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One Acoustic Localization Algorithm with Four-Element Array Based on Region Division

Linlin Cui, Ping Song, Gengchen Shi
Key Laboratory of Biomimetic Robots and Systems, Beijing institute of technology, Beijing, 100081, China.
cuilinlinxinxiang@126.com

Summary
At present, the space intersection acoustic localization algorithm based on TDOA only uses a simplex localization method. However, it is found that the localization errors near the area of the line connecting the two arrays' centers are more than the other regions. We herein propose the acoustic localization algorithm based on the region division. In such algorithm, we set four spatial four-element arrays, confirm the array aperture, relative elevation, boundary and distance between arrays based on the size of the localization area and the principle of minimizing the mean value of area errors, and then divide the area into 16 sub-regions to each of which we apply different pair of the arrays. With crackers as the sound sources, we randomly selected three sound source points with the size of 200 m × 200 m in Beijing suburb, China and made repeated experiments for three times at each point. The experiment results indicate that the localization errors of each point are all less than 0.5 m.

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1. Introduction

The passive acoustic localization method based on time difference of arrival (TDOA) is used to calculate the sound location by measuring the delays among acoustic sensors [1, 2]. In recent years, there are four-element array, five-element array, six-element array, circular array and others which are commonly used for acoustic localization. But the pitch angle with the four-element array is related to the azimuth angle, and its localization accuracy is not good [3]. A better location accuracy can be obtained by using five-element array, but the pitch angle has great impacts on the localization accuracy [4, 5, 6]. Although the five-element spatial array can effectively eliminate the effects of velocity [7], the single array can't reach a practicable level with the high accuracy. In addition, the localization region has not been treated differently in the previous acoustic localization algorithms [8]. The same algorithm has been used in the whole location region [9]. Against the aforesaid disadvantages of the acoustic localization algorithm, we propose a spatial intersection acoustic localization algorithm based on region divisions. It can also effectively eliminate the influence of velocity on acoustic location and improve the accuracy of acoustic localization.

2. The location model

Four space angles (i.e., the azimuth angle and the pitch angle) will be calculated with four four-element arrays' the time delays. Then we can confirm four Bearing Lines, and calculate the coordinates of sound source through the spatial intersection of Bearing Lines. Due to the occurrence of errors, the two Bearing Lines cannot be intersected to one point in space. At first, the midpoints of common perpendicular segment of each two bearing lines are used to indicate the coordinates of sound source. And then the final coordinates of sound source can be obtained by the acoustic localization based on region division. Diagrams of the intersection of two four-element arrays are shown in Figure 1.

The node 1 $(R, R, 0)$, node 2 $(-R, R, H)$, node 3 $(-R, -R, 0)$ and node 4 $(R, -R, H)$ are in the X_2-Y_2-Z_2 coordinate system. The t_{21}, t_{31}, t_{41} are the delays which are respectively against node 2, node 3, node 4 relative to node 1. H is the relative elevation. R is the array aperture. r is the distance from the sound source to array center. r_1 is the distance from the sound source to node 1.

$$\begin{aligned}
(x-R)^2 + (y-R)^2 + z^2 &= r_1^2, \\
(x+R)^2 + (y-R)^2 + (z-H)^2 &= (r_1 + ct_{21})^2, \\
(x+R)^2 + (y+R)^2 + z^2 &= (r_1 + ct_{31})^2, \\
(x-R)^2 + (y+R)^2 + (z-H)^2 &= (r_1 + ct_{41})^2.
\end{aligned} \tag{1}$$

We can get equation set (2) by deducing equation set (1),

$$\begin{aligned}
4Rx - 2Hz &= 2ct_{21}r_1 + (ct_{21})^2 - H^2, \\
4Rx + 4Ry &= 2ct_{31}r_1 + (ct_{31})^2, \\
4Ry - 2Hz &= 2ct_{41}r_1 + (ct_{41})^2 - H^2.
\end{aligned} \tag{2}$$

