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TSaT-MUSIC: a novel algorithm for rapid and accurate ultrasonic 3D localization

Kyohei Mizutani[1*], Toshio Ito[1], Masanori Sugimoto[1] and Hiromichi Hashizume[2]

Abstract

We describe a fast and accurate indoor localization technique using the multiple signal classification (MUSIC) algorithm. The MUSIC algorithm is known as a high-resolution method for estimating directions of arrival (DOAs) or propagation delays. A critical problem in using the MUSIC algorithm for localization is its computational complexity. Therefore, we devised a novel algorithm called Time Space additional Temporal-MUSIC, which can rapidly and simultaneously identify DOAs and delays of mul-ticarrier ultrasonic waves from transmitters. Computer simulations have proved that the computation time of the proposed algorithm is almost constant in spite of increasing numbers of incoming waves and is faster than that of existing methods based on the MUSIC algorithm. The robustness of the proposed algorithm is discussed through simulations. Experiments in real environments showed that the standard deviation of position estimations in 3D space is less than 10 mm, which is satisfactory for indoor localization.

Keywords: MUSIC-Algorithm, Ultrasound, Adaptive Array, Computational Complexity, 3D Localization, DOA-Delay Estimation

1 Introduction

In recent years, localization techniques have attracted considerable attention in ubiquitous computing communities.There have been many studies on localizing objects by using ultrasonic signals; for example, indoor positioning [1-3] or robotics [4,5]. There are several requirements for localization techniques, including accuracy, robustness, and ease of deployment.

We propose a new localization technique using the Time Space additional Temporal MUSIC (TSaT-MUSIC) algorithm, a variant of the MUltiple SIgnal Classification (MUSIC) algorithm [6]. The principle advantage of the TSaT-MUSIC algorithm is its low computational complexity compared with other variants of the MUSIC algorithm.

The MUSIC algorithm is a well-known method for direction of arrival (DOA) or propagation delay estimations. As the algorithm conducts null steering of incoming waves, it shows higher resolution than the main beam steering methods such as the delay and sum beamforming methods. There have been many studies on 3D localization using MUSIC algorithm; for example, [7]. The Spatial-MUSIC (S-MUSIC) algorithm, which is just called the MUSIC algorithm, is used for DOA estimations. Another variant of the MUSIC algorithm called Temporal-MUSIC (T-MUSIC) offers propagation delay estimates. By using these algorithms, we can identify either the DOA or the delay but not both simultaneously.

To estimate the DOA and delay simultaneously using these algorithms, two main famous approaches have been proposed. The first applies the MUSIC algorithm to spatial- and frequency-domain data at the same time; for example, 2D-MUSIC [8], 2D-TDM MUSIC [9], and JADE-MUSIC [10]. This approach conducts a 2D search of angle and time. Thus, its computational complexity becomes very large. The second approach integrates other DOA or delay estimation methods with the MUSIC algorithm, such as [11]. For instance, TST-MUSIC [12] uses beamforming and temporal filtering methods. Compared with the first approach, the second approach has less computational complexity. However, it still requires high computation times, because the computational complexity increases in proportion to the number of incoming waves.

* Correspondence: mizutani@itl.t.u-tokyo.ac.jp
[1]Department of Electrical Engineering and Information Systems, School of Engineering, University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
Full list of author information is available at the end of the article

Our proposed algorithm can estimate DOA and delay values simultaneously in an entirely different manner from the existing approaches. The procedure of the TSaT-MUSIC algorithm is as follows. First, sets of DOA and delay values are estimated using the S-MUSIC and T-MUSIC algorithms, respectively. Next, the true pairs of DOA and delay values are decided by applying the T-MUSIC algorithm at a sensor different from the sensor used in the first step. As a result, we can estimate DOAs and delays with only three MUSIC algorithm executions. The original TSaT-MUSIC algorithm is for DOA-delay estimation in a 2D space and can easily be extended to a localization method in a 3D space.

One advantageous point of MUSIC algorithms used for 3D localization is that we can design a compact receiver array. In this study, a small L-shaped receiver array (about 36 mm × 36 mm) is implemented to evaluate the performance of the TSaT-algorithm for 3D localization.

