The Hong Kong Polytechnic University

Department of Rehabilitation Sciences

Optimizing the Ultrasound Echoes of Electronic Bat Ears

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A thesis submitted in partial fulfillment of the requirements for the

Degree of Master of Philosophy

2010 July

CERTIFICATION OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

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_____9/6/2010____ (Date)

Abstract of thesis entitled "Optimizing the Ultrasound Echoes of Electronic Bat Ears" submitted by Dongjin SONG for the degree of Master of Philosophy at the Hong Kong Polytechnic University in May 2010.

ABSTRACT

The electronic "Bat Ears" was designed to encode the spatial information of the physical environment with ultrasonic echoes and convert the spatial information into audible sound to guide people with visual disabilities. The electronic "Bat Ears" emits ultrasound pulses through a transducer (a transmitter located in the center) and receives the ultrasound echoes via two transducers (two receivers located on the left and right side). The ultrasound echoes detected by the two receivers are transformed to the audible frequency range. The binaural audio signals are delivered via two earphones. In the past few years, the electronic "Bat Ears" has been demonstrated to be effective for enhancing the mobility of people with early blindness. However, two problems have to be addressed to make the electronic "Bat Ears" calculate the accurate location of obstacles. Firstly, crosstalk between the transmitter and receivers affect the true ultrasound echo signals and thus, adversely affect the performance of the electronic "Bat Ears". Secondly, because the human auditory system considers two kinds of information, i.e., the interaural time differences (ITDs) and interaural intensity differences (IIDs), to localize the sound and the attenuation

properties of ultrasound (high frequency) and sound (low frequency) are different, this will also hurt the effectiveness of the electronic “Bat Ears”.

This thesis addressed the aforementioned two issues in an attempt to enhance the performance of the electronic “Bat Ears”. To eliminate the crosstalk in the output of electronic “Bat Ears”, we analyzed the output of the electronic “Bat Ears”, examined the properties of the crosstalk signal, and eliminated the crosstalk through both computer simulation and newly developed experimental circuits. The crosstalk was identified as the signal received from each ear when there was no obstacle in the front of the electronic “Bat Ears”. An analog to digital (A/D) convertor with sampling frequency of around 40 kHz read the signal to a computer or digital signal processor (DSP). The signal saved in the computer or DSP was replayed every time after an emission of ultrasound pulse was made. This signal was subtracted from the received signal in each ear in a synchronized manner to minimize the crosstalk. The crosstalk was significantly decreased using the newly implanted circuits in the “Bat Ears”.

To compensate the difference in the attenuation properties of ultrasound and audible sound, we proposed an explicit method to construct a matching relationship between the output of electronic “Bat Ears” and the theoretical audible sound. Using the results from our first study, we obtained a great improvement in the current electronic “Bat Ears”. The results from our second study would likely be further investigated and implemented in a future version.

RELEVANT PUBLICATIONS

Conference:

Dongjin SONG, Li-Xi HUNG, Chetwyn CHAN, and Jufang HE, "Optimization of The Ultrasound Echoes of Electronic Bat Ears", *International Workshop on Neural Coding, Tainan, May 8th to May 13th 2009. (Poster)*

Dongjin SONG and Jufang HE, "Optimizing the Ultrasound Echoes of Electronic 'Bat Ears'", *International Auditory Workshop, Shen Zhen, Jan. 2th-4th, 2009. (Presentation)*

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List of Abrrivations

frequency modulated (FM)

interaural time difference (ITD)

interaural intensity difference (IID)

characteristic delay (CD)

characteristic frequency (CF)

just-noticeable difference (JND)

knowles electronics manikin for acoustic research (KEMAR)

head related impulse responses (HRIRs)

head-related transfer functions (HRTFs)

electronic travel aids (ETA)

electronic orientation aids (EOA)

nearest neighbor (NN)

support vector machine (SVM)

Chapter I Introduction

This chapter briefly describes the motivation, objectives, and the outline of this thesis.

1.1Motivation

The electronic “Bat Ears” (Pan and He, 2002; He et al., 2005) was developed to guide the movements of blind people. It was designed based on the principle of binaural sensors and was mounted on a pair of glasses that can be worn conveniently. Two versions of electronic “Bat Ears” are shown in Figure 1.1.

When the electronic “Bat Ears” is operational, the transmitter (located in the central of the glasses) emits 40 k Hz ultrasound pulses for 2.5 milliseconds (ms) in the beginning of each time cycle (approximately 100 milliseconds). If these ultrasound pulses meet with any obstacle, they will be reflected back. Afterward, the two receivers (located at the left and right sides of the glasses) detect the ultrasound echoes, and the corresponding echo signal is amplified and demodulated in the receiver modules. Because the demodulator is composed of a multiplier and a low pass filter, the ultrasound echo signal is first multiplied by the frequency modulated (FM) signal (A signal directly generated by the transmitter module with frequency range from 40 k Hz to 42.6 k Hz in each time cycle) and then processed with a low pass filter. Finally, a low frequency signal is extracted and used to drive the earphones of electronic “Bat Ears”. Using the audible sound of the electronic “Bat Ears”, blind people can perceive the spatial information of the environment.

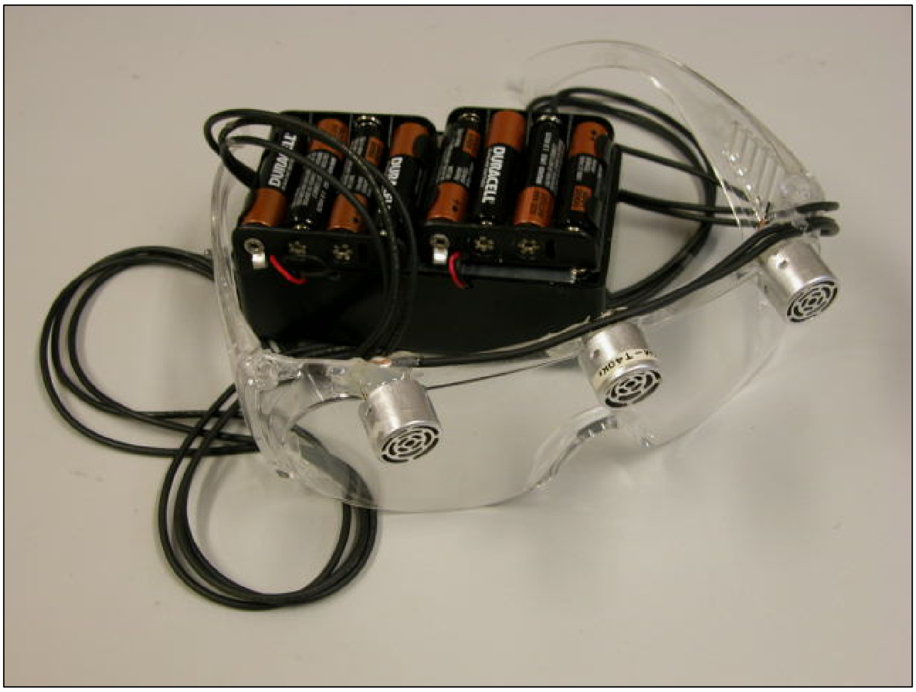
In the past experimental studies, the electronic “Bat Ears” has shown great effectiveness in enhancing the mobility of people with early blindness. However, two potential problems prevent the electronic “Bat Ears” from perceiving accurate spatial information (especially the azimuth information). First, crosstalk between the transmitter and receiver modules may interfere with the true echo signal in the receivers of electronic “Bat Ears”, thereby decreasing the effectiveness of the electronic “Bat Ears”. Second, ultrasound and audible sound have different attenuation properties; they use different characteristics (ultrasound: interaural intensity differences (IIDs); audible sound: interaural intensity differences (IIDs) and interaural time differences (ITDs)) to identify location of the obstacles. Because the output of the electronic “Bat Ears” is only dependent on the detected ultrasound IIDs while neglect the ITDs which are important for identifying the azimuth information, people may not perceive the accurate azimuth information when wearing the electronic “Bat Ears”

In this thesis, we studied the aforementioned two problems of the electronic “Bat Ears” to find ways of enhancing its performance.

To eliminate the crosstalk between the transmitter and receiver modules, we analyzed the output of the electronic “Bat Ears” under different obstacles settings, studied the properties of the crosstalk signal, and extracted the crosstalk signal. Then, we performed an offline as well as online study to subtract the crosstalk signal from the output of the electronic “Bat Ears”. For the offline study, two methods were proposed to simulate the subtraction. For the online study, newly developed experimental circuits were used to perform the subtraction.

To compensate for the attenuation differences between ultrasound and audible sound when they propagate, we studied the different attenuation properties of ultrasound and audible sound, and presented a method to construct a matching relationship between the theoretical audible sound and the output of the electronic “Bat Ears”.

With the results of the first study, we obtained great improvement in the current electronic “Bat Ears”. The results of the second study would enable us to further improve the electronic “Bat Ears”.



(a)

(b)

Figure 1.1 Two versions of electronic “Bat Ears”. (a) The first version of electronic “Bat Ears”. (b) The latest version of electronic “Bat Ears”.

1.2 The objectives of the study

To study the crosstalk signal between the transmitter and receiver modules, we recorded and analyzed the output of the electronic “Bat Ears” with different obstacles settings. We also distinguished the crosstalk signal from the output of the electronic “Bat Ears”.

To eliminate the crosstalk between the transmitter and receiver modules of the electronic “Bat Ears”, we first performed an offline study to determine how it can be done effectively and then designed experimental circuits to eliminate the crosstalk signal from the output of the electronic “Bat Ears” in an online setting.

To eliminate the effect of the attenuation differences between ultrasound and audible sound, we studied the different attenuation properties of the ultrasound and audible sound and constructed a matching relationship between the output of the electronic “Bat Ears” and the theoretical audible sound.

1.3 Outline of the thesis

This thesis is organized as follows:

Chapter I introduces the background and the objective of the study.

Chapter II provides a literature review about the fundamentals of ultrasound, the principles of binaural sound localization, the different kinds of binaural sensors applications, and the different kinds of devices for aiding people with blindness.

Chapter III describes the methodology used in this thesis, including the principle of the electronic “Bat Ears”, the experimental tools, and experimental designs.

Chapter IV presents the experimental results, including the recording results, offline study results, online study results, and matching study.

Chapter V discusses about the recording results, online study results, and the matching study results.

Chapter VI concludes this thesis by discussing its significance, limitations, and suggesting directions for future works.

Chapter II Literature Review

This chapter introduces the basic concepts of ultrasound, the principle of binaural sound localization, the different applications of binaural sensors, and the different kinds of devices for aiding people with blindness.

2.1 Fundamentals of ultrasound

The frequency range of sound audible to humans is approximately 20 to 20,000 Hz. Ultrasound is cyclic sound that has a frequency greater than the upper limit for the human hearing. In the past, ultrasound has been applied in different fields, e.g., penetrating a medium, measuring the reflection signature, and supplying focused energy. Other applications of ultrasound include medical diagnosis, ultrasound cleaning, ultrasound humidification, ultrasound identification, ultrasound range finding, and so on and so forth.

2.1.1 Wavelength

The wavelength λ represents the distance the ultrasound propagates over one spatial cycle, and it is defined by the following equation:

$$\lambda = v / f \,, \tag{2.1}$$

where v is the ultrasonic velocity, and f is the frequency.

When ultrasound is used for detecting obstacles, the obstacle size should be larger than half a wavelength of the ultrasound at the corresponding frequency.

2.1.2 Attenuation

Ultrasonic attenuation (Thurston and Pierce, 1999; Rose, 1999) is caused by the loss of energy in the ultrasonic wave when it propagates through a medium. The attenuation reduces the amplitude of the ultrasonic wave. Many factors will affect the amplitude and waveform of the ultrasonic wave, such as energy absorption, beam spreading, dispersion, nonlinearity, transmission at interfaces. To define ultrasonic attenuation quantitatively, the attenuation coefficient is defined by the following equation:

$$A = A_0 \cdot e^{-\alpha x} \tag{2.2}$$

where A represents the peak amplitude of the ultrasonic wave at distance x, and A_0 represents the initial peak amplitude. The attenuation coefficient α can be given in nepers per meter (Np/m) or decibels per meter (dB/m) and is highly dependent on the frequency (Ihara, 2008).

2.1.3 Reflection and transmission

When an ultrasonic wave propagates perpendicularly onto an interface between two mediums (as shown in Figure 2.1), a part of the wave is reflected back to Medium 1, and the remainder is transmitted to Medium 2. The reflection coefficient R is defined as the ratio of the amplitude of the reflected wave A_R to that of the incident wave A_I. The transmission coefficient T is defined as the ratio of the amplitude of the transmitted wave A_T to that of the incident wave A_I. R and T are given by the following expressions:

$$R = \frac{A_R}{A_I} = \frac{z_1 - z_2}{z_1 + z_2} \tag{2.3}$$

$$T = \frac{A_T}{A_I} = 2 \cdot \frac{z_1}{z_1 + z_2} \tag{2.4}$$

where z denotes the acoustic impedance, and subscripts 1 and 2 represent Medium 1 and Medium 2. When the two media have very different impedances, most of the ultrasonic wave is reflected. When the two media are identical, there is maximum transmission of the ultrasonic wave (Ihara, 2008).

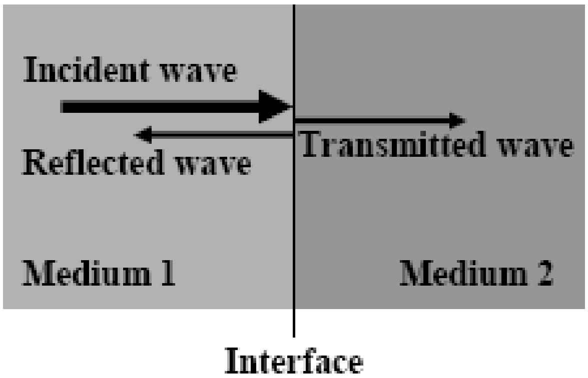


Figure 2.1 Normal reflection and transmission at an interface between two media (Ihara, 2008).

