DEVELOPMENT OF THE SOURCE RECONSTRUCTION SYSTEM BY COMBINING SOUND SOURCE LOCALIZATION AND TIME REVERSAL METHOD

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ABSTRACT

This study explored the target sound source location at unknown situation and processed the received signal to determine the location of the target, including the reconstructed signal of source immediately. In this paper, it used triangulation sound sources localization and time reversal method (TRM) to reconstruct the source signals. The purpose is to use a sound source localization method with a simple device to quickly locate the position of the sound source. This method uses the microphone array to measure signal from the target sound source. Then, the sound source location is calculated and is indicated by Cartesian coordinates. The sound source location is then used to evaluate free field impulse response function which can replace the impulse response function used in time-reversal method. This process reduces the computation time greatly which makes possible for a real time source localization and source signal separation.

Keywords: Triangulation, Source localization, Time reversal, Time difference of arrival.

1. INTRODUCTION

In recently, the quality of audio is an important factor for the system of speech recognition, such as cellphones, cars, computers and intelligent robots. The audio cannot be recognized due to distortion of the environmental noise. For the clarity and quality of voices, the sound source of localization and separation is highly desired. To solve the problem of sound signal separation, time reversal method (TRM) is a simple and efficient way. In addition, the impulse response function can be computed by using source localization. In the paper, two methods of triangulation and time reversal are reviewed.

Triangulation is based on free field as the sound waves transmit along a straight line [1-3]. This method of source localization needs $n + 1$ receivers in a $n + 1$ dimensional space. Two parameters of source localization can be categorized. One is the interval of time between source and receiver (time of arrival, TOA); the other one is the time difference between two sensors of receiver array [4-6] (time difference of arrival, TDOA). Wu and Zhu researched sound localization of triangulation in three dimensional space, which is a simple and efficient way [7]. Quazi referred that the errors of TOA and TDOA would affect accuracy of source localization [8].

Time-reversal method (TRM) is based on principle of reciprocity of sound by propagating a reversal signal in time series to compensate distortion due to path effect in propagation and to focus signal at original source location. In recent years, TRM has been widely applied in optics, electromagnetism [9], medical imaging [10], nondestructive test [11], and underwater communication. TRM has two properties, which are self-focusing and easy to be realized. The concept of TRM in time domain is equivalent to phase conjugation in frequency domain [12]. Dungan and Dowling, Sabra and Dowling researched the property of TRM in shallow water of ocean and discussed the quantity [13-15], the spacing and the measuring distance of array hydrophones on TRM focusing in 2000. In 2006, TRM had been applied for target detection in ocean by Sabra who used the property of self-focusing to overcome the reverberation environment [16]. In 2010, Wu *et al*. applied a combination procedure of TRM and deconvolution process for a multiple audio signal separation problem in atmosphere [17].

In the present study, the sound signal separation technique will be developed by combining the triangulation source localization and time reversal method. In section II, the theories of TRM and source localization is discussed, including computing the impulse response function. In section III, the experiments would be implemented which combining TRM and source localization in free field. In section IV, the conclu-

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sions of TRM and source localization are shown to verify this approach in the present study.

2. BASIC THEORY

The objective of study is to explore the target sound source location at unknown situation and processed the received signal to determine the location of the target, including the reconstructed signal of source immediately. In this paper, it used triangulation sound sources localization and time reversal method (TRM) to reconstruct the source signals. The purpose is to use a sound source localization method with a simple device to quickly locate the position of the sound source. Two theories of this study are presented in following sections.

2.1 Time Reversal

Suppose $s(t)$ is the source, $p_m(t)$ is the m^{th} signal of receiver, $h_m(t)$ is the impulse response function of environment between the source and the m^{th} receiver (shown as Fig. 1). The m^{th} signal of receiver can be expressed as follows:

$$p_m(t) = h_m(t) \otimes s(t) \tag{1}$$

where $\otimes$ denotes convolution integration. In the previous results, the target signal of source can be reconstructed by self-focusing property of TRM. The reconstructed signal is described as follows:

$$z(t) = \sum_{i=1}^{m} h_i \otimes p_i(-t) = \sum_{i=1}^{m} h_i(t) \otimes \left[h_i(-t) \otimes s(-t) \right] \tag{2}$$

The concept of time reversal (time domain) is equal to the phase conjugate in frequency domain. Equation (2) can be rewritten as follows:

$$Z(\omega) = H(\omega) \times H^*(\omega) \times S^*(\omega) = G(\omega) \times S^*(\omega) \tag{3}$$

where G is an even function or gain function (superposition property).