The objective of this paper is to prove that the proposed method reduces the computational complexity of sound source localization and still retains the satisfactory level of accuracy. Thus, we conduct comparative evaluations using the TST-MUSIC algorithm, which is one of the fastest and most accurate localization methods using MUSIC algorithms.

In this paper, a brief introduction of the MUSIC algorithm is first presented. then, the proposed algorithm and its 3D localization method are explained. Subsequently, the results of computer simulations, and experiments in real environments using the TSaT-MUSIC algorithm are reported.

2 The MUSIC algorithm

2.1 Data model

First, we define the data model that is adopted in this paper. Figure 1 shows the configuration of a sensor array. We assume that the transmitted signal consists of multicarrier ultrasonic waves and that a linear sensor
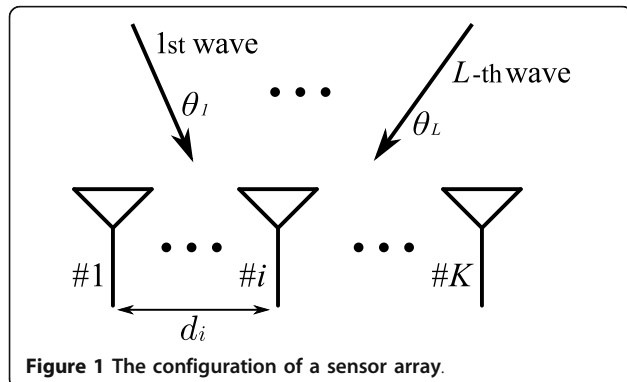

Figure 1 The configuration of a sensor array.

array is used. The numbers of sensors and frequencies are defined as K and M, respectively. By using the Fourier transform for received signals at each sensor, we obtain a received data matrix X. The dimension of X is $K \times M$. We define the received data for the mth frequency at the kth sensor as $x_{k,m}$, so X can be written as:

$$X = \begin{bmatrix} x_{1,1} & \cdots & x_{1,M} \\ \vdots & \ddots & \vdots \\ x_{K,1} & \cdots & x_{K,M} \end{bmatrix}.$$

Then, two received data vectors can be defined. A vector S_m ($m = 1, 2,..., M$) is the received data vector at the mth frequency, and a vector T_k ($k = 1, 2,..., K$) is the data received at the kth sensor. Thus, S_m and T_k can be expressed as:

$$S_m = \left[x_{1,m}, x_{2,m}, \ldots, x_{K,m} \right]^T$$
$$T_k = \left[x_{k,1}, x_{k,2}, \ldots, x_{K,M} \right]^T,$$

where the superscript $[\cdot]^T$ denotes the matrix transpose operation. Next, we introduce the mode vector a_m (θ_l) ($m = 1, 2,..., M$), where θ_l is the angle of the lth wave. $a_m(\theta_l)$ is defined as:

$$a_m (\theta_l) = \left[\exp \left(j \Psi_{m,1} (\theta_l) \right), ..., \exp \left(j \Psi_{m,K} (\theta_l) \right) \right]^T.$$

$\Psi_{m,k}(\theta_l)$ ($k = 1,2,...,K$) is the phase of the lth wave of the mth frequency at the kth sensor and is expressed as:

$$\Psi_{m,k} (\theta_l) = -2\pi f_m \frac{d_k \sin \theta_l}{c},$$

where c is the velocity of sound, f_m is the mth frequency, and d_k is the distance between the kth sensor and the 1st sensor (as shown in Figure 1). Assuming that the receiving waves are plane waves, S_m can be written as:

$$S_m = A_m F + N,$$
$$\begin{cases} A_m = [a_m (\theta_1), ..., a_m (\theta_L)] \\ F = [F_1, ..., F_L]^T \end{cases}, \tag{1}$$

where F_l is the complex amplitude of the lth wave, and N is the Gaussian noise vector with zero means and equal variances σ^2.

