Localization and Synchronization for 3D Underwater Acoustic Sensor Networks

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Abstract. Three-dimensional Under-Water Acoustic Sensor Networks (UWASN) are supposed to be deployed for many applications. However, a protocol for sensors' self-localization and time-synchronization in UWASN remains a challenge problem. In this paper, we developed a multilateration algorithm which could reliably localize and synchronize underwater sensor networks by acoustic ranging. To our best knowledge, this is the first scheme which could achieve both them for 3D UWASN simultaneously. Simulation results are also given to illustrate its effectiveness.

1 Introduction

Three-dimensional Under-Water Acoustic Sensor Networks [1, 2] could enable a broad range of applications including but not limit to: Ocean Sampling, Environmental Monitoring, Undersea Explorations, Disaster Prevention, Assisted Navigation, Distributed Tactical Surveillance and Mine Reconnaissance [2]. Different from existing small-scale Underwater Acoustic Network [21, 22, 23], UW-ASNs rely on localized monitoring and coordinated networking amongst a large number of underwater sensors. An example large-scale real-time 3D UW-ASN for military purpose is illustrated in [4].

Compared with ground-based sensor networks, some challenges are fundamentally different in underwater research. Among all those open issues for 3D UW-ASNs, distributed underwater GPS-free localization and time synchronization service is the most critical one. As the basis of self-organization, sensors' self-localization and time-synchronization are key requirements for every sensor network [19]. Most ground sensor networks rely on GPS or anchor nodes with GPS receivers for localization and synchronization. The problem is: in underwater environment, GPS is unavailable, and anchor nodes could only be placed on the water surface. What's more, underwater signal propagation delay and physical water properties have profound implications on most existing localization and time synchronization algorithms [5, 6, 7, 20]. Further more, most researches discuss 2-D scenarios and only a few concerns with 3-D underwater scenarios. No existing protocols could meet the demands to implement a localized, relatively accurate e networking technology in a 3D aquatic environment [7].

In this paper, we developed a multilateration algorithm for reliably localizing and synchronizing underwater sensor networks by acoustic ranging. To our best

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knowledge, this is the first scheme which could achieve them for 3D UWASN simultaneously. Our contributions can be summarized as follows:

- Identify the assumptions and goals of localization and time synchronization for military purpose Large-scale Real-time 3D Underwater Acoustic Sensor Networks.
- Present the basic idea of achieving localization and synchronization for large scale 3D underwater sensor network in a short latency. Through atomic multilateration and iterative multilateration, we provide a simple but effective scheme for self localization and time synchronization
- Error propagations introduced in iterative multilateration process are successfully controlled.

The paper is organized as follows. Section 2 presents some background and related works. Section 3 formally introduces the problem and the assumptions used. In section 4 we present our effective but simple method. Simulation results and discussions are provided in Section 5. The paper is concluded in Section 6.

2 Background and Related Works

2.1 Localization and Time Synchronization in Terrestrial Sensor Networks

GPS- based localization and synchronization is the most important 3D localization system today. For terrestrial sensor networks, the task of localization and time synchronization could be easy by simply embedding a GPS receiver into each node. Or, anchor nodes (i.e. nodes whose locations and times are already known by GPS receivers) could be used to help the organization of passive nodes (i.e. nodes whose locations and time are yet unknown).

For time synchronization, anchors could broadcast the synchronization packets in the speed of light to passive nodes. Localization is a litter more complex, and a number of distributed localization schemes have been proposed to date. These schemes can be broadly classified into two categories: range-based schemes, and range-free schemes [7]. Distributed range-based positioning algorithms use range or bearing information obtained by range technologies like ToA (Time of Arrival), RSSI (Receiver Signal Strength Indicator), TDoA (Time Difference of Arrival) and AoA (Angel of Arrival). They generally have three positioning phases: (i) the distance estimation phase, where nodes use one or combinations of those range technologies to estimate distances to nearby nodes; (ii) the position estimation phase, where a system of linear equations is generally solved using a least squares approach to estimate the position of the node, and finally (iii) a refinement phase, where the accuracy of the algorithm is improved by using an iterative algorithm. The N-Hop Multilateration Scheme [8], the Hop-TERRAIN and Refinement Scheme [10], Ad Hoc Localization System (AHLoS) [9] and Ad Hoc Positioning System (APS) “Distance Propagation” and “Euclidian Propagation” Schemes [11] all fall into this category.

