Estimation of Time Difference Using Cross-Correlation in Underwater Environment

[Abstract]

Recently, underwater acoustic communication (UWAC) has been studied by many scholars and researchers. In order to use UWAC, we need to estimate time difference between the two signals in underwater environment. Typically, there are three methods to estimate the time-difference between the two signals such as estimating the arrival time of the first non-background segment and calculate the temporal difference, calculating the cross-correlation between the two signal to infer the time-lagged, and estimating the phase delay to infer the time difference. In this paper, we present calculating the cross-correlation between the two signals to infer the time-lagged to apply UWAC. We also present the experimental result of estimating the arrival time by using cross-correlation. We get EXCORR = 0.003055 second as the estimation error in mean absolute difference.

Key word : Cross-correlation, Time difference, Underwater acoustic communication, Underwater environment, Hydrophone.

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Ⅰ. Introduction

Because the electromagnetic wave cannot propagate in underwater differ from ground, we use acoustic communication. However, acoustic communication in underwater environment have several problems such as the velocity of sound wave is slow as 1.5km/s, limited frequency bandwidth, time varying multipath according to time, and reflection in sea level and ocean floor. The acoustic signals are reflected, scattered and absorbed by variation of sea level, caused by wind specially. The transmitting signals are also received with large distortion due to media characteristics. Therefore, it is well known that the acoustic communication in underwater environment is very difficult.

Recently, underwater acoustic communication (UWAC) has been studied by many scholars and researchers. Direct-sequence code division multiple access (DS-CDMA) [1]-[4], orthogonal-frequency division multiplexing (OFDM) [1],[5]-[7], and multi-input multi-output (MIMO) [1],[8], modulation and error correction[9], and others [10]-[11], techniques that can transmit high-speed data are used in UWAC.

In order to use UWAC, we need to estimate time difference between the two signals in underwater environment. To do this, we have to acquire two pinger periodically broadcast a signal with stable frequency through hydrophone in underwater environment. Typically, there are several method to estimate the time-difference between the two signals such as estimating as the arrival time of the first non-background segment in both signals and calculate the temporal difference.

In this paper, we present calculating the cross-correlation between the two signals to infer the time-lagged to apply UWAC. We also present the experimental result of estimating the arrival time by using cross-correlation.

Ⅱ. Time Difference Estimation using Cross Correlation

2-1 Data preprocessing

There is an array of $N_h$ hydrophones which record the acoustic signal with sampling frequency $F_s$. In the example showed in Fig. 1, there are two impulsive segments locating around 0.7755 and 1.8449 second in the data of the first hydrophone.

The problem is to estimate the time-difference between the two signals, three methods can be applied: (1) estimating the arrival time of the first non-background segment in both signals and calculate the temporal difference.

The input signal from each hydrophone is an integer array valued in range $(-2^{16}, 2^{16})$. The purpose of preprocessing is to normalized the value range into (-1,1).

$$z_t = \frac{x_t}{\max|x_t|}, 0 \leq t \leq T-1 \tag{1}$$

where $x_t$ is a data sample and T is the total number of data sample.

2-2 Preliminaries

Given two discrete-time real-valued signal $x_1(n)$ and $x_2(n)$ of duration $N$ and a lag $l$, the cross-correlation between $x_1$ and $x_2$ is given by equation (2).

$$r_{x_1x_2}(l) = \begin{cases} \sum_{n=0}^{N-1-l} x_1(n+l)x_2^*(n) & l \geq 0 \\ r_{x_1x_2}^*(-l) & l < 0 \end{cases} \tag{2}$$

where $x^*$ denotes the complex conjugate of x.

The calculation of cross-correlation is similar to convolution and thus is can be calculated by using the discrete Fourier transform(DFT). Of course there are many ways to calculate convolution but the calculation of Fourier transform is the fastest. After the cross-correlation is computed, the time difference is calculated as $\Delta_l = \frac{l_0}{F_s}$, where

$$l_0 = \arg \max_l |r_{x_1x_2}(l)|.$$
2-3 Algorithm

An algorithm for calculating sample cross-correlation function is following as:

**Input:** Real-valued signal \( x_1(n), \ x_2(n) \) of duration \( N \), sampling frequency \( F_s \), number of lags \( N_l \)

**Output:** Time difference \( \Delta_t \) between \( x_2(n) \) and \( x_1(n) \)

1. Find \( n_{FFT} \) is the smallest power of 2 which larger than or equal to \( 2N-1 \);
2. Compute the discrete-time Fourier transform \( X_1(k), \ X_2(k) \);
3. Calculate the Cross Power Spectrum:
   \[
   P_{x_1x_2}(k) = X_1(k) \cdot \overline{X_2(k)}
   \]
   where \( X^* \) denotes the conjugate of \( X \);
4. Compute the inverse DFT \( \hat{x}(n) \) from \( P_{x_1x_2}(k) \);
5. Normalization:
   \[
   \hat{x}(n) = \frac{\hat{x}(n)}{A_0}
   \]
   where \( A_0 = \sqrt{\left(\sum_{n=0}^{N-1} (x_1(n))^2\right)\left(\sum_{n=0}^{N-1} (x_2(n))^2\right)} \)
6. Shift the array \( \hat{x} \) such that the maximum value is aligned at the middle of the array;
7. Create \( r \) of length \( 2N_l+1 \) from \( \hat{x} \) from \( (n_{FFT} / 2 - N_l) \) to \( (n_{FFT} / 2 + N_l) \) corresponding to lags \( N_l, N_l-1, ..., 0, ..., N_l-1, N_l \)
8. \( \hat{l}_0 = \arg \max | \hat{r}(l) | \) \( 0 \leq l \leq 2N_l + 1 \) - \( N_l \)
9. \( \Delta_t = \frac{\hat{l}_0}{F_s} \)

