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Sound Source based Mobile Robot Control for Human Following in a Networked Intelligent Space

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Abstract

This research addresses sensor-based tracking problems for autonomous cleaning mobile robot in a networked sensor space. To solve the problem, the difference among the traveling times of the sound source to each of three microphones has been used to calculate the distance and orientation of the sound source from the cleaning mobile robot, which carries the microphone array. The cross-correlation between two signals has been applied for detecting the time difference between two signals, which provides reliable and precise value of the time difference compared to the conventional methods. To generate the tracking direction to the sound source, fuzzy rules are applied and the results are used to control the cleaning mobile robot in a real-time. Finally the experiment results show that the proposed algorithm works well, even though the mobile robot knows little about the environment.

Keywords: *Cleaning mobile robot, navigation, human following, tracking, estimation*

1. Introduction

Recently, various kinds of robot localization have been introduced for human service in intelligent space. As an approach with a long history, the localization schemes of the mobile robot using the sound source have been studied continuously [1-2]. The sound has been used to identify the location of the speaker for pet robots and intelligent service robots. The sound source also can be used as an alternative for the camera, which cannot detect objects without proper illumination [2]. There several detection algorithms of the sound sources for the auditory system of the robots. They are using the transfer function of the robot head, a beam forming method using several microphone arrays, or using the artificial ears [3-6]. However these are very sensitive to noise, and subjected to the time delay caused by the obstacles. Because of the reflections and absorptions of the sound signal, the location estimation of the sound source becomes worse. Therefore for the tracking of the sound source by a mobile robot, the sound source detection algorithm needs to be robust against the environment and also adaptive to the varying environment [7-8].

The sound source tracking system has performed well in a quiet laboratory environment. However, most of applications of the sound source tracking exist in outdoor environments, such as, disaster area and battle fields. To rescue a man who is moaning weakly and moving here and there, a very high performance sound source detection system is required. In practice, the signal coming into the microphone array is so obscure and noisy to identify the location of the sound source by the mobile robot that is tracking or searching the sound source [9-12].

In this research, to overcome these difficulties in the sound source detection, we based the location of the sound signal at the different microphones on the arrival time difference of the sound signal between the different microphones. To track the sound source by a mobile robot, the Fuzzy rule-based control algorithm has been proposed and applied. For

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simulating the tracking of a mobile sound source, the sound sources are located in straight, curved, and circular paths, which shows not only the estimation accuracy of the sound source but also the tracking performance of the mobile robot [11-14].

This paper consists of six sections, including this introduction. Section II proposes the algorithm for detecting the sound source. The sound source tracking algorithm for the Cleaning mobile robot is going to be explored for minimizing the tracking error in section III. The section IV illustrates the experimental environment to verify the effectiveness of the proposed algorithms for tracking the sound source in real-time.

2. Detection and Tracking of Sound Source

To estimate the distance to the sound source, three microphones are installed in a line as Figure 1. There is a constant distance (= 15 cm) gap among the three microphones M_1, M_2 and M_3 in a line. The distances from each of the microphones to the sound source are defined as R_1, R_2 and R_3 which can be estimated using the traveling time of the sound signal.

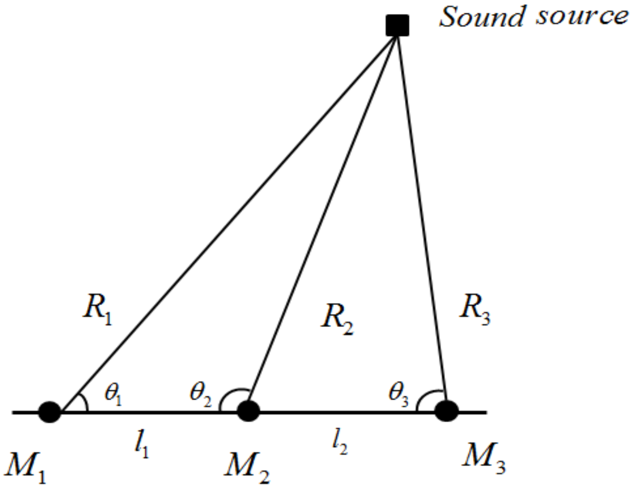


Figure 1. Distance Measurement Principle in 2D Space

From Figure 1, the distances to the microphones from the sound source can be represented as R_1, R_2 and R_3 as follows:

$$R_1 = (v \cdot t_1 =)x\ ,\quad R_2 = (v \cdot t_2 =)x + v \cdot \Delta t_{12}\ ,\quad R_3 = (v \cdot t_3 =)x + v \cdot \Delta t_{13} \tag{1}$$

