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A Sea Test of Mobile Underwater Localization

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ABSTRACT

Localization and tracking of underwater moving objects are of great interest in many applications. This thesis presents a recent sea test on underwater localization carried out in the Sizihwan coastal area near Kaohsiung, Taiwan, May 2013, where three stationary nodes are used to localize one mobile node via acoustic communications based on orthogonal frequency-division multiplexing (OFDM) modems. Experimental results show that the estimated trajectory of the underwater mobile node agrees well with the track recorded by global positioning system (GPS).

PUBLICATIONS RELATED TO THE THESIS

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Chapter 1

INTRODUCTION

Localization has always been an important task for underwater acoustic sensor networks (UWSNs), since the data collected from sensor nodes can be more meaningful if the data sets are tagged with location information. The global positioning system (GPS) is widely used in terrestrial localization, but it is not suitable for underwater environments, where acoustic signals are used instead of electromagnetic waves because of the severe attenuation and absorption of radio frequency signals in underwater scenarios. Traditional underwater acoustic localization schemes are based on long base line (LBL), short baseline line (SBL), and ultra short baseline (USBL) systems. Recently, there are a variety of localization techniques based on message passing among underwater nodes inside a network; see recent surveys in [1, 2]. Based on the orthogonal frequency-division multiplexing (OFDM) modems [3–5], some localization solutions have been validated in pool and lake tests [6, 7].

This paper presents sea test results of two different scenarios. The first is a current mapping experiment, where four stationary nodes were deployed. The current

profile can be plotted based on the travel time difference between reciprocal transmissions [8]. Here we use these data to investigate the accuracy of OFDM modems on the estimation of travel times. The second is a mobile localization test, where three stationary nodes were used to track one moving node that broadcast messages periodically along its path. We show that the trajectory of the mobile node can be estimated based on the distances between the mobile node and stationary nodes by looking up the arrival times of the decoded messages recorded by the stationary nodes.

Chapter 2

ONE-WAY TRAVEL TIME ESTIMATION IN A STATIONARY SETTING

2.1 One-way Travel Time Estimation in A Stationary Setting

The current mapping experiment was carried out on May 23 and May 24, 2013. Four OFDM modems from AquaSeNT [4] were deployed as stationary nodes in the tests, which were denoted as Nodes 4, 5, 7, and 9, respectively. The four modems were deployed to four different positions within one to several kilometers between one and another, as shown in Fig. 2.1.1. All the four nodes were deployed following the same configuration shown in Fig. 2.1.2(a), where the OFDM modem was fixed in a stationary position by the anchor, and the surface buoy included battery packs, power control board, GPS, and wireless communication module. The OFDM modems and buoys

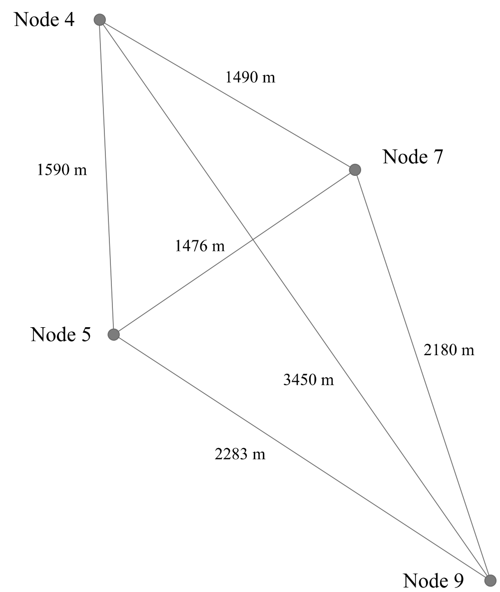
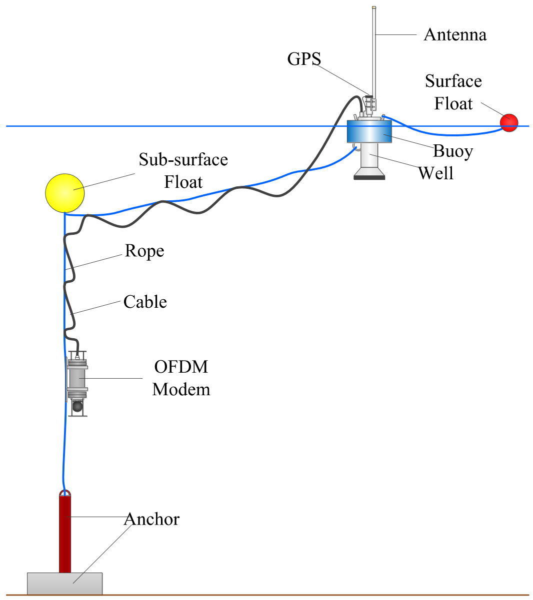