Distributed range-free localization schemes are schemes that do not uses range or bearing information, they can be further classified into hop count based schemes and area-based schemes. The centroid scheme [12], DV-Hop [13] and Density aware Hop-count Localization (DHL) [14] fall into this category. The advantage of these schemes lies in their simplicity, as sensors do not need to make any ToA, RSSI, TDoA or AoA measurements. However, range free schemes only provide a coarse estimation of a node's location. It's clear that rang-free algorithms are not suitable for military purpose sensor networks due to their inaccuracy.

2.2 Localization and Time Synchronization for UW-ASNs

Underwater localization can be achieved by utilizing the low speed of sound in water, which permits relatively accurate timing of signals. These node distance data can later be used to perform localization calculation, similar to that of terrestrial localization. The performance of different range-based positioning schemes in underwater sensor networks is simulated and compared in [6]. The problem is: first, under these schemes, not all the nodes in the system can be localized, even though the network might be fully connected. For example, the nodes which do not satisfy the position uniqueness conditions described in [8] might not be able to calculate their locations. Second, their refinement phase requires a relatively long time which is inappropriate for many task. What's more, few of they concerns 3D scenarios.

A dedicated time synchronization protocol: Time Synchronization for High Latency Acoustic Networks (TSHL) is proposed in [15], which well manages the errors induced by the large propagation latency. Localization is not provided in this algorithm. A distributed 3D space coverage scheme and a detection/classification scheme are studied for tactical underwater surveillance systems in [3]. Localization and time synchronization are not needed for this system due to its unusual deployment method.

2.3 3D Space Partition and Localization

In 3D applications, the shape of the cell must be a polyhedron that tessellates a 3D space. According to [16, 17], the truncated octahedron is the best choice. For a given cell radius Rs, truncated octahedron could tessellate the space with the minimum cell number. Figure 1 is taken from 3D NET software [18] to illustrate its tessellation.

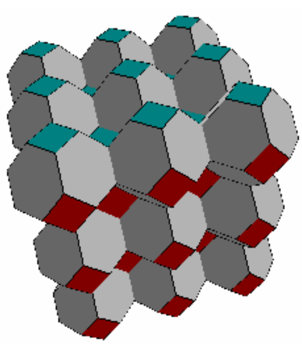

Fig. 1. Truncated octahedron tessellation

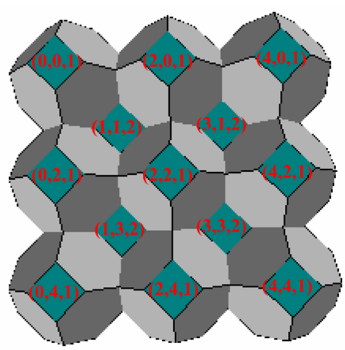

Fig. 2. Surface arrange

3 Problem Statement

A dedicated self organization method which could achieve both localization and time synchronization for large scale 3D underwater sensor networks is needed. The main assumptions and the goals of this work are defined as follows:

Assumptions

- The sensors are densely distributed over a 3D underwater space. The 3D space should be partitioned into equal sized non-overlapping cells. In order to maintain connectivity, the distance between one a node and any other active node in its first-tier neighboring cell can not exceed the transmission range.
- All underwater sensor nodes are identical and initially unknown about its location and time. They have identical transmission/sensing range and the transmission/ sensing region of each node can be represented by a sphere of radius R_t / R_s which having the sensor at its center.
- The anchor nodes are buoys on the surface of the ocean which already known their locations and time without errors.
- Unlike radio speed used in GPS, underwater sound speed is variable. For simplicity, we assume that in one node's transmission range the speed is constant.

Goals

- Find an algorithm to achieve both localization and time synchronization for large-scale real-time 3D underwater sensor networks in a short latency.
- Identify the best way to partition the network into cells in three-dimension such that the cell number is minimized. Given a sensor range R_s, deduced the minimum transmission range R_t to maintaining full connectivity. And given the calculated coordinates, a sensor should determine its belonging cell.
- Control error propagation hence improves localization and time synchronization accuracy.

