LOCALIZATION IN UNDERWATER ACOUSTIC SENSOR NETWORKS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

MEHMET TALHA IŞIK

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

AUGUST 2007

Approval of the thesis:

LOCALIZATION IN UNDERWATER ACOUSTIC SENSOR NETWORKS

submitted by **MEHMET TALHA IŞIK** in partial fulfillment of the requirements for the degree of **Master of Science in Electrical and Electronics Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ____________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. İsmet Erkmen ____________
Head of Department, **Electrical and Electronics Engineering**

Assoc. Prof. Dr. Özgür Barış Akan
Supervisor, **Electrical and Electronics Engineering Dept., METU** ____________

Examining Committee Members:

Prof. Dr. Semih Bilgen ____________________
Electrical and Electronics Engineering Dept., METU

Assoc. Prof. Dr. Özgür Barış Akan ____________________
Electrical and Electronics Engineering Dept., METU

Prof. Dr. Kemal Leblebicioğlu ____________________
Electrical and Electronics Engineering Dept., METU

Asst. Prof. Dr. Ali Özgür Yılmaz ____________________
Electrical and Electronics Engineering Dept., METU

Dr. Altan Koçyiğit ____________________
Informatics Institute, METU

Date: ________________

I thereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name :

Signature :

ABSTRACT

LOCALIZATION IN UNDERWATER ACOUSTIC SENSOR NETWORKS

Işık, Mehmet Talha

M.Sc., Department of Electrical and Electronics Engineering

Supervisor: Assoc. Prof. Dr. Özgür Barış Akan

August 2007, 45 pages

Underwater Acoustic Sensor Networks (UW-ASNs) have the potential to enable many applications such as environmental monitoring, undersea exploration and distributed tactical surveillance. In order to realize the potential gains of these applications, it is essential that the sensor nodes can be accurately located in a three dimensional underwater sensor network topology. Although many localization protocols have been proposed recently for terrestrial sensor networks, the unique characteristics of the underwater acoustic communication channel, such as high and variable propagation delay, necessitate new localization protocols. In order to address this need, a localization protocol for UW-ASN, Three-Dimensional Underwater Localization (3DUL), is presented in this thesis. 3DUL achieves network-wide *robust* 3D localization by using a distributed and iterative algorithm. Importantly, 3DUL exploits only three surface buoys for localization. The sensor nodes leverage the low speed of sound to accurately determine the inter-node distances. We show through simulation experiments that the localization accuracy does not degrade significantly

with an increase in the number of nodes, making 3DUL scalable.

Keywords: Underwater Acoustic Sensor Networks, 3D Localization, AUV Tracking

ÖZ

SUALTI AKUSTİK SENSÖR AĞLARINDA YER BELİRLEME

Işık, Mehmet Talha
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Özgür Barış Akan

Ağustos 2007, 45 sayfa

Sualtı Akustik Sensör Ağları (SASA), çevre gözetleme, sualtı araştırmaları ve dağıtık taktiksel gözetim gibi birçok uygulamayı mümkün kılacak potansiyele sahiptir. Bu uygulamaları gerçekleştirebilmek ve sualtı dünyasıyla ilgili bilgilerimizi arttırmak için sensör düğümlerinin üç boyutlu bir sualtı sensör ağı topolojisinde yerlerinin belirlenmesi gerekmektedir. Son zamanlarda karasal sensör ağları için birçok yer belirleme protokolü önerilmiştir. Ancak, sualtı akustik kanalının yüksek ve değişken gecikme gibi kendine has özellikleri, SASA'lar için yeni yer belirleme protokollerinin geliştirilmesini gerekli kılmıştır. Bu ihtiyacı karşılamak için bu tezde SASA'lar için bir yer belirleme protokolü, Üç Boyutlu Sualtı Yerbelirleme (ÜBSY), sunulmaktadır. ÜBSY'de sensör düğümleri akustik sinyalin görece yavaş hızını kullanarak diğer sensörlere olan uzaklıklarını belirler. Bu uzaklıkları kullanan dağıtık ve yinelemeli bir algoritma üç boyutlu yer belirlemeyi gerçekleştirir. ÜBSY yer belirleme için sadece üç yüzey şamandırası kullanır. Yapılan başarım deneyleri yer belirleme performansının sensör düğümü arttıkça önemli derecede düşmediğini

göstermektedir. Bu da ÜBSY'yi ölçeklenebilir kılmaktadır.

Anahtar Kelimeler: Sualtı Akustik Sensör Ağları, Üç Boyutlu Yer Belirleme, AUV İzleme

To my scintillating wife,
Bahar

ACKNOWLEDGMENTS

I would like to express my gratefulness and deepest respect to my advisor, Dr. Özgür B. Akan. I am indebted to Dr. Akan for his constant support during my graduate study. This thesis would not be completed without his mentorship and trust.

I also thank Dr. Semih Bilgen, Dr. Kemal Leblebicioğlu, Dr. A. Özgür Yılmaz and Dr. Altan Koçyiğit who kindly agreed to serve in my M.Sc. Examining Committee.

A special thanks goes to my brother, R. Ali Işık, for his invaluable and seamless support. He has been a father, a mentor and a friend to me.

I also would like to thank all the members of the Next Generation Wireless Communications Laboratory for the wonderful ambiance they created. I am especially thankful to Alper Bereketli and Barış Atakan for their intimate friendship.

I am also grateful to my father, Yunus Z. Işık, for his love, support and encouragement.

Finally, I thank my brilliant wife, Bahar, who supported me during my seemingly endless working hours even at the very first days of our marriage. Her patience and encouragement were instrumental for the completion of this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

3D	Three Dimensional
3DUL	Three Dimensional Underwater Localization
AoA	Angle of Arrival
ASW	Anti-Submarine Warfare
AUV	Autonomous Underwater Vehicle
CTD	Conductivity, Temperature, Depth
GIB	GPS Intelligent Buoy
GPS	Global Positioning System
LBL	Long Baseline
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SBL	Short Baseline
TDoA	Time Difference of Arrival
ToA	Time of Arrival
TL	Transmission Loss
UNL	Underwater Node Localization
UW-ASN	Underwater Acoustic Sensor Network
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 Underwater Acoustic Sensor Networks

The oceans play key roles in climate regulation and are essential for nutrient production, oil retrieval and transportation. They cover nearly 71% of the surface of the earth. Consequently, there is a vast interest in monitoring them for scientific, environmental, commercial and military reasons. Despite this interest, the aquatic environments of our earth are largely unexplored due to the lack of technology which would provide accurate, real-time and fine grained spatio-temporal sampling.

The current approach for ocean monitoring is to deploy underwater sensors that record data during the monitoring mission, and then recover the sensors. However, this approach does not allow real-time monitoring since the recorded data cannot be retrieved until the sensors are recovered. This is unacceptable especially for surveillance applications. Moreover, there is no interaction between the onshore control systems and the underwater sensors. This makes the adaptive tuning of the instruments, and the reconfiguration of the system impossible. Additionally, underwater sensors are prone to failures because of fouling and corrosion. However, the failures of the sensors cannot be detected until they are recovered which can cause the complete failure of a monitoring mission [1].

The recent advances in the area of underwater acoustic communication paved the way for the development of Underwater Acoustic Sensor Networks (UW-ASNs) which is the enabling technology for exploring and monitoring the world under the surface of the water in a timely and effective fashion. UW-ASNs consist of underwater sensors and vehicles that are deployed to the region of interest to perform collaborative monitoring tasks. The sensors and vehicles self-organize in an autonomous network and sample the aqueous environment.

UW-ASNs will enable a broad range of applications such as ocean sampling networks, environmental monitoring [36, 38], disaster prevention, distributed tactical surveillance [5], mine reconnaissance, seismic monitoring and equipment monitoring. Besides, Autonomous Underwater Vehicles (AUVs) and freely floating autonomous robots such as drogues which are equipped with underwater sensors are envisioned to participate in exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. Experiments demonstrated that these vehicles can improve the observation and prediction of the characteristics of the oceanic environment [13].

UW-ASN can perform pollution monitoring for chemical, biological and nuclear agents. In addition, UW-ASNs can perform ocean current and wind monitoring, and biological monitoring such as tracking of fish or micro-organisms. Also, UW-ASNs can improve weather forecast, detect climate change, and understand and predict the effect of human activities on marine ecosystems.

AUVs and fixed underwater sensors can collaboratively monitor areas for surveillance, reconnaissance, targeting, and intrusion detection systems. For example, in [5], a 3D underwater sensor network is designed for a tactical surveillance system that is able to detect and classify submarines, Small Delivery Vehicles (SDVs) and divers based on the sensed data from mechanical, radiation, magnetic, and acoustic microsensors. Underwater sensor networks can perform better than the traditional radar/sonar systems and enable the detection and classification of low signature targets by also combining measures from different types of sensors [1].

1.2 Localization in Underwater Acoustic Sensor Networks

In order to realize the potential gains of underwater applications described above, it is essential that the sensor nodes know their positions in a three dimensional topology. Associating the sampled data with three dimensional position information considerably increases the capability of the underwater sensor network. For example, consider an underwater sensor network which is part of an Anti-Submarine Warfare (ASW) system. A sensor reading without location information about a possible submarine passing by is at best useful to raise the alarm. By combining the data with location information, the submarine can be tracked and the necessary precautions can be taken more effectively. Moreover, position information can be used by geographical routing protocols [4], [20] which are promising for underwater environments with their scalability and limited required signaling features [2].

There are many energy-efficient localization techniques proposed for terrestrial sensor networks [22, 24]. However, a fast and reliable communication channel between the nodes of the network, as assumed by these protocols, does not hold in underwater scenarios. In the underwater environment, acoustic communication is the typical physical layer technology since radio or optical communications are not practically feasible [2].

Underwater acoustic communication channel has unique characteristics such as limited capacity and high propagation delay. The delay is due to the five-orders-of-magnitude difference in the speed of sound in water compared to RF propagation. Another challenge is that the speed of sound changes depending on temperature, pressure and salinity which causes the propagation path to be curved. Moreover, the sensor nodes move due to water currents. Hence, the existing localization protocols for wireless sensor networks (WSN) cannot be applied to the underwater node positioning problem. On the other hand, there exist very few proposals for underwater localization in the current literature [6, 14, 39, 23]. However, none of them provides a scalable, fine-grained, dynamic, three-dimensional yet practical localization solution for UW-ASN.

In this thesis, we introduce the *Three Dimensional Underwater Localization* (3DUL) algorithm that seeks to achieve 3D localization in large-scale underwater acoustic sensor networks in a dynamic, timely, energy-efficient, simple and accurate fashion. It has been tailored to match the unique requirements of UW-ASN.

3DUL initially exploits only three anchor nodes[1] at the surface of the water and then diffuses their global position information into all directions in a 3D dynamic underwater network topology. 3DUL does not assume the presence of designated anchor nodes deployed underwater. Importantly, 3DUL also does not require time synchronization.