FIGURE 2.1.1: The topology of four stationary nodes deployed for current mapping

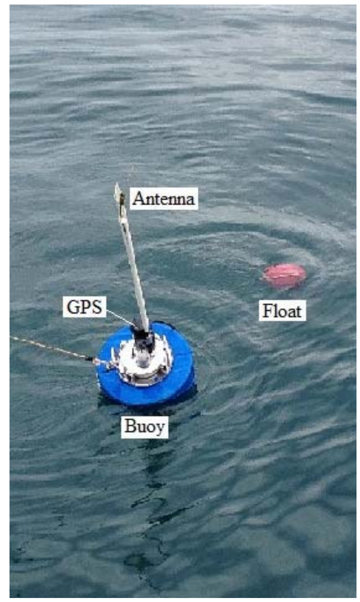
were remotely controlled through another wireless communication module which was mounted on the Shoushan Mountain, Kaohsiung, Taiwan, through radio communications and could further relay the message to Internet. One of the deployment setups is shown in Fig. 2.1.2(b).

During the tests, acoustic messages were transmitted among four stationary nodes for around 500 times, and each of the OFDM modems can work as a transceiver. All the nodes were synchronized with the PPS signal from the GPS, with a timing accuracy up to 1 μs. We calculate the one-way travel time by comparing the local time when the message was received with the time stamp when the message was transmitted. Since all the nodes are stationary and their positions are known, we are only concerned about the travel time difference between any two nodes, and our objective is to evaluate the accuracy of the timing estimates provided by the modems.

The analysis of the one-way travel time estimates is summarized in Table 2.1.1,



(a) Illustration



(b) Deployment

FIGURE 2.1.2: Deployment of a stationary node under a surface buoy.

where both the means and standard deviations of the one-way travel times are included. We can see that the measurements are stable and consistent to each other. The standard deviations of one-way travel times of every two stationary nodes are no more than 0.5 millisecond, corresponding to a distance about 0.75 meter. The last row of Table 2.1.1 shows the reciprocal one-way travel time differences of two different stationary nodes, from which we can see that the mean time differences are less than 1 millisecond, which means that the reciprocal distance measurements are off by less than 1.5 meters.

Table 2.1.1: The one-way travel time estimates in the stationary modem deployment

Node pairs	4, 5	4, 7	4, 9	5, 7	5, 9	7, 9
Distance [m]	1590	1490	3450	1476	2283	2180
Travel time $t_{\mathrm{A}\to\mathrm{B}}$: Mean [ms]	1060.72	993.40	2299.89	984.22	1521.89	1453.96
St.D. [ms]	0.35	0.28	0.28	0.24	0.24	0.38
Travel time $t_{\mathrm{B}\to\mathrm{A}}$: Mean [ms]	1061.26	993.03	2299.94	984.21	1522.12	1453.79
St.D. [ms]	0.23	0.50	0.29	0.17	0.23	0.35
Difference $t_{\mathrm{A}\to\mathrm{B}} - t_{\mathrm{B}\to\mathrm{A}}$: Mean [ms]	0.65	0.43	0.05	0.03	0.23	-0.12
Abs. value of $\lvert t_{\mathrm{A}\to\mathrm{B}} - t_{\mathrm{B}\to\mathrm{A}} \rvert$: Mean [ms]	0.66	0.44	0.25	0.24	0.32	0.38

Chapter 3

MOBILE LOCALIZATION TEST

The mobile localization test was carried out on May 28, 2013, in the Sizihwan coastal area near Kaohsiung. Three OFDM modems were deployed with surface buoys working as stationary nodes, which were denoted as Nodes 5, 7, and 9, respectively. Node 4 was towed by a ship which cruised around the area as a moving node. The GPS map of three stationary nodes and the moving node is shown in Fig. 3.0.1, from which we can see that the moving node started cruising from the northwest of Node 5, and ended near Node 9.

