Underwater Acoustic Relative Positioning System Based on Complementary Set of Sequences

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Abstract—The development of positioning systems using underwater acoustic is a new research field. One of the main advantages of such a positioning system over absolute ones is that an external infraestructure is not needed, because only the distances between the buoys are used to obtain their positions. In this work, a relative positioning system using underwater acoustic is presented. This system consists of four buoys that emit an acoustic signal, coded with orthogonal Complementary Set of Sequences (CSS). The times of flight are then obtained by means of correlation processes. The use of orthogonal CSS also allows the emission from the four buoys simultaneously. When the times of flight are obtained, the position of the buoys can be computed with the Multidimensional Scaling technique algorithm (MDS). Some simulations of the performance of the system are also presented.

Index Terms—Underwater acoustics, relative positioning system, CDMA ultrasonic signals

I. INTRODUCTION

Underwater acoustic systems have experienced a growing interest since a few decades ago. Using these systems, environmental parameters can be monitored, submerged robots and vehicles can be controlled and sonar experiments are performed. To sum up, it is an inexpensive way to implement a communication system in this medium and the most general solution, due to the high atenuation suffered by electromagnetic waves in water.

In the last years, some works dealing with positioning systems using underwater acoustic have appeared [1] [2]. Those works were about absolute positioning systems, in which the positions of the buoys were obtained from a GPS signal, using this information to localize later some submerged objects.

In sonar or positioning systems, an accurate measure of the time of flight of the signal is needed in order to obtain a good estimation of the position of the target. One way to achieve this accuracy is by coding the emitted signal [3] and obtaining then the time of flight by means of a correlation process. This solution has been widely used in airborne systems, but there are few references for water environments. Using underwater acoustic, a system with such characteristics can be found in [4], where a signal was coded and correlated at the receiver. However, the use of coded signals in underwater environments and especially, in positioning systems using underwater acoustic, has not been explored enough.

In this work, a relative positioning system is presented. This system consists of four buoys. Two of them need to be anchored at a fixed position, and the other two could freely move through the sea surface. The acoustic signals are coded using orthogonal Complementary Sets of Sequences (CSS), allowing the simultaneous emission of the four buoys. Eventually, the signals will reach the buoys, where through a correlation process the times of flight from each other buoy are estimated. These times of flight are fed to the Multidimensional Scaling technique algorithm (MDS), which calculates the positions of the buoys.

In chapter II a brief description of an underwater acoustic propagation model can be found. The positioning system is described in chapter III, where the configuration of the buoys, as well as the coding scheme and the positioning algorithm are revised. Chapter IV shows some simulated results for a particular environment and different configurations, whereas chapter V outlines the conclusions and future work.

II. UNDERWATER ACOUSTIC PROPAGATION MODEL

In order to obtain realistic simulated results, an underwater acoustic propagation model has been developed and used to calculate the physical properties of the received signals. There are four main effects that are calculated by the propagation model: multipath structure, sound speed profile, transmission loss and Doppler spread.

As the sound waves propagate through the sea following different paths, several signals will arrive at the receiver, each of them following a different path with different arrival times, interfering among themselves: this is the multipath structure. This structure is obtained by a ray tracing technique, that considers the energy of the wave to be confined in different paths, or rays [5].

The sound speed is calculated using the UNESCO standard equation [6]. The variations in sound speed with depth provide the sound speed profile. If there were no change in the sound speed value, the rays would follow a straight line [7]. However, if there were a change in the value, they would curve due to Snell law. This consideration is crucial for the correct calculation of the multipath structure.

Transmission loss gathers all the energy losses that the acoustic waves suffer as they travel through the medium. Three causes of energy loss are considered in the model: geometrical spreading, absorption loss and rebound loss at the surface and the bottom.

In the sea, swell must be considered. This swell is assumed to be dependent on wind speed, causing a moving reflection point and, as a consequence, a Doppler spread in the surface-reflected signal. This Doppler spread will worsen the properties of these signals. Lastly, all of the signals are affected by an additive white gaussian noise. All of these effects are put together, obtaining a set of arrivals that will interfere at a certain times and with certain amplitudes.

Considering this propagation model, the simulations obtained with the relative positioning system proposed are more accurate and closer to reality. A more exhaustive description of the model can be found in [8].

III. DESCRIPTION OF THE RELATIVE POSITIONING SYSTEM

In this chapter, the entire positioning system operation is described. First, the environmental and system properties are presented. Next, the coding scheme based on CSS is reviewed, and finally the MDS algorithm is described.