3DUL follows a two-phase process to perform 3D localization. During the first phase, the sensor nodes with unknown locations determine their separations to neighboring anchors by leveraging the low speed of sound. In the second phase, the sensor nodes use pairwise distances to three anchor nodes and depth information to project the anchors onto their horizontal levels and form a virtual geometric structure. If the structure is *robust*, the sensor node locates itself through dynamic trilateration and becomes an anchor. Then, it can assist other nodes in determining their positions. This process dynamically iterates along all directions in 3D topology to determine the locations of as many nodes as possible. Performance evaluations reveal that 3DUL is able to successfully spread the global location information of three surface anchors throughout the UW-ASN. Moreover, its simple algorithm allows the UW-ASN to adapt to the dynamic environment of the water world.

1.3 Organization of the Thesis

This thesis is organized in six chapters. In Chapter 2, we present a review of related work on localization algorithms in UW-ASNs. The operation of 3DUL is described in Chapter 3 and a pseudo-algorithm is also presented. In Chapter 4, we characterize the possible sources of error and present a detailed analysis of 3DUL. Performance evaluation and simulation results of 3DUL are presented in Chapter 5. Finally, the thesis is concluded in Chapter 6.

[1] A node is referred to as an anchor node if it has knowledge of its global position.

CHAPTER 2

RELATED WORK

Classical methods of underwater positioning are Long Baseline (LBL) and Short Baseline (SBL) systems [17]. In LBL systems, an array of transponders is deployed at a known position. Underwater nodes send an acoustic signal which is then returned by each transponder after it is received. The position is calculated by determining the propagation time between the underwater node and each transponder, estimating the sound speed and knowing the geometry of the transponder array [17].

In SBL systems, the node has a multi-element receiver array that makes it possible to measure the angle and the range to an anchor. The node is tracked from a surface ship. By measuring the arrival time difference of a single sonar ping between two or more hydrophones, the bearing from the node to the anchor can be determined. When the anchor responds to node interrogation, then the time delay can also be calculated. The distance and the direction to the anchor allows for position estimation and navigation [17].

None of these approaches suits well to ad-hoc underwater sensor networks. In the LBL system, the deployment of the transponders on the seabed and surveying their position is a difficult, time-consuming and expensive process. In SBL systems, the need for a ship in the operation region is not suitable for many applications and greatly increases the cost.

In [37], an underwater GPS concept was introduced. Instead of deploying transponders on the seabed and trying to determine their positions, the system consists of floating surface buoys. They are equipped with GPS receivers and broadcast satellite information underwater, via acoustic telemetry. The underwater nodes receive these messages from the buoys and compute their own positions locally.

A different, yet related approach to acoustic underwater positioning has actually been implemented and is available commercially: the so-called GPS Intelligent Buoy (GIB) system [30]. This system consists of four surface buoys equipped with GPS receivers and submerged hydrophones. Each of the hydrophones receives the acoustic impulses emitted periodically by a synchronized pinger installed on-board the underwater platform and records their times of arrival. The buoys communicate via radio with a central station where the position of the underwater target is computed.

In [2], multihop underwater sensor networks are envisioned which use surface buoys to communicate with the user onshore. These buoys are endowed with long-range tranceivers, GPS receivers and acoustic modems. Therefore, GPS-inspired solutions are naturally suitable to the underwater positioning problem. However, they only serve a limited area. The underwater nodes should be within the range of at least three such buoys to determine their positions. In addition, the centralized algorithm of the GIB system would incur unacceptable latencies for an underwater network consisting of hundreds of sensor nodes communicating via low speed acoustic signals.

The research closest to our work is the localization effort in the sensor networks domain. Underwater sensor networks share many of the design goals and characteristics of terrestrial sensor networks such as energy efficiency and limited node ability. Existing localization algorithms developed for terrestrial sensor networks can be broadly divided into two classes. The first class is based on signal strength measurement [15, 6]. These algorithms are useful to give proximity information of nodes with low cost, but they are not able to provide accurate location information.

The second class is based on distance measurements between sensor nodes and is generally referred to as *range-based* algorithms. These algorithms consist of two basic phases: ranging and estimation. During the ranging phase, each sensor node determines the distances between itself and its one-hop neighbors. In the estimation phase, the sensor node combines these distances to determine its location. The most popular methods for ranging phase employ either received signal strength indicator (RSSI), angle-of-arrival (AoA) or time-based techniques (ToA, TDoA).

RSSI technique is based on calculating the propagation loss and translating this loss into a distance estimate using theoretical and empirical propagation models. The accuracy of this technique is highly sensitive to multipath and fading, which may result in large errors. AoA systems estimate the angle at which signals are received and use geometric relationships to calculate node positions. The problem with this approach is that it is expensive and obtaining precise angle estimates is often difficult.

TDoA systems use a radio signal to synchronize the clocks of the sender and receiver. They transmit a radio signal at the same time a sound or ultrasound signal is transmitted. Since the radio propagation time is so small the clocks of two nodes are well synchronized. Unfortunately, underwater networks will not be able to leverage this combination of RF and acoustic communication due to the strong attenuation of RF signals. On the other hand, the low speed of sound in water permits accurate timing of signals. Propagation time can be directly translated into distance on the estimated signal propagation speed. In [16], range resolution of +/- 5 meters over a range of 1 km has been reported.

In [7], a survey of localization algorithms is overviewed along with their applicability to the underwater medium. The challenges unique to the underwater environment are also discussed. In [6], a centralized range-free scheme for underwater sensor networks is proposed which estimates the area where the sensor nodes reside rather than their exact locations. This algorithm can be useful for applications requiring only coarse location estimates. However, it is not appropriate for most of the applications where fine-grained location information is indispensable such as in a military setting. Moreover, a centralized scheme incurs latency which is amplified with the low propagation speed of the acoustic signal.

The only effort for a scalable localization algorithm in UW-ASNs is the work in [40]. The paper proposes a network with three types of nodes: surface buoys, anchor nodes, and ordinary nodes. The anchor nodes are distributed throughout the network and employ long-range acoustic links to directly talk with the surface buoys. The ordinary nodes are cannot directly talk to the surface buoys because of cost. The paper divides the localization process into two sub-processes: anchor node localization and ordinary node localization. However, the authors do not discuss the anchor node localization process and assume that the anchor nodes can localize themselves with the help of the surface buoys using existing systems like [3]. The authors also assume that all the nodes can estimate their distances to their neighbors with one-way message exchange by employing techniques such as ToA. During the anchor node localization process, the anchors and the surface buoys exchange messages. The ordinary nodes can also receive these messages and just like the anchor nodes, they can determine their distances to the surface buoys too and thus localize themselves using the technique employed during the anchor localization process. This makes the ordinary node localization process unnecessary. Besides, this work assumes the presence of large number of (10%, 20% of all nodes) designated static anchor nodes deployed underwater which is hard to realize. Furthermore, the assumption of using ToA technique implies time synchronization between the nodes which is not practical to achieve and to maintain in underwater environment. Hence, there is a need for a distributed localization algorithm in UW-ASNs that gives particular importance to low-complexity and accuracy.

To address this need, in this thesis, Three Dimensional Underwater Localization (3DUL) is proposed, which enables fine-grained, scalable localization with minimum energy expenditure. Starting with three anchors at the surface of the water, it spreads the global position knowledge across the underwater network by using a distributed and iterative scheme.

A general drawback of the iterative algorithms is that they propagate measurement errors, resulting in poor overall coordinate assignments [24]. However, 3DUL mitigates the effect of error propagation by leveraging the low speed of sound to accurately determine the timing between the nodes and by imposing a robustness condition on becoming an anchor. The detailed 3DUL protocol description and operation principles are explained in Chapter 3.

CHAPTER 3

THREE DIMENSIONAL UNDERWATER LOCALIZATION ALGORITHM (3DUL)

In this chapter, we introduce 3DUL protocol in detail. The primary objective is to dynamically achieve network-wide 3D localization accurately, timely and efficiently. We begin by giving a targeted underwater sensor network model and an overview of 3DUL. Then, we explain the operation of its algorithm in detail.

3.1 Architecture

A possible deployment of a three-dimensional underwater acoustic sensor network is shown in Fig. 3.1. Three surface buoys float at the surface of the water to which we refer as *anchor* nodes. These buoys are equipped with GPS receivers to determine their global positions and medium range RF transceivers (radios such as 802.11) to communicate with each other. Moreover, they are also equipped with an acoustic transceiver for communications with underwater sensors. In addition, at least one of them is equipped with a long range RF and/or satellite transceiver to communicate with the onshore sink. Unlike the anchors deployed at seabed at LBL systems, surface buoys can effectively utilize solar energy.

A large number of underwater sensor nodes are deployed at different depths. These might be anchored to the ocean bottom and equipped with a floating buoy. Therefore, these sensor nodes have limited moving capability and are referred to as *semi-stationary* sensor nodes. In addition to these *semi-stationary* sensor nodes,

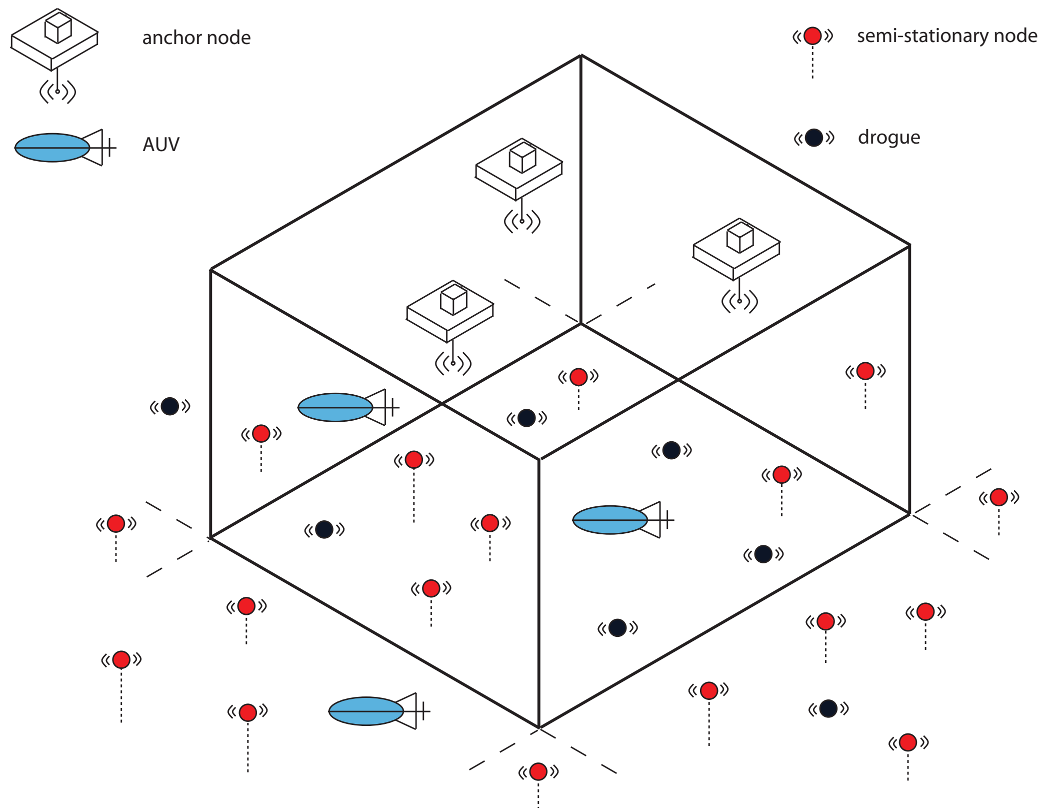

Figure 3.1: Two-way message exchange between the anchor and the unknown node during the Ranging phase.

the network can have propelled autonomous robots (e.g., AUV) and freely floating autonomous robots (e.g., drogue [16]). We refer to these sensor nodes and robots (AUVs) as *unknown* nodes because their positions are not known a priori.