2.2 Binaural sound localization

Many factors affect the process of sound perception. For binaural perception, “Duplex Theory of Sound Localization” (Rayleigh, 1907) provided the first comprehensive analysis. Rayleigh noted that the perceived location of the source of an incoming sound is dominated by two physical cues: the interaural time difference (ITD) and the interaural intensity difference (IID).

2.2.1 Physical cues

The interaural time difference (ITD) results from the fact that the sound takes longer time to reach the ear that is farther from the source. The interaural intensity difference (IID) is produced because the “shadowing” effect of the head prevents some of the sound energy from reaching the ear that is farther from the sound source. IIDs are most pronounced at frequencies above (approximately) 1.5 kHz, and ITDs are generally useful for stimulus components at frequencies below (approximately) 1.5 kHz (Wang and Brown, 2006). If we assume the head is a completely spherical and uniform surface, as shown in Figure 2.2, then the ITD produced by a sound source propagating from azimuth of θ radians can be approximately denoted by the following expression (Kuhn, 1977; Shaw, 1997):

$$\tau = (a / c) 2 \sin\theta, \tag{2.5}$$

where a a denotes the radius of the head, and c denotes the speed of sound.

When frequencies are below (approximately) 500Hz, the ITD can be denoted by the following expression:

$$\tau = (a / c)(\theta + \sin\theta) \tag{2.6}$$

when frequencies are above (approximately) 2 kHz.

Values of IIDs can be measured by putting probe microphones in the ears. IIDs have been found to be empirically dependent on the position of the sound source and the frequency of sound (Wang and Brown, 2006).

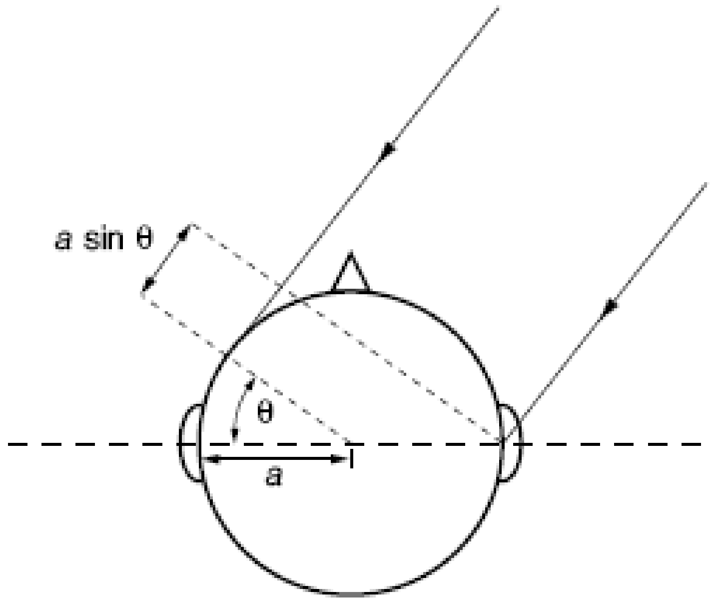


Figure 2.2 Interaural differences of time and intensity impinging on an ideal spherical head from a distant source. An interaural time delay (ITD) is produced because it takes longer for the signal to reach the more distant ear. An interaural intensity difference (IID) is produced because the head blocks some of the energy that would have reached the farther ear, especially at higher frequencies. (Wang and Brown, 2006)

2.2.2 Physiological foundations of ITD and IID

Many models of binaural processing are based on the cross-correlation of signals to the two ears, after being processed by the auditory periphery (Wang and Brown, 2006). This kind of models is supported by the fact that the cells in the inferior colliculus of the brainstem are sensitive to signals with a specific ITD, independent of the frequency (Rose et al., 1966). Since Rose, different experiments have been performed to characterize the distribution of the characteristic delay (CD which is defined as the difference in neuron travel time) of IID-sensitive cells in the inferior colliculus (Yin and Kuwada, 1984; Kuwada et al., 1997) and the medial geniculate body (Stanford et al., 1992). These studies have shown that IID-sensitive cells tend to exhibit characteristic delays over a broad range of ITDs, and the density of characteristic delays decreases when the ITD absolute value increases (Wang and Brown, 2006). Meanwhile, McAlpine et al. (McApline et al., 1996) proposed that most ITD-sensitive units exhibit characteristic delays that occur in a narrow range close to approximately one-eighth of the period of a cell's characteristic frequency (CF).

There is some debate on the anatomical origin of characteristic delays. Some believe the delays are of neural origin, caused either by synaptic delays or slowed conduction delays (Young and Rubel, 1983; Carr and Konishi, 1988), while others believe characteristic delays can also occur if higher processing centers compare the timing information derived from auditory-nerve fibers with different CFs (Schroeder, 1977; Shamma et al., 1989). Generally speaking, the predictions of binaural models are not dependent on whether internal delays are caused by neural or mechanical phenomena (Wang and Brown, 2006).

For IIDs, many previous works have reported cells that appear to respond to IIDs at different levels of the brainstem (Boudreau and Tsuchitani, 1968; Caird and Klinke, 1983).

2.2.3 Single source sound localization

Human ears are very sensitive to even small differences in interaural time and intensity. For example, in case of low frequency pure tones, the just-noticeable difference (JND) for IID is of the order of 1dB, while for ITDs, it is of the order of 10us (Hershkowitz and Durlach, 1969; Domnitz and Colburn, 1977). Wightman and Kistler presented a framework/methodology for evaluating the head-related transfer functions (HRTFs), which describe the transmission of sounds in the free field to the ears (Wightman and Kistler, 1989a; Wightman and Kistler, 1989b; Wightman and Kistler, 1997). Based on their framework, they found that subjects were able to describe the azimuth and elevation of free-field stimuli consistently and accurately. Furthermore, based on various manipulations of the virtual stimuli, they also presented that localization of free-field stimuli is dominated by ITD information (especially for low frequencies). ITD information should be consistent with frequency to play a role in sound localization and IID information plays a role in eliminating ambiguities which cause front-back confusions of position (Wightman and Kistler, 1997; Wang and Brown, 2006).

To measure ITD, IID, and other stimulus attributes, an anatomically realistic manikin such as the knowles electronics manikin for acoustic research (KEMAR) (Burkhard and Sachs, 1974) can be used. Examples of recording using a KEMAR manikin are shown in Figure 2.3.

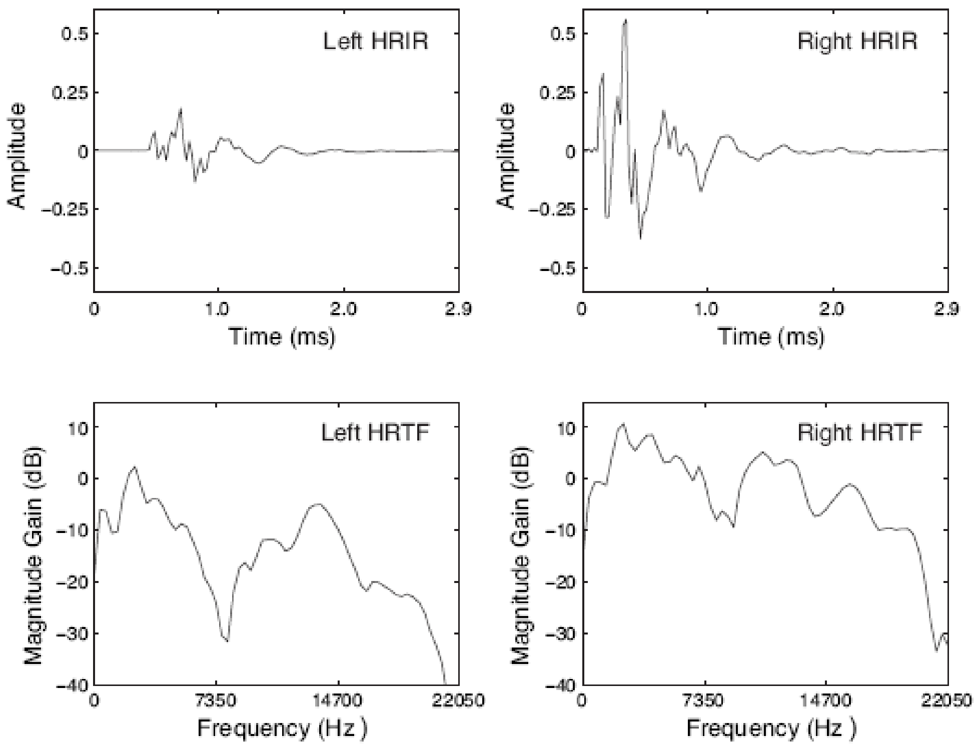


Figure 2.3 Head related impulse responses (HRIRs) (top row) and the corresponding head-related transfer functions (HRTFs) (bottom row) recorded at the left and right ears of a KEMAR manikin, in response to a source placed at an azimuth of 40° to the right of the head with 0° elevation. The stimulus is more intense in the right ear and arrives first in the right ear before reaching the left ear (Gardner and Martin, 1994; Wang and Brown, 2006).

2.3 Binaural sensors

Insects, such as crickets (Lund et al., 1998; Horchler et al., 2003) and small animals like the small brown bat (Horiuchi and Hynna, 2001; Shi and Horiuchi, 2004), have binaural hearing abilities that rely on intensity or level differences in the sound received by each hearing sensor. Intensity measurement is used because the distance between their hearing organs is very small. For large animals like owls and human beings, the time delay between signals received in each ear are measured to determine the azimuth, i.e., the sound stimuli from each ear are compared to locate the azimuth of the source (Lewinger et al., 2006). Inspired by this biological mechanism, many different kinds of binaural sensors have been developed.

2.3.1 Principle of binaural sensors

Generally, at least three transducers are used in binaural sensors: a transmitter and two receivers. The transmitter, located in the center, emits sound pulses (ultrasound wave). The two receivers, located at the two sides of the transmitter, detect the echoes reflected from the obstacle and encode spatial information.

Figure 2.4 shows an example of the configuration of a binaural sensor system.

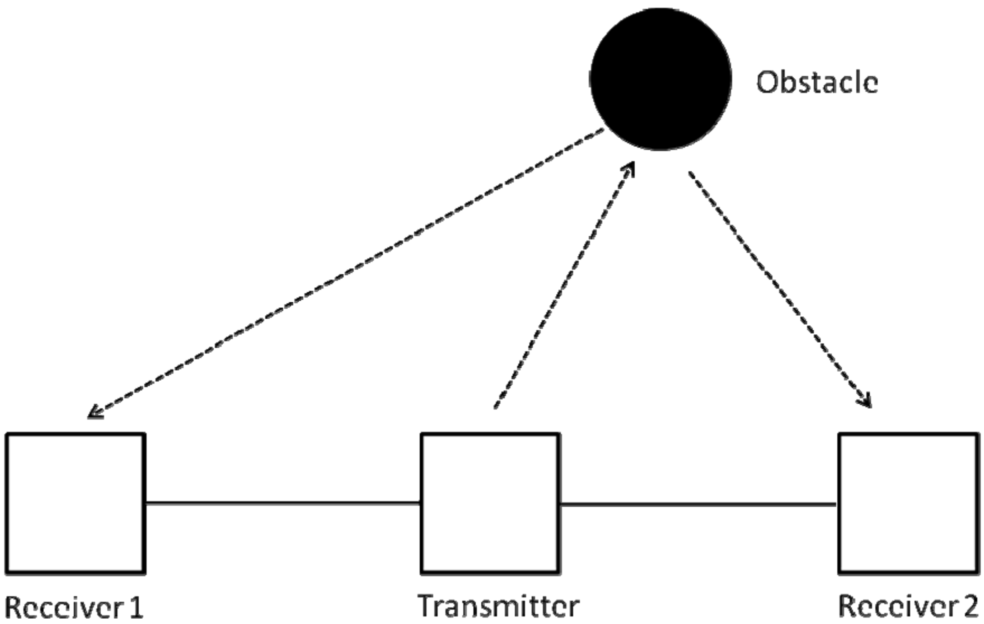


Figure 2.4 The principle of binaural sensors. The transmitter is located in the central, and the two receivers are located at each side of the transmitter. The transmitter emits the ultrasonic wave, and when the ultrasonic wave meets with an obstacle, it is reflected back to the two receivers. Through the IID and ITD difference, the two receivers are able to locate both the distance and azimuth of the obstacle.

2.3.2 Applications of binaural sensors

In the past few years, binaural sensors have been demonstrated to be effective and have been widely applied for perceiving the spatial information of the environment. Binaural sensors, inspired by biological mechanisms, usually have a central transmitter and two receivers at each side, separated by a distance. They are able to detect objects located in a planar environment. Therefore, binaural sensors are widely used to localize obstacles and control vehicles, robots, etc.

Kažys et al. (2000) demonstrated that the performance of the ultrasonic binaural sensor was sufficient for the purpose of navigation of semi-autonomous vehicles through a series of experiments. Subsequently, Kažys et al. (2002) performed experiments to investigate the spatial resolution of ultrasound coordinate measurement (as shown in Figure 2.5). Their experiment results showed that the analyzed ultrasonic binaural coordinate measuring system can reliably determine spatial coordinates in the range of distances of up to 20 m from the receivers and up to ± 12 m from the symmetry axis, with an error less than ± 0.2 m.

Besides Kažys and his collaborator's research, other researchers have also developed different kinds of binaural sensors for varied applications. For example, Kuc (1996) fused binaural sonar information to perform object recognition tasks; Mwakibinga and Lee (2005) designed and built a test bed to control the altitude of a small unmanned aerial vehicle by using a binaural bat echolocation system (as shown in Figure 2.6); Peremans and Reijniers (2005) developed a robotic system that reproduces the echolocation system of bats at a functional level (as shown in Figure 2.7); and Lewinger et al. (2006) successfully developed an autonomously mobile robot that can function in a cluttered environment using the binaural sensors (as shown in Figure 2.8). Moita et al. (2007) introduced a binaural sonar configuration with capability to detect and identify walls, edges and corners in real-time. Pinho et al. (2008) presented a Bayesian system of auditory localization of the distance, azimuth and elevation using binaural sensors only.

