Robotic Sound Localization

Background

Using only auditory cues, humans can easily locate the source of a sound. Most of the time we don't even notice when we orient ourselves towards a speaker. Sound localization can be accomplished without head movement using binaural hearing. Two basic mechanisms have been described: interaural time differences (ITD) and interaural level differences (ILD). An automated system capable of localizing sound sources would have many applications, including short-range tracking of mobile robots.

Purpose

The purpose of this project was to create a stationary tracking system capable of estimating the azimuthal angle of a receiver relative to a sound source. I chose to base the system on an ILD approach, using the directional differences in sound amplitude detected by each sensor in a static array to determine the angle relative to the sound source.

Procedure

I first constructed and tested a reliable tone source with a fixed amplitude, a controllable frequency and an omnidirectional speaker housing. My final design used a variable-frequency square wave generator and a crystal earphone as the sound source.

Next, I designed and tested circuitry to convert the amplitude of sound waves detected by a microphone into a DC voltage that could be read as an input by a computer. I also needed a housing for the microphone that ensured that its sensitivity was directional. Because of the complexity of interactions between factors such as reflections, refraction, interference and resonance, it was necessary to test the housing designs experimentally. A computer-controlled turntable allowed me to test my designs at specific angles relative to the sound source. The basic housing structure had a single opening, a short tube of adjustable length, and space for a cone and/or baffle. I tested the directional characteristics of different housing designs using various funnel sizes, tube lengths and signal frequencies.

Using the data from the turntable experiments, I was able to simulate static arrays of different numbers and arrangements of sensors. I developed an algorithm that fitted the signal strength data from specific, known angles to a parabolic curve. The maximum value of the regression estimated the angle to the sound source.

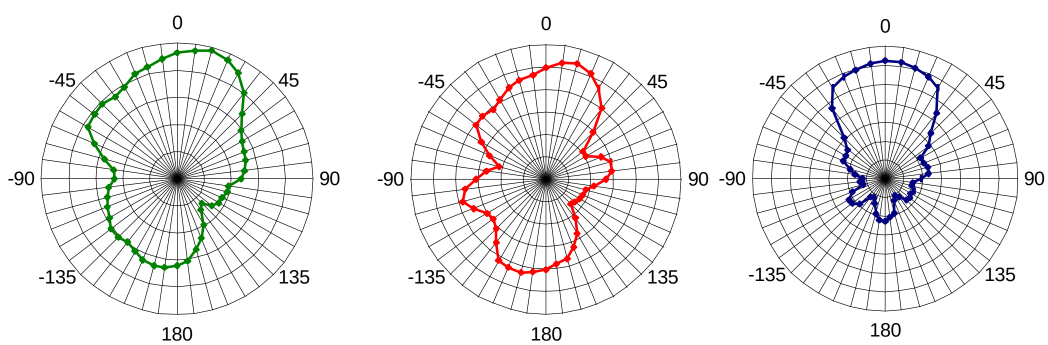
Based on my simulation results using a single microphone, I built a static radial array of seven sensors spaced 35 degrees apart. I also measured the accuracy and precision of the estimated azimuthal angle using the same funnel sizes, tube lengths and signal frequencies that had been tested on the turntable.

Results and Discussion

Figure 1 shows examples of data collected using the turntable. The graphs show the responses of three sensor designs incorporating different microphone housings.

Figure 1. Sample Angle versus intensity graphs for three sensor designs. Intensity measured as the peak amplitude of the incoming signal. Sound source located at 0 degrees. Sound frequency: 2150 Hz

(a) No Tube or Cone **(b) Tube** **(c) Tube and Cone**



The plot shown in figure 1c was obtained using the design I selected for the static array. The housing had a 2 cm wide tube that was 4 cm long, and a 7 cm long funnel that was 10.5 cm wide. Between –52.5 degrees and +52.5 degrees the signal amplitude is a smooth curve that resembles a parabola. Therefore, a quadratic function can be used to model the data, and its maximum value will be near 0 degrees.

I ran many simulations using both turntable and static array data. Table 1 shows the results of an experiment using different numbers of sensors for the angle estimation.

Table 1. Mean estimated angles ± S.D. using different numbers of points for calculation. Data were generated using a static radial array of 7 sensors spaced 35 degrees apart. Distance from source to array: 50 cm. 100 observations for each.

Angle Relative to Sound Source	Number of Sensors Used for Polynomial Regression				
	3	4	5	6	7
0	-2.9 ± 2.9	-28.1 ± 11.9	5.7 ± 3.6	-5.5 ± 5.0	8.9 ± 4.3
17.5	21.3 ± 2.9	-68.9 ± 5.9	37.9 ± 11.4	13.6 ± 9.2	20.7 ± 23.5

If seven detectors are spaced 35 degrees apart, three sensors will always fall within the range of the curve (±52.5 degrees). However, the use of data from sensors other than the three that register the largest response decreases the accuracy and precision of the system.