Similarly, we introduce a new mode vector $g_k(\tau_l)$ ($k = 1, 2,..., K$), where τ_l is the propagation delay time of the lth wave. g_k is defined as:

$$g_k (\tau_l) = \left[\exp \left(-j 2\pi f_1 \tau_l \right), ..., \exp \left(-j 2\pi f_M \tau_l \right) \right]^T.$$

By using g_k, T_k can be written as:

$$T_k = G_k F + N, \tag{2}$$

where G_k is:

$$G_k = \left[g_k(\tau_1), ..., g_k(\tau_L) \right].$$

2.2 The S-MUSIC algorithm

The S-MUSIC algorithm is for DOA estimation. This algorithm is used with single-frequency signals. By Equation (1), the correlation matrix calculated using Sm is given as:

$$
\begin{aligned}
Rss &= E\left[S_m S_m{}^H \right] \\
&= A_m E\left[FF^H \right] A_m{}^H + E\left[NN^H \right] \\
&= A_m \alpha A_m{}^H + \sigma^2 I \left(\alpha \equiv E\left[FF^H \right] \right),
\end{aligned}
$$

where the superscript $[\cdot]^H$ denotes the Hermitian operation. The eigenvectors of Rss are the orthogonal direct sum of the signal subspace and the noise subspace. Assuming that the incoming waves are incoherent and that the value of L is smaller than that of K, we can derive the MUSIC spectrum by using the eigenvectors u_i ($i = L + 1,..., K$) that span the noise subspace of Rss. The MUSIC spectrum can be written as:

$$Ps(\theta) = \frac{a_m{}^H(\theta) a_m(\theta)}{a_m{}^H(\theta) UU^H a_m(\theta)} \ (U \equiv [u_{L+1}, ..., u_K]). \qquad (3)$$

The DOAs can be obtained as the peak values of $Ps(\theta)$ by changing the angle θ. As can be seen in Equation (3), the number of incoming waves L is given. If L is unknown, Akaike Information Criteria (AIC) or Minimum Description Length (MDL) [13] can be used to estimate L. When the incoming waves are coherent, the S-MUSIC Algorithm does not work properly. Therefore, spatial smoothing preprocessing (SSP) [14] is used to suppress the coherence.

2.3 The T-MUSIC algorithm

The T-MUSIC algorithm is for propagation delay estimations. It differs from the S-MUSIC algorithm in that the T-MUSIC algorithm uses only one sensor and multiple-frequency waves. We therefore use a received data vector T_k.

Considering the Equation (2), the form of this equation corresponds to that of Equation (1). Thus, we can derive the MUSIC spectrum of propagation delays $Pt(\tau)$ in the same way as in the S-MUSIC algorithm. When the eigenvectors of the correlation matrix calculated using T_k are defined as v_i ($i = 1, 2,..., M$), $Pt(\tau)$ can be described as:

$$Pt(\tau) = \frac{g_k{}^H(\theta) g_k(\theta)}{g_k{}^H(\theta) VV^H g_k(\theta)} \ (V \equiv [v_{L+1}, ..., v_M]). \qquad (4)$$

The propagation delays are obtained by finding the peak values of $Pt(\tau)$ in the same way as in the S-MUSIC algorithm.

When the bandwidth of the multicarrier waves is f_d, the T-MUSIC algorithm can estimate a delay time to an accuracy of $1/f_d$.

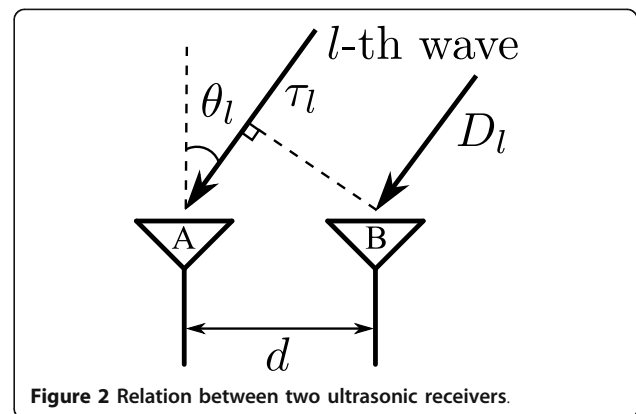## 3 The TSaT-MUSIC algorithm
3.1 Principle