The deployment setup of the stationary nodes was the same with the previous deployment shown in Fig. 2.1.2(a) and Fig. 2.1.2(b). The deployment illustration of Node 4 is shown in Fig. 3.0.2(a), where the OFDM modem was mounted with a V-fin, which could keep the OFDM modem on a certain depth while both of them were being towed by the ship. It can be seen from Fig. 3.0.2(a) that there exists a location offset between the GPS device and the OFDM modem when the ship moves. One picture of the deployment of Node 4 is shown in Fig. 3.0.2(b).

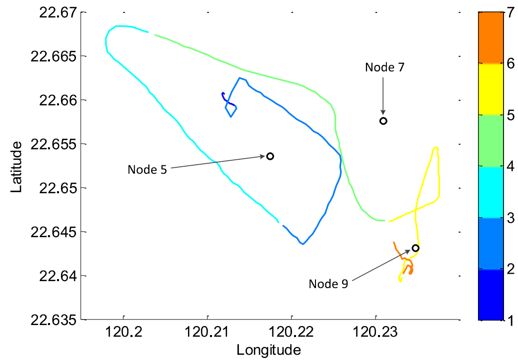
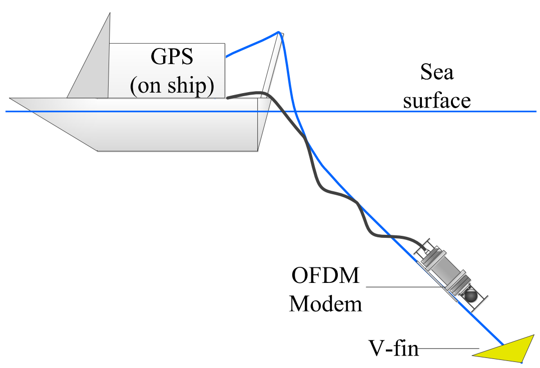
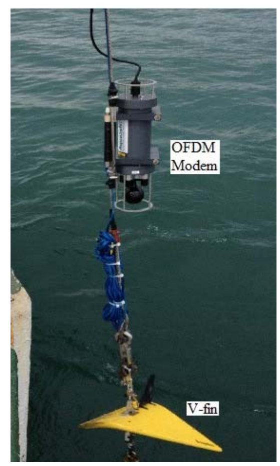


FIGURE 3.0.1: The GPS map of three stationary nodes and one moving node



(a) Illustration



(b) Deployed node

FIGURE 3.0.2: Deployment of the mobile node

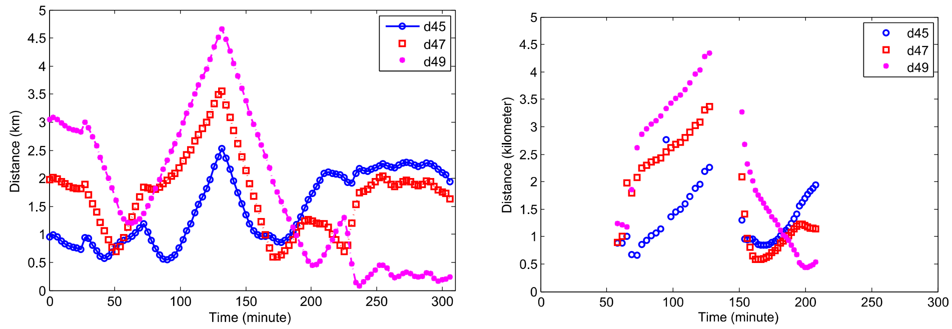
The track of Node 4 is given by the GPS onboard the ship. All the nodes were synchronized with the PPS signal from the GPS, with a timing accuracy up to 1 μs. Node 4 periodically broadcast messages during its movement, while all the stationary nodes recorded the arrival times of the decoded messages. By reading the log-file of the OFDM modems, we can see those transmitting and arrival times recorded by each of the modems. Then we calculate the one-way travel time of the acoustic wave between different two nodes, thus the distances between different nodes can easily

obtained where the sound speed is assumed to be 1500 m/s.