The goal is to accurately estimate the positions of as many *unknown* nodes as possible in a simple, accurate, timely and more importantly scalable fashion.

3.2 Overview

3DUL is a two phase protocol. During the first phase, a sensor node estimates the distances between itself and its neighboring anchors. It also acquires the depth of the anchors. We call this phase of the algorithm as *Ranging*. The details of the ranging phase operation are given in Section 3.3.

Once the distances to at least three anchors are estimated, the sensor node initiates the second phase of the 3DUL algorithm, which is called *Projection and Dynamic Trilateration*. During this phase, the sensor node projects three anchors onto its horizontal level using the depth information and checks whether it forms a *robust virtual anchors plane* (see Section 3.4) with the three anchors. If so, it locates itself through trilateration and becomes an anchor. The details of the second phase are given in Section 3.4.

When an *unknown* node becomes an *anchor*, it advertises its new status to the network and assists in spreading the location information across the network. This process repeats iteratively to dynamically achieve network-wide localization. Therefore, 3DUL does not require additional static anchor nodes deployed throughout the network a priori. In Section 3.5, we show the diffusion of the location information into the three dimensional topology.

3DUL requires that the sensor nodes be equipped with CTD (Conductivity, Temperature, Depth) sensors [27] to estimate the sound speed. The depth information is also used during the projection of the anchor nodes.

Note that 3DUL employs two-way message exchange to estimate the propagation delay and uses estimated sound speed to find the inter-node distances. Therefore, 3DUL protocol does not require time synchronization between the nodes.

3.3 Ranging Phase

In this phase, a sensor node determines pairwise distances to its neighboring anchors. When the network is deployed, each of the three anchor nodes at the surface broadcasts an *anchor_ranging* packet which contains its identity. In underwater environment, all the nodes in the network may move passively with currents. Therefore, to keep the localization information up-to-date, the surface anchors broadcast *anchor_ranging* packets periodically. If an *unknown* sensor node receives at least three *anchor_ranging* packets from different anchors, it initiates the *Ranging phase* of the algorithm by broadcasting a *ranging* packet to determine its separation to three anchors. 3DUL first estimates the propagation delay between the unknown node and the anchor nodes by using the two-way message exchange technique employed in classical sender-receiver synchronization approach. Then, it multiplies the propagation delay with the estimated speed of sound to obtain the range information.

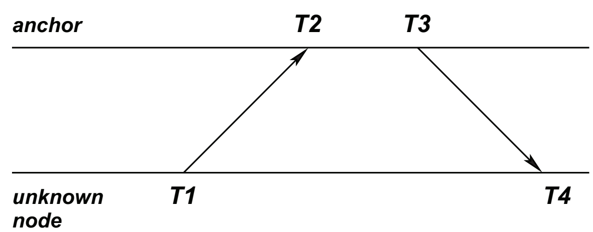

Figure 3.2: Two-way message exchange between the anchor and the unknown node during the Ranging phase.

The two-way message exchange between an *anchor* and an *unknown node* is shown in Fig. 3.2. Recall that 3DUL neither assumes nor requires any time synchronization between the *anchors* and *unknown nodes*. $T1$ and $T4$ are measured by the local clock of the *unknown node*, whereas $T2$ and $T3$ are measured by the local clock of the *anchor*. At $t = T1$, the *unknown node* sends a *ranging packet* to the anchor which contains the value of $T1$. The anchor receives this packet at $t = T2$ and at $t = T3$ sends back an *acknowledgment packet* to the *unknown node* which contains the values of $T2$, $T3$, its coordinates and depth z. Initially, $z = 0$ since the three anchors which start the localization process float at the surface. The *unknown node* receives the packet at $T4$.

$$T2 = T1 + \delta + t_{prop}$$
$$T4 = T3 - \delta + t_{prop}$$

where δ is the clock drift between the *unknown* node and the anchor, t_{prop} is the propagation delay. Then, the *unknown* node can estimate the propagation delay as:

$$t_{prop} = \frac{(T2 - T1) + (T4 - T3)}{2} \tag{3.1}$$

The distance between the anchor and the *unknown node* is then

$$d = t_{prop}c$$

where c is the estimated speed of the sound.

A naive implementation of the *Ranging* phase would allow an anchor node to send as many *acknowledgment* packets as it has received *ranging* packets. One straightforward way to optimize this phase would be to pack several *acknowledgment* packets, send them together in one reply and thus conserve valuable energy.

If a sensor node can determine the distances to three anchors, i.e., if it gets *acknowledgment* packets from three anchors, it initiates the *Projection and Dynamic Trilateration* phase as explained in Section 3.4.

Note that the accuracy of ranging can be affected by the inaccuracies in the estimation of t_{prop} and c. However, in Section 4, we clearly show that the sensor nodes are able determine the inter-node distances with high accuracy.

3.4 Projection and Dynamic Trilateration Phase

In this phase, a sensor node performs 3D localization by using the distance and depth information obtained during the ranging phase. Each sensor node projects three neighboring anchors onto its horizontal level as in Fig. 3.3 and checks if it forms a *robust virtual anchors plane* with them.

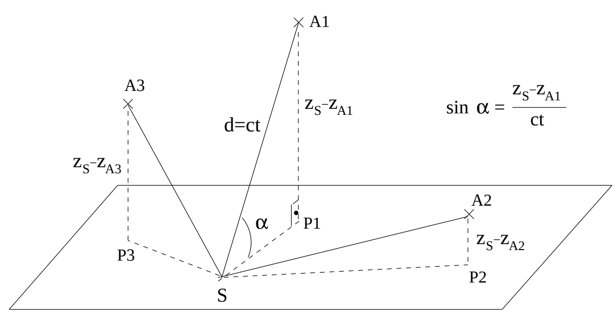

Figure 3.3: Projection: P_1, P_2, P_3 are the projection points of the three anchors;

A *robust virtual anchors plane* exploits the notion of *robust quadrilateral* defined for node localization problem in terrestrial wireless sensor networks [22]. Here, we combine the *robust quadrilateral* with the projection of *anchor* nodes to achieve robust 3D localization with three anchors. A *robust virtual anchors plane* consists of three virtual *anchors* and one *unknown* node which are fully connected and are "well-spaced" such that even in the presence of noise, the relative positions of the nodes are unambiguous.

Consider the plane shown in Fig. 3.3 which can be decomposed into four triangles: $\Delta P_1P_2P_3$, ΔSP_1P_2, ΔSP_1P_3 and ΔSP_2P_3. A triangle is regarded as *robust* if it satisfies

$$a \sin^2 \theta > d_{min}$$

where a is the length of the shortest side and θ is the smallest angle of the triangle. d_{min} is a threshold that depends on measurement noise [22]. Then, a *robust virtual anchors plane* is defined as a fully-connected quadrilateral whose four sub-triangles are robust. If the plane turns out to be robust, then the *unknown node* becomes an *anchor* and broadcasts an *anchor_ranging* packet to assist its neighboring *unknown nodes* with localization. This process repeats itself iteratively to achieve network-wide localization. Hence, 3DUL can dynamically perform localization by diffusing the location information from the surface anchors to the network without employing designated anchors deployed underwater and without requiring time synchronization.

The new anchors remain as anchors only for a finite duration of time. As AUVs and drogues move constantly, they either remain as anchor for couple of seconds or do not become an anchor at all. This decision mainly depends on the speed of the corresponding AUV or drogue. If it moves too fast, it will be at a very different location at the time a nearby unknown node attempts to use it as an anchor. If the new anchor is a semi-stationary node then it could stay as an anchor for a longer duration of time. The duration during which the node remains as anchor depends on its movement characteristics. For example, if it is anchored very near to the ocean bottom it will move in a small area and hence could stay as an anchor longer than the nodes that are anchored nearer to the surface.

If the plane formed with the selected three anchors fails to be robust then all the possible combinations of triplets of anchors are tried until a robust plane is found. Otherwise, the node is not localized.

It is very important that the triangle formed by the surface buoys be always *robust*. After manual deployment from a ship or aerial deployment from an airplane, it may occur that the buoys lose their *robust* triangle form. To correct for this, they can be equipped with a simple propeller and a motor. The global positions of the surface buoys can be monitored by the user and if need arises they can be moved into the appropriate direction to keep the *robust* triangle form.

3.5 Diffusion of Location Information

The three anchors which float on the surface of the water are responsible for only initiating the localization process and for spreading the global location information throughout the UW-ASN. 3DUL is a dynamic iterative algorithm. The global location information of the surface anchors is first spread to the *unknown* nodes that are within the acoustic communication range of the three surface anchors. The three dimensional volumes illustrating the ranges of the surface anchors are shown in Fig. 3.4. Then, those sensor nodes that are *robustly* localized and have become anchor nodes assist in dynamically diffusing the location information across the network.

3DUL does not put nor imply any restriction on the orientation of the anchor nodes with respect to the *unknown* node. As long as the unknown node forms a robust virtual anchors plane, the anchors can reside anywhere within the communication sphere of the *unknown* node. This flexibility for the location of the anchors endows the UW-ASN with the capability of 3D diffusion of location information.