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Because $c(t_{21}, t_{31}, t_{41})$, $H \ll r_1$, we can get equation set (3) which includes x, y, z:

$$\begin{aligned} x &\approx c(t_{31} - t_{41} + t_{21})r_1/4R, \\ y &\approx c(t_{31} + t_{41} - t_{21})r_1/4R, \\ z &\approx c(t_{31} - t_{41} - t_{21})r_1/2H. \end{aligned} \tag{3}$$

The formulas of angles can be deduced based on the plane wave hypothesis [10, 11] and TDOA. $r_1 \approx r$, we can get equation set (4) which includes φ and θ. There are lots of methods to obtain the delays, such as Generalize Cross Correlation, Cross-power Spectral Phase, Least Mean Square-Adaptive filtering and Parameter Model Method [12, 13]. And GCC is used in our paper.

$$\begin{aligned} \tan\varphi &= \frac{y}{x} \approx \frac{t_{31} + t_{41} - t_{21}}{t_{31} - t_{41} + t_{21}}, \\ \tan\theta &= \frac{\sqrt{x^2 + y^2}}{z} \\ &\approx \frac{\sqrt{(t_{31} + t_{41} - t_{21})^2 + (t_{31} - t_{41} + t_{21})^2}}{t_{31} - t_{41} + t_{21}} \frac{H}{2R}. \end{aligned} \tag{4}$$

The bearing line could be got by using φ and θ. At last the sound source coordinate can be obtained by calculating the midpoint of the common perpendicular segment of two bearing lines. The formulas effectively eliminate the influence of velocity on acoustic location.

The layout scheme of Area A (with the size of 500 m × 500 m) is shown in Figure 2. The centers' coordinates of the four arrays are $(Q, 0, 0)$, $(-Q, 0, 0)$, $(0, Q, 0)$ and $(0, -Q, 0)$. Q is a positive number with the unit as meter (m).

P_{mn} is the localization result of sound source coordinate by using the mth array and the nth array. The number m is from 1 to 4. The number n is from 1 to 4. And m is not equal to n. P_{mn} is equal to P_{nm}. And P is equal to $(P_{12} + P13 + P_{14} + P_{23} + P_{24} + P_{34})/6$.

We calculate the average errors of X-coordinate, Y-coordinate and Z-coordinate. The Monte Carlo times are 500 times. The delay standard deviation is 60 microseconds. Because the errors with Q changing from 50 m to 250 m are much less than the errors with Q changing from 5m to 50 m. We here list errors with Q value changing from 50 m to 250 m in Figure 3.

Figure 3 shows that the area error average of sound source is smallest when Q is 100 m. It can be calculated similarly that the optimal value of array relative elevation is 1.5 m, and the optimal value of array aperture is 2.1 m, and the optimal value of array boundary is 21 m with the principle of minimum area error average.

The localization area is divided into 16 parts which can be seen from Figure 4. They are Area A_i in the first quadrant, Area B_i in the second quadrant, Areas C_i in the third quadrant and Areas D_i in the fourth quadrant. The number i is from 1 to 4. The value of array boundary is d.

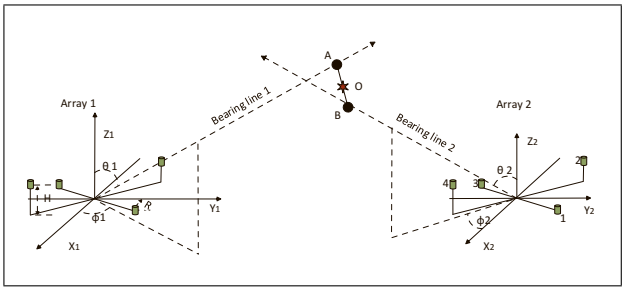

Figure 1. The two bearing lines and the intersection point.