By applying the T-MUSIC and S-MUSIC algorithms to L incoming waves at sensor A in the sensor array their DOA and propagation delay values are described as (θ_1, θ_2,..., θ_L) and (τ_1, τ_2,..., τ_L) as shown in Figure 2. By applying T-MUSIC again at sensor B in the same sensor array, propagation delays can be estimated as (D_1, D_2,..., D_L). The path length of the lth incoming wave arriving at sensor A is $d \sin \theta_l / c$ longer than that of the wave arriving at sensor B, where d is the distance between the two sensors. Therefore, we can plot L^2 points as possible DOA-delay pairs in the ($d \sin \theta$, $c\tau$) space. These points are called "candidate points". Here, the following equation must be fulfilled:

$$c\tau_l - d \sin \theta_l = cD_l \ (l = 1, 2, ..., L). \qquad (5)$$

We define the Equation (5) drawn in the ($d \sin \theta$, $c\tau$) space as "path difference lines". Theoretically, there can be only one point that represents a correct DOA-delay pair on each line. In the situation shown in Figure 3, for example, the pair of DOA and delay values are estimated as (θ_1, τ_2), (θ_2, τ_3), (θ_3, τ_1).

In real environments, however, the correct point is not always on the line because of noise. Hence, we calculate the distance dist(i,j,l) between each candidate point ($d \sin \theta_i$, $c\tau_j$) and the path different line $c\tau - d \sin \theta = cD_l$ as:

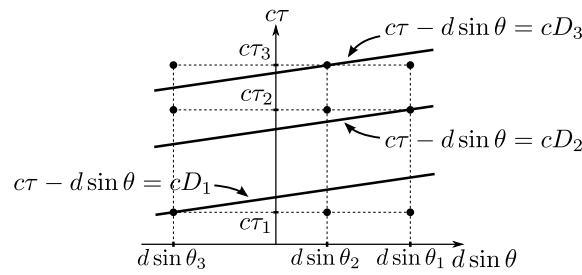$$\text{dist}(i, j, l) = \frac{1}{\sqrt{2}} |c\tau_j - d \sin \theta_i - cD_l|. \qquad (6)$$

Figure 2 Relation between two ultrasonic receivers.

Figure 3 An example of $d \sin \theta$ - $c\tau$ plots.

Then, the points with the minimum distance are selected as true points.

3.2 3D localization using the TSaT-MUSIC algorithm

The TSaT-MUSIC algorithm allows us to simultaneously obtain the DOA and delay values in a 2D space. By using an L-shaped ultrasonic sensor array as shown in Figure 4, TSaT-MUSIC can be extended to a 3D localization algorithm.

We can estimate two angles, θ_a and θ_b, and one time delay τ_c by using two sensor arrays Aa and Ab, and the sensor Sc, respectively. The pairs of θ_a and τ_c, and θ_b and τ_c can be decided by TSaT-MUSIC. As shown in Figure 5, the position of the transmitter from Sc is described as:

$$\left(x_0, y_0, z_0\right) =$$
$$\left(c\tau_c \cos \theta_a, c\tau_c \cos \theta_b, c\tau_c \sqrt{1 - \left(\cos^2 \theta_a + \cos^2 \theta_b\right)} \right).$$

Hence, we can estimate the transmitter's position by using the TSaT-MUSIC algorithm.

3.3 Computational complexity

The procedure of the TSaT-MUSIC algorithm includes one S-MUSIC calculation and two T-MUSIC calculations. The computational complexity of the S-MUSIC algorithm can be written as max (O (K^3), O (hK^2)), where h is the number of searches conducted along the DOA axis, O (K^3) is the computational complexity of the eigenvalue decomposition of *Rss*, and O (hK^2) is that of the 1D spatial search. In the same way, the computational complexity of T-MUSIC can be expressed as max (O (M^3), O ($h_t M^2$)), where h_t is the number of searches conducted along the time delay axis. Because K is generally smaller than M, the computational complexity of the TSaT-MUSIC algorithm is given by max(O (M^3),O($h_t M^2$)).

On the other hand, the computational complexity of the 2D-MUSIC algorithm is max (O ($(KM)^3$), O (hh_t $(KM)^2$)) and that of the TST-MUSIC algorithm is max (O (LM^3), O ($Lh_t M^2$)). This means that the TST-MUSIC algorithm must perform the T-MUSIC calculation at least L times. Consequently our proposed algorithm is theoretically faster than the existing method using the MUSIC algorithm.