The ability of 3DUL of diffusing the location information into all directions provides great flexibility for the placement of the surface anchors. Most importantly, they need not be floating on top of the operation region. In Section 5, we present results of simulations where the anchors are placed near the edges of the network and

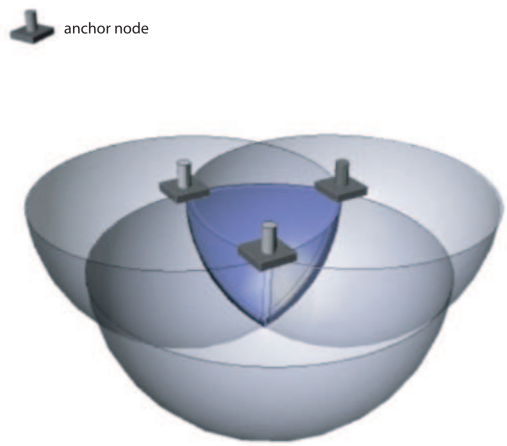

Figure 3.4: Hemispheres representing the acoustic communication range of the surface anchors.

yet successfully diffuse the global location information throughout the UW-ASN. 3DUL protocol operation is outlined in Algorithm 1.

Algorithm 1: Algorithm of the 3DUL protocol operation. n is the number of received anchor_ranging packets, m is the number of received acknowledgement packets from anchors. IsRobust(d_1, d_2, d_3) tests the triangle with sides d_1, d_2, d_3 for robustness. a, b, c are the pairwise distances between the anchors and z_1, z_2, z_3 are the depths of the anchors.

if $n \geq 3$ **then**
    Broadcast $ranging$ packet
end
foreach *received* $acknowledgment$ *packet* **do**
    $t_{prop} = \frac{(T2-T1)+(T4-T3)}{2}$
    $d_A = t_{prop}c$ /*Distance to the anchor*/
    $m = m + 1$
end
if $m \geq 3$ **then**
    repeat
        Pick three neighbor anchors: (A_1, A_2, A_3)
        Project the anchors
        $d_{P1} = \sqrt{d_{A1}^2 - z_1^2}$
        $d_{P2} = \sqrt{d_{A2}^2 - z_2^2}$
        $d_{P3} = \sqrt{d_{A3}^2 - z_3^2}$
        /*Test for robustness*/
        if *IsRobust(a, b, c) AND*
            IsRobust(d_{P1}, d_{P2}, b) AND
            IsRobust(d_{P2}, d_{P3}, c) AND
            IsRobust(d_{P1}, d_{P2}, a) **then**
              P_S=TRILATERATE(P_{P1}, d_{P1}, P_{P2}, d_{P2}, P_{P3}, d_{P3})
        end
    until *(S is robustly localized) OR (all combinations of triplets of neighbor anchors are used)*
end

CHAPTER 4

ERROR ANALYSIS OF 3DUL

In this chapter, we analyze 3DUL in detail and point out the sources of error which affect its accuracy. We first analyze the projection process and determine an upper bound for the error on the distance between the *unknown* sensor node and the virtual anchor. We also show that the underwater sensor nodes can determine the pairwise node distances sufficiently accurate by leveraging the low speed of the acoustic signal.

4.1 Projection Accuracy

Each sensor node employs the following simple geometric relationship, as shown in Fig. 3.3, to project an anchor node onto its horizontal level:

$$
\begin{aligned}
r &= \sqrt{d^2 - (z_S - z_A)^2} \\
&= \sqrt{c^2 t^2 - (z_S - z_A)^2}
\end{aligned}
$$

where r is the distance between the sensor node and the virtual anchor, d is the actual distance between the sensor node and the anchor, c is the sound speed, t is the propagation delay, z_S is the depth of the sensor node and z_A is the depth of the anchor node. Each of these parameters are estimated by the sensor nodes and thus have an uncertainty associated with them.

The error on the computation of r associated with the uncertainty on sound speed, propagation time and depth difference can be estimated by the error propagation formula and is bounded by:

$$\begin{aligned}
\Delta r &\leq \tfrac{\partial r}{\partial c}\Delta c + \tfrac{\partial r}{\partial t}\Delta t + \tfrac{\partial r}{\partial z_S}\Delta z_S + \tfrac{\partial r}{\partial z_A}\Delta z_A \\
&= \tfrac{2ct^2\Delta c}{2\sqrt{c^2t^2-(z_S-z_A)^2}} + \tfrac{2c^2t\Delta t}{2\sqrt{c^2t^2-(z_S-z_A)^2}} + \\
&\quad + \tfrac{2(z_S-z_A)\Delta z_S}{2\sqrt{c^2t^2-(z_S-z_A)^2}} + \tfrac{2(z_S-z_A)\Delta z_A}{2\sqrt{c^2t^2-(z_S-z_A)^2}} \\
&= \tfrac{t\Delta c + c\Delta t + 2(\frac{z_S-z_A}{ct})\Delta z}{\sqrt{1-(\frac{z_S-z_A}{ct})^2}}
\end{aligned} \tag{4.1}$$

where $\Delta r, \Delta c, \Delta t, \Delta z_S$ and Δz_A are the errors in r, c, t, z_S and z_A, respectively. We assume $\Delta z = \Delta z_S = \Delta z_A$.

We now concentrate on each of the parameters one by one and analyze their contributions to the error.

4.1.1 Error in Propagation Delay

3DUL relies on two-way exchange of messages to estimate the propagation delay. During the message exchange, we assume that the *localization* packets can be timestamped at the MAC layer. The packet is time-stamped after it is constructed at the above layer, passed down to the MAC layer and the wireless medium has been successfully captured by the node. Similarly, at the receiver side, the received packet is time-stamped at the MAC layer before it is passed to the upper layers. This is essential since it removes the non-deterministic parts of the packet delay when it traverses a wireless link between two sensor nodes. The recently developed low-cost acoustic modem in [35] allows this type of low level access.

When it is assumed that the clocks of the two nodes are synchronized except for an offset value, δ, (3.1) perfectly eliminates the offset and finds the propagation delay. However, this is hardly the case since the clocks are imperfect and may run at slightly different rates. Consider the following model for the clocks of the sensor node *S* and the anchor node *A*,

$$f_S(t) = at + b$$
$$f_A(t) = t \tag{4.2}$$

where a is the skew, b is the offset, and t is the global reference time. Consider the sensor node *S* and the anchor node *A* exchanging timestamps as shown in Fig. 3.2, with $T_1 = f_S(t_1)$, $T_2 = f_A(t_1 + t_{prop})$, $T_3 = f_A(t_3)$, $T_4 = f_S(t_3 + t_{prop})$. The corresponding error in propagation delay can be calculated as

$$\begin{aligned} \Delta t_{prop} &= t_{prop} - \tfrac{(T2-T1)+(T4-T3)}{2} \\ &= \tfrac{(1-a)(t_3-t_1+t_{prop})}{2} \\ &= \tfrac{(1-a)(t_3-t_1+\frac{d}{c_{av}})}{2} \end{aligned} \tag{4.3}$$

The error increases linearly with the distance between two sensor nodes. For Berkeley motes, the upper bound for skew given in the datasheet [26] is 40ppm. The average sound speed is $c_{av} = 1500$m/s. Even when $d = 1500$m and $t_3 - t_1 = 1$s, the error in propagation delay is $\Delta t = 40\mu$s.

4.1.2 Error in Sound Speed

Another source of error affecting the accuracy of the 3DUL is the varying speed of the sound in the water. Its value depends on temperature, pressure and salinity of the water and can change between 1450m/s and 1550m/s [18]. Many formulas have been proposed to estimate the speed of sound in terms of temperature, salinity and pressure of the water [10, 9, 19, 8]. The nine-term equation developed in [19] is computationally efficient and has an accuracy of about 0.1m/s [11]. It models the underwater acoustic propagation speed as

$$c(T,S,z) = A + BT + CT^2 + DT^3 + E(S-35) + \\ +Fz + Gz^2 + HT(S-35) + JTz^3 \qquad (4.4)$$

where $c(T,S,z)$ is in m/s, T is the temperature in $^\circ$C, S is the salinity in *ppt* (parts per thousand), and z is the depth in m. The coefficients are constants and are given in Table 4.1 [19]. This equation and the coefficients are based on high quality temperature and salinity versus depth profiles of 15 representative worldwide stations [19].

Table 4.1: Coefficients of the Mackenzie's nine-term formula

A	1448.96 $m\ s^{-1}$
B	4.591 $m\ s^{-1}\ ^\circ\mathrm{C}^{-1}$
C	-5.304 $10^{-2}\ m\ s^{-1}\ ^\circ\mathrm{C}^{-1}$
D	2.374 $10^{-4}\ m\ s^{-1}\ ^\circ\mathrm{C}^{-3}$
E	1.340 $m\ s^{-1}$
F	1.630 $10^{-2}\ s^{-1}$
G	1.675 $10^{-7}\ m^{-1}\ s^{-1}$
H	-1.025 $10^{-2}\ m\ s^{-1}\ ^\circ\mathrm{C}^{-1}$
J	-7.139 $10^{-13}\ m^{-2}\ s^{-1}\ ^\circ\mathrm{C}^{-1}$

The error on the sound speed computation can be estimated by the error propagation formula. Accordingly, the error is bounded by [25]:

$$\begin{aligned}\Delta c &\leq \tfrac{\partial c}{\partial T}\Delta T + \tfrac{\partial c}{\partial S}\Delta S + \tfrac{\partial c}{\partial z}\Delta z \\ &= (B + 2CT + 3DT^2 + H(S-35) + Jz^3)\Delta T + \\ &\quad +(E + HT)\Delta S + (F + 2Gz + 3JTz^2)\Delta z\end{aligned}$$

The contribution of depth uncertainty can be safely neglected. When $\Delta T = 0.1\,°\mathrm{C}$ and $\Delta S = 0.75$ [27], in the ranges of $5 - 30\,°\mathrm{C}$ and $34 - 39$, the maximum error is less than 1.5 m/s. Underwater sensor nodes equipped with CTD sensors can estimate the speed of sound. In [34], an experiment is reported where underwater sensor nodes can successfully measure the temperature and pressure of the water.

4.1.3 Overall Error

In order to see the overall error suffered during the projection process we now plug our findings into (4.1). We assume $\Delta c = 1.5$m/s, $\Delta t = 100\mu$s, $c = 1500$m/s and $\Delta z = 0.1$m. The results are shown in Fig. 4.1 where we plot Δr with modifying the inter-node distance d and $sin\alpha = \frac{z_S - z_A}{ct}$ (see Fig. 3.3).