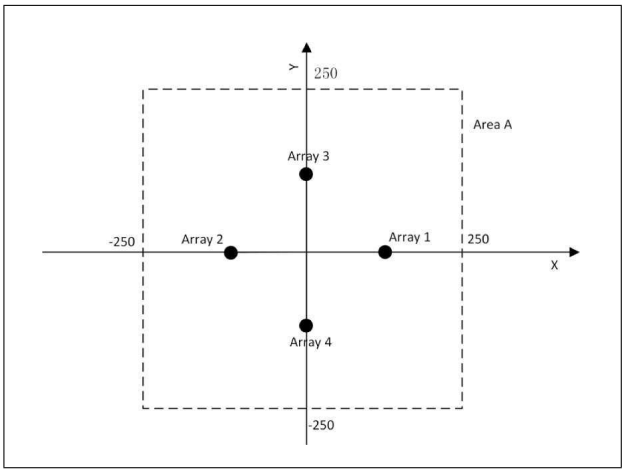

Figure 2. The layout of four arrays.

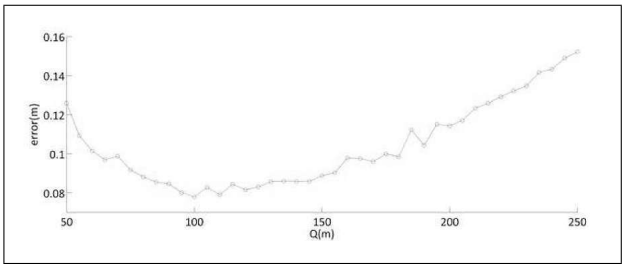

Figure 3. The variation of errors by following the increasing Q (50 m to 250 m).

Taking the areas in the first quadrant as an example:

$$\begin{aligned} Area1: &\left\{ (x,y) \left| \begin{array}{l} (x \geq 0)\&(y \geq 0)\& \\ \big(y > (-x + d + Q)\big)\| \\ \quad \big(y < (-x + d - Q)\big) \\ \&\big(y > (x - d - Q)\big) \\ \quad \&\big(y < (x + d + Q)\big) \end{array} \right. \right\}, \\ Area2: &\left\{ (x,y) \left| \begin{array}{l} (x \geq 0)\&(y \geq 0)\& \\ \big(y > (-x + d - Q)\big)\| \\ \quad \big(y < (-x + d + Q)\big) \end{array} \right. \right\}, \\ Area3: &\left\{ (x,y) \left| \begin{array}{l} (x \geq 0)\&(y \geq 0)\& \\ \big(y \leq (x - d - Q)\big) \end{array} \right. \right\}, \\ Area4: &\left\{ (x,y) \left| \begin{array}{l} (x \geq 0)\&(y \geq 0)\& \\ \big(y \geq (x + d + Q)\big) \end{array} \right. \right\}. \end{aligned} \tag{5}$$

The other three quadrants' division can be placed by using the symmetry principle.

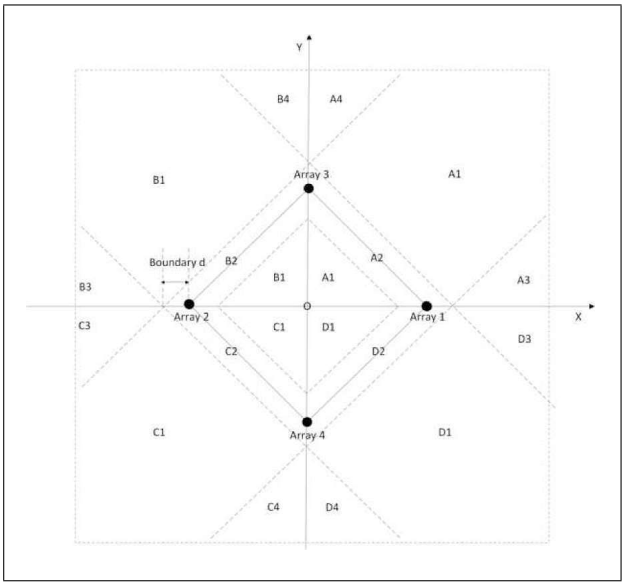

Figure 4. The division of the localization area.