4 Simulations
4.1 Simulation setting

We conducted two computer simulations using a PC (Dell Latitude D630, CPU: Intel(R) Core2Duo 2.60 GHz,
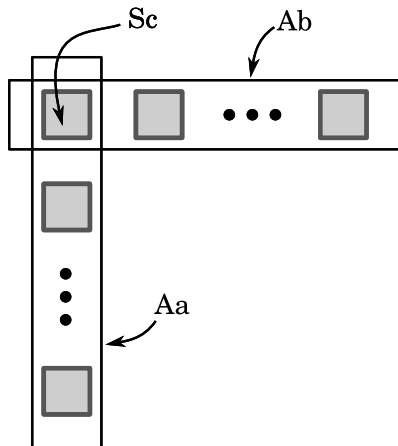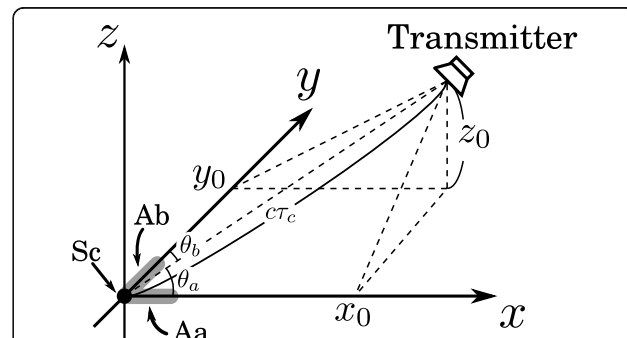

Figure 4 An L-shaped sensor array.

Figure 5 The position of the transmitter.

Memory: 2.0 GB) and GNU Octave 3.0.1. The transmitted multicarrier ultrasonic wave has six subcarriers that are orthogonal to each other. The multicarrier wave $x(t)$ can be expressed as:

$$x(t) = \sum_{i=0}^{N-1} a_i \sin \left\{ 2\pi \left(f_0 + i\Delta f \right) t + \phi_i \right\},$$

where N is the number of subcarriers (here, $N = 6$), f_0 is the center frequency, Δf is the interval of the subcarriers, a_i is the amplitude of the ith carrier, and φ_i is its initial phase. In this simulation, all the subcarriers have the same amplitude, and their initial phases are given so that the transmitted wave has a peak amplitude at the half time of the transmission period (0.5 ms). The frequencies of the subcarriers are 34-39 kHz (their interval was 1 kHz). Because the bandwidth of the wave was 5 kHz, the theoretical time resolution was 0.2 ms. In the simulations, DOA-delay estimations in the 2D space were conducted using a linear array sensor consisting of 16 receiver sensors at 5-mm intervals. The SNR (Signal Noise Ratio) of the multicarrier wave is set to 20 dB by adding Gaussian noise.

As we plan to use the TSaT-MUSIC algorithm for rapid ultrasonic imaging by detecting reflectors, all sound sources transmit the same signal in this simulation. Therefore, receiving waves at a receiver array become coherent. To control the effect of the coherence, we use the spatial smoothing method [14] in S-MUSIC and T-MUSIC algorithm, respectively. In 2D localization simulations, the number of sensors in a subarray (K), the number of frequencies (M), and the number of searches conducted along the time delay axis (h_t) were set to 11, 15, and 1,000, respectively.

From the principle of the TSaT-MUSIC algorithm as described in the previous section, its angular and range resolutions are same as those of the 1D S-MUSIC and T-MUSIC algorithms, respectively. Therefore, comparative evaluations between the proposed method and the TST-MUSIC algorithm are conducted through computer simulations shown in this section and experiments in real environments shown in the next section.

4.2 Computational complexity and accuracy

The DOA and delay values were set as shown in Table 1 by changing the number (L) of incoming waves. The simulations of the TSaT-MUSIC and TST-MUSIC algorithms for each L were conducted 1,000 times, and their average computation times and values of the root mean square error (RMSE) were measured. Figure 6a shows the simulation results of the computation times. From the figure, we find that the TSaT-MUSIC algorithm can estimate DOAs and delays in almost a constant time. On the other hand, the computation time of the TST-MUSIC algorithm increases linearly as L increases. This is consistent with the theory discussed in Section 3.3. Therefore, the computational complexity of the TSaT-MUSIC algorithm is proved to be less than that of the TST-MUSIC algorithm. Figure 6b shows the simulation results of the RMSE. These values were calculated by estimated positions of a sound source at (-60°, 0.6 ms). From the figure, we find that the values of RMSE using the TSaT-MUSIC algorithm is higher than that using TST-MUSIC algorithm regardless of the number of waves. However, all the RMSE values of the TSaT-MUSIC algorithm are less than 6 mm, which indicates the satisfactory level of accuracy.