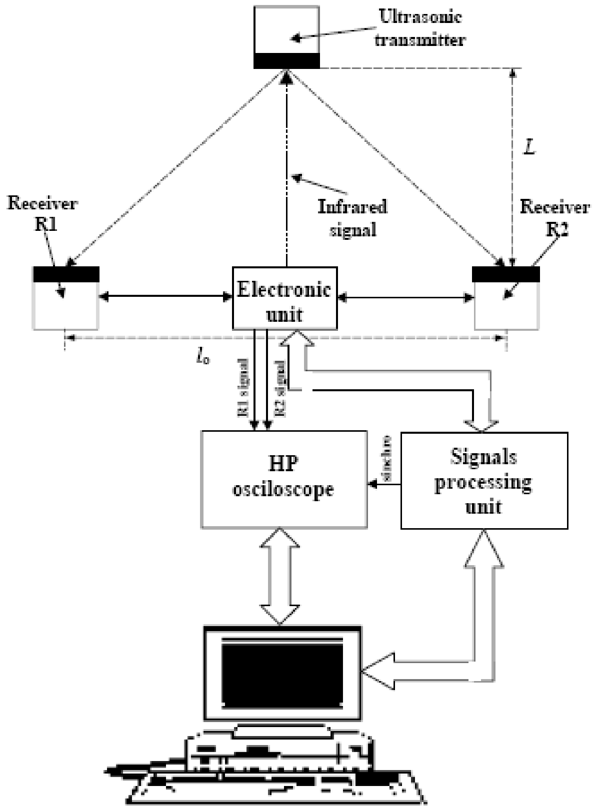


Figure 2.5 Kažys et al.'s experimental system for investigating the spatial resolution of ultrasound coordinates measurement (Kažys et al., 2002).

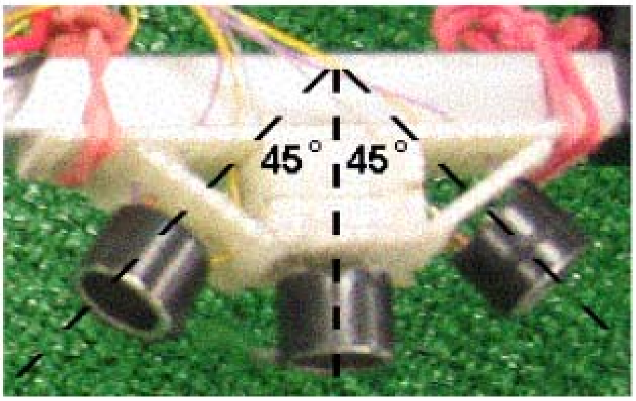


Figure 2.6 Mwakibinga and Lee's binaural bat echolocation system. The ultrasonic microphones are positioned at 45° away from the aim of the ultrasonic speaker (Mwakibinga and Lee, 2005).

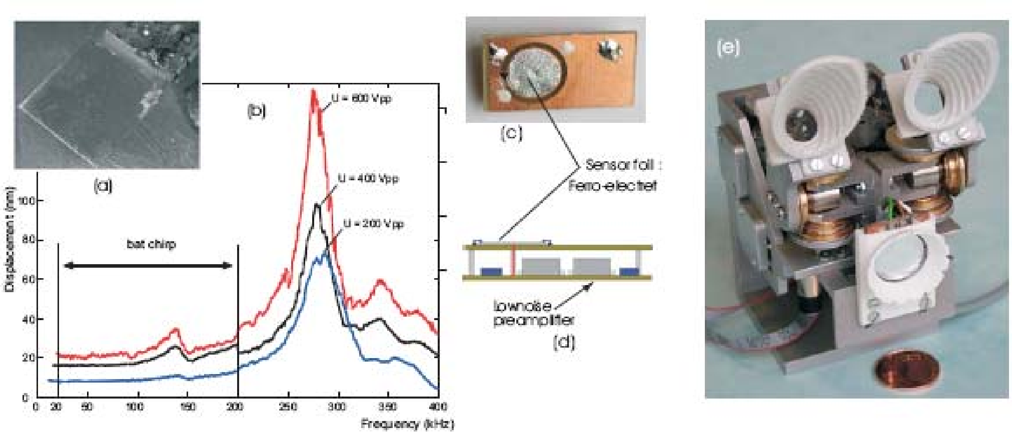


Figure 2.7 Peremans and Reijniers's system. (a) EMFi transmitter (15x15mm). (b) Frequency response of the transducer surface displacement. (c) The sandwich structure of the ultrasonic receiver. (d) The EMFi transducer foil acting as a receiver is glued to the top layer of the sandwich. (e) The bio-mimic head prototype (Peremans and Reijniers, 2005).

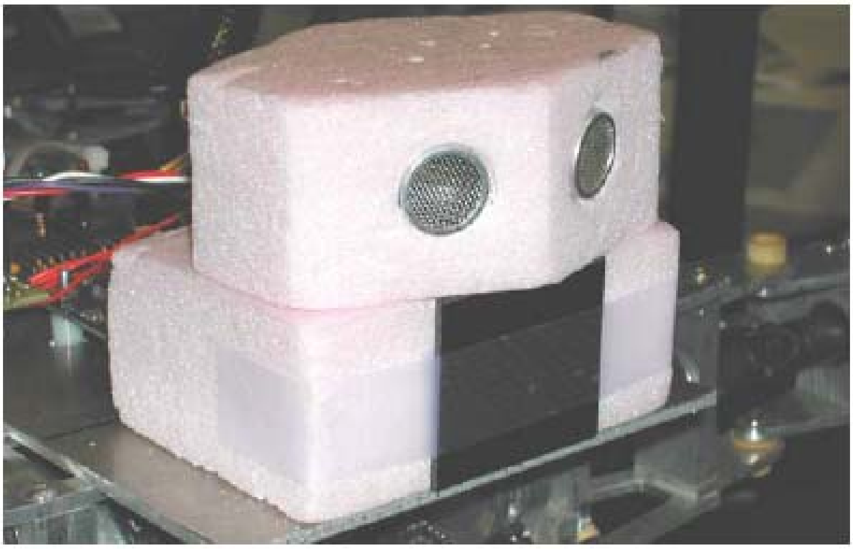


Figure 2.8 Lewinger's binaural sensors. Binaural ultrasonic sensor pod with a single ultrasonic emitter (located behind the black square) and angled dual receiver above (Lewinger et al., 2006).

2.4 Devices for helping blind people

In recent years, different kinds of devices have been developed to enhance the ability of people with blindness to perceiving spatial information of the environment and enhance their mobility. For example, Farcy et al. (2006) presented electronic travel aids (ETA) to help visually impaired people avoid obstacles (as shown in Figure 2.9) and electronic orientation aids (EOA) to aid visually impaired people in finding their way in an unknown environment. Su et al. (2001) developed a portable communication aid, which allows deaf-blind people to communicate with others without the help of an assistant. Bousbia-Salah and Fezari (2007) introduced a navigation aid to enable blind and visually impaired people to detect any obstacles and navigate easily and safely. The aid is able to give information to the blind about urban walking routes and provides real-time information on the distance of over-hanging obstacles ahead of the user, up to six meters away along the travel path.

Because binaural sensors are effective and have been widely used for perceiving the spatial and azimuth information of the environment, they are suitable for making devices that can help blind people enhance their navigation abilities. For instance, De Volder et al. (1999) developed the substitution prosthesis for blind persons through audition. Their device emits ultrasonic wave in the center and detects the echoes at left and right sides through two receivers. The echoes are decoded into audible sound, which is broadcast through two earphones. Using this device, a pole (9cm in diameter and 2m in height) within 6 meters can be detected, with an auditory frequency of 10.8 kHz. Kay (2000) developed a high-resolution octave band air sonar device for helping blind people sense the spatial information and image objects or obstacles in the environment. By collecting echoes from the ultrasonic transmitters, the device can perceive tonal characteristics, which include information of nature of surface, as well as range, direction, and dimensions of objects or obstacles. Bensaoula et al. (2006) presented an auditory guidance system for the blind. Their system is composed of two parts: a sonar system for sensing the environment and a system to detect floor obstacles (as shown in Figure 2.10).

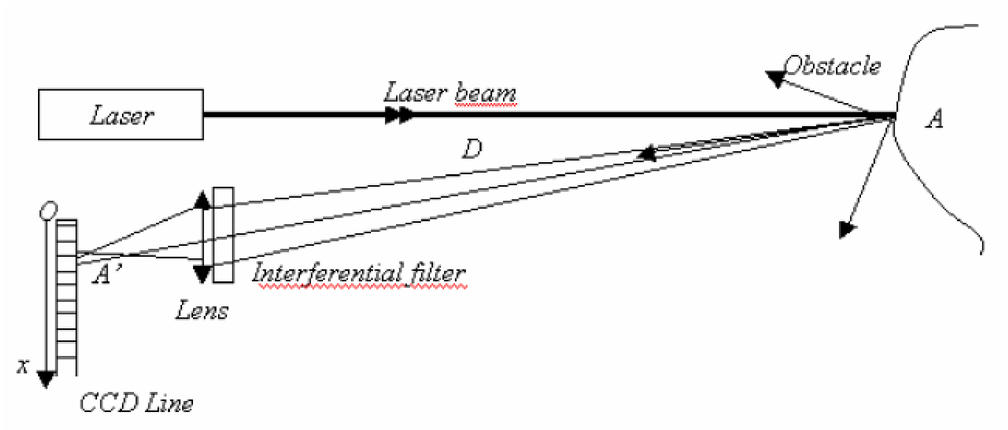


Figure 2.9 The basic principle of the ETA developed by Farcy et al. The laser diode emits a collimated 1-mW 670-nm laser beam. The beam meets the obstacle at a distance D and creates a laser spot A. The image of the laser spot A captured through the lens on the CCD line is A'. The position of A' on the line gives the distance D. As shown in the figure, for large xA', D is short. While the basic principle is very simple, the main difficulty is avoiding interference from natural light (up to 130klux on sunny summer days). Hence, there is a need for additional optical and electronic systems (Farcy et al., 2006).

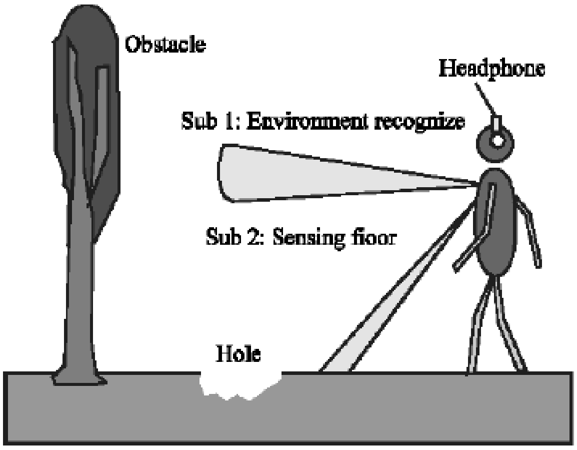


Figure 2.10 The principle of Bensaoula et al.'s device (Bensaoula et al., 2006).

Chapter III　Methodology

In this chapter, we introduce the detailed principles of the electronic “Bat Ears”, the experimental equipments, and the experiment designs.

3.1. The principle of electronic “Bat Ears”

The electronic “Bat Ears” (Pan and He, 2002; He et al., 2005) is a kind of binaural sensor developed to help blind people enhance their navigation ability. Unlike the binaural sensors for localizing obstacles/controlling robots and the aforementioned devices for helping blind people, the electronic “Bat Ears” uses ultrasound to locate the obstacles and audible sound to encode the spatial information. The schematic diagram of the electronic “Bat Ears is shown in Appendix A.

The electronic “Bat Ears” has one transmitter located in the center and two receivers located in each side of the glasses. One example of the electronic “Bat Ears” is shown in Figure 3.1. The arrows in the figure show the positions of the transmitter and the receivers.

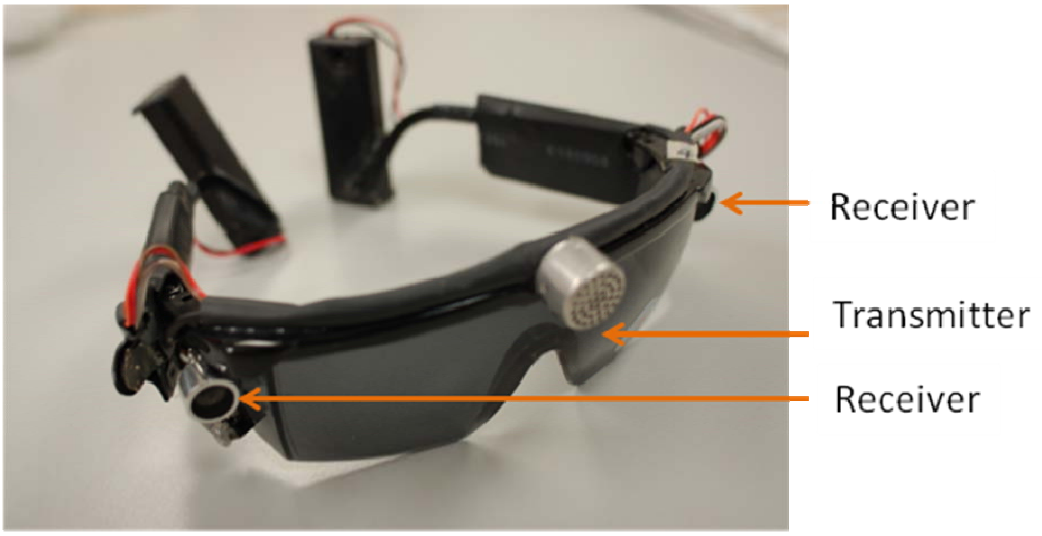


Figure 3.1 The electronic “Bat Ears” used in the experiment. One transmitter is located in the center, and a receiver is located on each side of the glasses.