The selection of intersection algorithm in different areas:

First, the first sound source coordinate can be calculated by uniting Array 1, Array 2, Array 3 and Array 4. P is as the initial localization result of sound source. P2 is the final localization result.

Second, taking the initial sound source coordinate (P) as the judging criteria to judge which area the sound resource is;

Finally, making further accurate calculation about where the sound source is located. The details are listed as follows:

Area A1: P2 can be calculated by intersecting Array 1 and Array 2.

Area A2: If the distance from P1 to the x-axis is bigger than the distance to the y-axis, then P2 can be calculated by intersecting Array 1 and Array 2. Otherwise, P2 can be calculated by intersecting Array 3 and Array 4.

Area A3: X-coordinate of P2 is calculated by intersecting Array 3 and Array 4. Y-coordinate and Z-coordinate are calculated by intersecting Array 1 and Array 3.

Area A4: Y-coordinate of P2 is calculated by intersecting Array 1 and Array 2. X-coordinate and Z-coordinate are calculated by intersecting Array 1 and Array 3.

And the other areas' results can be obtained with the similar way.

The layout of arrays in Area A is symmetric around the origin point, for easy figures we here only selected the first quadrant region of Area A to make the error analysis. The error distribution of sound source is shown in Figure 5.

The left part of Figure 5 shows the error distribution of X-coordinate. The middle part of Figure 5 shows the error distribution of Y-coordinate. The right part of Figure 5 shows the error distribution of Z-coordinate. The results show that the errors of X and Y are less than 0.35 m. And the error of Z is less than 0.2 m.

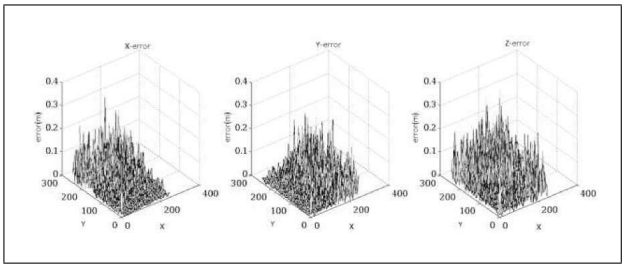

Figure 5. The error distribution of sound sources.

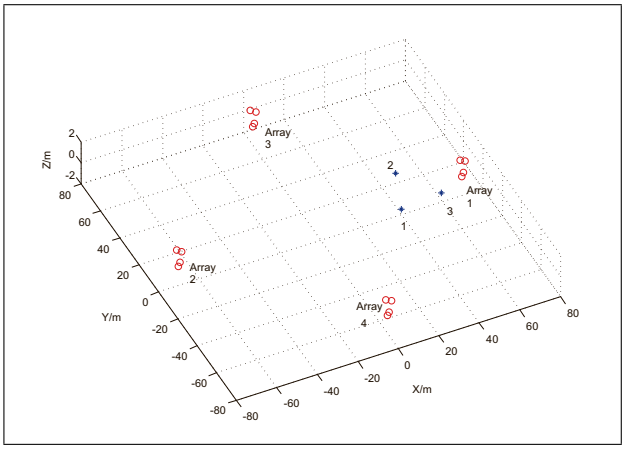

Figure 6. The array layout and locations of three sound sources.