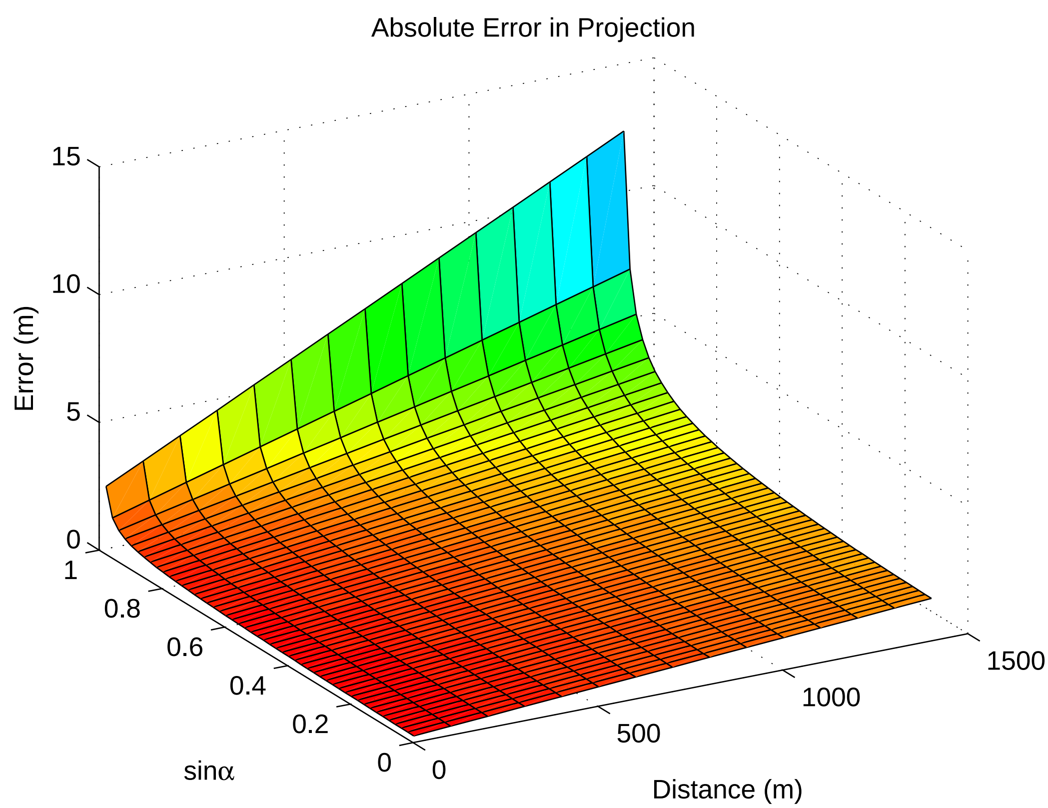

Figure 4.1: Absolute error in projection.

Accordingly, as long as $sin\alpha$ is less than 0.9, the absolute error in r is comfortably less than 5m. As $sin\alpha$ approaches towards 1, the absolute error increases. However, it is less than 15m even when $sin\alpha = 0.99$ and $d = 1500$m. In the extreme case when $sin\alpha = 1$, it means that the sensor node and the anchor node are vertically aligned.

A better insight can be gained by plotting the relative error, $\frac{\Delta r}{r}$, which is shown in Fig. 4.2. It can be observed that the error is less than %5 when the sensor node and the anchor node are more than 100m apart. However, when d is less than 100m, the relative error increases rapidly as $sin\alpha$ gets beyond 0.9.

These results dictate that the anchor selection procedure during the Projection and Dynamic Trilateration phase (3.4) should be made carefully. Specifically, the anchors which are less than 100m away should be used only when $sin\alpha \leq 0.9$.

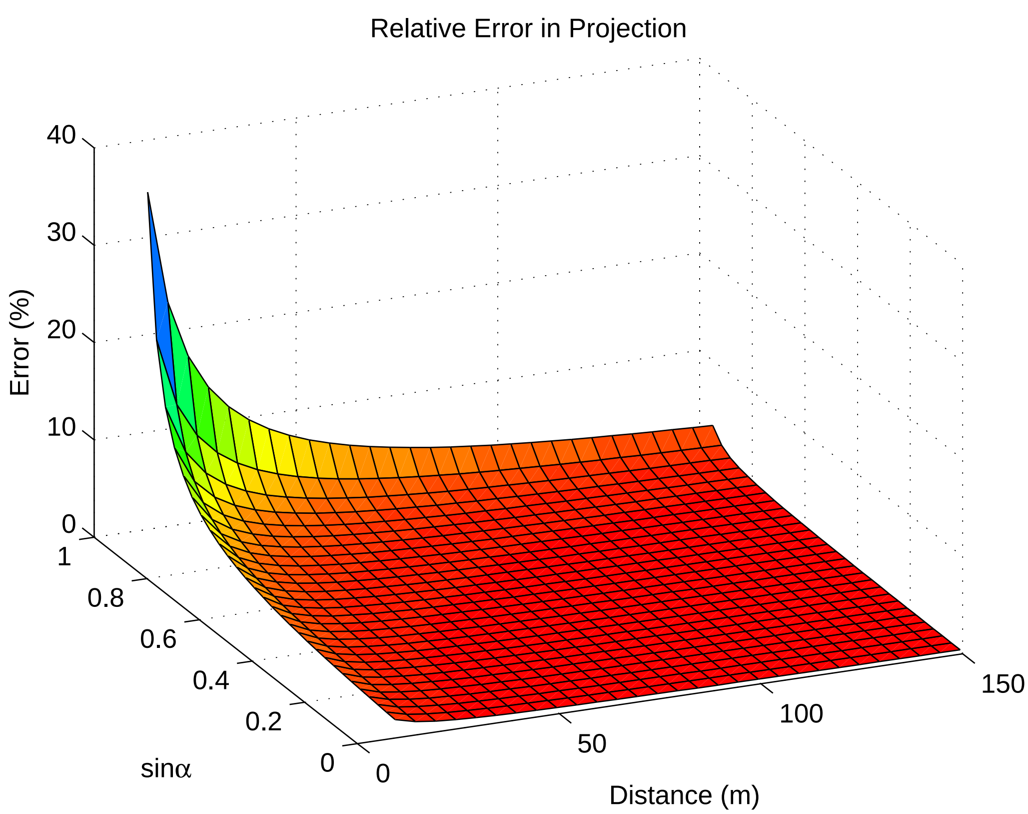

Figure 4.2: Relative error in projection.

4.2 Virtual Anchors Plane

Once a sensor node determines its separation to three anchors, it moves to the second phase of 3DUL where it checks the *virtual anchors plane* formed by itself and three anchors for robustness. In [22], the authors have explained the challenges of network localization and developed the idea of *robust quadrilateral* which minimizes the possibility of flip and flex ambiguities in the presence of noise in distance measurements. We combine the *robust quadrilateral* with the projection of anchor nodes to perform robust 3D localization.

The virtual anchors plane is regarded as *robust* if the four triangles constituting it (see Figure 3.3) are *robust*. A triangle is regarded as *robust* if $a\,\sin^2\theta > d_{min}$ where a is the shortest side and θ is the smallest angle of the triangle. By choosing a suitable d_{min} depending on σ, the standard deviation of measurement noise, the probability of error is bounded. For example, if d_{min} is 3σ, for Gaussian noise, the probability of error for a given virtual anchors plane is less than $\%1$ [22].

CHAPTER 5

PERFORMANCE EVALUATION OF 3DUL

In this chapter, we present results evaluating the performance of 3DUL algorithm. We begin by describing the simulation environment and evaluation criteria.

5.1 Simulation Setup

We created an evaluation environment using ns-2 [31]. Accordingly, we have developed underwater acoustic communication channel since the underwater acoustic channel is significantly different from wireless radio channel. We set the signal propagation speed to $1500m/s$. Additionally, the underwater nodes estimate their depths and the speed of sound with inaccuracies of $\pm 1m$ and $\pm 1.5m/s$, respectively. The data rate is set to 15kbps and the operating frequency is $50kHz$.

When evaluating the algorithm's performance, we are interested in how both node degree and propagation models for different kinds of channels of common occurrence in the sea affect the results. Node degree was varied by modifying the transmission power. We implemented two propagation models from [32]:

- The *shallow water sound channel* models the communication in waters with depth lower than $100m$. In this environment, sound signal is trapped between the water surface and the sea bottom. It propagates by repeated reflections from both surface and bottom. Therefore, multipath propagation and Doppler spread play a key role in the communications performance[2].

The transmission loss in the shallow water sound channel increases with increasing frequency and distance. For the ranges of interest to UW-ASNs, the transmission loss in the shallow-water sound channel is

$$TL = 20logr + \alpha r + 60 - k_L \tag{5.1}$$

where r is the range in meters, α is the absorption coefficient in dB/m and k_L is a near-field anomaly dependent on the sea state and bottom type.

- The *deep water sound channel* is used to model the communication in deep oceans. The transmission loss in the deep sound channel is

$$TL = 10logr_0 + 10logr + \alpha r \tag{5.2}$$

where r is the range in meters and α is the absorption coefficient in dB/m. r_0 can be considered to be the transition range between spherical spreading and cylindrical spreading. Its magnitude is between 1450m and 3650m [33]. Contrary to the shallow water sound channel, the deep water sound channel does not suffer from multipath propagation and has remarkable transmission characteristics. However, for typical ranges targeted for UW-ASNs, the transmission loss in deep water sound channel is generally higher.

5.2 Evaluation Criteria

The first metric by which we evaluate the performance of 3DUL is simply the mean-square error in Euclidean 3D space. Specifically, we look at how the computed locations differ from the actual locations. This error is expressed as

$$\sigma_p^2 = \sum_{i=1}^{N} \frac{(\hat{x}_i - x_i)^2 + (\hat{y}_i - y_i)^2 + (\hat{z}_i - z_i)^2}{N} \tag{5.3}$$

where N is the number of nodes, $\hat{x}_i$, $\hat{y}_i$ and $\hat{z}_i$ are the coordinates of node i determined by 3DUL, and x_i, y_i and z_i are the actual coordinates of node i.

Second, we compare σ_p^2 to the mean-square error in distance measurements.

This way, we can see how well the algorithm determines the inter-node distances and how well it performs the localization of the *unknown* nodes using these noisy distance measurements. The mean-square error of the distance measurements is

$$\sigma_d^2 = \sum_{i=1}^{M} \frac{(\hat{d}_i - d_i)^2}{M} \tag{5.4}$$

where M is the number of computed inter-node distances, $\hat{d}_i$ is the measured value of distance i, and d_i is the actual value of distance i.

Another useful metric is the proportion of nodes in the entire network that could be localized successfully by 3DUL. Let L be the number of underwater nodes that are successfully localized by the algorithm and N be the total number of nodes in the network. We define *localization coverage* as

$$R = \frac{L}{N} \tag{5.5}$$

The *average communication cost* of the algorithm is also an important performance metric and is defined as

$$C = \frac{M}{L} \tag{5.6}$$

where M is the number of messages sent by all the nodes in the network.

The time required for localization, t_{loc}, will also be given for each simulation. During the simulations, the surface anchors broadcast their positions only once and at the beginning. Normally, the surface anchors broadcast their positions periodically to keep the localization information up-to-date.

