings. Underwater object detection is really significant as it helps to detect enemy war submarines and if such one is detected, necessary measures can be taken by the concerned authority.

For detection of objects in underwater, most of the works that have been accomplished, are done in two dimensional (2D) space. In [4], the writers proposed a propagation model and evaluated it by maximum likelihood (ML) estimation and Cramer-Rao bound (CRB) method. Furthermore, the writers in [5] introduced 2D distributed particle filter based object locating and tracking strategies using clustered USWNs. But works related to this topic in 3D are being carried out recently. In [6], a 3D underwater acoustic sensor network (UW-ASN) is implemented which works in two phases, namely passive listening and active listening. The arrival time of the echo coming from an object is utilized to measure the distance from object to sensor. Trilateration is then used to determine the location of the object. Most prominently, in [7], [8], 3D cluster based cubic sensor architectures are proposed and implemented. When an intruder comes in the presence of the sensor network, the sensors in the cube sense the arrival of the intruder and the locations of these sensors are transmitted to the CH in the cube. Then this data from the CH is transferred to the upper cube's CH and subsequently to an onshore BS. The BS then calculates the location of the intruder. In [9], underwater target tracking technique is explored in EM-acoustic combination.

In this paper, the purpose is to explore a different technique to detect an underwater object in 3D space using EM wave with the help of law of reflection and drawing spheres. The model comprises of a signal source or a transmitter, a 3D sensor field, CHs and a BS. If there is an object on the transmission signal line, the signal from the source gets reflected from the surface of the object and received by the sensors which in turn transfer the location of the sensors to the BS. From the data collected in the BS, the location of the surface point is calculated. We have proposed an algorithm that eliminates the sensors according to the power they receive. If the sensor power is less than a certain threshold, the particular sensor is excluded from the next step of calculation. The number of effective sensors is dependent on the number of the spheres. Meticulous simulations are done to evaluate the overall system performance by varying different parameters of the setup.

The rest of the paper is organized as follows: general outline of the system model in Section II with object detection technique in section III. Simulation results are discussed and analyzed in section IV followed by the summary of findings in section V.

II. System Model

A. Proposed Architecture

This section of the paper discusses the overall network model of the system and how the components of the network are distributed. The system comprises of a source that transmits an EM wave by varying the angle of incidence on the surface of the underwater object. If the signal is incident on the surface, then the signal gets reflected from a particular point of the surface of the object. Our objective is to determine this surface point. For this, a 3D sensor field is proposed throughout the whole region of observation with each small block of SNs having it's own CH for data transmission. The SNs are distributed in equal distance in a cubic pattern. When a SN receives the reflected signal, the power received at the sensor (P_s) is calculated and if the power is greater than a certain threshold (P_{th}), then the SN is assumed to be fully active. The SNs whose received power is less than the threshold, are excluded from the next steps. The active SNs transfer the data to CH and from then the data is transferred to BS and the overall location estimation calculation is done there. Fig. 1 shows the basic view of the network model of the system.

In the figure, there are only a few small blocks of the cubic sensor field is shown for understanding. In practical situation, the sensor field will be distributed throughout the whole region. The sensor field and source are assumed to be framed in a corrosion free steel cage, which is firmly tied with the ground level. This system works by following the law of reflection, i.e, angle of incidence, θ_i = angle of reflection, θ_r. The distance from source to object and sensor is assumed to be in short range due to EM communication. The overall detection technique is discussed in the section III in details.

B. Link Model

Propagation path loss P_L (dB) of EM wave in underwater environment can be given by [10]

$$P_L = L_{\alpha,\epsilon} \quad (1)$$

where $L_{\alpha,\epsilon}$ is the attenuation loss in water due to water conductivity and complex permeability in dB. The path loss is

$$20 \times 2\pi \times (log_{10}e) \times \sqrt{(\sigma \times f \times 10^{-7})} \quad (2)$$

which is in dB/m, f is the transmission frequency in Hz and σ is the conductivity of the water in S/m.