3.1 Collected Data

The initial position measurements of the mobile node, which we get from the GPS device and are considered as the reference values, are in the form of latitude-longitude format. In order to see the distance differences between the modem recorded data and the GPS data, we convert the GPS measurements from geographical coordinates in term of latitude and longitude to the distance metric in kilometer, and the relative distances among nodes are presented in Fig. 3.1.1(a). The legend "d45" represents the distances from Node 4 to Node 5, the legend "d47" means the distances from Node 4 to Node 7, and the legend "d49" denotes the distances from Node 4 to Node 9. We can see that the variation of the three distances is consistent with our observation of the GPS track.

The distance measurements are needed in the localization algorithm to compute the position of the mobile node. The distance measurements are converted from the one-way travel times. We have collected 143 groups of available data from the log files of the modems, where every single group of data provides three one-way travel time measurements which are corresponding to the distance estimates between mobile Node 4 and other three stationary nodes. These collected data groups will be used to estimate the trajectory of the mobile node.



(a) From GPS (b) From Modem

FIGURE 3.1.1: The distance measurements (a) converted from the GPS coordinates and (b) from the modems

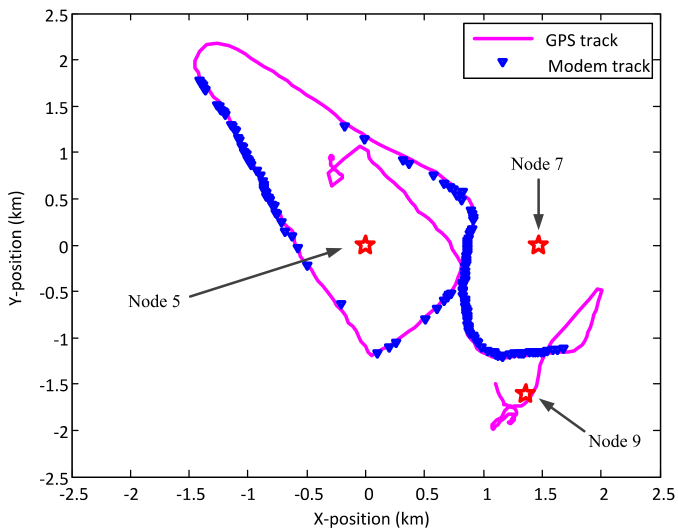


FIGURE 3.1.2: The comparison of two tracks

3.2 The Localization Algorithm

Based on the collected log files, the localization algorithm is implemented as follows.

- At time epoch i, the distance from Node 4 to the kth stationary node is calculated based on one-way travel time as

$$\hat{d}_{i,k} = c\Delta t_{i,k} \tag{3.2.1}$$

where c is the sound speed set at 1500 m/s, $\Delta t_{i,k}$ is the one-way travel time between Node 4 and the kth stationary node, $\hat{d}_{i,k}$ is the estimated distance between Node 4 and the kth stationary node. Nodes 5, 7, and 9 are indexed by $k = 1, 2, 3$, respectively.

- At time epoch i, the position of Node 4 is found via a least-squares formulation as:

$$(\hat{x}_i, \hat{y}_i) = \arg \min_{(x_i, y_i)} \sum_{k=1}^{N} \left[\hat{d}_{i,k} - \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2} \right]^2 \tag{3.2.2}$$

  where (x_k, y_k) is the location of the kth stationary node acquired from the GPS on the surface buoy, $(\hat{x}_i, \hat{y}_i)$ is the estimated location of the moving Node 4. Eq. (3.2.2) is solved by a two-dimensional grid search on (x_i, y_i).

3.3 The Estimated Track

In order to solve the least-squares formulation shown in (3.2.2), we first set the coordination of Node 5 as (0, 0) and derive the coordinations of the other two stationary nodes. Then, within an area around the stationary nodes, and with the distances from mobile node to the stationary nodes as inputs, we implement the exhaustive search to find the best solution for each position of the mobile node.