5.3 Evaluation Results

We compare our results with those obtained in [40]. We refer to the localization protocol presented in that paper as UNL (Underwater Node Localization). For this comparison, we use a 100m x 100m x 100m 3-dimensional topology and distribute 500 underwater nodes randomly throughout the network as done for UNL. Also, we use the same three metrics as UNL: *localization coverage*, *localization error* and *av-*

erage communication cost. Localization coverage and average communication cost are the same as defined above. Localization error is the average distance between the estimated positions and the real positions of all localized nodes. As in [40], we normalize this absolute localization error to the node communication range. During the simulation, all of the nodes stay at their initial positions. Hence, when an underwater node is localized and becomes an anchor, it remains so for the rest of its lifetime. The results are shown in Figures 5.1, 5.2, 5.3. Each data point on the plots represents a single run of the simulation. A line fitting the data points is overlaid on each plot.

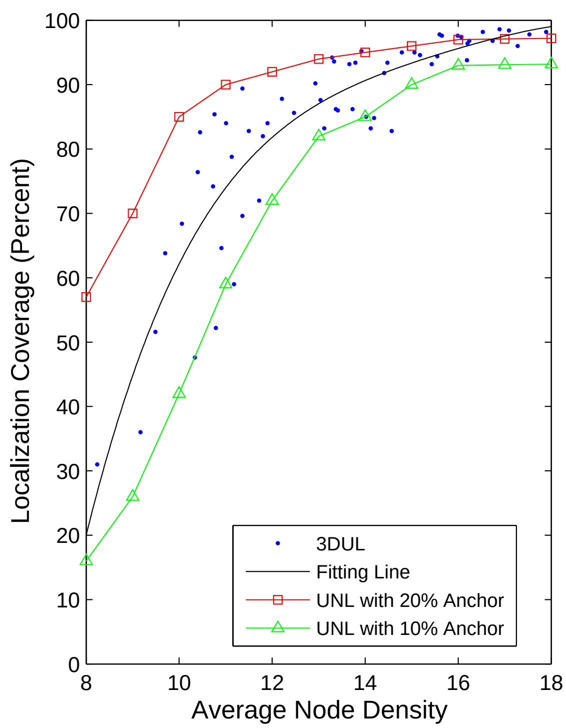

Figure 5.1: The localization coverage vs. the average node density.

5.3.1 Localization Coverage

According to the Figure 5.1, 3DUL outperforms UNL in terms of localization coverage when UNL employs 10% of the nodes in the network as anchor. When UNL employs 20% of the nodes as anchor, 3DUL outperforms UNL when the average node density is high. It should be noted that UNL employs static anchor nodes deployed underwater which are assumed to know their exact locations. Moreover, these anchor nodes are distributed all over the network. 3DUL does not make this assumption. In 3DUL scheme, the only nodes that are assumed to know their exact locations are the three surface anchors. Next, we compare 3DUL and UNL in terms of localization error.

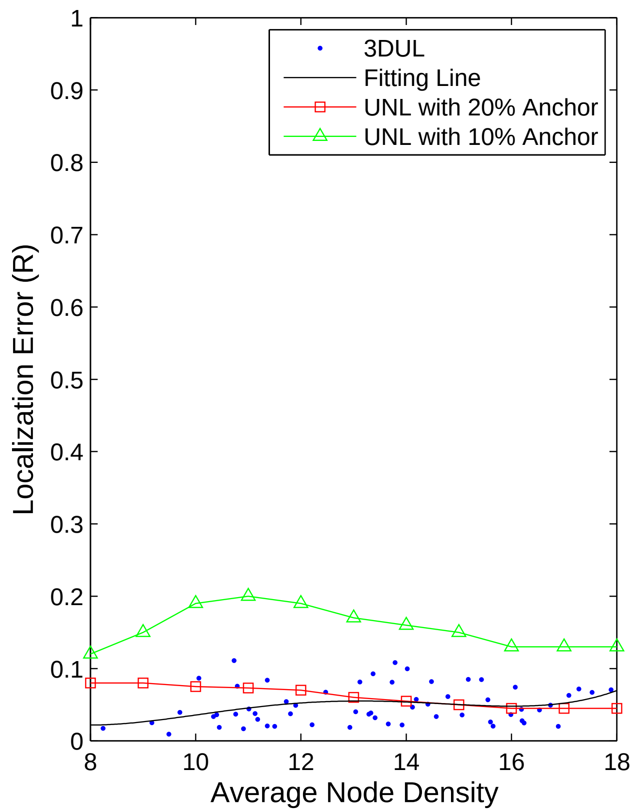

Figure 5.2: The localization error vs. the average node density.

5.3.2 Localization Error

The localization error with varying average node density is shown in Fig. 5.2. According to Fig. 5.2, 3DUL outperforms UNL even when UNL employs 20% of the nodes as static anchor. The localization error in 3DUL does not depend much on the node density. As explained in Section 3.4 an underwater node localizes itself whenever it forms a robust virtual anchors plane with three anchors without differentiating between the anchors. On the other hand, UNL uses a scheme where the anchor nodes are associated with a confidence value. During the localization process, the nodes choose the anchors with higher confidence values. With increasing node density, the nodes have more anchors to choose from. Therefore, the error in UNL scheme decreases as the nodes have more neighbors.

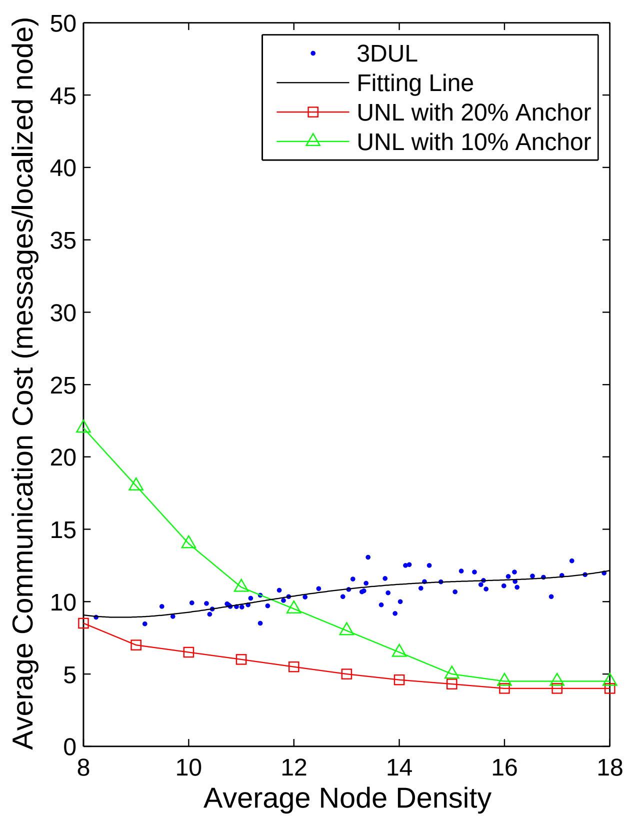

Figure 5.3: The average communication cost vs. the average node density.

5.3.3 Average Communication Cost

The average communication cost incurred by 3DUL does not change significantly with increasing node density and stays nearly constant as seen in Fig. 5.3. In contrast, the number of messages exchanged in UNL scheme decreases as the average node density increases. According to the results, UNL outperforms 3DUL especially at high average node density. However, UNL ignores two important issues. First of all, in UNL the nodes measure the inter-node distances by employing ToA technique which implies that the clocks of the nodes are synchronized. However, time synchronization is not mentioned in [40] and the messages required to synchronize the nodes and to constantly keep their clocks updated are not taken into account. It is clear that time synchronization brings additional communication overhead. 3DUL neither assumes nor requires time synchronization. Secondly, the anchor nodes are assumed to be localized. The number of messages required to be exchanged between the anchor nodes and the surface buoys for anchor node localization process are not counted. On the contrary, 3DUL does not make any of these assumptions. As explained in Section 3.3, the inter-node distances are measured with by using the two-way message exchange method. Therefore, 3DUL neither assumes nor requires time synchronization. Also, there is no anchor node in the water which possesses the knowledge of its exact location.

5.3.4 Deep Water

In the second simulation, we analyze the deep water performance of 3DUL. For this purpose, we use an UW-ASN with 1000m x 1000m x 1000m 3-dimensional topology. The network consists of 100 randomly placed, static underwater nodes and three surface anchors. The deep water sound channel is used with $\alpha = 15.95 dB/km$ and $r_0 = 10000m$. The results are shown in Figures 5.4 and 5.5 where the 3D and 2D coordinates of the underwater nodes determined by 3DUL are compared to the actual coordinates in three and two dimensional plots, respectively. The surface anchors are placed near one of the edges and are shown with circles. A line connects the coordinates determined by 3DUL algorithm to actual coordinates of the node showing the amount of positioning error. Only, the nodes that could be localized are shown. The error metrics of the simulation are given in Table 5.1.

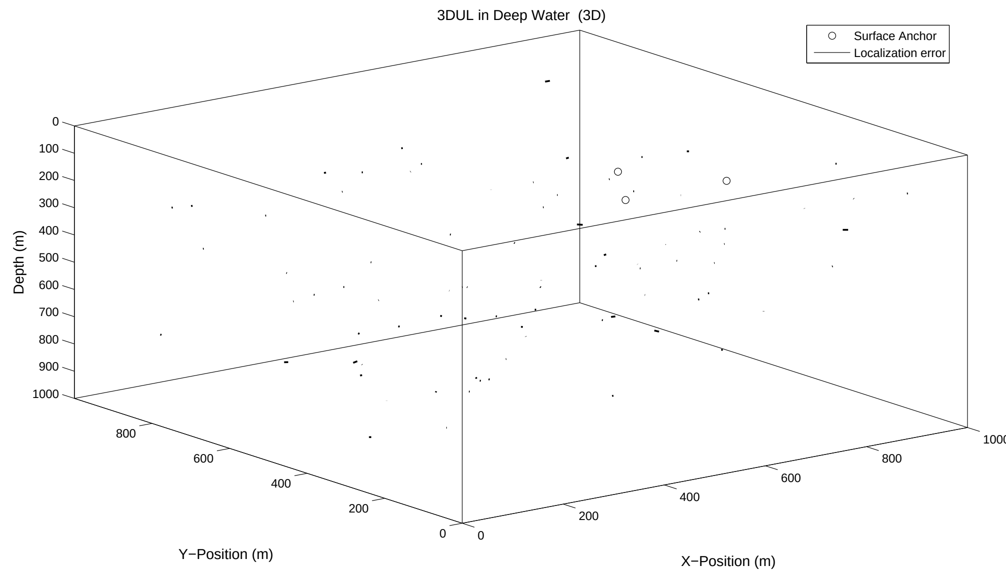

Figure 5.4: The 3D coordinates determined by 3DUL compared to actual coordinates of localized underwater nodes in deep water settings. The nodes are stationary. Lines show the amount of error for each node's position. The surface anchors are shown with circles.