4 Our Methods

A. Basic Idea

A sensor need to obtain only two coordinates (x, y) in 2D sensor networks. While in 3D scenarios, (z) coordinates are also needed. First we illustrate the relations between anchor nodes and passive nodes. A anchor node could transmit a synchronize packet to a passive node which is try to calculate its (x, y, z) . The packet contains anchor node's coordinates $(x0, y0, z0)$ and the transmit time $t0'$. Let v be the speed of sound, and t be the receive time of the packet which is still unknown. If a passive node receive from at least 5 anchor nodes, its location and local time could be presented as shown in (1), $(xi, yi, zi, ti'), i \in [0,1,2,3,4]$ are the locations and transmit times of 5 synchronize packets. Here we assume the first packet is from $(x0, y0, z0, t0')$, and let $(\Delta t1', \Delta t2', \Delta t3', \Delta t4')$ denotes the arrival time shift of packet 1, 2, 3 and 4. Linear least square solutions are given in (2)-(5).

$$\begin{cases} \sqrt{(x0-x)^2+(y0-y)^2+(z0-z)^2} = v*(t-t0') \\ \sqrt{(x1-x)^2+(y1-y)^2+(z1-z)^2} = v*(t+\Delta t1'-t1') \\ \sqrt{(x2-x)^2+(y2-y)^2+(z2-z)^2} = v*(t+\Delta t2'-t2') \\ \sqrt{(x3-x)^2+(y3-y)^2+(z3-z)^2} = v*(t+\Delta t3'-t3') \\ \sqrt{(x4-x)^2+(y4-y)^2+(z4-z)^2} = v*(t+\Delta t4'-t4') \end{cases} \quad \begin{cases} t0 = t0' \\ t1 = t1'-\Delta t1' \\ t2 = t2'-\Delta t2' \\ t3 = t3'-\Delta t3' \\ t4 = t4'-\Delta t4' \end{cases}$$

$$\begin{cases} \sqrt{(x0-x)^2+(y0-y)^2+(z0-z)^2} = v*(t-t0) \\ \sqrt{(x1-x)^2+(y1-y)^2+(z1-z)^2} = v*(t-t1) \\ \sqrt{(x2-x)^2+(y2-y)^2+(z2-z)^2} = v*(t-t2) \\ \sqrt{(x3-x)^2+(y3-y)^2+(z3-z)^2} = v*(t-t3) \\ \sqrt{(x4-x)^2+(y4-y)^2+(z4-z)^2} = v*(t-t4) \end{cases} \tag{1}$$

$$A = \begin{bmatrix} 2(x0-x1) & 2(y0-y1) & 2(z0-z1) & (t0^2-t1^2) & 2(t1-t0) \\ 2(x0-x2) & 2(y0-y2) & 2(z0-z2) & (t0^2-t2^2) & 2(t2-t0) \\ 2(x0-x3) & 2(y0-y3) & 2(z0-z3) & (t0^2-t3^2) & 2(t3-t0) \\ 2(x0-x4) & 2(y0-y4) & 2(z0-z4) & (t0^2-t4^2) & 2(t4-t0) \end{bmatrix} \in C^{4x5}, \quad M = \begin{bmatrix} x \\ y \\ z \\ v^2 \\ v^2 t \end{bmatrix} \in C^{5x1},$$

$$B = \begin{bmatrix} (x0^2-x1^2)+(y0^2-y1^2)+(z0^2-z1^2) \\ (x0^2-x2^2)+(y0^2-y2^2)+(z0^2-z2^2) \\ (x0^2-x3^2)+(y0^2-y3^2)+(z0^2-z3^2) \\ (x0^2-x4^2)+(y0^2-y4^2)+(z0^2-z4^2) \end{bmatrix} \in C^{4x1}, \qquad A*M=B, \qquad M=A^{-1}*B \tag{2}$$

Our basic idea is simple: Multilateration. First, we put a set of anchors somewhere on the surface, and a group of nearby passive nodes can be located and synchronized; these nodes became new anchor nodes and thereafter broadcast new synchronize packets to a larger range; one by one, tier by tier, the whole network are expected to be totally organized in a short latency. However, a minimum density of sensors is required to guarantee the multilateration. Despite an anchor node's location and transmit time, a special field “Tier number” is added to synchronize packet content. Tier number refers to the tier of the transmitted nodes in the multilateration. We defined anchor nodes in tier 0; a node record all tier numbers of the packets which used in its calculation; after localization , new anchor node would use the largest tier number plus 1 as its own tier for broadcasting. First in part B, we determine the best cell partition method and cell numbering rule. Given a sensor range, we also Other details are given in part C.

B. Cell Partition and Numbering

Using the approach in [16] and [17], we partition the 3D space to the shape of truncated octahedrons. After partitioning the 3D space into shaped cells, the transmission range Rt of the nodes should be at least equal to the distance between the furthest points of two first-tier neighbor cells. Thus in topology control, we could keeping only one node active at a time inside each cell hence minimizes the number of active nodes and maximizes network lifetime while maintaining full connectivity [17]. Suppose a sensor's sensing range is Rs, then the radius of the cell $R = \frac{1}{2} Rs$ could ensure full coverage for any active sensor in a cell. Let the side length of hexagons as a, we can get $Rt = \frac{\sqrt{85}}{5} Rs$.