Where t_1, t_2, and t_3 represent the traveling time of the sound signal from the sound source to the three corresponding microphones. Applying the scheme to three microphones, the angles to the sound source can be obtained. The entering angle of the sound signal to the first microphone, θ_{M1} is represented as.

$$\theta_{M1} = \cos^{-1} \frac{R_1^2 + l_1^2 - R_2^2}{2R_1 l_1} \tag{2}$$

The coordinates of the microphones are known a priori since the location of the mobile robot can be controlled and monitored by the proper sensors. The coordinates of the sound source can be computed by using the distances from microphones to the sound source and the known coordinates of the microphones.

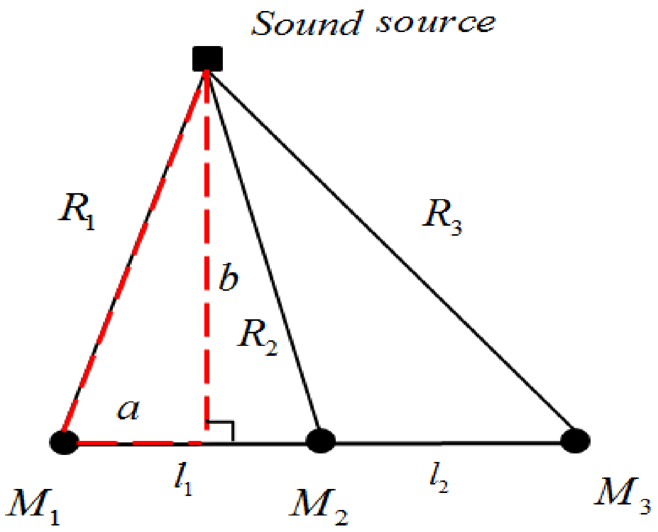


Figure 2. Coordinates Computation in 2D space

In Figure 2, the coordinates of the microphone locations are set as $M_1 = (0, 0)$, $M_2 = (l_1, 0)$, and $M_3 = (l_1 + l_2, 0)$ when the M_1 is set as the origin and the x-axis is set along the microphones. The triangle, ΔSM_1M_2, is formed by the microphones and the sound source. Using the distances of R_1, R_2 and R_3 the coordinates of the sound source, $S = (a, b)$ can be calculated. From the Pythagorean theorem for the two triangles formed by the broken line, the two equations are obtained as:

$$a^2 + b^2 = R_1^2 \tag{3}$$

$$(l_1 - a)^2 + b^2 = R_2^2 \tag{4}$$

Solving the two equations, the coordinates (a, b) can be obtained:

$$a = \frac{R_1^2 - R_2^2 + l_1^2}{2l_1} \tag{5}$$

$$b = \sqrt{R_1^2 - \left(\frac{R_1^2 - R_2^2 + l_1^2}{2l_1}\right)^2} \tag{6}$$

Therefore the location of the sound source, S(a,b), can be estimated.

$$S = \left(\frac{R_1^2 - R_2^2 + l_1^2}{2l_1}, \sqrt{R_1^2 - \left(\frac{R_1^2 - R_2^2 + l_1^2}{2l_1}\right)^2}\right) \tag{7}$$

3. Tracking a Moving Object

Tracking the sound sources requires an intelligent algorithm since the driving direction and orientation need to be changed according to the estimated position and orientation of the sound source dynamically. From the current location, how to efficiently drive to the estimated sound source is a real time task to the mobile robot. Therefore in this research Fuzzy rule-based algorithm has been adopted for the tracking control [11]. The performance of the Fuzzy model depends on the structure of the Fuzzy rules and to obtain high performance from the Fuzzy rule-based system, an optimization process is required in general [13-14]. The Fuzzy rules are given as:

Rule : IF Distance is $A_D{}^i$ and Angle is $B_A{}^i$ Then Left-Output is $X_L{}^i$ and Right-Output is $X_R{}^i$ (8)

Where $X_L{}^i, X_R{}^i$ are displacements of left and right wheels, respectively and $A_D{}^i, B_A{}^i$ are the distance and angle between the mobile robot and the sound source, respectively.