Table 5.1: Error Metrics of Deep Water Simulation

metric	value
σ_d	0.16 m
σ_p	3.75 m
t_{loc}	17.57 s
Node Degree	12.63
R	82/100

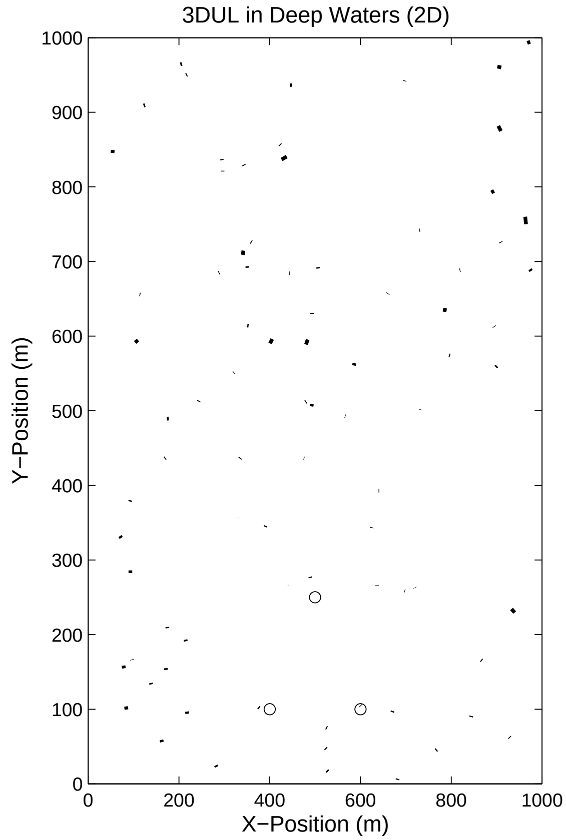

Figure 5.5: The 2D coordinates determined by 3DUL compared to actual coordinates of localized underwater nodes in deep water settings. The nodes are stationary. Lines show the amount of error for each node's position. The surface anchors are shown with circles.

According to the results, the underwater nodes can determine inter-node distances fairly accurately as demonstrated by the small value of σ_d. In addition, 3DUL successfully localizes %82 of the nodes in the network in less than 18s. On the other hand, the localization error, σ_p, is considerably larger than the measurement error in σ_d due to the error propagation. It should be noted that the surface anchors are placed near the edge of the topology. Nevertheless, 3DUL can successfully diffuse their global location information throughout the network.

5.3.5 Shallow Water

In the third simulation, we make the shallow water analysis of 3DUL. The simulated UW-ASN has a 1000m x 1000m x 100m topology. 150 nodes are randomly distributed and are static. The shallow water propagation model is used with $\alpha = 15.95dB/km$ and $k_L = 3dB$. The results are shown in Figures 5.6 and 5.7 where the 3D and 2D coordinates of the underwater nodes determined by 3DUL are compared to the actual coordinates in three and two dimensional plots, respectively. The surface anchors are again placed near one of the edges and are shown with circles. A line connects the coordinates determined by 3DUL algorithm to actual coordinates of the node showing the amount of positioning error. Only, the nodes that could be localized are shown. The error metrics of the simulation are given in Table 5.2.

Accordingly, with a lower average node density as compared to deep water simulation, 3DUL is able to localize nearly %90 of the nodes in 20s. However, the localization error, σ_p, is larger. One reason is that there are more nodes in the network. Although 3DUL forces the underwater nodes to form robust structures with the anchors, it is an iterative scheme and therefore suffers from error propagation. As more nodes are localized, the error generally increases.

Table 5.2: Error Metrics of Shallow Water Simulation

metric	value
σ_d	0.17 m
σ_p	6.23 m
t_{loc}	20.01 s
Node Degree	10.97
R	132/150

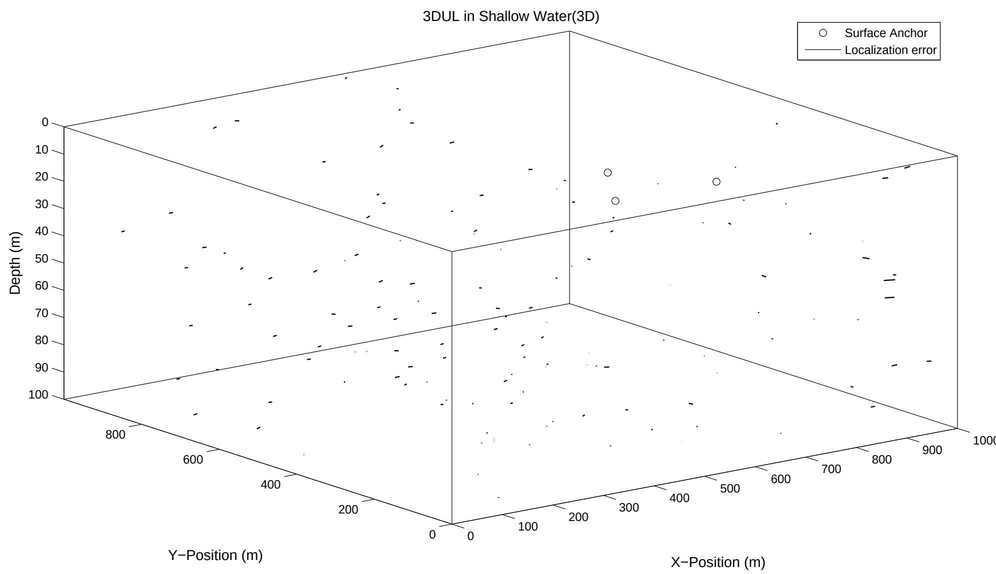

Figure 5.6: The 3D coordinates determined by 3DUL compared to actual coordinates of localized underwater nodes in shallow water settings. The nodes are stationary. Lines show the amount of error for each node's position. The surface anchors are shown with circles.

5.3.6 Effect of Mobility

Here, we investigate the mobility factor. The underwater nodes move towards a randomly determined position with a speed of 1m/s and while conserving their initial depth. There are no semi-stationary node in the network. When an underwater node is localized and becomes an anchor, it remains as anchor for 5 seconds. The results are given in Table 5.3.

The nodes can still determine the inter-node distances very well and the localization success rate is %90. On the other hand, the localization error, σ_p, is increased to 8.86m. This is due to the fact that the nodes constantly move and hence the new anchors spread their location information as they are moving. When an anchor gives out his location information to an unknown node, it could be 5m away from the point where it is localized.

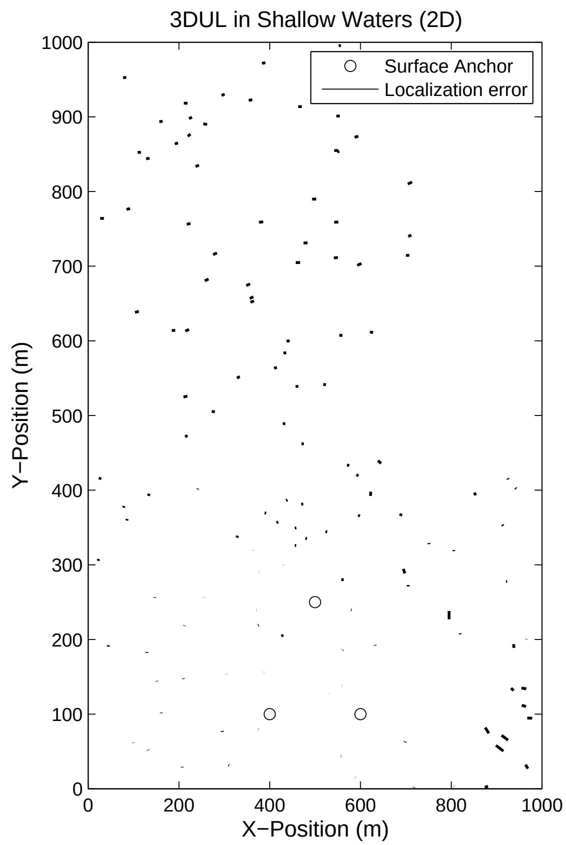

Figure 5.7: The 2D coordinates determined by 3DUL compared to actual coordinates of localized underwater nodes in shallow water settings. The nodes are stationary. Lines show the amount of error for each node's position. The surface anchors are shown with circles.

5.3.7 Localization of AUVs

In this section, we show that 3DUL can localize mobile underwater vehicles such as AUVs and drogues. The results of the simulation are shown in Figure 5.8 and 5.9. The topology of UW-ASN is the same as the simulation in Section 5.3.4. All the nodes are stationary and remain as anchors once they are localized. After 20s a mobile underwater node enters the network at the point (500, 0) with a 10m/s constant speed and 500m depth. The mobile node broadcasts *ranging* packets every other second. The actual path and the path as determined by 3DUL algorithm are

Table 5.3: Error Metrics of Mobile Network Simulation

metric	value
σ_d	0.33 m
σ_p	8.86 m
t_{loc}	18.61 s
Node Degree	11.56
R	135/150

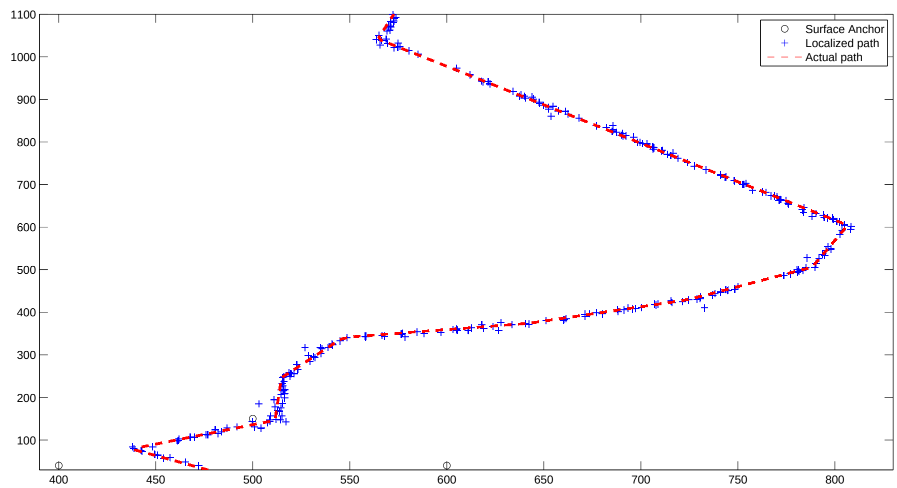

Figure 5.8: The path determined by 3DUL compared to the actual path of the AUV at depth 500m. The surface anchors are shown with circles.

shown in Figure 5.8. The change of mean square error of AUV's location with time is shown in Figure 5.9. At 200s, the mean square error, σ_p is 7.30m.