4.3 Robustness

When positions of ultrasonic transmitters change, two or more candidate points become close to a path difference line. Figure 7 shows that two candidate points almost lie on a path difference line, when transmitters are placed at points (125.7,713.0), (-939.5, 341.9), and (746.38,430.9) (unit: mm). In order to investigate the robustness of the TSaT-MUSIC algorithm in such situations, simulations were conducted by setting SNRs between 0 and 50-dB at 5-dB intervals. Probabilities of selecting a true point were calculated through simulations conducted 100 times for each SNR as shown in Figure 8. The figure demonstrates that the probabilities are 30 to 40% when the SNRs are lower than 30 dB. However, when they are 30 dB or higher, the probabilities are almost 100%. We are now investigating the reason why the performance of the proposed algorithm deteriorates when the SNR is lower than 30 dB. At the moment, we suppose that it is due to the effects of the coherence between receiving signals. When the SNR is higher than 30 dB, the effects of the coherence are controlled and the proposed algorithm retains higher probabilities of selecting true points.

4.4 3D localization simulations

In this simulation, the L-shaped sensor array consisting of 15 receiver sensors at 5-mm intervals was used. The same signals were transmitted from transmitters, and the spatial smoothing method was applied in the same way as in the 2D localization simulations. The SNR was set to 20 dB. Because the L-shaped sensor array had 8 sensors on each side, the number of waves which could be classified was up to 4. Hence, the number of transmitters was set to 3.

Table 1 The DOA and delay time values of incoming waves

DOA [degrees]	-60	-45	-30	-15	0	15	30	45	60
Delay time [ms]	0.6	1.2	1.8	2.4	3.0	3.6	4.2	4.8	5.4

The transmitters were placed at points Ta (800, -300, 400), Tb (0, 200, 2,000), and Tc (-900, -850, 700) (unit: mm). The L-shaped sensor was placed in the x-y plane in the same way as in Figure 5. The average and standard deviations of the transmitters' positions were calculated for 25 simulations.

The results of the simulations are shown in Table 2. They show that the TSaT-MUSIC algorithm selected correct pairs of DOA and delay values. Differences between the true and estimated positions came from errors in the S-MUSIC or T-MUSIC algorithms.

5 Experiments

5.1 Configuration of experimental system

The configuration of the experimental system is shown in Figure 9. The signal processing board includes A/D converters and an operational amplifier. First, the PC receives the trigger signal that is sent by the signal processing board.

Next, the waveform generator (ADLINK DAQe-2501) creates signals that are sent to the ultrasonic transmitters (PIONEER PT-R4, Figure 10a) through the amplifier. The ultrasonic wave is transmitted from the transmitter to the receiver sensor array, where 15 ultrasonic sensors (SPM0204UD5 from Knowles, Figure 10b) are arranged in an L-shaped manner (the interval between sensors is 5 mm) for 3D localization experiments. Finally, the signals received at the ultrasonic receiver are sent to the PC through the signal processing board. The parameters of the ultrasonic waves used in this experiment (such as frequencies and phases of subcarriers) were the same as those used in the computer simulations.

5.2 3D localization using TSaT-MUSIC

3D localization experiments in real environments were conducted by using the TSaT-MUSIC algorithm to estimate the positions of three ultrasonic transmitters. These transmitters were set at the same positions as in the simulations in Section 4.

The measured average and standard deviation values of the ultrasonic transmitters' positions were obtained as shown in Table 3. All standard deviation values were less than 10 mm, proving that the accuracy of the proposed algorithm was satisfactory for indoor 3D localization. The differences between the true positions and calculated average positions were larger in the real experiments than in the computer simulations. One reason for this was inaccurate placement of the transmitters and receivers. Sensor characteristics such as directivity might also affect the performance of the 3D localization. The other reasons for this performance deterioration in real experiments seemed related to the attenuation of the transmitted signals or multipath problems that were not taken into account in the simulations. To improve the accuracy of the proposed algorithm, intensive investigations through further experiments are necessary.