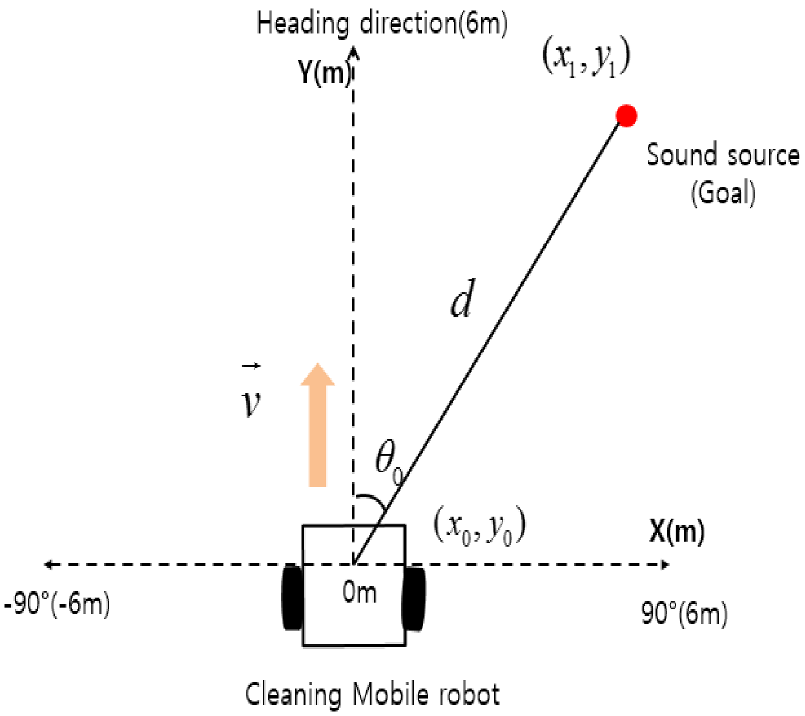


Figure 3. Moving Direction Kinematics by Sound Source

The tracking direction of the mobile robot to the sound source is represented as S, which is determined by the Fuzzy interference using the input variables d for the distance and θ for the angle to the sound source. Practical range of d is 0 m ~ 8 m, and that of angle θ is -90° ~ 90°. S also provides the input to the Left and Right motors as a voltage of 0 V ~ 12 V. For the de-fuzzification to determine the output value, Mamdani's center of weight method has been used with the qualitative language variables as shown in Figure 4.

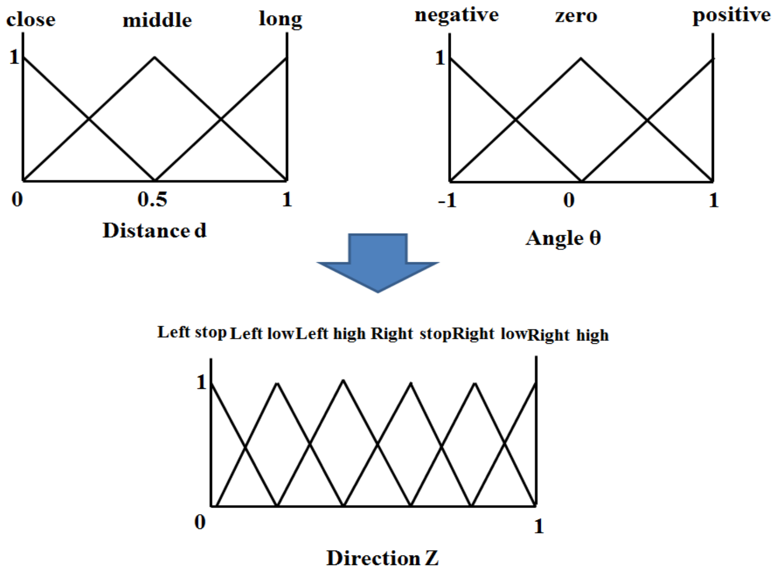


Figure 4. Fuzzy Input and Output Variables

The input and output Fuzzy rules are summarized in Table 1.

