Performance evaluation of a back-to-back speaker system using a low-cost single board computer as a digital signal processor

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Abstract. A back-to-back speaker system with a user-designed filter results in a low-frequency cardioid-like radiation pattern where a back-facing loudspeaker is used to suppress the radiation in the rear direction. This paper presents an application of a low-cost single board computer as a digital signal processor on a back-to-back speaker system to obtain a cardioid-like radiation pattern in the low-frequency range. The system consists of two loudspeakers and a US$7 Orange Pi Zero PC. The loudspeakers are closely spaced and mounted in a back-to-back arrangement. A cancellation filter, which is identified in advance in an anechoic chamber using the filtered-x least mean square (FxLMS) algorithm, is used in the Orange Pi Zero PC. A buffering technique is used to make the PC act as a real-time-like signal processing unit. The performance evaluation was conducted under two conditions which were offline and online filtering. In offline filtering, sounds with and without cancellation were pre-prepared. On the other hand, in online filtering, the sound was simultaneously filtered and played. This paper also indicates conditions, for which the system exhibits great performance.

1. Introduction
Designs of back-to-back speaker systems that produce sound in the front direction while keeping the energy of the sound radiated towards rear directions low have been studied intensively because of their useful applications \cite{1, 2, 3}. When designing alarm systems with multiple loudspeakers to be installed in hallways, it is recommended to use loudspeakers with a directional characteristic \cite{4}. Directional loudspeakers would benefit people in emergency situations. This enables them to follow a particular direction to a safe exit determined by the louder sound. Moreover, concerning sound intelligibility, a directional loudspeaker is more preferable \cite{5}.

One of the methods for designing a directional speaker system is based on a combination of two loudspeakers, a microphone, and a signal processing unit \cite{2, 3}. Simply mounting two closely spaced loudspeakers back-to-back can result in a low-frequency cardioid-like radiation pattern. The pattern is obtained by utilizing the back-facing loudspeaker, with an appropriate filter, to produce an anti-sound signal. This signal is used to suppress the radiation from the front loudspeaker at the location of the microphone in the rear direction. By observing the output of the loudspeakers at the microphone, the cancellation filter can be identified as a result of the filtered-x least mean square (FxLMS) algorithm.
This paper presents an example of the application of a low-cost single board computer as a digital signal processor (DSP) in the back-to-back speaker system. A cheap single board computer such as Raspberry Pi was introduced in 2012, and nowadays there are so many single board computers that run Linux and are quite powerful and cheap. Since it is equipped with a Wi-Fi module that means it can communicate and remotely control two ordinary loudspeakers to achieve an intelligent speaker system with a directional characteristic. Moreover, if the speaker system is part of an “Internet of things” (IoT) network, using a customizable and programmable small computer would be of increasing convenience and flexibility when transmitting a sound to only selected loudspeakers in the network.

2. Speaker System Configuration

2.1. Signal Processing Unit and Software

The signal processing unit to which we interfaced loudspeakers is an Orange Pi Zero PC [6] as shown in Fig. 1. This is a small computer with the dimensions of 48 mm x 45 mm and weight of only 26 g. It can run the latest Ubuntu Xenial 16.04 operating system (OS) stored on a MicroSD card. To operate, the computer is supplied with only a 5VDC/1A source, and thus it does not consume a lot of power. The Orange Pi Zero PC was chosen because it is popular, flexible, and inexpensive (costs US$7–10) computer based on ARM Cortex A7 Quad-core 1.2 GHz with 256/512 MB DDR3. The GPU of the PC is a Mali-400MP2 with 600 MHz clock speed. Equipped with Wi-Fi module and Ethernet port which allows easy access to the PC through SSH remote login. The Python programming language which has a wide variety of audio signal processing libraries is also installed by default.

2.2. Active Control Technique

Active control technique is a method for reducing unwanted sound by estimating a cancellation filter, which is utilized by a secondary sound source to produce an anti-sound signal. The technique works well to suppress sounds at low frequency (<1000 Hz) [7]. Figure 2(a) shows the schematic diagram of the filtered-x least mean square (FxLMS) algorithm used to obtain a low-frequency cardioid-like radiation pattern. The pattern is achieved by utilizing the back-facing loudspeaker to produce the anti-sound signal, anti \( d(n) \), as a result of the cancellation filter \( W(z) \). Before identifying the filter \( W(z) \), the transfer functions \( P(z) \) and \( H(z) \) from the front and back loudspeakers to the cancellation point are first estimated by presenting a time stretched pulse signal (TSP) over the loudspeakers [8]. The cancellation filter \( W(z) \) is then calculated based on the schematic diagram of the FxLMS algorithm where the filter \( C(z) \) is assumed to be the estimation of the \( H(z) \). Once the filter \( W(z) \) is obtained, it is used by the Orange Pi Zero PC to filter the input signal \( x(n) \) that goes to the back-facing loudspeaker as shown in Fig. 2(b).
2.3. Online filtering and Measurement Setup