In TRM, it is an important to find the impulse response function. The effect of TRM is affected by the accuracy of impulse response function. Followings show the method and theory of source localization.

2.2 Source Localization

The method of source localization is based on triangulation. Suppose a source point and field point in a free field, the Green's function can be expressed as follows:

$$G(r_s, r_f) = e^{ikr} / r \tag{4}$$

where

$$r = | r_s - r_f | \tag{5}$$

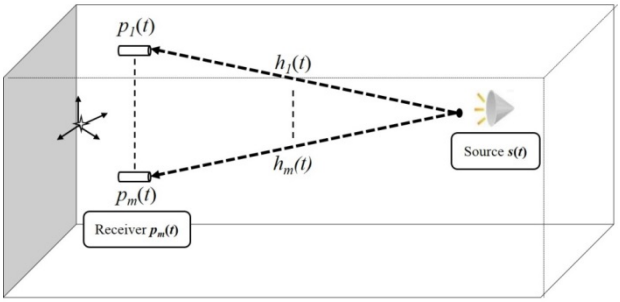


Fig. 1 The diagram of TRM.

The impulse response function $h(t)$ is shown as Fig. 1. Suppose five-microphones array is in free field space, the coordinates of five microphones are (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3), (x_4, y_4, z_4) and (x_5, y_5, z_5), respectively. The unknown source coordinate (x, y, z) can be solved as follows:

$$\begin{aligned}
&\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} \\
&\quad = \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} + (c\Delta t_{12}) \\
&\sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} \\
&\quad = \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} + (c\Delta t_{13}) \\
&\sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2} \\
&\quad = \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} + (c\Delta t_{14}) \\
&\sqrt{(x-x_5)^2+(y-y_5)^2+(z-z_5)^2} \\
&\quad = \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} + (c\Delta t_{15})
\end{aligned} \tag{6}$$

where c is the sound speed in air. Δt_{12}, Δt_{13}, Δt_{14} and Δt_{14} are the delay time between 1st and 2nd, 1st and 3rd, 1st and 4th, 1st and 5th, respectively. The triangulation for solving coordinate of source can be more accurate with more simulation equations.

The key factor of triangulation is to compute TODA. The cross-correlation can be used for computing the TDOA between two microphones. Suppose two signals of microphones are $x_1(t)$ and $x_2(t)$ in time domain. The cross-correlation function can be expressed as following equation:

$$R_{(x_1,x_2)} = \int_{-\infty}^{\infty} x_1(\tau) \cdot x_2(t+\tau)\, d\tau\,. \tag{7}$$

The maximum of τ is the delay time between two microphones.

The flow chart of source localization is shown as Fig. 2. The first step is to compute the TDOA between one microphone and the other microphone. Then, the unknown source coordinate can be solved using the simultaneous equations. Finally, the impulse response function between source and each microphone can be computed. Next section demonstrates the combining of source localization and TRM via experiments.

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3. EXPERIMENTS

3.1 Setup of Experiment

There are two cases of experiments for verifying the efficiency and performance in this research. The first case is a test for source localization, and the second one is to combine source localization and TRM. All the cases use five-microphone array (free-field PCB microphone) and one speaker in a meeting room. The accuracy of source localization would be affected by the noise and reflections in the environment. The indicator for estimating error of source localization could be defined as follows:

$$E = \frac{|\vec{r} - \vec{r}_b|^2}{|\vec{r}_b|^2} \times 100\% . \quad (8)$$

where, $\vec{r}$ and $\vec{r}_b$ represent the computed position and original position, respectively. The detailed parameters and processes of experiments are described as follows.

3.2 Case 1: Analysis of Source Localization

Figure 3 shows the flow chart of experiment by using source localization.