The relationship between signal frequency and the accuracy of the estimated angle using the static array was complex. I hypothesized that the directional gain of the sensors, and the resulting accuracy of the estimated angle, would depend on the dimensions of the cone and tube relative to the wavelength of the sound. Testing demonstrated that 2150 Hz generated the most accurate results. This frequency was related to the structure of the sensor, the length of the tube (4 cm) being approximately ¼ wavelength.

Having selected a frequency for my sound source, I tested the array using the same combinations of cone and tube dimensions that had been tested on the turntable.

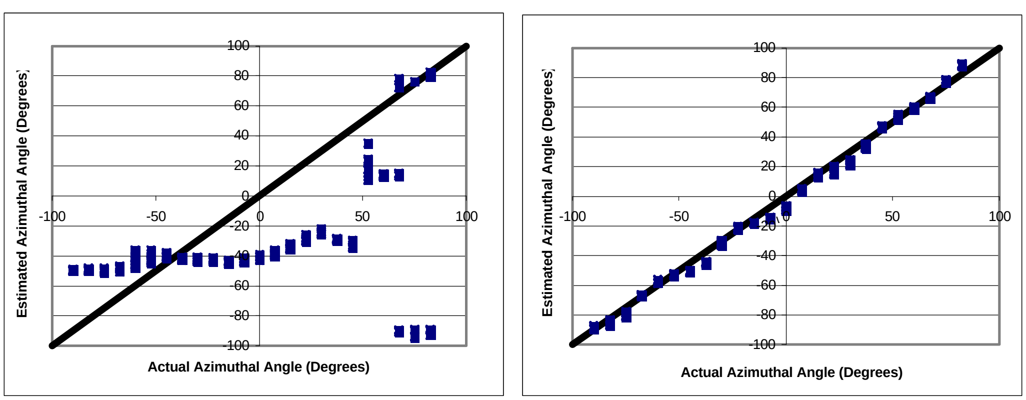
The design selected based on the results from a single sensor (4 cm long tube, 10.5 cm wide funnel) produced the most accurate and precise angle estimated (Table 2). This confirmed the trends seen in the turntable experiments.

Table 2. Calculated angles and standard deviations for different combinations of cones and tubes. Distance to sound source: 100 cm, frequency: 2150 kHz, 20 observations for each treatment. Data were generated using a static radial array of 7 sensors, 35 degrees apart.

Tube Length (cm)	Cone mouth Diameter (cm)	Estimated angle to sound source (Actual Angle: 0 degrees)	Estimated angle to sound source (Actual Angle: 17.5 degrees)
4.0	10.5	-3.0 ± 1.6	15.7 ± 2.5
5.0	10.5	-1.5 ± 1.2	30.6 ± 10.5
5.0	8.0	1.7 ± 2.9	-38.4 ± 374.8
5.0	2.0	2.5 ± 6.8	64.6 ± 197.2
8.0	8.0	9.5 ± 16.3	29.7 ± 23.5
8.0	10.5	3.3 ± 3.4	27.0 ± 8.4
8.0	10.8	0.5 ± 2.4	28.1 ± 23.3
8.0	2.0	-12.0 ± 93.0	-28.4 ± 24.4
4.0	8.0	1.3 ± 5.5	3.2 ± 7.5
4.0	10.8	1.8 ± 1.6	-47.6 ± 131.0
4.0	8.0	1.9 ± 2.2	15.0 ± 8.1
4.0	10.5	-1.3 ± 1.5	10.2 ± 2.9
4.0	10.8	-0.2 ± 2.4	15.8 ± 2.0

At a distance of 50 cm, the final array design could locate the direction of the sound source with an accuracy of about ±3 degrees (Figure 2).

Figure 2. Actual versus estimated angles using two sensor housings: tube only (L) and tube and funnel (R). The black line represents perfect estimation. Data based on 10 samples at each angle (-90 degrees to +90 degrees in 7.5 degree increments) taken at a distance of 50 cm and frequency of 2150 Hz.



The system was very susceptible to environmental noise. Use of multiple samples compensated for some of the noise, but this did not eliminate biases introduced by such acoustical effects as reflected signals from fixed surfaces in the vicinity of the array.

Conclusions

I have shown that it is possible to determine the direction of a sound source with a single static array of directional sensors. Because it does not move, it can calculate the position more quickly than a rotating detector and it is not subject to mechanical failure. The accuracy of this system is comparable to that reported for humans (Yost 2000).

It may be possible to further refine the system using genetic or neural programming instead of polynomial regression, improving the sensor design, or incorporating phase and timing measurements into the calculations. Furthermore, it should be possible to use a similar process with directional radio antennae. Such a system would have a greater range, and could be used to track wildlife, cell phones or a robot exploring on the surface of another planet.

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