3.1.1 Transmitter module

In the transmitter module of the electronic “Bat Ears”, two kinds of signals are generated. One is a 40 KHz ultrasound signal, and the other is the frequency modulated (FM) signal (40 KHz ~ 42.6 KHz). With the control of the MCU (AT89C2051), the 40 KHz ultrasound is emitted only in the first 2.5 ms of each time cycle (about 100 ms). For the FM signal, it is generated at the third ms of each time cycle and lasts for 96 ms in the same time cycle (with frequencies ranging from 40 KHz to 42.6 KHz). The FM signal is sent to the receiver module to demodulate the echo signal. The detailed principle of the transmitter module is shown in Figure 3.2 and the assembly language code for control the transmitter module is shown in appendix C.

3.1.2 Receiver module

In each receiver module, ultrasound echoes are detected, amplified, demodulated, and output. Because the demodulator consists of a multiplier and a low pass filter, the amplified ultrasound echo signal is first multiplied with the FM signal and then filtered by the low pass filter. Finally, an audible signal is obtained and output through the earphones to help the blind user perceive the spatial information. The principle of the receiver module of the electronic "Bat Ears" is shown in Figure 3.3.

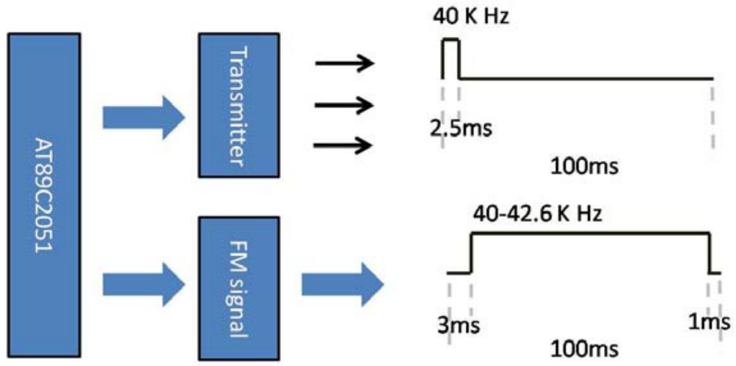


Figure 3.2 Diagram of the principle of the transmitter module of the electronic "Bat Ears".

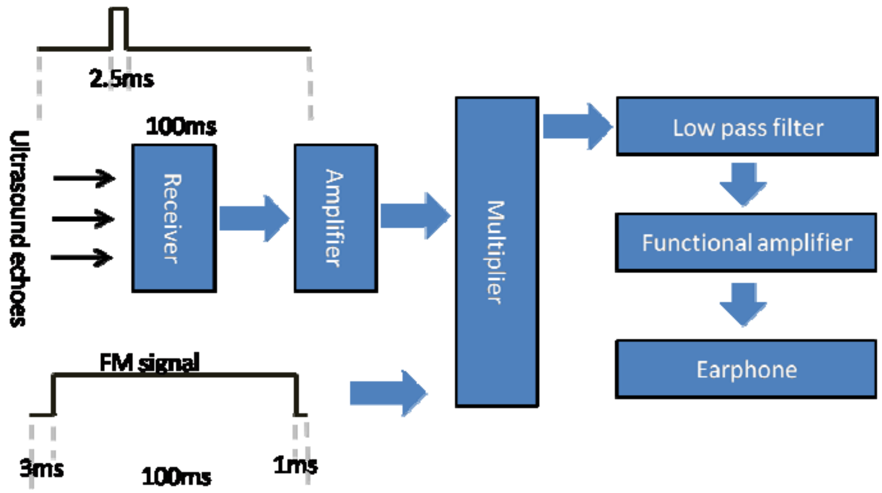


Figure 3.3 Diagram of the principle of the receiver module of the electronic "Bat Ears".

3.2. Experimental equipments

In our experiment, different kinds of equipments were used for recording and analyzing the output signal of the electronic "Bat Ears". These equipments included the KEMAR manikin (type 45BA), the digital signal collection card, obstacles of different sizes, the audio sound source, the digital oscillograph, and MATLAB.

3.2.1 The KEMAR manikin

The KEMAR Manikin (Type 45BA) (Burkhard and Sachs, 1974) is an acoustic research equipment obtained from Knowles Electronics. It permits reproducible measurements for establishing the performance of hearing aids and other electro-acoustic devices, as well as the quality of binaural recordings. Because this head and torso simulator is based on the worldwide average human male and female head, and torso dimensions meeting standard ANSI S3.36/ASA58-1985 and IEC 60959:1990, it is widely used for hearing-aid testing, earphone testing, headset testing, and binaural recording.

In this study, the KEMAR Manikin (as shown in Figure 3.4 (a)) was used for recording the output of the electronic "Bat Ears".

3.2.2 Data acquisition device

The National Instrument (NI) 6521 card (NI datasheet, as shown in Figure 3.4

(b)) was used for collecting the output signal of the KEMAR Manikin. This card was optimized for superior accuracy at fast sampling rates. It provided an onboard NI-PGIA 2 amplifier designed for fast settling times at high scanning rates, ensuring 16-bit accuracy even when measuring all available channels at maximum speed.

3.2.3 The obstacles

In the empirical study, we used different sizes of obstacles (10 × 10 cm, 20 × 20 cm, 30 × 30 cm, 40 × 40 cm, 50 × 50 cm) for evaluating the performance of the electronic “Bat Ears”. Because these obstacles were made of cardboards with a smooth surface, they can reflect most of the ultrasound with directional consistency. One example of an obstacle is shown in Figure 3.4 (c).

3.2.4 The digital oscillograph

In our study, the digital oscillograph (MOS 6014A, as shown in Figure 3.4 (d)) was used to test the performance of the electronic “Bat Ears” and the newly designed experimental circuits. The digital oscillograph utilizes a microprocessor for output control and data processing. It can perform many functions that simulation/analog oscillograph cannot do, e.g., leading triggering, combined triggering, blurred capture, wave processing, hardcopy export, soft disk recording, and long term waveform storage. Generally, the bandwidth of a digital oscillograph exceeds 1GHz and the performance is better than simulation oscillograph in many aspects.

3.2.5 MATLAB

MATLAB is a numerical computing environment for efficient matrix manipulation, plotting of functions and data, implementation of algorithms, simulation, and creation of user interfaces.

In this study, we used MATLAB to collect and analyze data, implement algorithms, and perform simulations.

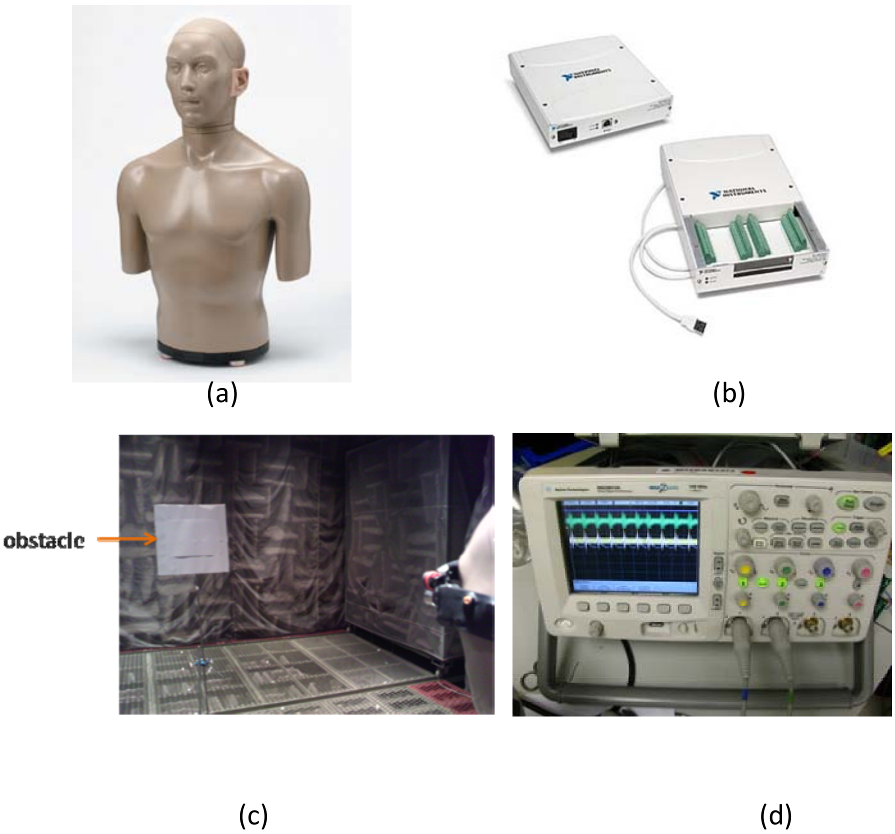


Figure 3.4 Experimental equipments used in the study. (a) The KEMAR manikin (Type 45BA). (b) National Instrument (NI) 6521 card. (c) The acoustic lab for data collection and one obstacle. (d) The digital oscillograph.

3.3. Experimental design

The key questions in our study are: (1) how the crosstalk signal affects the performance of the electronic “Bar Ears”; (2) how to eliminate crosstalk signal in the output of the electronic “Bat Ears”; and (3) how to build a matching relationship between the theoretical audible sound (direct propagation in air) and the output of electronic “Bat Ears”.

To identify the effects of crosstalk signals on the performance of the electronic “Bat Ears”, we recorded the output of the electronic “Bar Ears” with different obstacle sizes, distances, and azimuths. After analyzing these recording results, we could distinguish the crosstalk signal from the true echo signal by both intuitive comparison and theoretical analysis.

To eliminate crosstalk signal, we first performed offline simulations to subtract crosstalk signal from the output of the electronic “Bat Ears”. Afterward, we designed experimental circuits to implement the simulations in an online setting.

To construct a matching relationship between the audible sound and the output of the electronic “Bat Ears”, we first found a matching relationship between the location of the obstacle and the output of the electronic “Bat Ears”. After that, we calculated the theoretical sound intensity and phase based on the location of the obstacle.

3.3.1 Recording

After placing the electronic "Bat Ears" on the head of KEMAR manikin, we used the National Instrument (NI) 6521 card to record the output of electronic "Bat Ears" with different settings, i.e., obstacles of different sizes, at different distances, and different azimuths. All recording was processed in the Acoustic Laboratory in the Department of Mechanical Engineering, Hong Kong University.

Sizes: Five different sizes of obstacles were used in the study: 10 × 10 cm, 20 × 20 cm, 30 × 30 cm, 40 × 40 cm, and 50 × 50 cm. We kept the center of the obstacles in the same plane as the electronic "Bat ears" when they were used for recording. The surface of the obstacle was perpendicular to the radius (as shown in Figure 3.6).

Distances: Obstacles were placed at different distances from the manikin to explore the relationship between the distance of the obstacle and the output of the electronic "Bat Ears". The distances were set at 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 3.5 m, and 4 m.

Azimuths: Obstacles were placed at different azimuths for each fixed distance to study the relationship between the azimuth of the obstacle and the output of the electronic "Bat Ears". The azimuths were set at 0°, -15° (left), +15° (right), -30° (left), and +30° (right).

The positions of the obstacles at different distances and azimuths are shown in Figure 3.5. Detailed configurations of the recording settings are shown in Figure 3.6.

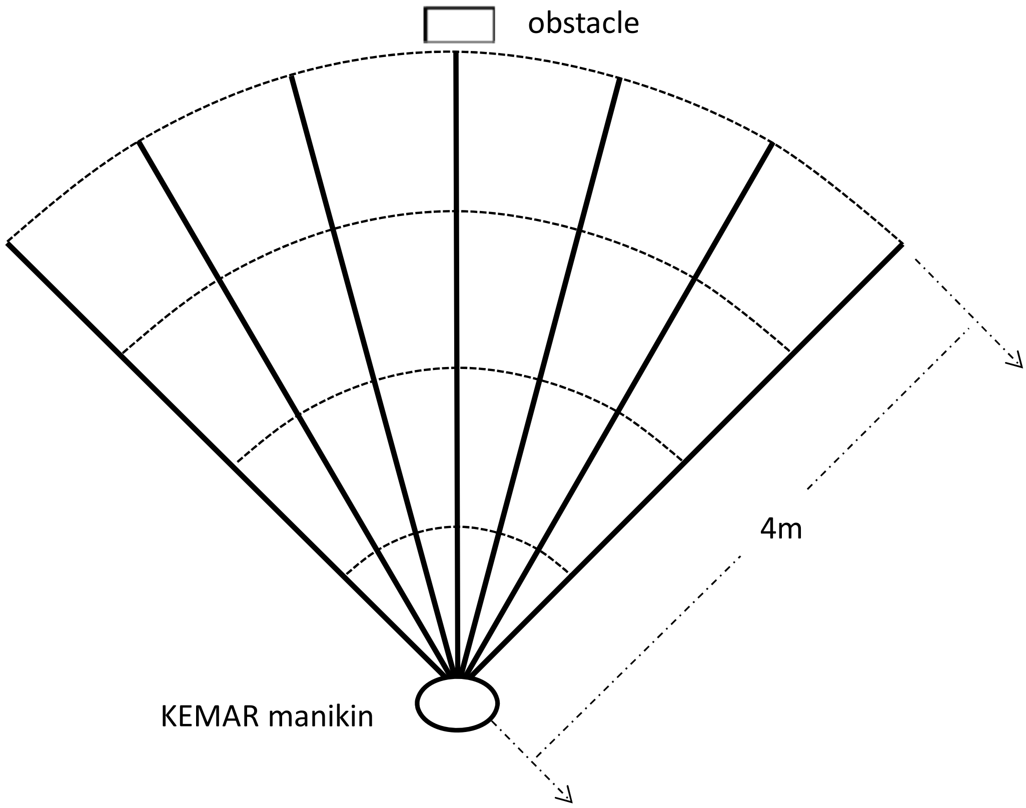


Figure 3.5 Different positions of obstacles for recording the output of the electronic "Bat Ears". Each intersecting point of radius and arc was a position for recording.