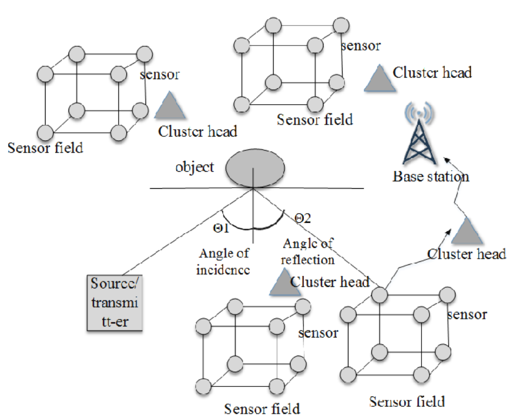

Fig. 1. A 2D overview of the network model.

C. Performance Metric

For evaluating the performance of the proposed detection technique which will be discussed in section III, performance metrics are defined below, which is used to calculate the error in location estimation in perspective of distance.

If *(x,y,z)* is the true position of the source, then the absolute distance *r* between the true source location and approximated target location is assumed as a measure of error and *r* is given by

$$r = \sqrt{(x_{est} - x)^2 + (y_{est} - y)^2 + (z_{est} - z)^2} \quad (3)$$

where $(x_{est}, y_{est}, z_{est})$ is the estimated target point on the object. Then, the absolute percentage of error is denoted as e_p and determined by

$$e_p = |\frac{r_{est} - r_{act}}{r_{act}}| \times 100\% \quad (4)$$

where r_{act} is the actual distance from the source to the point on the surface of the object and r_{est} is the estimated distance from the source to the object point.

III. Proposed Object Detection Technique

The detection scheme proposed here involves drawing spheres with different radii around the approximated location of the object. The radius of each sphere is determined from the minimum threshold power P_{th} required for a sensor to be in active mode and the distance of the propagating wave.

A. Selection of Range for Object Detection

At first, an EM signal is transmitted from the source in a particular angle in reference with *x* axis of the *xy* plane. We assume a directional antenna with low beamwidth. As the highest power will be transmitted through the center of the main lobe, a line is assumed in this direction through the center. This transmission signal line is represented by AB as shown in Fig. 2.

Next, the highest possible distance point C is selected as the initial estimated position of the object on the AB line on the basis of the furthest CH whose coverage area intersects with the AB line. This point is selected such that the reflected wave traveling back is detected by one SN at or above threshold power. If the point is estimated very far, then the signal will not propagate back to be detected by any SN. The distance from A to C is the range for the object detection technique.

B. Zones and Points

The range for object detection is then divided into *n* number of zones. *k* equidistant points are then selected for each zone, where the first point is the rightmost point of the corresponding zone as shown in Fig. 3. Therefore, *P* = *nk* is the total number of points.

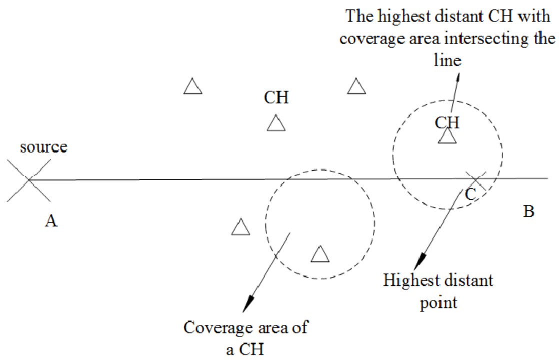

Fig. 2. A 2D view of transmission signal line and the highest possible range on it.

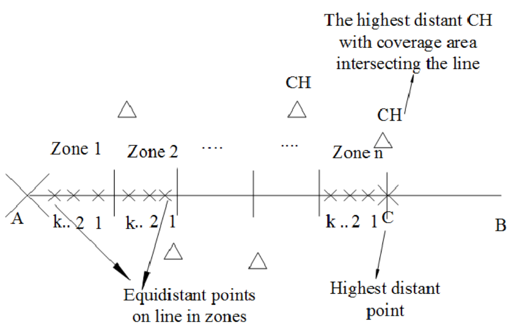

Fig. 3. Range of detection is divided in various zones.