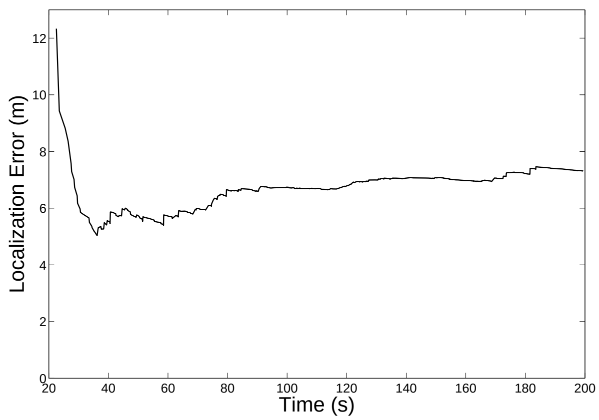

Figure 5.9: The localization error suffered by the AUV over time.

CHAPTER 6

CONCLUSION

Localization is an indispensable part of many underwater sensor network applications. In this thesis, Three-Dimensional Underwater Localization (3DUL), a 3D localization algorithm for underwater acoustic sensor networks, is presented. 3DUL is a distributed, iterative and dynamic solution to the underwater acoustic sensor network localization problem that exploits only three anchor nodes at the surface of the water. The algorithm starts at the anchor nodes and iterates along all directions in 3D topology. Through analysis and simulation we showed that 3DUL can localize the sensor nodes fairly accurately by leveraging the low speed of sound. Moreover, by imposing a robustness condition, 3DUL mitigates the effects of error propagation phenomena and is a scalable protocol.

We presented performance evaluation results of 3DUL in terms of localization coverage, localization error and communication cost. The behavior of 3DUL in deep and shallow waters is analyzed by employing specific underwater sound channel models. The effects of passive node mobility on localization performance is also analyzed. Finally, we demonstrated that 3DUL can be successfully used for AUV localization.

As future work, we will analyze the effects of d_{min} to the performance of 3DUL. d_{min} is the threshold used to determine the robustness of a triangle. It causes a triple tradeoff between localization coverage, localization error and communication cost. A greater threshold decreases the localization error. At the same time, however, it also causes a decrease in localization coverage and an increase in communication cost. We will show how to set d_{min} in order to maximize the performance of 3DUL.

We will also improve the implementation of the Ranging phase. By employing a smarter algorithm, we plan to decrease the number of *acknowledgment* packets sent by the anchors. This way, the average communication cost incurred by 3DUL will decrease significantly.

The operation of 3DUL begins with three anchors at the surface of the water. As illustrated in Section 3.5, the first nodes that are localized are those that lie in the neighborhood of the surface anchors. These nodes are responsible of diffusing the location information. We will analyze the effects of the number of these nodes on localization performance. We will find the ideal number of nodes that should be in the neighborhood of the surface anchors for best performance.

REFERENCES

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater Acoustic Sensor Networks: Research Challenges," *Ad Hoc Networks (Elsevier)*, vol. 3, pp. 257-279, May 2005.

[2] I. F. Akyildiz, D. Pompili, and T. Melodia, "State-of-the-Art in Protocol Research for Underwater Acoustic Sensor Networks," in *Proc. of the First ACM International Workshop on UnderWater Networks (WUWNet),* Los Angeles, California, USA, September 2006.

[3] T. C. Austin, R. P. Stokey, K. M. Sharp, "PARADIGM: a buoy-based system for AUV navigation and tracking," *OCEANS 2000 MTS/IEEE Conference and Exhibition, 2000*, Providence, RI, USA, 2000.

[4] P. Bose, P. Morin, I. Stojmenovic, and J. Urrutia, "Routing with Guaranteed Delivery in Ad Hoc Wireless Networks," *ACM Wireless Networks*, vol. 7(6), pp. 609-616, Nov. 2001.

[5] E. Cayirci, H. Tezcan, Y. Dogan, and V. Coskun, "Wireless sensor networks for underwater surveillance systems," *Ad Hoc Networks*, in press; doi:10.1016/j.adhoc.2004.10.008.

[6] V. Chandrasekhar, W. K. G. Seah, "Area Localization Scheme for Underwater Sensor Networks," in *Proc. of IEEE OCEANS Asia Pacific Conference,* Singapore, May 16-19, 2006.

[7] V. Chandrasekhar, W. KG Seah, Y. S. Choo, H. V. Ee, "Localization in underwater sensor networks: survey and challenges," in *Proc. of the First ACM International Workshop on UnderWater Networks (WUWNet),* Los Angeles, California, USA, September 2006.

[8] C. T. Chen, F. J. Millero, "The Sound Speed in Seawater," *Journal of the Acoustical Society of America*, vol. 62, pp. 1129-1135, 1977.

[9] C. S. Clay, H. Medwin, *Acustical Oceanography,* Wiley-Interscience, New York 1977.

[10] V. A. Del Grosso, "New equations for the speed of sound in natural waters (with comparison to other equations)," *Journal of the Acoustical Society of America*, vol. 56, pp. 1084-1091, 1974.

[11] B. D. Dushaw, P. F. Worcester, B. D. Cornuelle, B. M. Howe, "On equations for the speed of sound in sea water," *Journal of the Acoustical Society of America*, vol. 93, pp. 255-275, 1993.

[12] N. Farr, A. D. Chave, L. Freitag, J. Preisig, S. N. White, D. Yoerger, F. Sonnichsen, P. Titterton, J. Bolstad, D. Leonard, "Optical Modem Technology for Seafloor Observatories," in *Proc. IEEE OCEANS'05 Conference,* September 2005.

[13] E. Fiorelli, N. Leonard, P. Bhatta, D. Paley, R. Bachmayer and D. Fratantoni, "Multi-AUV Control and Adaptive Sampling in Monterey Bay," in *Proc. of IEEE Autonomous Underwater Vehicles: Workshop on Multiple AUV Operations (AUV04)*, Sebasco, ME, USA, June 2004.

[14] J. E. Garcia, "Ad hoc Positioning for Sensors in Underwater Acoustic Networks," in *Proc. of IFIP/TC6 NETWORKING 2007,* pp. 108-119, May 2007.

[15] T. He, C. Huang, B. M. Blum, J. A. Stankovic, T. Abdelzaher, "Range-Free Localization Schemes for Large Scale Sensor Networks," in *Proc. of MOBICOM,* 2003.

[16] J. Jaffe, C. Schurgers, "Sensor Networks of Freely Drifting Autonomous Underwater Explorers," in *Proc. of the First ACM International Workshop on UnderWater Networks (WUWNet),* Los Angeles, California, USA, September 2006.

[17] J. Leonard, A. Bennett, C. Smith and H. Feder, "Autonomous underwater vehicle navigation," MIT Marine Robotics Laboratory Technical Memorandum 98-1, 1998.

[18] X. Lurton, *An Introduction to Underwater Acoustics,* Springer, New York, 2002.

[19] K. V. Mackenzie. "Nine-term equation for sound speed in the oceans," *Journal of the Acoustical Society of America*, vol. 70, pp. 807-812, 1981.

[20] T. Melodia, D. Pompili, I. F. Akyildiz, "Optimal local topology knowledge for energy efficient geographical routing in sensor networks," in *Proceedings of IEEE INFOCOM 04,* Hong Kong SAR, PRC, March 2004.

[21] D. L. Mills, "Internet Time Synchronization: The Network Time Protocol " In Z. Yang and T. A. MArsland, editors, *Global States and Time in Distributed Systems.* IEEE Computer Society Press, 1994.

[22] D. Moore, J. Leonard, D. Rus, S. Teller, "Robust Distributed Network Localization with Noisy Range Measurements," in *Proc. of ACM SenSys,* Baltimore, MD, USA, Nov. 2004.

[23] A. K. Othman, A. E. Adams, C. C. Tsimenidis, "Node Discovery Protocol and Localization for Distributed Underwater Acoustic Networks," in *Proc. of Advanced International Conference on Telecommunications and International Conference on Internet and Web Applications and Services (AICT-ICIW'06),* pp. 93, August 2006.

[24] N. B. Priyantha, H. Balakrishnan, E. Demaine, and S. Teller, "Anchor-Free Distributed Localization in Sensor Networks," in *Technical Report 892, MIT Laboratory for Computer Science,* April 2003.

[25] S. Salon, A. Crise, P. Picco, E. de Marinis, and O. Gasparini, "Sound speed in the Mediterranean Sea: an analysis from a climatological data set," *ANNALES GEOPHYSICAE*, vol. 21, part 3, pp. 833-846, 2003.

[26] Atmel, "http://www.atmel.com", August 2007.

[27] StarOddi, "http://www.star-oddi.com", August 2007.

[28] E. Statnikov, "Speed of Ocean Currents," The Physics Factbook, http://hypertextbook.com/facts/2002/EugeneStatnikov.shtml, August 2007.

[29] M. Stojanovic, "Acoustic (underwater) Communications," in J.G. Proakis, editor, *Encyclopedia of Telecommunications.* John Wiley and Sons, 2003.

[30] H. G. Thomas, "GIB buoys: An interface between space and depths of the oceans," in *Proc. of IEEE Autonomous Underwater Vehicles*, pp. 181-184, Cambridge, MA, USA, 1998.

[31] ns-2 (The Network Simulator), "http://www.isi.edu/nsnam/ns/", August 2007

[32] R. J. Urick, "Principles of Underwater Sound for Engineers," McGraw-Hill, 1967.

[33] R. J. Urick, "Low Frequency Sound Attenuation in the Deep Ocean," *Journal of the Acoustical Society of America*, vol. 29, 1957.

[34] I. Vasilescu, K. Kotay, D. Rus, "Krill: An Exploration in Underwater Sensor Networks," *The Second IEEE Workshop on Embedded Networked Sensors, 2005. EmNetS-II* May 2005.

[35] J. Wills, W. Ye, and J. Heidemann, "Low-power acoustic modem for dense underwater sensor networks," in *Proc. of the First ACM International Workshop on UnderWater Networks (WUWNet),* Los Angeles, California, USA, September 2006. ACM.

[36] X. Yang, K. G. Ong, W. R. Dreschel, K. Zeng, C. S. Mungle and C. A. Grimes, "Design of a wireless sensor network for long-term, in-situ monitoring of an aqueous environment," *Sensors 2*, 2002 455-472.

[37] W. J. Youngberg, "Method for extending GPS to Underwater Applications," US Patent 5,119,341, June 2 1992.

[38] B. Zhang, G. S. Sukhatme, and A. A. Requicha, "Adaptive sampling for marine microorganism monitoring," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2004.

[39] Y. Zhang, L. Cheng, "A Distributed Protocol for Multi-hop Underwater Robot Positioning," in *Proc. of IEEE International Conference on Robotics and Biomimetics,* pp. 480-484, August 2004.

[40] Z. Zhou, J. H. Cui, S. Zhou, "Localization for Large-Scale Underwater Sensor Networks," in *Proc. of IFIP/TC6 NETWORKING,* pp. 108-119, May 2007.