Figure 3.6 The detailed recording configurations.

3.3.2 Offline study

Offline simulations were performed to find a potential solution for eliminating the crosstalk between the transmitter and receiver modules. The simulations were based on an intuitive idea: if the crosstalk signal maintained similar waveforms in all recordings, the recording result of a no-obstacle case would be used as the reference, i.e., the crosstalk signal, to eliminate the crosstalk effect in the present time cycle; otherwise, the crosstalk signal of the previous time cycle would be used as the reference.

3.3.3 Online study

When an obstacle was placed in front of the electronic “Bat Ears” (within the detection range), the output of the electronic “Bat Ears” would consist of a crosstalk signal and an echo signal. Because the crosstalk signal would interfere with the true echo signal and affect the performance of the electronic “Bat Ears”, an online study was conducted to subtract the crosstalk signal through experimental circuits designed for the purpose. The experimental circuit should be able to (1) store the crosstalk signal in the flash memory, (2) output the crosstalk signal with the same time cycle as the output of the electronic “Bat Ears”, and (3) make the phase of the crosstalk signal consistent with the output of the electronic “Bat Ears”.

Figure 3.7 shows the details of the functions of the expected experimental circuit.

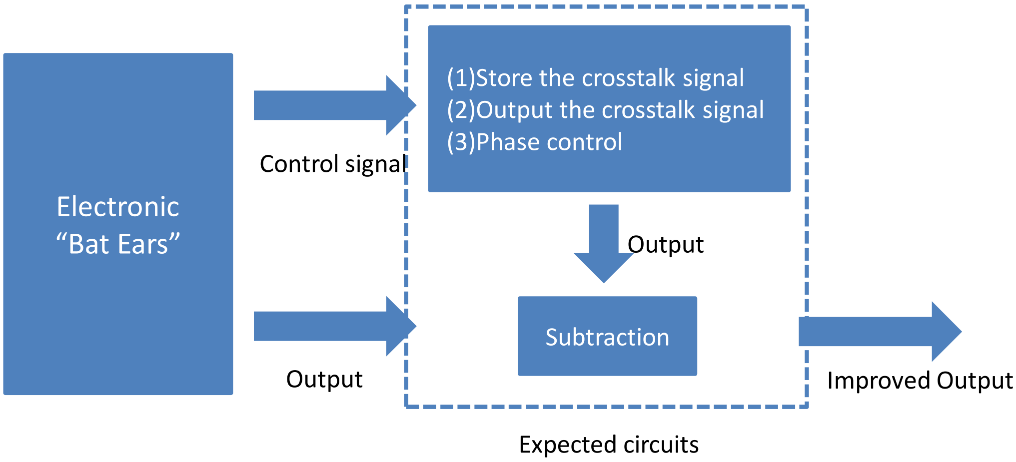


Figure 3.7 Details of the functions of the expected experimental circuit.

3.3.4 Matching

Ultrasound and audible sound have different attenuation properties; they use different characteristics (ultrasound: interaural intensity differences (IIDs); audible sound: interaural intensity differences (IIDs) and interaural time differences (ITDs)) to identify location of the obstacles. Because the output of the electronic “Bat Ears” is only dependent on the detected ultrasound IIDs while the ITDs which are important for identifying the azimuth information are neglected, people may not perceive the accurate azimuth information when wearing the electronic “Bat Ears”. This limitation may impede the decoding of accurate directional information by the electronic “Bat Ears”.

To address this problem, a matching relationship was constructed between output of the electronic “Bar Ears” and the theoretical audible sound that directly propagates (from the same location as obstacle) in the air. After this matching relationship was constructed, the output of the electronic “Bat Ears” can be converted into audible sound, which is more effective for discriminating the location (both the IIDs and ITDs are considered).

After firstly constructing a matching relationship between the output of electronic “Bat Ears” and the location, the theoretical sound intensity was calculated using equation (2.2). The theoretical phase difference, i.e., the interaural time difference (ITD), was calculated using equation (2.5) when the frequencies were below (approximately) 500 Hz, and by equation (2.6) when the frequencies were above (approximately) 2 kHz. In the two equations, a denotes the radius of the head, and c denotes the speed of sound.

Chapter IV Experimental results

This chapter presents the experimental results and the corresponding analysis.

We first report the recording results with different obstacle settings, i.e., no obstacles, obstacles of different sizes, at different distances, and different azimuths. This study aimed to (1) distinguish the crosstalk signal from the echo signal in the output of the electronic “Bar Ears” and (2) study characteristics of the echo signal when an obstacle was placed in different positions.

After distinguishing the crosstalk signal, we extracted it and conducted the offline simulations to eliminate it from the output of the electronic “Bat Ears”. The purpose of the study was to find feasible solutions to eliminate the crosstalk signal.

Based on the offline study results, we performed an online study to implement the offline methods with experimental circuits. We designed programs to control the experimental circuit via MCU to eliminate the crosstalk signal of the electronic “Bat Ears” in an online setting.

Even though the crosstalk signal was eliminated, the electronic “Bat Ears” may still not be able to perceive accurate direction information of the obstacle because ultrasound and audible sound have different attenuation properties when they propagate in the air. The output of the electronic “Bat Ears” relies only on the detected ultrasound IID while neglecting the ITD that is important for discriminating the azimuth information. Hence, people may not perceive the accurate azimuth information by wearing the electronic “Bat Ears”.

Therefore, we used an explicit method to construct a matching relationship between the output of the electronic “Bat Ears” and the theoretical audible sound signal. After this matching relationship was constructed, the conversion between the output of the electronic “Bat Ears” and the audible sound signal (when the audible sound source locates at the same place of obstacle) can be implemented easily, thereby enhancing the performance of the electronic “Bat Ears”.

4.1. The recording results

The results of the processing of recordings in the acoustic lab of Hong Kong University are described below.

4.1.1. No obstacles

We recorded the output signal of the electronic “Bat Ears” with no obstacles in the acoustic lab. The aim was to obtain a reference signal for comparison. Figure 4.1 shows the recording results. There were two channels because there were two receivers in the electronic “Bat Ears”: the signal of left channel came from the left receiver, and the signal of right channel came from the right receiver. The signal of the left (right) channel was not equal to the echo signal detected by the left (right) receiver; it was the earphone/output signal of the electronic “Bat

Ears".

In each channel, we can observe an envelope signal around 2 KHz. Because there were no obstacles in the experimental environment, this envelope signal was the crosstalk signal if it maintained a stable waveform with different recording settings.

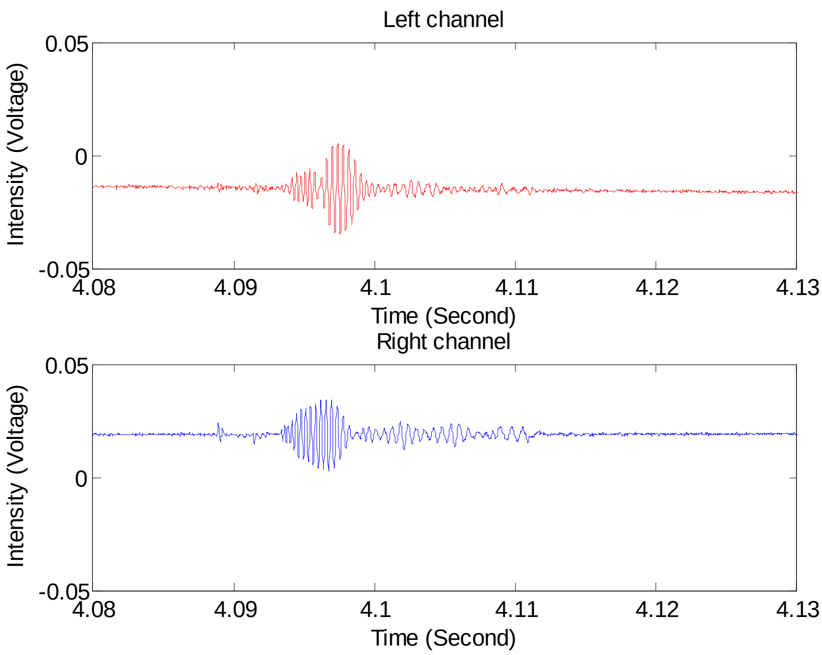


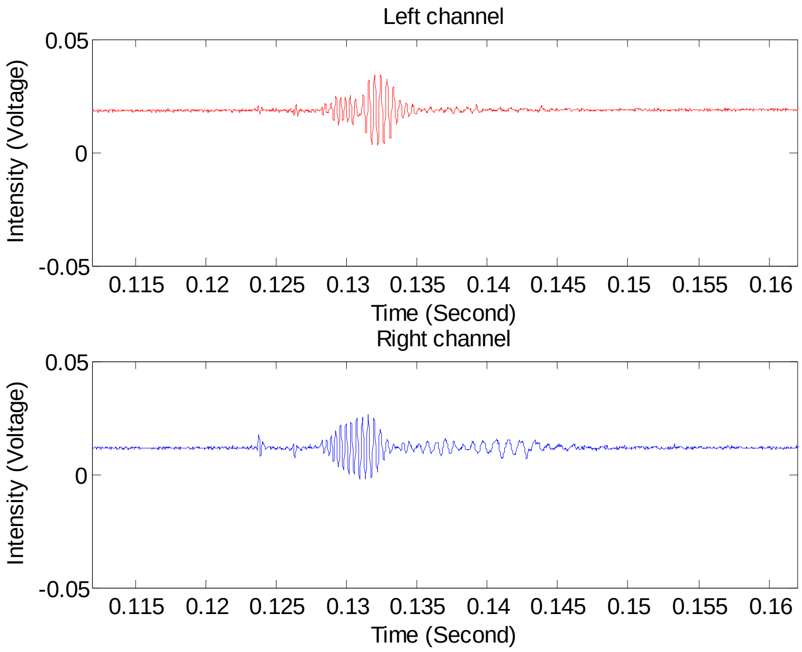
Figure 4.1 The output signal of the electronic "Bat Ears" with no obstacles in the experimental environment.

4.1.2. Obstacles with different sizes

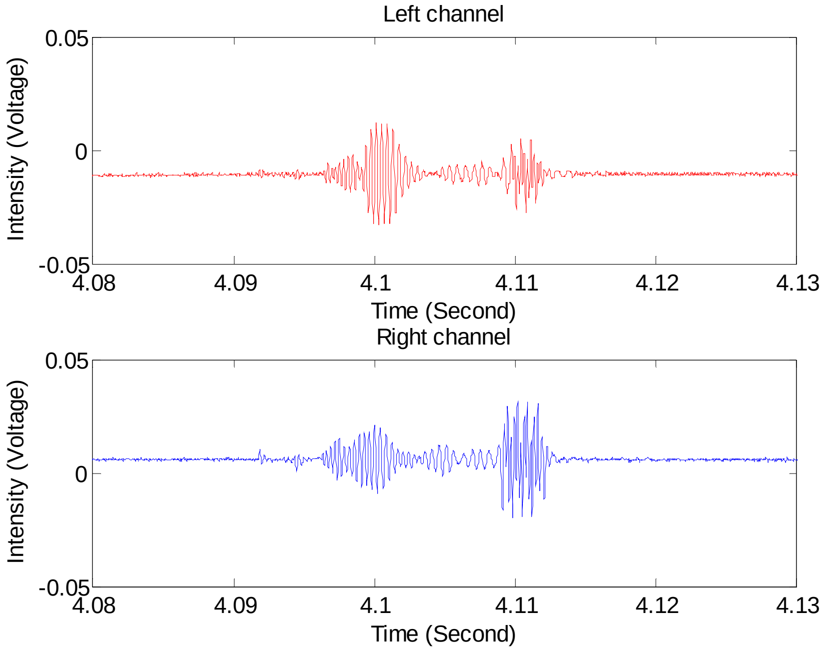
The electronic "Bat Ears" was tested with different sizes of obstacles: 10 × 10 cm, 20 × 20 cm, 30 × 30 cm, 40 × 40 cm, and 50 × 50 cm. The relationship between the output of electronic "Bat Ears" and the sizes of obstacles was studied.

The recording results for the 20 × 20 cm and 50 × 50 cm obstacles are shown in Figure 4.2. They were both recorded with a fixed distance of 3 m and azimuth of 0°. The recording result in Figure 4.2 (a) had the same waveform as Figure 4.1. Therefore, the electronic “Bat Ears” cannot detect the 20 × 20 cm obstacle at this distance and azimuth. In Figure 4.2 (b), there are two envelopes. The first envelope is the crosstalk signal because its waveform is similar to that in Figure 4.1. The second envelope represents the echo signal because the time delay between the second envelope and the trigger signal was exactly equal to the ultrasound propagation time, i.e., 3x2/340=17.6 ms.

Based on a comparison of Figure 4.2 (a) and Figure 4.2 (b), we learned that the signal in Figure 4.1, i.e., the first envelope in Figure 4.2(b), was the crosstalk signal. Furthermore, we also learned that the bigger the obstacle is (with fixed distance and azimuth), the stronger the echo signal will be.



(a) Size 20 × 20 cm.