There are 143 groups of input data in total, which lead to 143 position estimates of Node 4 within the track of the cruise. The distances we get from modems are shown in Fig. 3.1.1(b), which look consistent with the reference GPS measurements shown in Fig. 3.1.1(a). However there are discontinuous points existing in three distances due to the discontinuity of the acoustic communications between the moving node and stationary nodes.

The locations of the mobile node are superimposed on the GPS track as shown in Fig. 3.1.2. One can see that the estimated trajectory of the mobile node agrees well with the track recorded by GPS.

3.4 Error Analysis and Discussions

The following error analysis is based on selected 25 groups of data, due to the difficulty of finding the corresponding reference data from the GPS information recorded exactly at the same time for the other 118 groups of data.

3.4.1 Relative Ranging Error

We first evaluate the ranging accuracy based on one-way travel time estimation. Define the relative ranging error as:

$$\mathrm{RRE} = \frac{1}{N_1 N_2} \sum_{i=1}^{N_1} \sum_{k=1}^{N_2} \left| \frac{d_{i,k} - \hat{d}_{i,k}}{d_{i,k}} \right|, \tag{3.4.1}$$

where $\hat{d}_{i,k}$ is obtained through (3.2.1), $N_1 = 25$ is the number of data groups, $N_2 = 3$ is the number of anchor nodes, $d_{i,k}$ is the distance between the moving node and the kth stationary node computed based on the GPS coordinates. Over the 25 groups of data, the RRE is 0.82% as computed based on (3.4.1).

There are three main sources of ranging errors. The first is that the one-way travel time $\Delta t_{i,k}$ in (3.2.1) is obtained by comparing the time stamps from modem log files, which indicates the first arrivals of the underwater multipath channels. The identification of line-of-sight (LOS) path in the presence of dense multipath channels

depends on the channel multipath structure and the signaling bandwidth. The second source of error is that the speed of sound is set at 1500 m/s, which might not be accurate for a particular environment. One could calibrate the sound speed during the experiment. The third is that the location offsets between the GPSs on the buoys and the OFDM modems mounted by the anchors. One could obtain the positions of the deployed OFDM modems more accurately by using an acoustic pinger under the ship with a precise GPS, which was not carried out.

3.4.2 Localiztion Accuracy

Now we investigate the localization performance where the locations reported by the GPS device on the ship are used as reference, since the "ground truth" of Node 4 is unknown. The locations recorded by GPS are the closest location information we have. The root mean square error (RMSE) on the location estimates is evaluated as follows.

$$\text{RMSE} = \sqrt{\frac{1}{N_1}\sum_{k=1}^{N_1}\left[(\hat{x}_i - \tilde{x}_i)^2 + (\hat{y}_i - \tilde{y}_i)^2\right]}, \qquad (3.4.2)$$

where $(\hat{x}_i,\ \hat{y}_i)$ denotes the estimated positions of Node 4, and $(\tilde{x}_i,\ \tilde{y}_i)$ represents the GPS recorded positions. $N_1 = 25$ is the number of data groups.

The value of RMSE is computed as 126.7 meters based on (3.4.2). Taking the average distance of Node 4 to three anchor nodes, which is 1713.4 meters over the 25 groups of data, into consideration, the relative localization accuracy is 7.4%.

The location error has three major sources. The first one is that the GPS device (GPS18x LVC from Garmin) has a maximum error of 15 meters of its own in recording position information. We use those position information as the reference, so the error

would be involved in the localization result. The second source of error is that we have assumed the position recorded by GPS device is exactly where the modem was, as shown in Fig. 2.1.2(a), what truly happened is that the GPS device was onboard the ship and the modem was several meters behind the stern of the ship. There is a distance between the true positions of the modem and the GPS, about 10 meters. The third error is that the modem transmitted message with an approximate period of tens of seconds, while the GPS only recorded location information every one minute. So we have to look for the nearest GPS information to modem measurements as references to determine the accuracy of localization. By doing this, we are actually comparing two positions that have several seconds of time difference within the cruise track of the ship. These issues lead to a root-mean-square-error as high as 126.7 meters.

Chapter 4

CONCLUSIONS

This thesis summarizes the performance results of a sea test of mobile underwater localization in May 2013. The track of the mobile node was produced based on the modem log files that recorded the time stamps encoded in the messages and the local arrival times. The estimated trajectory of the underwater mobile node agreed well with the track recorded by GPS.