The microphones array is fixed on the origin of coordinate (two dimensional plane). One speaker continuously plays signals (white noise and clap), and it moves along the six points of three different paths. The device of data acquisition and computer would compute the unknown source coordinate by using source localization. The results of experiments are shown in Fig. 4. The blue lines are the real position of source, and red lines are the calculated values of source localization. The errors of source localization with different parameters are shown in Table 1. The maximum average of error is equal to 11.3%, and minimum value is equal to 7.1%. It means that the technique of source localization can find unknown source coordinate with high accuracy.

3.3 Case 2: Combining Source Localization and Time Reversal

Figure 5 shows the setup and flow chart of this experiment. The key point of time reversal is to find an accuracy of impulse response function (IRF) in the environment. Two methods can calculate the impulse response function; one is to set a reference microphone near the source position, and the other one is to process the source localization. The source localization allows that the impulse response function can be implemented in a real-time process (about 0.65 seconds). Nevertheless, the process by using reference microphone can only evaluate impulse response function off-line which is not a real time process. In this case, the performances of two methods would be compared. Figure 6 shows the results of source localization (29 points), and Table 2 lists the averages of cross-correlation coefficients. The comparison of distance (to origin) and cross correlation between source and three conditions is shown in Fig. 7. According to the results in Fig. 7, the average of cross-correlation coefficient between source and the reconstructed source signal can be increased from 0.42 to 0.52 by combining source localization and TRM. Although the value of cross-correlation coefficient is 0.72 by using reference microphone and TRM, the off-line process is over 10 seconds.

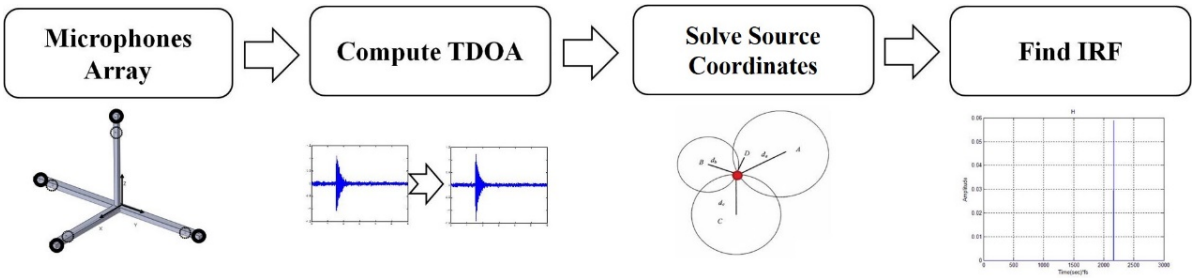


Fig. 2 The flow chart of source localization.

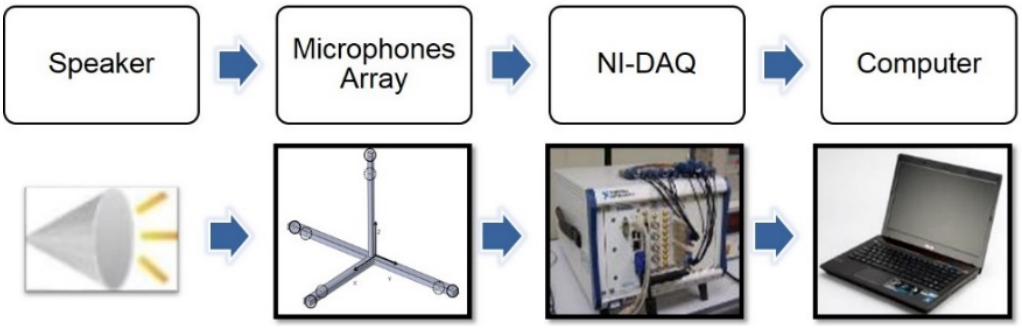


Fig. 3 The flow chart of case 1.