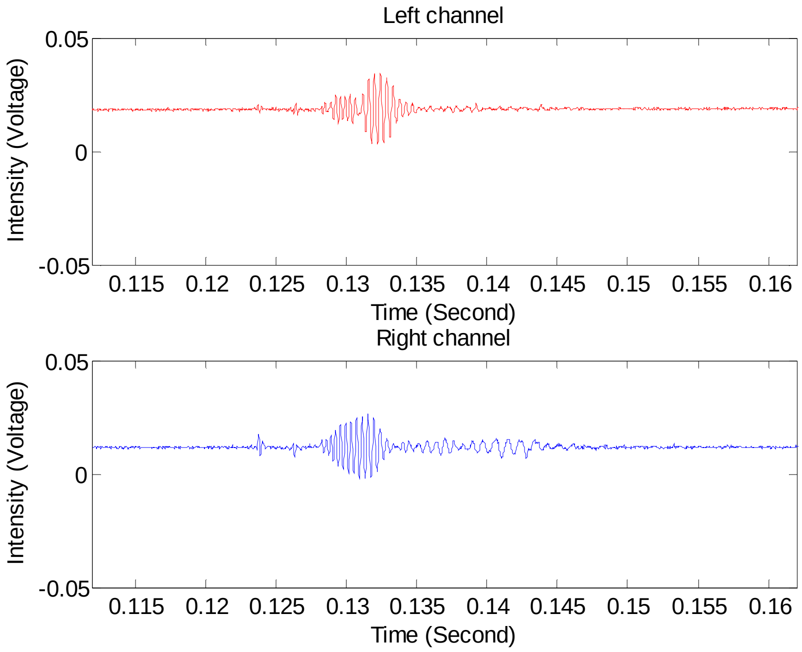
(b) Size 50 × 50 cm.

Figure 4.2 Output signals of the electronic "Bat Ears" for different obstacle sizes. (a) The recording result for an obstacle of size 20 × 20 cm, distance of 3 m, and azimuth 0°. (b) The recording result for an obstacle of size 50 × 50 cm, distance 3 m, and azimuth 0°.

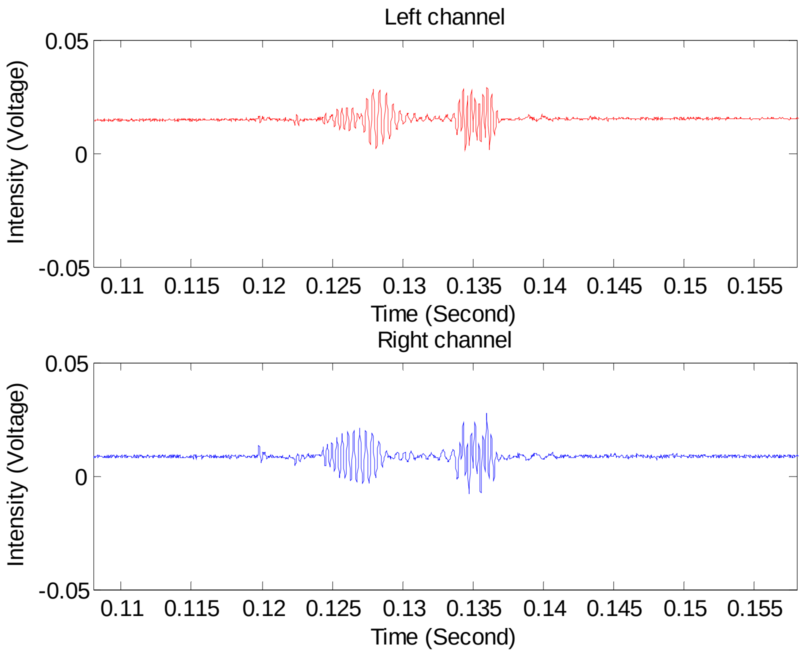
4.1.3. Obstacles with different distances

We tested the electronic "Bat Ears" for obstacles placed at different distances: 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 3.5 m, and 4 m. This experiment was performed to study the relationship between the distance of obstacle and the output of the electronic "Bat Ears".

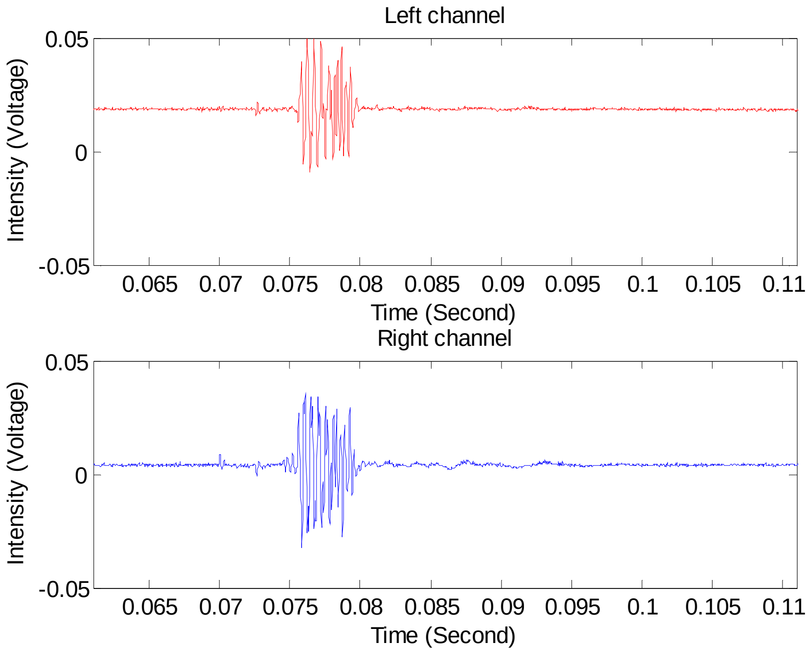
The recording results with 1 m, 2.5 m, and 3 m are shown in Figure 4.3 (with fixed obstacle size of 20 cm × 20 cm and azimuth of 0°). Figure 4.3 (a) has the same waveform as Figure 4.1, i.e., the electronic "Bat Ears" could not detect ultrasound echoes when the obstacle was placed at this location (size 20 × 20 cm, distance 3 m, and azimuth 0°). In Figure 4.3(b) (distance is 2.5 m), the first envelope is the crosstalk signal because its waveform is the same as Figure 4.1. The second envelope is the echo signal because the time delay between this envelope and the trigger signal was exactly the same as the expected ultrasound propagation time. In Figure 4.3 (c) (size 20 × 20cm, distance 1 m, and azimuth 0°), the intensity of the echo signal was stronger than that in Figure 4.3 (b), and the echo signal was mixed with the crosstalk signal.



(a) Distance 3 m.



(b) Distance 2.5 m.



(c) Distance1 m.

Figure 4.3 Output signals of the electronic "Bat Ears" for obstacles at different distances (size and azimuth were the same for all three distances). (a) 3 m. (b) 2.5 m. (c) 1 m.

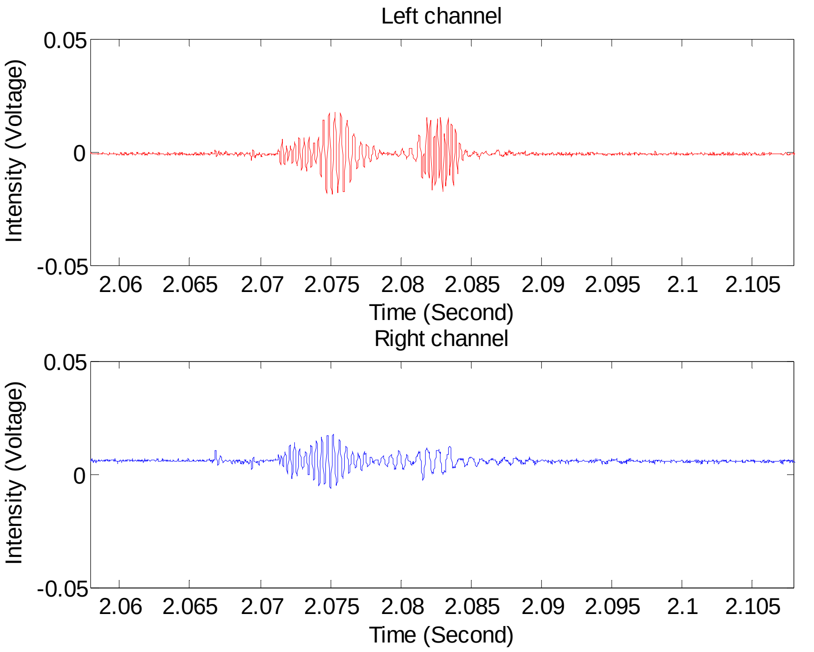
Based on a comparison of recording results in Figure 4.3, we learned that the intensity of the echo signal was correlated with the distance of the obstacle, i.e., the intensity of the echo signal increased as the distance of obstacle decreased. In addition, the crosstalk signal and echo signal were mixed together if the distance of the obstacle was very small (Figure 4.3 (c)). This may affect the performance of the electronic “Bat Ears” because the mixing may change the intensity and frequency of the echo signal.

4.1.4. Obstacles with different azimuths

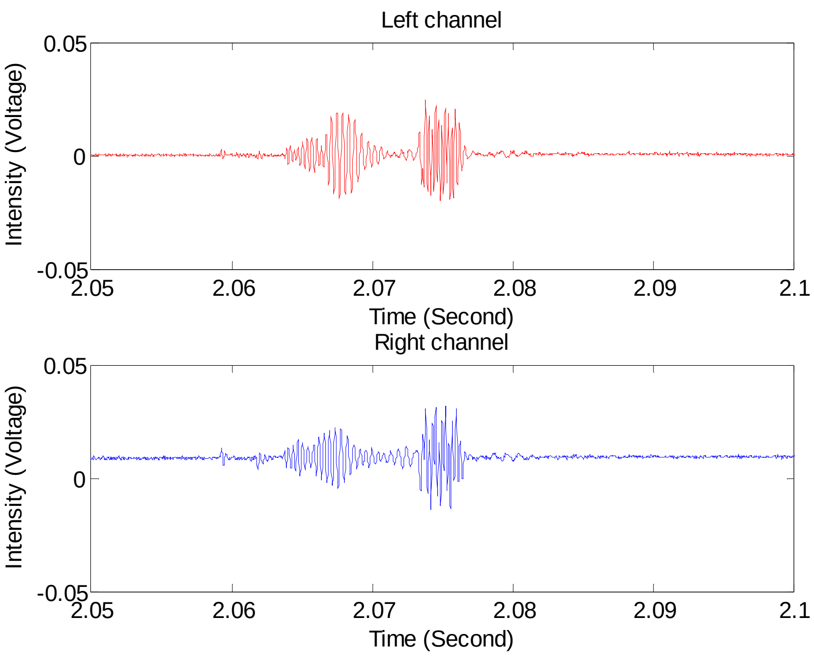
We also tested the electronic “Bat Ears” with different obstacle azimuth settings of 0°, -15°(left), +15°(right), -30°(left), and +30°(right) to study the relationship between the output signal of the electronic “Bat Ears” and different azimuth settings of the obstacle.

The recording results for different azimuths of 0°, -15° (left), and +15° (right) are shown in Figure 4.4 (with fixed obstacle size of 50 × 50 cm and distance of 2.5 m). When the obstacle was on the left (right), the intensity of the left (right) channel echo signal was stronger than that of the right (left) channel (Figure 4.4(a)). When the obstacle was in the center, the intensity of the left channel echo signal was equal to that of the right channel echo signal.

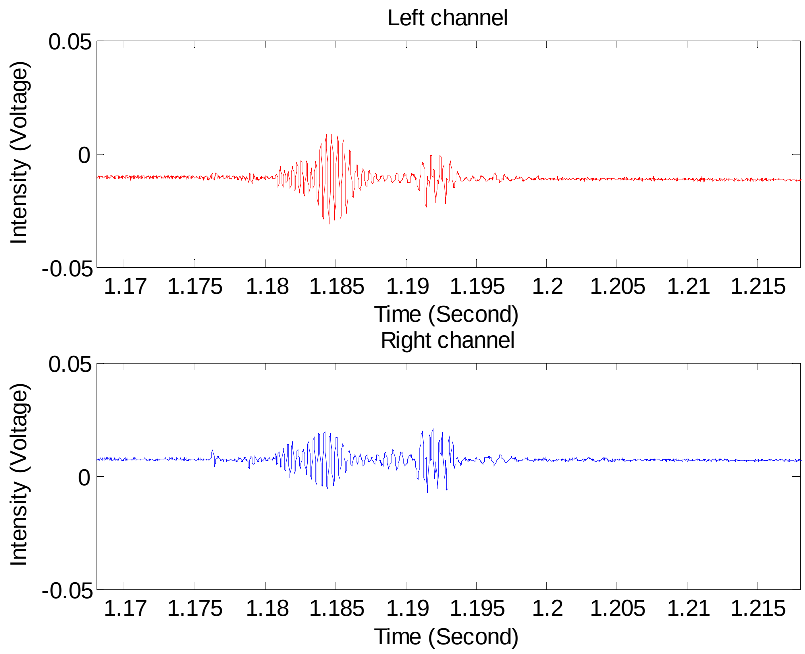
Although the echo signals of the two channels had significantly different waveforms when the obstacle was placed in the left, center, and right, it was hard to discriminate the azimuth of the obstacle through the output of the electronic "Bat Ears" because the crosstalk signal interfered with the waveforms of echo signal.



(a) Azimuth -15° (left).



(b) Azimuth 0° (center).



(c) Azimuth 15° (right).

Figure 4.4 Output signals of the electronic "Bat Ears" with different azimuths of obstacle; size (50 × 50 cm) and distance (2.5 m) are the same. (a) Azimuth -15° (left). (b) Azimuth 0° (center). (c) Azimuth 15° (right).

4.1.5. Discussion

The aforementioned recording results show that: (1) the crosstalk signal maintained similar waveform (intensity and frequency) for all the azimuths; (2) the echo signal was effective for encoding the distance and azimuth information of the obstacle; (3) the crosstalk signal interfered with the echo signal, and therefore, decreased the performance of the electronic "Bat Ears".

To optimize the output of the electronic "Bat Ears", i.e., to make it more effective/accurate for encoding distance and azimuth information, the crosstalk signal needs to be eliminated.