A buffering technique is used to make the Orange Pi Zero PC act as a real-time-like signal processing unit. As it is well known in audio processing, a sufficient buffer size is an important parameter for playing an audio signal. If a buffer size is too small, crackles or audio dropouts will happen. On the other hand, if a larger buffer size is used, it will increase audio latency. Moreover, a larger filter tap length also results in increasing the latency. In this paper, after preliminary experiments with the PC, we chose a buffer size of 256 samples and a filter tap length of 512 taps. A sampling frequency of 44100 Hz was used. The main Python libraries used for audio signal processing are “pyalsaaudio” [9] and “scipy” [10]. In addition, the loudspeaker used in the measurement was TASCAM-VL-S3 with a size of 0.11m(W) x 0.17m(H) x 0.138m(D). Polar radiation patterns of the back-to-back speaker system were measured using a 36-ch circular microphone array proposed in [11] as shown in Fig. 2(b). The microphone used was Audio Technica AT899.

3. Results and Discussion

In order to obtain a cardioid-like radiation pattern, the cancellation filter $W(z)$ used by the back-facing loudspeaker to produce an anti-sound signal in the rear direction should be estimated in advance. Figure 3 shows coefficients of the cancellation filter $W(z)$ estimated in the anechoic chamber based on the schematic diagram of the FxLMS algorithm shown in Fig. 2(a). The coefficients were used for implementation on the Orange Pi Zero PC to evaluate the performance of the PC as a digital signal processor (DSP).
similar radiation patterns were obtained for both offline and online conditions. Either blue or red line in the figure, it can be seen that cardioid-like radiation patterns could be played by the PC. Figure 4 shows polar radiation patterns in a low-frequency range for a single works well to achieve a cardioid-like radiation pattern in a low-frequency range. For the performance evaluation, the experiment was conducted under two conditions namely, offline and online filtering. In offline filtering, sounds with and without cancellation were prepared. On the other hand, in online filtering, the sound was simultaneously filtered and played by the PC. Figure 4 shows polar radiation patterns in a low-frequency range for a single loudspeaker, offline and online filtering. As shown in the comparison between the green line and either blue or red line in the figure, it can be seen that cardioid-like radiation patterns could be obtained using the cancellation filter W(z) for either offline or online filtering. In addition, the continuous filtering using a buffering technique, which actually created a delay for the online condition, has less effect on the low-frequency cardioid-like radiation patterns. As a result, very similar radiation patterns were obtained for both offline and online conditions.

Figure 5 shows the overall performance of polar radiation patterns as a function of direction and frequency. From the figure, it can be seen clearly that, in the direction of 180°, a significant attenuation of around 20 dB was achieved over a frequency range of 150 to 1000 Hz for both offline and online filtering. The front-to-back ratios over a frequency range of 150 to 1000 Hz were 22 ± 3 dB and 23 ± 3 dB for offline and online conditions, respectively. Generally, it can be said that a low-cost single board computer acted as a DSP in the back-to-back speaker system works well to achieve a cardioid-like radiation pattern in a low-frequency range.
4. Conclusions
This paper presented the application of a low-cost single board computer (SBC) as a digital signal processor (DSP) on a back-to-back speaker system to obtain a cardioid-like radiation pattern in the low-frequency range. The DSP to which the back-to-back speaker was interfaced is a US$7 Orange Pi Zero PC. The coefficient filter which results in the cardioid-like radiation pattern was estimated in advance and later used in the PC. Polar radiation pattern measurement was conducted under two conditions which were offline and online filtering. Experimental results showed that, for a frequency range of 150 Hz to 1 kHz, the front-to-back ratios were 22 ± 3 dB and 23 ± 3 dB for offline and online filtering, respectively. The cardioid-like radiation pattern for both conditions was also confirmed. In general, it can be said that a low-cost single board computer can act as a DSP in a back-to-back speaker system and works well to achieve a cardioid-like radiation pattern in the low-frequency range.

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