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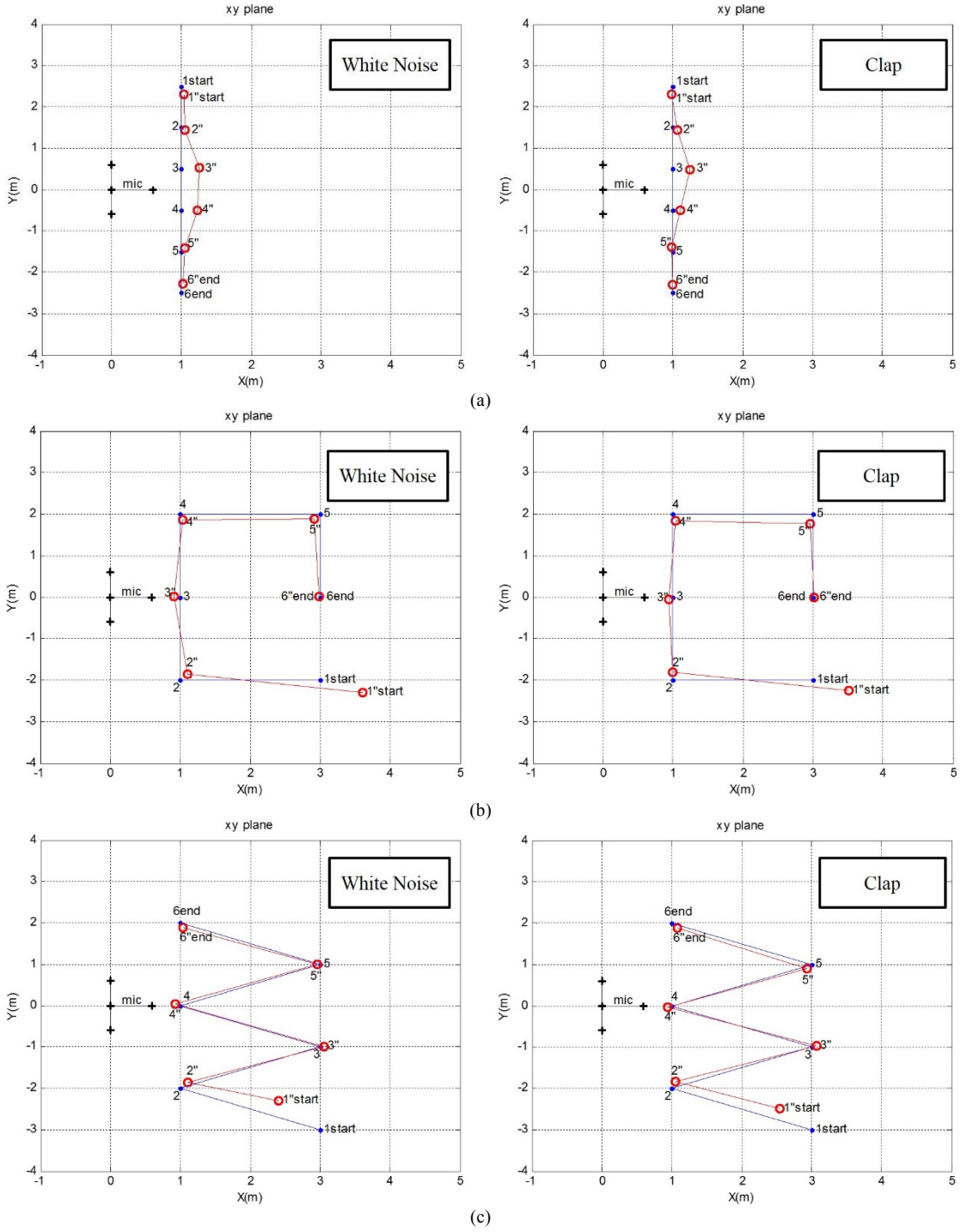


Fig. 4 The results of experiments with three different paths and sounds (●: real position of source; ○: calculated values of source localization).

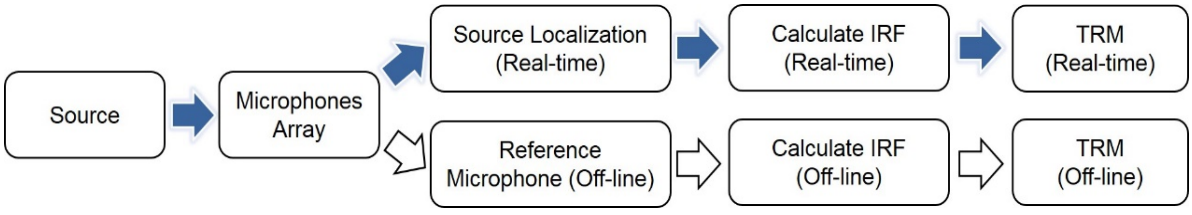


Fig. 5 The setup and flow chart of the experiment.