4.2. Offline study

Because the crosstalk signal maintained similar waveforms in all recording results and affected the effectiveness of the electronic “Bat Ears” in perceiving accurate spatial information, we performed an offline study to determine how we can effectively subtract it from the output of the electronic “Bat Ears”. Two different methods were examined. One method used the recording result of the obstacle-free case as the reference for subtracting the crosstalk signal in the present time cycle while the other used the crosstalk signal of the previous time cycle.

To realize the subtraction, we first adjusted the phase of the reference signal to make it consistent with the signal in present time cycle, and then we directly subtracted the reference signal from the signal in the present time cycle.

The result of the first method of subtraction is shown in Figure 4.5. As we can see in Figure 4.5 (c), although the subtraction did not thoroughly eliminate the crosstalk signal, it did decrease the intensity (decibel) of the original crosstalk signal in present time cycle. The residual crosstalk signal in the present time cycle was mainly caused by the intensity difference between the crosstalk signal in Figure 4.5 (a) and that in Figure 4.5 (b).

The result of subtracting the crosstalk signal from the previous time cycle is shown in Figure 4.6. Because the crosstalk signal of the last time cycle had nearly the same waveform as the crosstalk signal in the subsequent time cycle, the crosstalk signal in Figure 4.6 (a) was thoroughly eliminated.

Because both the two methods yielded acceptable subtraction results, we sequentially implemented these two methods with experimental circuits to eliminate the crosstalk signal in an online setting.

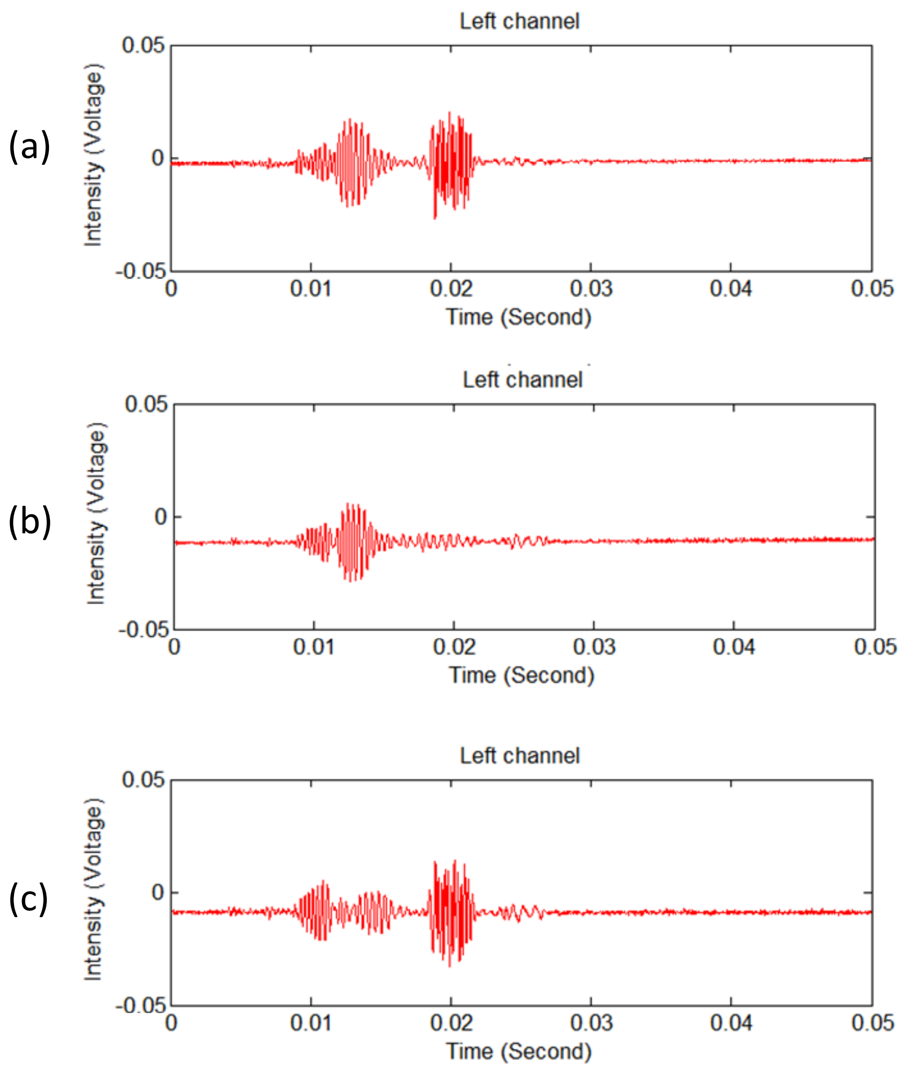


Figure 4.5 Result of the subtraction of the crosstalk signal with obstacle-free recording result as the reference. (a) Recording result in the present time cycle. (b) Recording result with no obstacles. (c) Result of subtraction of waveform in (b) from waveform in (a).

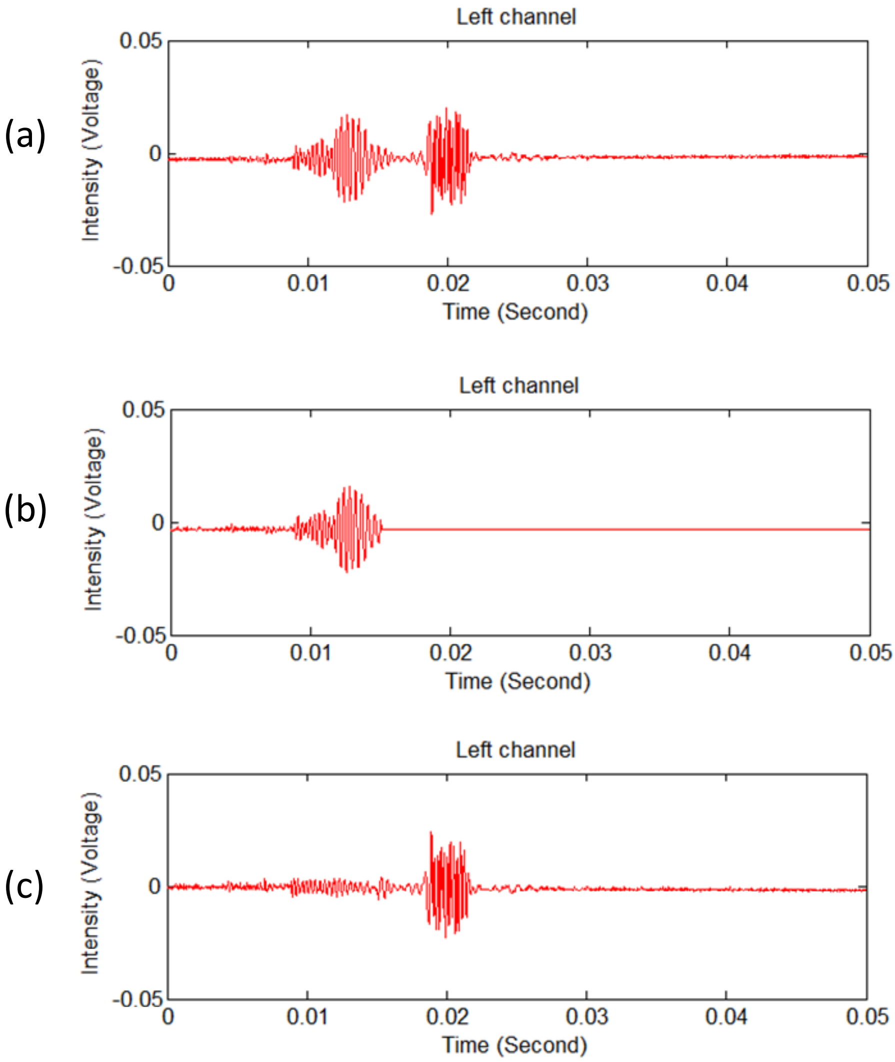


Figure 4.6 Result of the subtraction of the crosstalk signal from the last time cycle as the reference. (a) Recording result in the present time cycle. (b) Crosstalk signal of the last cycle. (c) The subtraction result, i.e., waveform of (b) subtracted from the waveform in (a).

4.3. Online study

To eliminate the crosstalk signal in the output of the electronic "Bat Ears" in an online setting, we designed an experimental circuit that can (1) store the crosstalk signal, (2) output the crosstalk signal with the same time cycle as the output of the electronic "Bat Ears", and (3) make the phase of the crosstalk signal consistent with that of the output of the electronic "Bat Ears". The principle of the experimental circuit is shown in Figure 4.7.

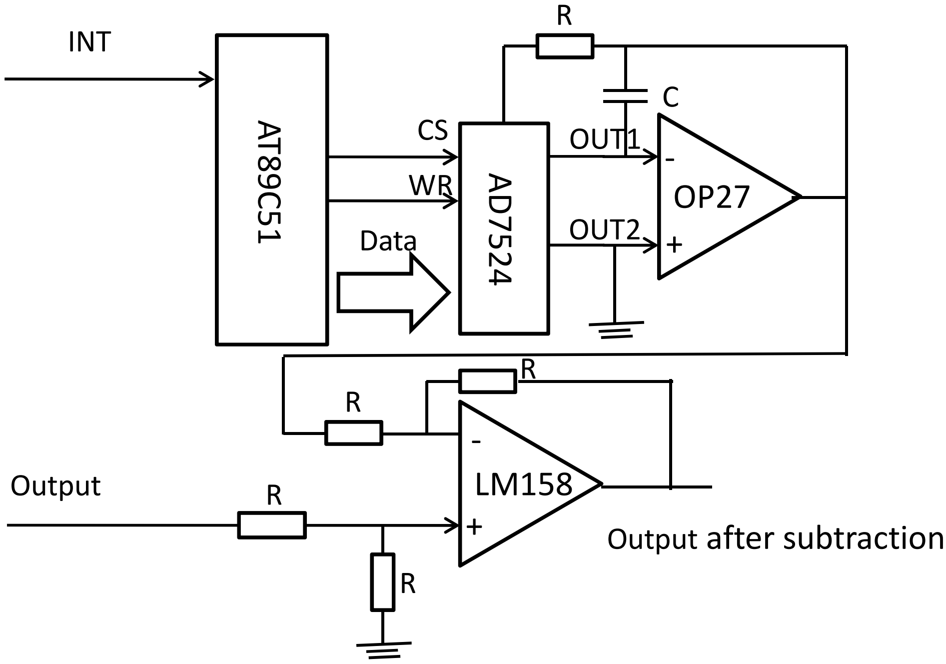


Figure 4.7 Schematic diagram of the principle of the experimental circuit.

4.3.1. Storing the crosstalk signal

After we obtained the recording result of the crosstalk signal, we used the MATLAB program to transform them into a table with a hex byte format and stored the table in the flash memory of AT89C51. The MATLAB program used for transformation is provided in Appendix B.

4.3.2. Output the crosstalk signal

By analyzing the frequency of the crystal oscillator (12M Hz) and the command execution time of the assembly language, we wrote a program to output the aforementioned table for a fixed frequency and a given time cycle.

The data output by AT89C51 was first processed with AD7524, which transformed the digital signal into an analog signal. Afterward, this analog signal was subtracted by the output of the electronic “Bat Ears” through the subtraction circuit.

4.3.3. Phase control

Although we could adjust the time cycle and the phase of the output of the AT89C51 to make it compatible with the output of the electronic “Bat Ears”, it was very time consuming to realize this in practice. To efficiently adjust the phase and time cycle of the output of the AT89C51, we used the interruption signal of the electronic “Bat Ears” to trigger the interruption program of AT89C51. The interruption signal was emitted in the beginning of each time cycle. If the interruption program of AT89C81 was enabled, it would output the stored table with a fixed phase and the given time cycle.

4.3.4. Results I

The experimental circuit for the first simulation method is shown in Figure 4.8. The related phase control result is shown in Figure 4.9. As we can see, the two signals had similar frequencies but slightly different intensities.

Figure 4.10 shows the output signal of the experimental circuit in a simple environment (single obstacle), and Figure 4.11 shows the output signal of experimental circuit in a complex environment (multiple obstacles). Because the two signals (i.e., the output of the electronic “Bat Ears” and the crosstalk signal output by the newly designed circuit) had slightly different intensities and frequencies, we could not thoroughly eliminate the crosstalk signal in the output of the electronic “Bat Ears”.

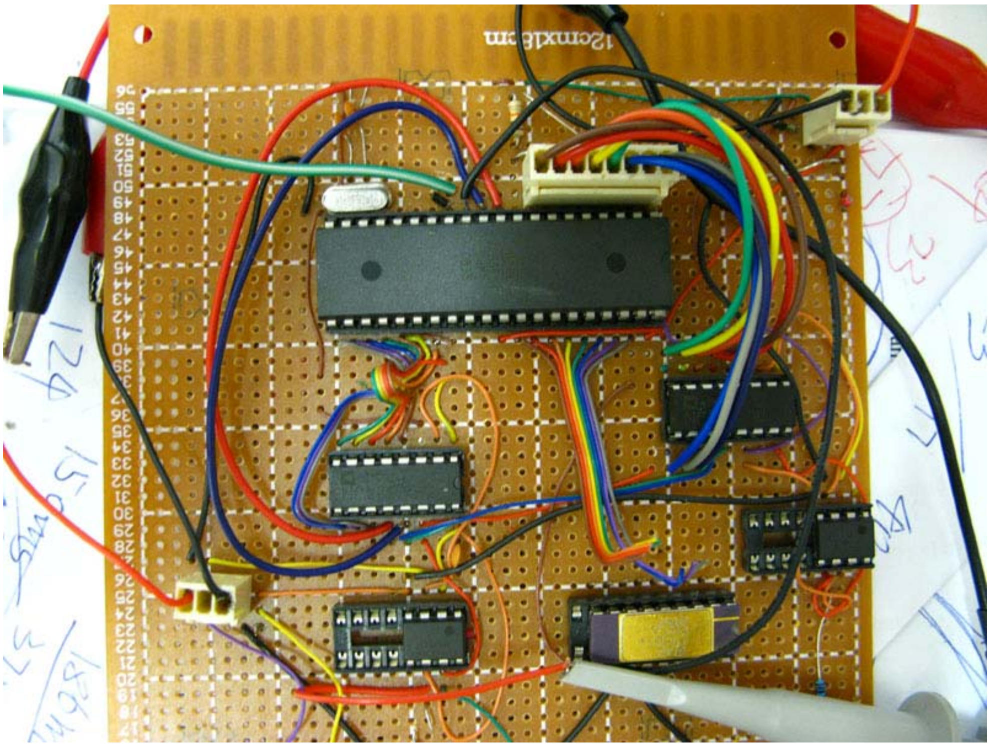


Figure 4.8 The experimental circuit for online study.