We take a half of 1st and 2nd hydrophone data for demonstration. The first step is to compute the DFT of the two signals. The 1st and 2nd hydrophone data and their corresponding magnitude of the DFT is showed in Fig. 2 and 3.

We compute the cross power spectrum and it shows in Fig. 4. Next, we compute the inverse DFT, normalize and shift the result as shown in Fig. 5.

Then, we find in the cross-correlation the peak which corresponds to the time-lagged between 2nd hydrophone data and 1st hydrophone data as shown in Fig. 6.

| Table 1. Referenced time difference of four hydrophones’ data. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | \( H_1 \)       | \( H_2 \)       | \( H_3 \)       | \( H_4 \)       |
| \( H_1 \)      | 0               | -0.000357       | 0.002877        | 0.000733        |
| \( H_2 \)      | 0.000357        | 0               | 0.003233        | 0.00109         |
| \( H_3 \)      | -0.002877       | -0.003233       | 0               | -0.002143       |
| \( H_4 \)      | -0.000733       | -0.00109        | 0.002143        | 0               |

The lag value is 466 corresponding to 0.001553 second. The estimation error is \( \Delta_E = ||0.001553 - (0.000357)|| = 0.00191 \) second (the number -0.000357 comes from table 1).

Where the data in row \( x \) and column \( y \) is the time difference between \( y \)th and \( x \)th hydrophone data. For example, in the equation (4).

For example, with \( N_H = 4 \), \( \Delta_E[l,l2] \) is given in table 2 and \( \Delta_E[l,l2] \) is the estimated time difference.

For example, with \( N_H = 4 \), we can calculate following equation (4).

\[
\Delta_E = \frac{1}{6} (|\Delta_E[1,2] - \Delta_E[1,2]| + |\Delta_E[1,2] - \Delta_E[1,3]| +
|\Delta_E[1,4] - \Delta_E[1,4]| + |\Delta_E[1,2] - \Delta_E[2,3]| +
|\Delta_E[2,4] - \Delta_E[2,4]| + |\Delta_E[3,4] - \Delta_E[3,4]|)
\]

We use a half of 1st hydrophone data for demonstration. The first step is to compute the DFT of the two signals. The 1st and 2nd hydrophone data and their corresponding magnitude of the DFT is showed in Fig. 2 and 3.
III. Evaluation of method for cross-correlation

In this evaluation, we first use the Matlab function xcorr to calculate the sample cross-correlation function in order to infer the time difference. Fig. 7 shows the cross-correlation result of 1st hydrophone data with the others including the autocorrelation with itself. We then translate those Matlab source code into C programming language with using the FFTW library [2] (http://fftw.org) for FFT computation.

The estimated results are showed in table 2 and 3. In table 2, time lag is the lag at which the cross-correlation yields maximum. Given lag $t_l$, the estimated time is given by $\Delta = \frac{t_l}{F_s}$ (seconds). Those result are showed in table 3.

### Table 2. Time lag from cross-correlation.

|     | $H_1$ | $H_2$ | $H_3$ | $H_4$ |
|-----|-------|-------|-------|-------|
| $H_1$ | 0     | 466   | -1271 | -99   |
| $H_2$ | -466  | 0     | -104  | 324   |
| $H_3$ | 1271  | 104   | 0     | 1208  |
| $H_4$ | 99    | -324  | -1208 | 0     |

### Table 3. Time difference estimated(in second) using cross-correlation.

|     | $H_1$ | $H_2$ | $H_3$ | $H_4$ |
|-----|-------|-------|-------|-------|
| $H_1$ | 0     | -0.001553 | 0.004237 | -0.00033 |
| $H_2$ | -0.001553 | 0     | 0.000347 | 0.00108 |
| $H_3$ | 0.004237 | -0.000347 | 0      | 0.004027 |
| $H_4$ | 0.00033 | -0.00108 | -0.004027 | 0      |
The estimation error in mean absolute difference is EXCORR = 0.003055 second. It means that this algorithm with the cross correlation can apply in the underwater system.

IV. Conclusion

In order to use UWAC, we need to estimate time difference between the two signals in underwater environment. To do this, we have to acquire two pinger periodically broadcast a signal with stable frequency through hydrophone in underwater environments.

In this paper, we presented calculating the cross-correlation between the two signal to infer the time-lagged. We also presented the experimental result of estimating the arrival time by using cross-correlation. We get EXCORR = 0.003055 second as the estimation error in mean absolute difference. In the future, we need to apply into real underwater environments including river and ocean.

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