Suppose we are tessellating a cuboid, we can arrange the area as shown in Figure 3(look from up): let square faces of truncated octahedrons align with the border of the target volume. Let $d = \sqrt{2}a$. After normalize all length and coordinates to d, we can numbering cells ID by their centre coordinates as that shown in Figure 3. If the transmission range Rt is set to be $\sqrt{34}a = \sqrt{17}d$, we could evaluate the broadcasting range for each sensor. The number of neighbors totally depends on sensor density and would greatly affect the multilateration process.

C. Atomic and Iterative Multilateration

In atomic phase, anchors are put in the surface centre of the target area. Passive nodes heard enough anchors are called tier 1 node, they could calculate their coordinates and clock times. After atomic multilateration phase, tier 1 nodes became new anchor nodes and thereafter broadcast new synchronize packets to a larger range. The iterative multilateration begins. As stated in part A, every passive node could deduce its location and time by received enough synchronization packets.

Calculations of nodes could simple follow (2). But due to precision limit, each calculated value has rounding errors. These errors would cause bigger errors in the subsequent calculations of other nodes, which are known as error propagation. What's more, some coefficient matrix of simultaneous linear equations (SLR) maybe "sick": litter error of input floating-point numbers may greatly change the solutions of system. These errors would iteratively amplify themselves in the iteration of tiers, which are proved by the simulations.

There are two solutions. First, we could alleviate the harm of error propagation in advance by limit some new anchor sensors from broadcasting which has a high probability to cause harm. A coefficient matrix's sick extent could be expressed as

$$cond(A)_v = \left\|A^{-1}\right\|_v \left\|A\right\|_v \quad (v = 1, 2, \infty) \tag{3}$$

So SLR with big $cond(A)_v$ could be regard as a "pollution candidate", and we can forbid such a sensor to propagates its information, but a proper boundary value for method 1 is hard to find and maybe related to scenario setting. Or, we can explore the diversity of received packets. By using super-coupled equations, a least-squares solution can be obtained as in (4). The second approach is adopted. A simple method for determining a sensor's respective cell number is also developed. The node's cell centre must be within a cubic, which has the node as the centre and has $2d$ as the length. Then a node could simply calculate all possible centers in this range and chooses the one has the minimum distance with it.

$$A=\begin{bmatrix} 2(x0-x1) & 2(y0-y1) & 2(z0-z1) & (t0^2-t1^2) & 2(t1-t0) \\ 2(x0-x2) & 2(y0-y2) & 2(z0-z2) & (t0^2-t2^2) & 2(t2-t0) \\ & & \cdots\cdots & & \\ 2(x0-xi) & 2(y0-yi) & 2(z0-zi) & (t0^2-ti^2) & 2(ti-t0) \\ & & \cdots\cdots & & \\ 2(x0-xn) & 2(y0-yn) & 2(z0-zn) & (t0^2-tn^2) & 2(tn-t0) \end{bmatrix} \in C^{nx5}, \quad M=\begin{bmatrix} x \\ y \\ z \\ v^2 \\ v^2 t \end{bmatrix} \in C^{5x1},$$

$$B=\begin{bmatrix} (x0^2-x1^2)+(y0^2-y1^2)+(z0^2-z1^2) \\ (x0^2-x2^2)+(y0^2-y2^2)+(z0^2-z2^2) \\ \cdots\cdots \\ (x0^2-xi^2)+(y0^2-yi^2)+(z0^2-zi^2) \\ \cdots\cdots \\ (x0^2-xn^2)+(y0^2-yn^2)+(z0^2-zn^2) \end{bmatrix} \in C^{nx1}, \quad i\in[1,n] \qquad \begin{cases} A^T A * M = A^T * B, \\ M=(A^T A)^{-1} * (A^T * B) \end{cases} \tag{4}$$

5 Results and Analysis

5.1 Evaluation Methodology

We have implemented the algorithm in a dedicated simulator. The target area is 30x20 km with 6 km depth, and almost 900 nodes are deployed in the volume. Sensors are uniformly distributed in the 3D space as an ideal deployment scenario. Each cell has only 1 sensor and it is placed near the centre of the cell. N is the number of required synchronize packets, and N-1 is the number of acquired equations. Thus N should not less than 7; because a cell has 14 neighbors, we set 14 as the upper boundary of N. The bigger is N, the more synchronized neighbors needed by an unsynchronized sensor. The evaluation metrics used in our experiments include: (i) localize right ratio: the localize right ratio is defined as the nodes which successful get its cell id versus the total nodes number; (ii) average distance error: the distance between a node's calculated position and its real position; (iii) average time error: the time difference between a node's calculated time and its real time; (iv) maximum tier number and (v) process complete time to evaluate the whole network performance.