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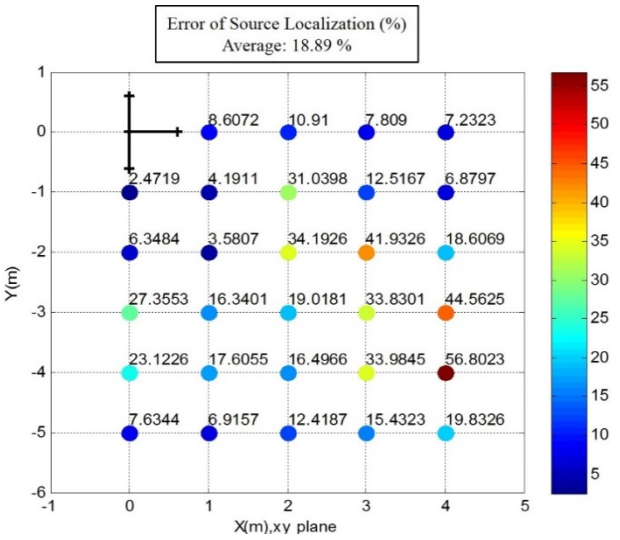


Fig. 6 The errors of source localization in 29 points.

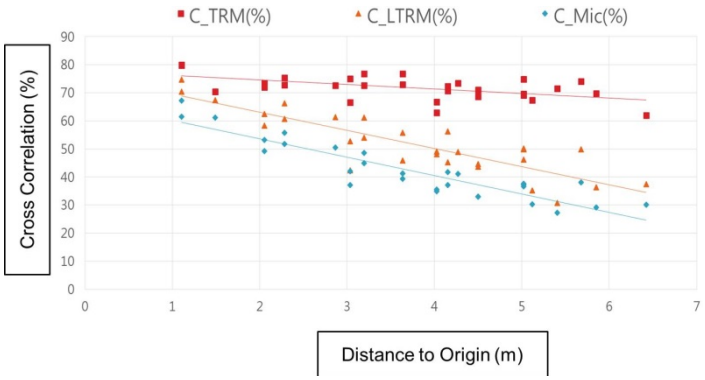


Fig. 7 The comparison of distance (to origin) and cross correlation between source and three conditions (C_TRM: time-reversal method with reference microphone; C_LTRM: Time-reversal method with source localization; C_Mic: Signals of microphones array).

Table 1 The errors of source localization with different paths and sounds.

Point	Path 1		Path 2		Path 3	
	White noise	Clap	White noise	Clap	White noise	Clap
1	7.06%	7.47%	18.93%	16.07%	21.49%	16.12%
2	4.90%	4.81%	7.97%	8.28%	7.78%	7.95%
3	22.20%	22.26%	8.78%	6.66%	2.02%	2.67%
4	20.15%	9.49%	6.44%	7.20%	9.34%	5.98%
5	5.15%	5.56%	3.66%	6.58%	1.24%	3.48%
6	8.34%	7.56%	0.55%	0.84%	5.37%	6.36%
Average	11.30%	9.53%	7.72%	7.60%	7.87%	7.09%

Table 2 The averages of cross-correlation coefficients between source and reconstructed source signal in the different conditions.

	Averages of Cross-correlation Coefficients
Microphones Array	0.42
Time-reversal with Reference Microphone	0.72
Time-reversal with Source Localization	0.52

4. CONCLUSIONS

In the present study, a source separation system is developed by combining source localization and TRM to reconstruct target source signal. According to the theory, target source can be focused and reconstructed by using TRM due to self-focusing property. It is a crucial factor to find the correct impulse response function of environment by using TRM. Notwithstanding the effect of combining source localization and TRM is not better than that by using reference microphone, the real time operation can be achieved with only 0.65 seconds operation time. From all the experimental results, the new developed source separation system provides a better performance of computing and operating. Also it will be helpful to develop a real time technique of multiple sound signal separation in the future.

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