A. Environmental and system properties

The relative positioning system consists of four buoys. Two of them need to be anchored at a fixed position, and the other two could freely move through the sea surface. One of buoys is considered the origin of the coordinate system, and so its position will always be $(0, 0)$ m.

At 1 meter depth in each buoy there is an hydrophone, acting both as an emitter and receiver. These hydrophones are supposed to send an omnidirectional signal in the horizontal plane, but this signal is limited between $\pm 20°$ in the vertical plane. Fig. 1 shows the configuration of the relative positioning system.

The positioning system is simulated to be deployed in the coast of Comodoro Rivadavia, Argentina. This city has a latitude of $-45.8647°$, and a bottom depth of 6 meters, few kilometers out to sea. This bottom is supposed to be sandy, with a density of 1941 $kg \cdot m^{-3}$ and a sound speed of 1749 $m \cdot s^{-1}$. A salinity of $34.1^0/_{00}$ and a pH of 7 are also considered, as well as a water density of 1024 $kg \cdot m^{-3}$. These values are between the most common that one can encounter in this medium [9]. The water temperature is assumed to be of $8.1°C$, and is a constant value in all the water column. This
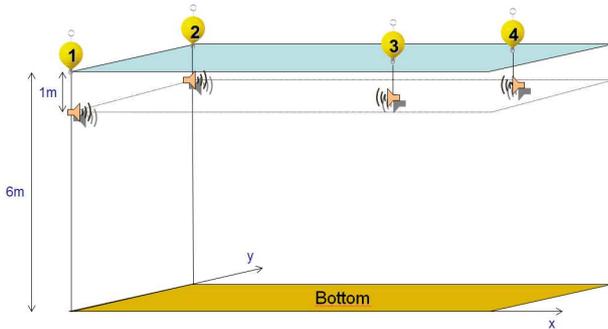

Figure 1. Positioning system configuration

temperature is the annual mean for the approximate latitude of Comodoro Rivadavia, using the Levitus Atlas [10].

B. Coding scheme

To obtain the times of flight between the different buoys more accurately, the acoustic signals are coded with Complementary Sets of Sequences, CSS [11].

In this particular case, as the system consist of four buoys, four orthogonal CSS are needed. Thus, the sum of the cross-correlation signals in each buoy would be ideally zero. Every buoy emits a complementary set of four sequences, each of them of length 64. These sequences are interleaved and modulated in BPSK with a carrier frequency of 20 kHz. All the buoys are supposed to be perfectly synchronized, thus emitting at the same time.

Then, every buoy will demodulate the received signal, which will consist of the signals from the other three buoys. These signals will have been affected by the phenomena described in chapter II. When the received signal is demodulated in a buoy, it is correlated with the codes of the other three, obtaining then the correlation peaks, that will provide the times of flight for the signals from each buoy. The measure of the time of flight is done from the maximum amplitude peak. Knowing the times of flight and the sound speed value, the distance between the buoys can be obtained. As the correlation peak is obtained when the entire coded signal has passed through the correlator, the temporary length of the emitted signal, t_{code}, must be substracted to obtain the correct arrival time. Thus, the distance between two buoys (i, j), d_{ij}, can be obtained from (1) as follows:

$$d_{ij} = (t_{ij} - t_{code}) \cdot c_t \tag{1}$$

Where t_{ij} is the time of flight obtained by the maximum amplitude correlation peak and c_t is the sound speed at the hydrophones depth. As the depth is small and the sound speed will be nearly constant, considering this particular value c_t will not provide a noticeable error.

C. MDS algorithm

In order to obtain the position of the buoys, the MDS technique has been used [12]. This is one of the simplest algorithms for relative positioning systems, but it provides good enough results for the first approach to the problem.

The position of the buoys are calculated knowing all the distances between them, which were obtained by (1). All the distances are collected in the matrix **D**, as can be seen in (2):

$$\mathbf{D} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ d_{21} & d_{22} & d_{23} & d_{24} \\ d_{31} & d_{32} & d_{33} & d_{34} \\ d_{41} & d_{42} & d_{43} & d_{44} \end{pmatrix} \tag{2}$$

A change in the coordenate system is applied to this matrix, obtaining another one, **B**, where now all the distances are referred to the centroid of the geometrical figure drawn by the buoys. The position of the buoys can be estimated by

factorizing **B** using Singular Value Decomposition (SVD). Finally, the positions are referred back to the original coordinate system. A more detailed explanation of this algorithm and an example of its use in a relative positioning system in air, can be found in [3].