The GPS devices used in the sea test were handset devices with low precision, and there existed location differences between GPS and the modems. These two factors instead of the modems' performance are the main source of errors. Future work will investigate the localization accuracy of the proposed algorithm based on improved test setups and focus on how to improve the ranging accuracy of the OFDM modems.

Appendix A

SOME DISCUSSIONS ON RMSE

Since we get a RMSE which is 126.7 meters, the localization result is not as good as we expected. Also if we take a look at the comparison of the two trajectories, the estimated track is apparently very close to the reference track. Thus, we are going to make some discussions below.

First, we plot the distribution of the RMSE for each of the 25 groups of data we used to derive final RMSE. The observation tells us that there are 11 groups of RMSE out of 25 that are lager than final RMSE, which is 126.7 meters. The interesting point is, among the 11 groups of data, 7 are in a sequence. So we check the GPS map Fig. 3.0.1, which shows the details of the cruise. The fact is that these 11 groups of data are measured and computed when the mobile node was moving away from all the three anchor nodes, and the distances between the mobile node and the three anchor nodes reached their maximum values during this period of cruise. We have the experience that once the target node is out of the triangle formed by the three anchor nodes, the localization accuracy will dramatically decrease. This could

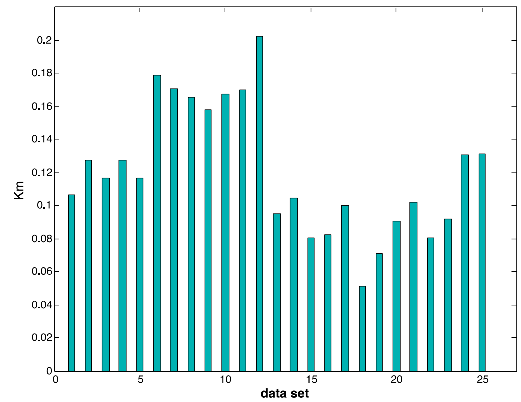
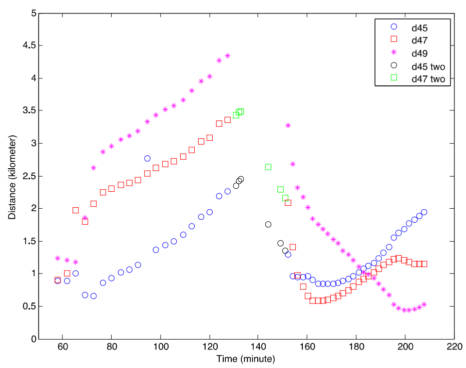
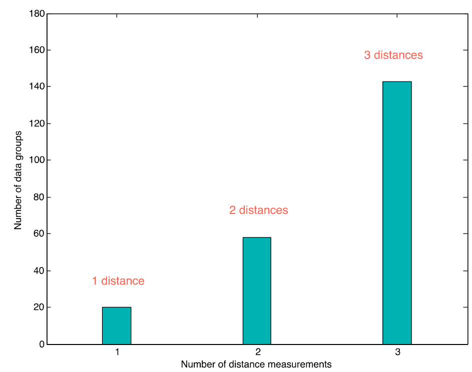


FIGURE A.0.1: The error distribution of 25 groups of data



(a) Modem decoded data with three and two distances



(b) Measurement histogram

FIGURE A.0.2: Modem decoded data and measurement histogram

explain why the distribution of the RMSE looks like that, and the measurements taken during the far end of the track contribute a lot to the large final RMSE.

Second, we draw the histogram of the successful transmissions with three distance measurements, two distance measurements and only one distance measurement respectively. We see from Fig. A.0.2 that most of the transmissions are successful. And those failure transmissions happened when the distances of the mobile node and three anchor nodes reached their maximum values, which convinces the conclusion we had about the effect of distance between mobile node and anchr node on the transimission.

Overall, we conclude that the large RMSE is mainly due to the selection of the data groups which is taken when the distances between mobile node and anchor nodes are very long. The other reasons include the synchronization problem between GPS device and modems, and the experiment settings. We believe that the improvement of the performance of the mobile underwater localization with OFDM modems could be achieved in the future with some fixes of the drawbacks.

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