5.2 Results

In this part, localization and synchronization characteristics with different N are given in Figure 3-5.

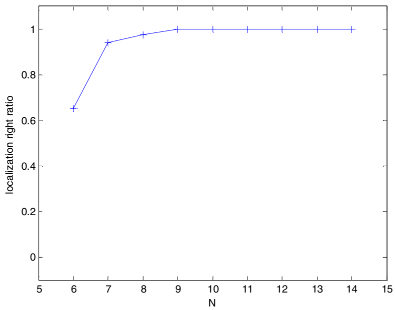

Fig. 3. Localization right ratio

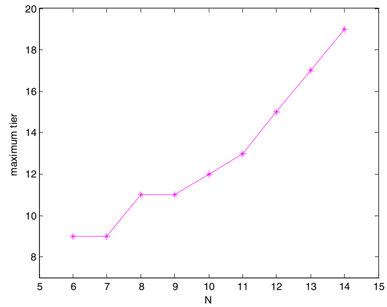

Fig. 4. Maximum tier number

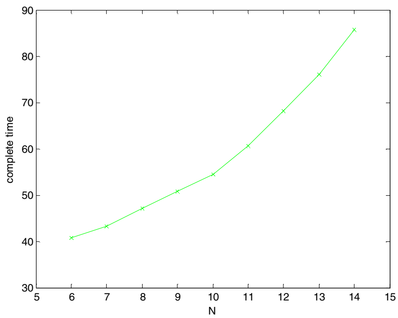

Fig. 5. Process complete time

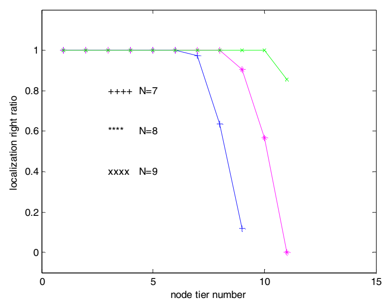

Fig. 6. Localization right ratio

As we can see, the total localization right ratio increases when N increases, while the maximum number of required tier and process complete time increase too. In Figure 6-8, localization and synchronization characteristics in different tiers are shown when N equals 6,7 and 8. With the tier number increases, localization right ratio drops and average distance/time error increase sharply. It is clear that more methods should be taken to control error propagation than least square equations. We

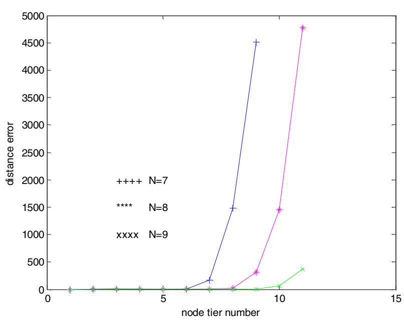

Fig. 7. Average distance error

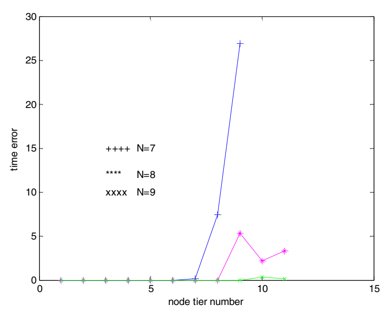

Fig. 8. Average time error

are currently consider: (i) neighbors selection, combine error estimation information in the multilateration to enable a node to select only "good" neighbors; (ii) weighted least square, adjust the impact of neighbors by their tier number; (iii) refinement, add a incremental refinement phase after initial estimation.

6 Conclusions

Under-Water Acoustic Sensor Networks (UW-ASN) are novel networking paradigms and some applications call for 3D space deployment for special military or civilian purpose. In such a network, sensor localization and synchronization remains a challenge problem. In this paper, we developed a service for reliably localizing and synchronizing underwater sensor networks by acoustic ranging. To our best knowledge, this is the first scheme which achieves localization and time synchronization simultaneously for 3D UW-ASN. We are currently working in three directions. First we will consider the influence to ranging by speed variance in underwater environment. Second, more methods should be taken to control error propagation than least square equations. Third, a separated synchronization phase and localization phase may greatly improve the performance.

Acknowledgment

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