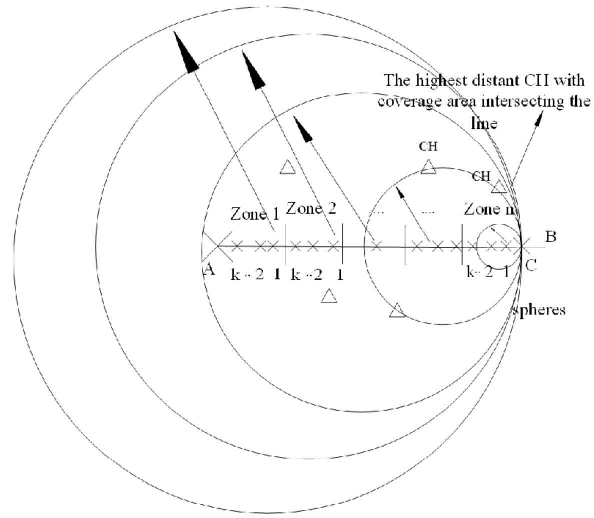

Fig. 4. Spheres along the line of transmission signal, one sphere for each zone.

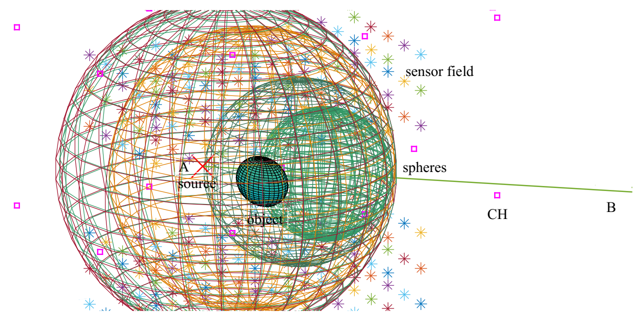

Fig. 5. Spheres along the signal propagation line.

C. Spheres

Next, spheres are drawn for each zone for detection purpose. The rightmost point of each zone is selected as the first point for drawing spheres. To determine the radius of a sphere for a zone, the power received from the source at this point is calculated via path loss model. If there were an object at this point on the way of transmitted signal, the signal would have got reflected and a far positioned SN would have received the signal at power equal to threshold power. The distance from the rightmost point and this SN is calculated. A sphere is then drawn by taking this distance as it's radius and the rightmost point as it's center. The spheres along the transmission signal line (one sphere for each zone) are shown in Fig. 4.

Each zone can have a single sphere or multiple spheres depending on how many points per zone are being used in calculation. For drawing the next sphere, next point in the same zone closer to the source on line AB is selected.

D. Algorithm

The source transmits the signal in a particular direction. If there is no reflected signal, the algorithm decides that the object does not lie on the signal line. Then the source will change the direction of signal transmission. If some part of an object lies on the propagation line AB, the signal gets reflected and the necessary information is transferred to the BS. Then the algorithm determines the range, divides the range into zones and points and draws spheres as discussed in section III.A-C. For demonstration, diagram for four zones and a sphere per zone is shown in Fig. 5.

The SNs inside these spheres which receive the reflected signal at threshold power or more, are differentiated from the other SNs by encircling them as shown in Fig. 6.

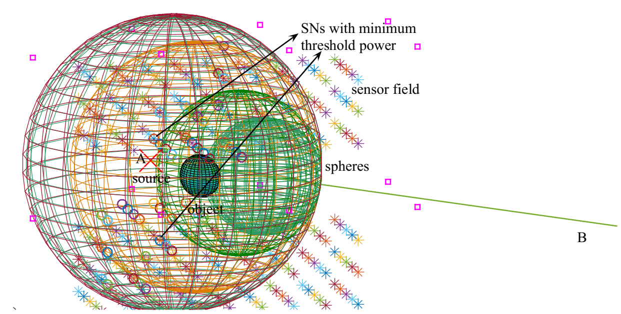

Fig. 6. Sensors with minimum threshold power are distinguished from other SNs.

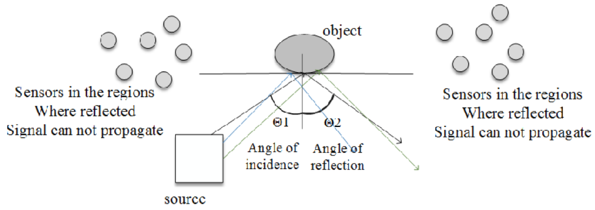

Fig. 7. Regions where reflected signal can not propagate.

According to law of reflection, reflected signal can not propagate in some regions as shown in Fig. 7. The SNs in these regions are excluded from the encircled ones for the next step.

A line CD is fitted through these remaining encircled SNs. If this line intersects the transmission signal line, then the intersection point is the desired surface point of the underwater object as shown in Fig. 8.