5.3 Comparisons with TST-MUSIC

Through experiments in real environment, we compared TSaT-MUSIC with TST-MUSIC in terms of RMSE values and computation times. Because TST-MUSIC algorithm is 2D localization algorithm, we conducted 2D localization experiment.

In the experiments, we used a linear sensor array including 16 receiver sensors arranged at 5-mm intervals. The other experimental settings were same as the 3D localization experiments described in this section. The localization measurements were taken 25 times. The transmitters were placed at points Ta(-300, 300), Tb(0, 1,000), and Tc(1,000, 800) (unit: mm), respectively. The measured values of RMSE are shown in Table 4. From this table, it is found that the accuracy
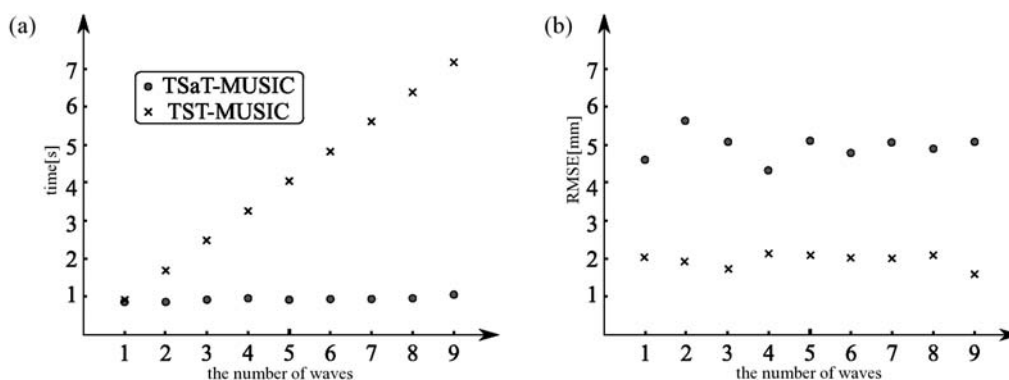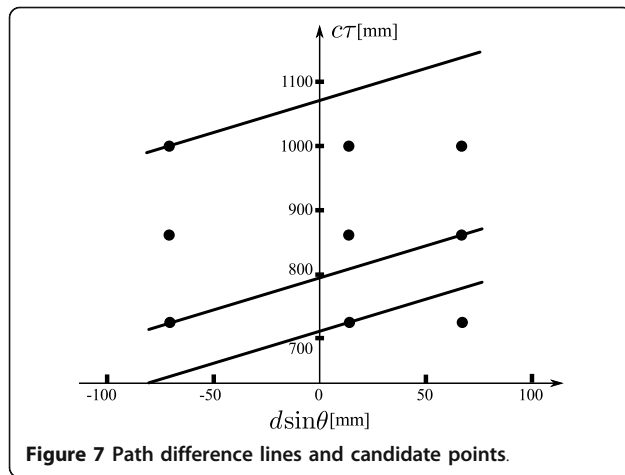

Figure 6 (a) Computation times of the TSaT-MUSIC and TST-MUSIC algorithms (b) RMSE of the TSaT-MUSIC and TST-MUSIC algorithms.

Figure 7 Path difference lines and candidate points.

differences between TSaT-MUSIC and TST-MUSIC are not so remarkable. In comparison with the simulation results in Section 4, the RMSE values of TSaT-MUSIC and TST-MUSIC became worse. This deterioration was presumably caused by the same reasons as discussed in the 3D localization experiment. As for the computation time, it was confirmed that the TSaT-MUSIC algorithm was 1.8 times faster than the TST-MUSIC algorithm. Thus, the experiments indicated that TSaT-MUSIC was smaller than TST-MUSIC in their computational complexity and still retains the satisfactory level of localization accuracy.