IV. RESULTS OBTAINED WITH THE RELATIVE POSITIONING SYSTEM

In this chapter, some results for the proposed positioning system are presented. The buoys are supposed to be deployed in the coast of Comodoro Rivadavia, whose environmental values where previously defined. The four buoys are in the following positions (x, y): $(0, 0)$ m, $(0, 500)$ m, $(350, 275)$ m and $(480, 400)$ m.

First, a characterization of the system will be presented, where the distance errors between real and estimated positions are given for different values of signal-to-noise ratio (SNR) and wind speed, w, for a particular position of the buoys. Lastly, some simulations of the positions obtained by the proposed system are shown.

A. Characterization of the system behavior

Due to the statistical properties of the dynamic effect of swell and the SNR, a characterization of the system has been performed. In this work, the SNR is defined as E_b/N_0, being E_b the energy per bit and N_0 the noise power spectral density, assuming an additive white gaussian noise. A hundred simulations have been run for the same values of wind speed and SNR, and nine different cases have been considered, obtaining for each one of them the average absolute error in the position of the buoys and its standard deviation, σ.

The SNR values used were 15 dB, 3 dB and -6 dB, obtaining then a strong signal in the first case, a considerable amount of noise in the second case and a very unfavorable situation in the third case, where the noise power is greater than signal power. As for the wind speed, three values were used: 0.1 $m \cdot s^{-1}$, 3.5 $m \cdot s^{-1}$ and 7 $m \cdot s^{-1}$, obtaining then a situation with almost no wind speed in the first case, a medium value for the wind speed in the second case, usually found in Comodoro Rivadavia, and a remarkable wind speed in the third case.

The results are shown in Fig. 2. The values for the first buoy are not given, as this buoy is the origin and it is always placed at $(0, 0)$ m, with no error associated. Knowing the position of the buoys, it has been tested that the further they are with respect to the origin, the larger the average absolute error becomes, as one could expect. There is an improvement on the system's performance for higher values of SNR: the average errors tend to become smaller as the SNR is higher. Another expected result, although less intuitive, is that for larger values of wind speed, the average absolute error becomes smaller. This behavior is due to the energy loss produced by surface rebounds, which will cause a smaller multipath effect, as more arrival paths are highly atenuated. From these results it can be concluded that multipath effect is the main handicap of the
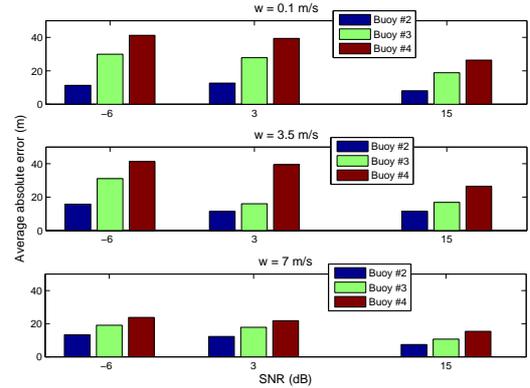

Figure 2.   Average absolute error obtained for the characterization

system, where the main source of errors would be the lack of wind speed, that would create a perfect reflection surface.

B. Relative Positioning System

In all the cases studied, the buoys are in the same position that in the characterization of the system. Different values of wind speed and SNR are tested as an example of the relative positioning system.

In the first case, a SNR of 6 dB and a wind speed of 3.3 $m \cdot s^{-1}$ are used. The result obtained by the MDS algorithm can be seen in Fig. 3 (a), where an absolute error of 11 cm is obtain in the worst estimation.

In the second case, a SNR of 3 dB and a wind speed of 1 $m \cdot s^{-1}$ are considered. The result obtained by the MDS algorithm is shown in Fig. 3 (b). In this case, a larger error appears. The worst absolute error has a value of about 52 m, which corresponds to a percent error of 8.3%.

The third case considers the same value of wind speed than the previous simulation, 1 $m \cdot s^{-1}$, and a SNR of 0 dB. Thus, the effect of the SNR can be seen with respect to the same value of wind speed. The result is represented in Fig. 3 (c), and shows a better estimation than the preceding case, due to the statistical effect of the dynamic effect of swell. For the same wind speed value, the results will depend on the atenuation and phase shifts that the acoustic waves suffer. These magnitudes are statistically modelled, so they change from one simulation to another, even for the same wind speed value.