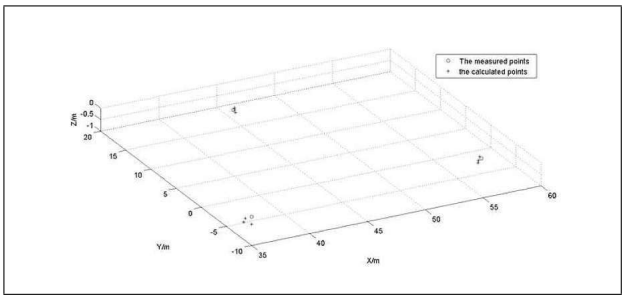

Figure 7. The measured points and the calculated points.

3. Experiments

With crackers as the sound source, we randomly selected three sound source points with the size of 200 m × 200 m in Beijing, China and made repeated experiments for three times at each point. Due to the limitation of experimental areas, the optimal value of array relative elevation is 1.3 m. The optimal value of array aperture is 1.8 m. The optimal value of array boundary is 11 m. Q is 70 m. The array layout and locations of three sound sources are shown is Figure 6. The measured points and the calculated points are shown is Figure 7. The absolute value of X, Y, and Z -coordinates' errors are shown is Figure 8. The four-element array is shown in Figure 9. The localization results are shown in Table I. The nine groups indicate that the localization accuracy are all within 0.5 m.

The paper [14] shows the errors of X and Y coordinates are less than 0.8 m, and the errors of Z-coordinate are between 1 m to 1.5 m. And they also use four arrays to cal-

Table I. The error comparison of three sound sources. The Number.1 made repeated experiments for three times. It is same to Number.2 and Number.3.

	Measured value (X Y Z \M)			Calculated value(x y z \m)		
	35.9360	-7.8415	-0.2058	35.4410	-7.4173	-0.4633
1	35.9360	-7.8415	-0.2058	35.5810	-7.4064	-0.3028
	35.9360	-7.8415	-0.2058	36.1150	-7.4127	-0.6276
	57.1430	-4.7435	-0.3748	56.9610	-4.8281	-0.2715
2	57.1430	-4.7435	-0.3748	56.8190	-4.8157	-0.5295
	57.1430	-4.7435	-0.3748	56.8159	-4.8666	-0.4161
	44.4280	15.3805	-0.2788	44.6310	15.5915	-0.2503
3	44.4280	15.3805	-0.2788	44.6712	15.6928	-0.3687
	44.4280	15.3805	-0.2788	44.5138	15.1571	-0.3655

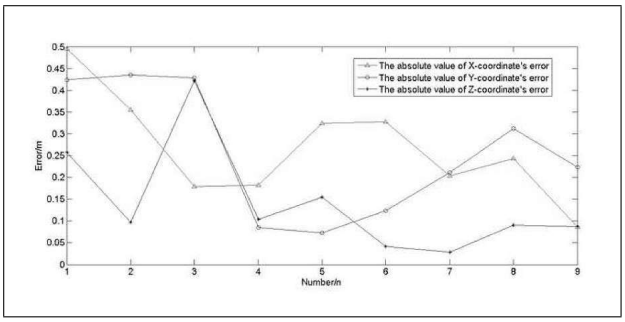

Figure 8. The absolute value of X, Y, and Z -coordinates' errors.



Figure 9. The four-element array.

culate the sound sources with the size of 200 m × 200 m. They make repeated five experiments for only one sound source. Our nine groups' localization accuracy are all less than 0.5 m. It shows our algorithm is better than paper [14].

4. Conclusion

The spatial intersection arrays based on region division can effectively eliminate the influence of velocity on localization algorithm. We use the criteria with minimum area error average to select the optimal value of array relative elevation, array aperture, array boundary and distance between arrays, and divide the whole detection region into 16 sub-regions where we apply different pair of the arrays. This algorithm is also applicable to different numbers of arrays, but the detection region will be divided into different numbers of sub-regions. However, due to restriction of experimental areas, the experiments are only conducted in area with the size of 200 m × 200 m to get the results of localization accuracy within 0.5 m. It still needs to be tested in broader areas to verify the commonality of this acoustic localization algorithm based on region division.

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