6 Conclusions and future work

We have proposed a new DOA-delay estimation algorithm called the TSaT-MUSIC algorithm. The remarkable feature of the algorithm is its small computational complexity compared with existing algorithms based on the MUSIC algorithm. This feature was proved through computer simulations. Moreover, the 3D localization technique using the TSaT-MUSIC algorithm was verified to show its satisfactory accuracy using
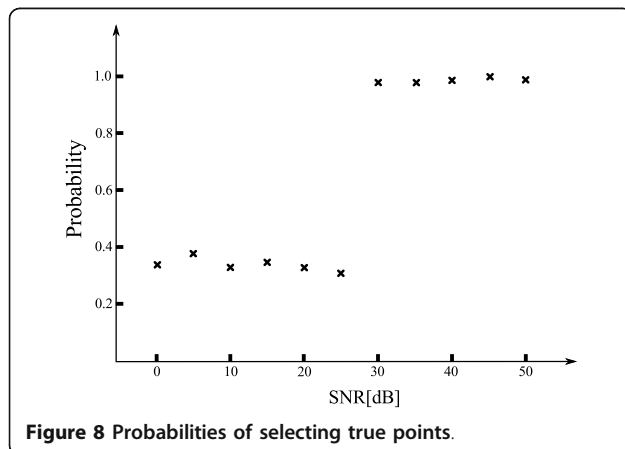

Figure 8 Probabilities of selecting true points.

Table 2 Results of the computer simulation (unit: mm)

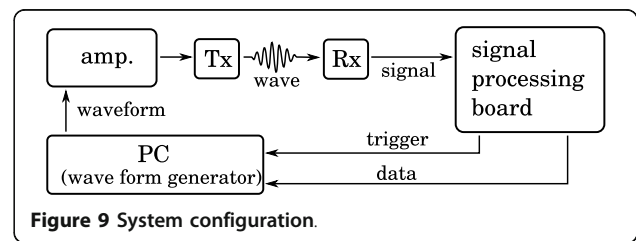|		*x*	*y*	*z*
	True position	800.00	-300.00	400.00
Ta	Average position	799.16	-310.17	393.58
	Standard deviation	1.12	3.84	4.34
	True position	0.00	200.00	2000.00
Tb	Average position	0.25	200.92	1999.70
	Standard deviation	3.66	5.51	0.66
	True position	-900.00	-850.00	700.00
Tc	Average position	-905.48	-837.14	708.40
	Standard deviation	2.50	6.56	8.37

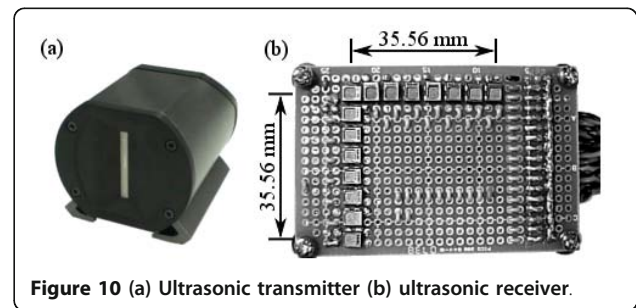**Figure 9 System configuration**.

Figure 10 (a) Ultrasonic transmitter (b) ultrasonic receiver.

computer simulations and experiments in real environments. There are several remaining issues to be investigated. Improving the performance of 3D localization using the proposed algorithm is one of the most important future tasks. Another important task is to improve the robustness of the TSaT-MUSIC algorithm

Table 3 Results of the experiment in real environments (unit: mm)

		x	*y*	*z*
	True position	800.00	-300.00	400.00
Ta	Average position	836.00	-320.06	401.20
	Standard deviation	0.415	1.71	2.2
	True position	0.00	200.00	2000.00
Tb	Average position	-23.73	251.65	2036.57
	Standard deviation	2.91	1.19	8.40
	True position	-900.00	-850.00	700.00
Tc	Average position	-918.74	-867.48	702.68
	Standard deviation	0.47	2.36	3.02

Table 4 Obtained values of RMSE (unit: mm)

	TSaT-MUSCI	TST-MUSIC
Ta	17.1	14.3
Tb	21.1	28.3
Tc	81.1	75.0

when a true point is not clearly identified due to placements of transmitters and low SNRs. We also plan to develop applications using our 3D localization technique, such as indoor positioning and robot navigation systems.

Author details
[1]Department of Electrical Engineering and Information Systems, School of Engineering, University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan [2]National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo, 101-8430, Japan

Competing interests
The authors declare that they have no competing interests.

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