If CD line does not intersect the AB line, then the combination of SNs with at least minimum power or more are changed in a way that this line intersects AB. For example, if this line is far right from AB, then some SNs from the encircled ones are excluded from upper right side and lower right side of CD and new SNs are included to it's upper left side and lower left side for a new line fitting. In Fig. 9, a 2D representation of the reflected wave CD shifting through SN exclusion and inclusion is shown. A 2D view is shown instead of 3D view due to the convenience of presenting the system before and after SN inclusion and exclusion. When this line CD intersects with the transmitted signal line AB, the algorithm stops shifting the SNs and decides the intersection point as the object location.

IV. Result and Analysis

A. Simulation Setup

Substantial MATLAB based simulations are carried out for evaluating the performance of the proposed object detection technique. The results presented here are found by averaging the result for more than 1000 individual and independent locations of the object. SN-SN distance in a small cubic sensor block is assumed as 5 m and the dimension of the network coverage region is $60 \times 60 \times 100$ m^3. Usually for fresh water,

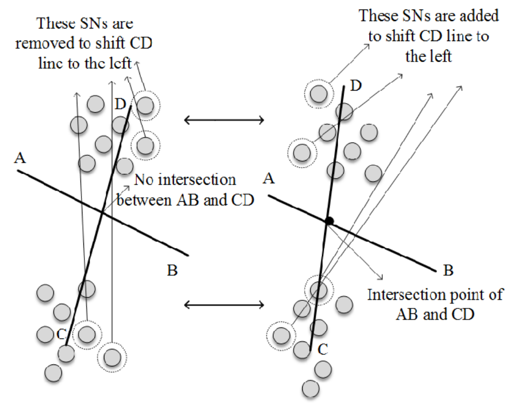

Fig. 9. Shifting of the reflected signal to intersect the transmission signal.

the value of σ is 0.01 S/m. But as we have considered saline water, σ = 4 S/m is taken [11]. Frequency, transmission power and detection threshold power values are taken as f = 5 kHz, P_{tX} = 3 W, P_{th} = -70 dBm respectively.

B. Result Analysis

When CDF of error is plotted for 1000 different positions of the object, it is observed how the CDF for each zone differs with one another. For demonstration, CDF of error for n = 2, 3 and 4 with k = 2 is shown in Fig. 10. For n = 2, e_p starts from 0.36, whereas for n = 3 and 4, e_p starts from 0.86 and 1.31 respectively. This plot shows that for n = 2, CDF curve is the least steep and for n = 4, CDF curve is the steepest. This implies that for n = 4, the variance in error is the smallest and a small variance indicates that the errors tend to be very close to the mean, and to each other. This is in line with the proposed method as with the increase in number of zones, SNs with minimum P_{th} for line fitting increase and the errors get close to one another for different positions of the object.

Fig. 11 illustrates the impact of number of spheres per zone on e_p. In this figure, e_p between actual distance and estimated distance from source to object is plotted against number of spheres per zone. This graph shows that in case of two zones (n = 2), when number of spheres per zone is

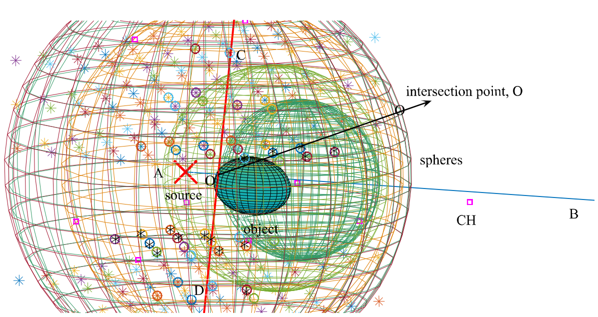

Fig. 8. Intersection point of incident signal and reflected signal.

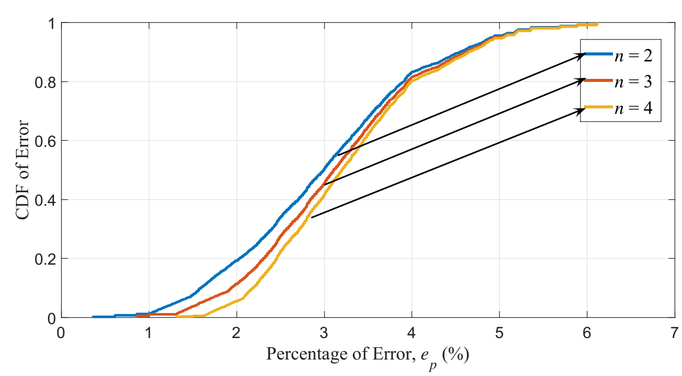

Fig. 10. CDF of percentage of error for different zones for two spheres.