Table 1. Input and Output Fuzzy Rules

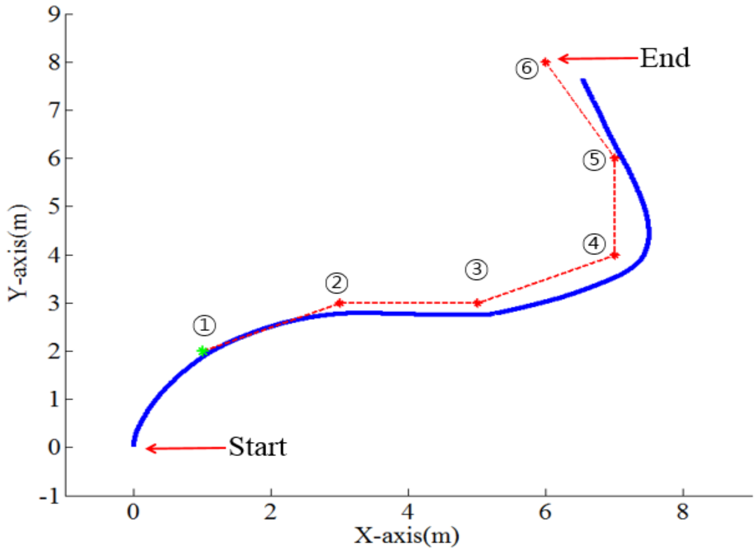
Dist / Ang	close	middle	long
negative	left stop right low	left stop right low	left low right high
zero	left low right low	left low right low	left high right high
positive	left low right stop	left low right stop	left high right low

The trajectory tracking performance of the mobile robot depends highly on the curvature of the path and velocity. Generally, high-speed motion on the curved path causes high tracking error because of the slippage that comes from the centripetal force. The slippage also varies highly depending on the friction between the wheels and the ground

4. Experimental Results

In order to realize as the method described previously, we conducted various trials of the sound source based tracker within intelligent space. To show the tracking performance of the curved trajectory of cleaning mobile robot, Figure 5 illustrates an experimental environment and the tracking performance of the cleaning mobile robot when the sound source is virtually moving straight and forward in the room. The initial orientation of the cleaning mobile robot is kept as 90° when it starts to track the sound source.

(a) Experimental Environment



(b) Curved Trajectory Driving Experiment

Figure 5. Experimental Environment and Tracking Performance

Table 2. Curved Trajectory Tracking Performance

No.	Angle/Distance	Reference	Error
1	43°, 1.8 m	45°, 2m	-2°, 0.2 m
2	54°, 1.8 m	50°, 2m	4°, 0.2 m
3	47°, 1.8 m	45°, 2m	2°, 0.2 m
4	48°, 1.6 m	50°, 2m	-2°, 0.4 m
5	48°, 1.5 m	50°, 2m	-2°, -0.5 m
6	47°, 1.5 m	45°, 2m	2°, -0.5 m

The initial orientation of the mobile robot is kept as 90° when it starts to track the sound source. Figure 5 is the curved trajectory experiment. Table II summarizes the tracking results and tracking errors of the sound sources.

5. Conclusion

In this paper, the sound source was tracked by a cleaning mobile robot, which carried an array of microphones detecting the distance and orientation to the sound source. The artificial sound is generated by clapping. The sound signal was received by the three microphones and the arrival time difference and its algorithms are utilized to identify the location and the orientation of the sound source. The goal of this research is for the mobile cleaning robot to track the sound source.

Further work will consist of the implementation of a precise learning pattern for 3D Detection algorithm in order to improve the estimation accuracy and the recognition ratio, while the development of an illumination robust position estimation in environment with many obstacles remains.

Acknowledgements

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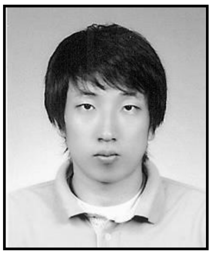

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