As expected, following the results from the characterization of the system, the SNR is not a parameter as crucial, within the limits considered, as the wind speed. The main source of errors is the wind speed and the signal degradation it introduces. The worst absolute error is about 3.3 m.

The last simulation uses a SNR of 0 dB and a wind speed of 0.2 $m \cdot s^{-1}$, which is one of the worst cases that can occur: a small value for the wind speed. The result obtained by the MDS algorithm is shown in Fig. 3 (d), which is a good result for the bad conditions considered. In this particular case, the worst absolute error is 4.86 m.

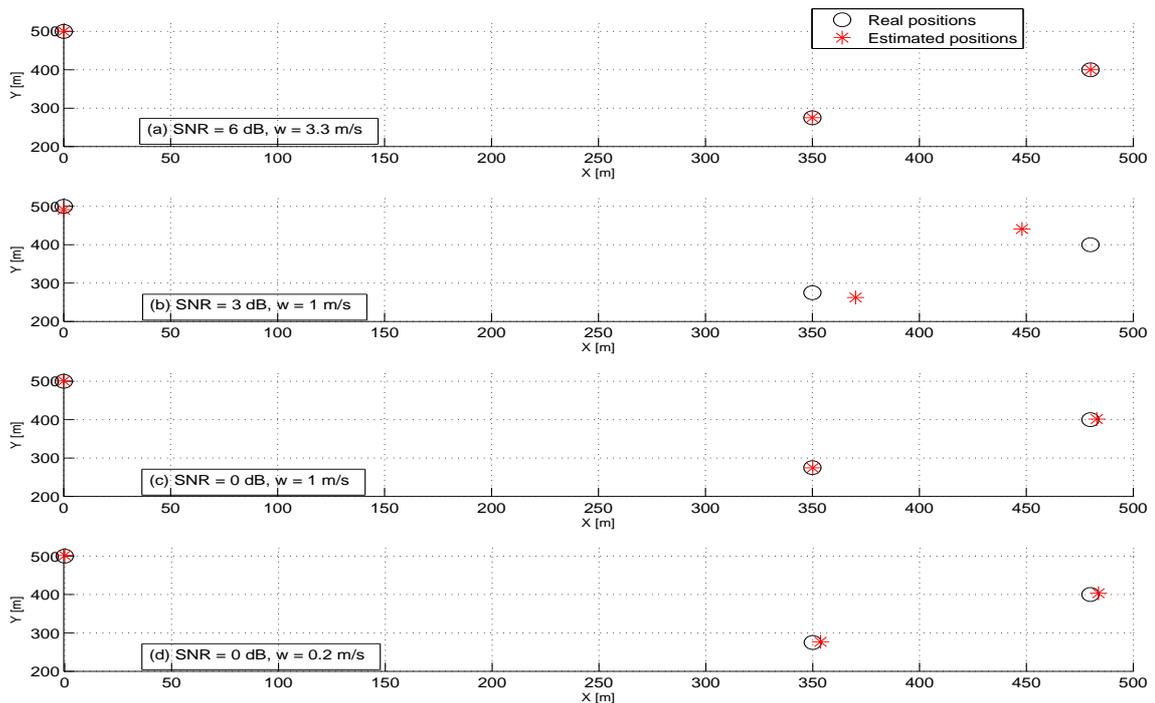In all the representations, the position of the first buoy has been omitted, due to its constant position at $(0, 0)$ m.

Figure 3. Positions obtained by the MDS algorithm

V. CONCLUSIONS

In this work, a relative positioning system based on underwater acoustic has been presented. This system has been simulated and characterized for different ranges of SNR and wind speed, showing a generally good performance in spite of the important multipath effect that appears when the wind speed has a value of few meters per second. Also, it is important to note that the positioning algorithm used in the simulations is one of the simplest ones, the MDS algorithm, which provides good results as a starting point, but a better performance could be achieved.

As a future work, some improvements could be made into the system. Instead of using 4-CSS of length 64 as the coding sequences, it can be studied which sequences are better suited for this kind of system, and another coding schemes apart from CSS can be looked for. The final estimated positions can be improved using more complex algorithms, or combining MDS with other techniques to refine the results, such as the Levenberg-Marquardt algorithm.

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