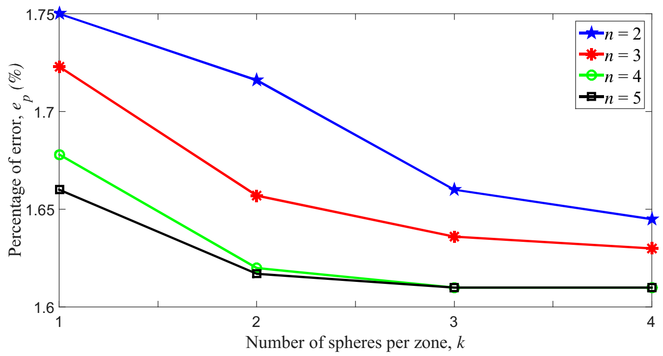

Fig. 11. Error curve for spheres per zone.

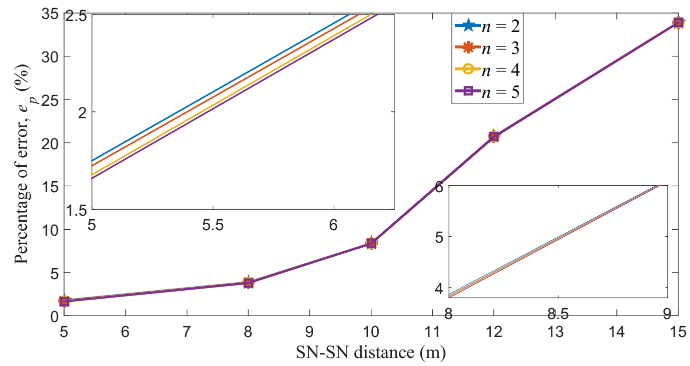

Fig. 12. Impact of SN-SN distance on percentage of error.

equal to 1, e_p starts from 1.75. As the number of spheres per zone increases, e_p decreases. This happens because with the increase in number of spheres per zone, the number of SNs that receive the reflected signal at P_{th} or more also increases. Consequently, as the number of SNs with minimum threshold power increases, the line fitting becomes more accurate. Therefore, the determination of intersection point of AB and CD becomes a more accurate estimation of the object location. As a result, e_p decreases. It is also observed that as n increases, e_p values for all the zone combinations decrease. This also reflects the notion that with the increase of zones, number of SNs with minimum threshold power increases. As a result, starting e_p values decrease. For n = 3, 4 and 5, the similar decreasing pattern of e_p with the increment in the number of spheres per zone is observed. This plot also reflects that e_p becomes constant with the increase of number of zones and spheres after a certain value.

Finally, Fig. 12 demonstrates the impact of SN-SN distance on the e_p for n = 2, 3, 4 and 5 with k = 1. For n = 2, e_p starts from 1.75 as can be seen from the top left inset. We can observe that with the increase in SN-SN distance, e_p increases as the number of SNs decreases. As a result, there are less SNs for line fitting and determination of the intersection point of the transmitted signal and fitted line becomes more erroneous. For n = 3, 4 and 5, e_p starts from 1.72, 1.68 and 1.66 respectively, which implies that with the increment in number of zones, object location algorithm has higher accuracy. Furthermore, the similar increasing pattern of e_p with the increment in SN-SN distance is observed.

V. Conclusion

In this paper, a novel technique for object detection, specifically a point on the surface of the object in underwater environment is proposed using EM wave. The proposed method involves determining a range for object detection, then dividing the range into a number of zones and points and finally drawing spheres with the points as the centers of the spheres. This method is assessed through percentage of error estimation between actual and estimated distances from source to object. The number of spheres and zones have substantial impact on the result. It is observed that the greater the number of spheres and zones, the less the error is in object detection i.e., the more is the accuracy of the method.

Shadow fading is not included in the process as then the shape of the spheres would become irregular and great difficulty would arise in detection. Future works will include the impact of shadow fading and object velocity on the overall system performance. We will also evaluate the detection delay performance and compare it with the acoustic counterpart.

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