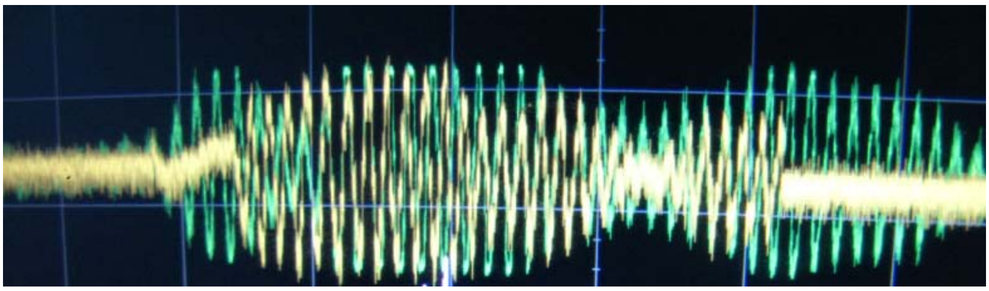


Figure 4.9 The phase control result. The green signal represents the crosstalk signal in the output of the electronic “Bat Ears”. The yellow signal represents the crosstalk signal generated by the newly designed experimental circuit.

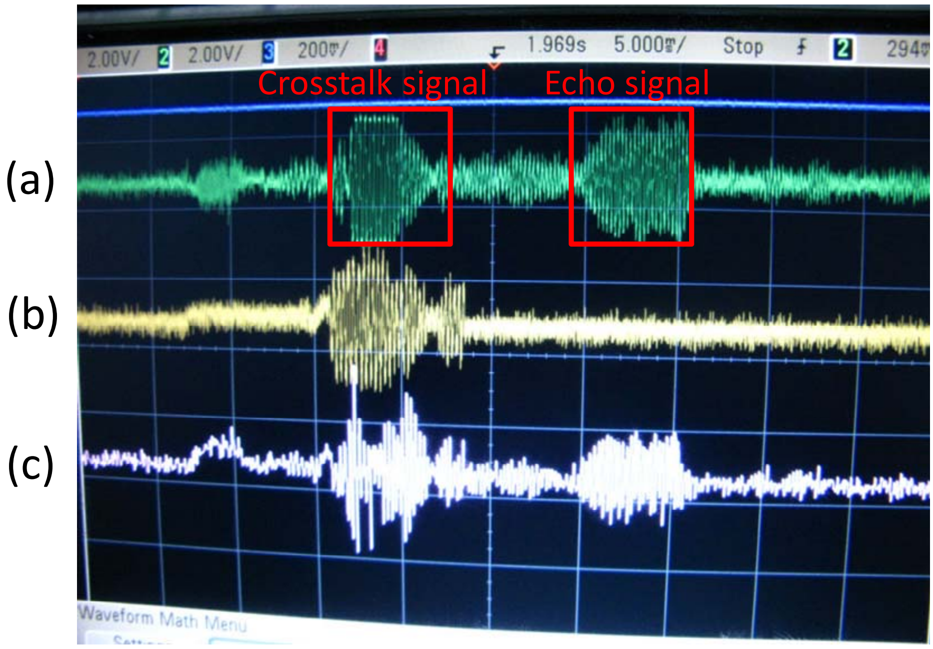


Figure 4.10 The output signal of the experimental circuit in a simple experimental environment, i.e., only one obstacle existed in the environment. (a) The output signal (green) of the electronic "Bat Ears". (b) The crosstalk signal (yellow) generated by the newly designed experimental circuit. (c) The output signal (pink) after subtraction.

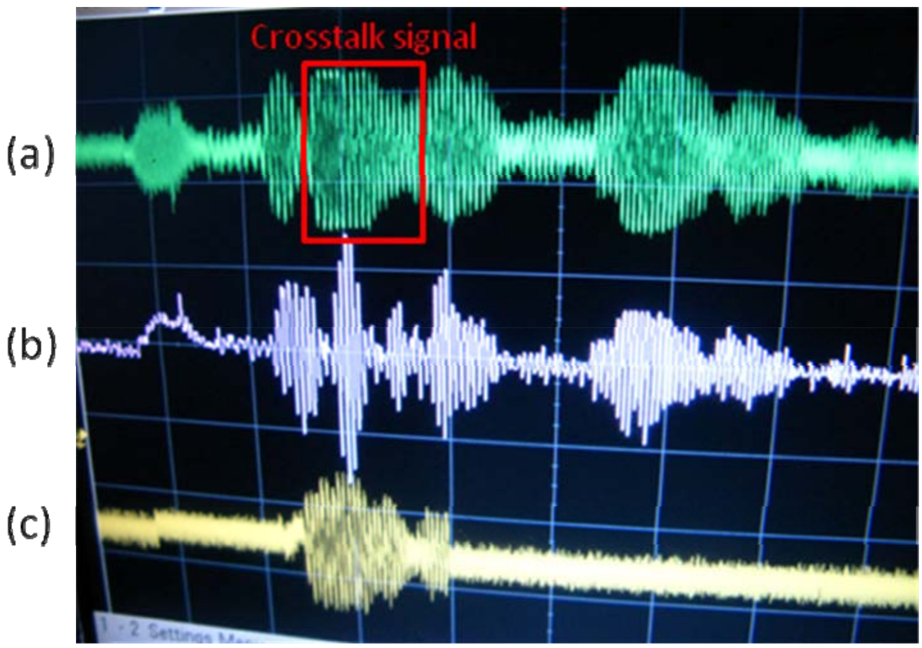


Figure 4.11 The output signal of the experimental circuit in a complex experimental environment, i.e., there were several different obstacles. (a) The output signal (green) of electronic "Bat Ears". (b) The output signal (pink) after subtraction. (c) The crosstalk signal (yellow) generated by the newly designed experimental circuit.

4.3.5. Results II

We could eliminate most of the crosstalk signal in the output of the electronic "Bat Ears" by using the experimental circuit in Figure 4.7. However, it was hard to thoroughly subtract it. This is because the output signal of the electronic "Bat Ears" and the crosstalk signal output by the newly designed circuit were recorded in different environments and under different battery conditions. Furthermore, because the AT89C51 is an 8-bit MCU, it constrained the output accuracy of the newly developed circuit.

To thoroughly eliminate the crosstalk signal in the output of the electronic "Bat Ears", we enhanced the aforementioned experimental circuit to enable it to update the table (storing the crosstalk signal) of the AT89C51 in an online setting. We used the ADC 0832 to transform the output of the electronic "Bat Ears" into 8-digit binary signals and then input them into the AT89C51 through the serial port under the control of a clock signal. In each time cycle, the AT89C51 not only output the table with controlled phase and frequency, but also updated the data of the table by the input of the serial port at the same time. The schematic diagram of the principle of the enhanced experimental circuit is shown in Figure 4.12.

According to the offline study result in Figure 4.6 and the experimental recording result in Figure 4.13, this enhanced experimental circuit was able to achieve a better elimination result. This was because the enhanced experimental circuit can update the table in the AT89C51 with the crosstalk signal of the last time cycle. This procedure eliminated the effect of different experimental environments and different battery conditions.

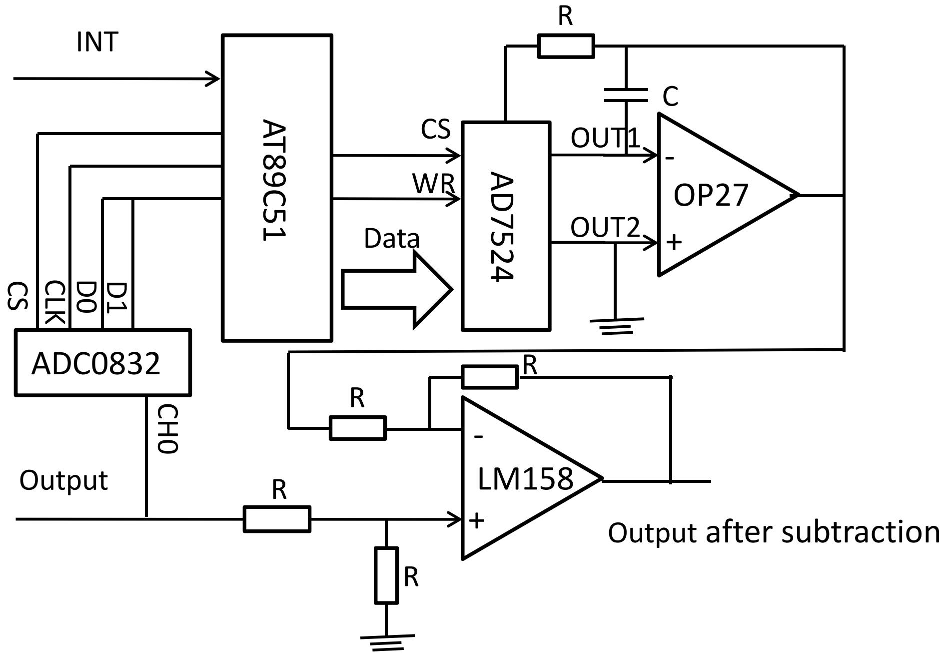


Figure 4.12 Schematic diagram of the principle of the enhanced experimental circuit.

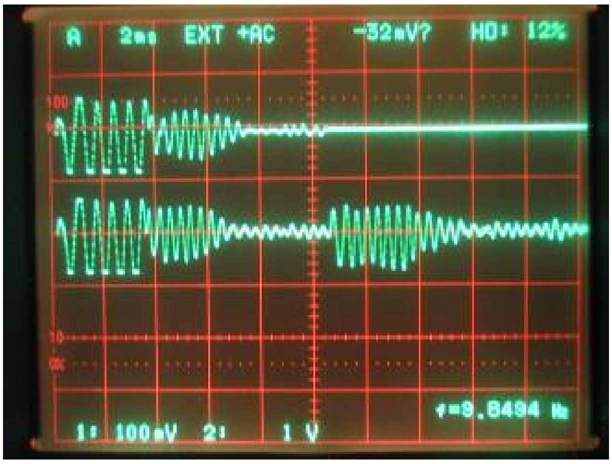


Figure 4.13 The output signal of the enhanced experimental circuit. (a) The output signal (bottom) of the electronic "Bat Ears". (b) The crosstalk signal (top) generated by the enhanced experimental circuit.

4.4. Matching results

To localize the sound, the human auditory system considers two kinds of information: the interaural time differences (ITDs) and interaural intensity differences (IIDs). For frequencies below 800 Hz, mainly the ITDs are used, while for frequencies above 1600 Hz, mainly the IIDs are used. For frequencies between 800 Hz and 1600 Hz, both mechanisms are used. According to equation (2.2), ultrasound and audible sound have different attenuation properties, which cause different IIDs. Because the output of the electronic “Bat Ears” only relies on the detected ultrasound IIDs to discriminate azimuth information and neglects the ITDs, people may not perceive accurate azimuth information when wearing the electronic “Bat Ears”. To solve this problem, we constructed a matching relationship between the audible sound and the output of the electronic “Bat Ears”. It was hard to directly construct the matching relationship between the audible sound and the output of electronic “Bat Ears”. Therefore, we used location information as the intermediary to solve this problem.

4.4.1. Location versus audible sound

Similar to ultrasound, given the location, the initial amplitude, and frequency information, the audible sound intensity at the two ears can be calculated by the following equation:

$$A = A_0 \cdot e^{-\alpha x}, \tag{4.1}$$

where A represents the peak amplitude of the audible sound propagated at distance x, and A_0 represents the initial peak amplitude. The attenuation coefficient α (depending on the frequency) is given in nepers per meter (Np/m) or decibels per meter (dB/m), and it is given by the following expression:

$$\alpha = \frac{0.1151}{v} U_t \tag{4.2}$$

where v is the velocity of the sound in meters per second, and U_t is in decibels per second.

Given the azimuth and distance information, the ITD can be calculated by equation (2.5) or (2.6).

In summary, given the frequency, the initial amplitude, and the location (including azimuth and distance) information, we can obtain both the IIDs and ITDs at the two ears. Generally, we selected frequencies between 800 Hz and 1600 Hz to output the audible sound because both the IIDs and ITDs work in this frequency band.

4.4.2. Location versus the output of the electronic "Bat Ears"

From the empirical studies in Section 4.1, we learned that with a fixed size of obstacle: (1) the echo signal decreased with increased distance; (2) echo signals of the two channels had the same intensity when the obstacle was in the center; (3) the echo signal of the left channel (right channel) was stronger than that of the right channel (left channel) if the obstacle was on the left (right). These results motivated us to construct an explicit matching relationship between the location and the output of the electronic “Bat Ears”.

We calculated standard deviations of the two channels recordings (D_L for left channel and D_R for right channel) in a time cycle. Then we obtained a coordinate (D_L, D_R) to represent each recording result. On plotting each recording result (Figure 4.14), we found that the recording results with obstacles in the center were approximately located in the line y=x, while recording results with obstacles in the left (right) was closer to the y (x) axis. The distance from the plotted coordinate to the origin in the figure is correlated with the actual distance from the obstacle to the electronic “Bat Ears”

Because of the aforementioned scattered properties, we can plot all recording results in Figure 4.14 and train a classifier, e.g., nearest neighbor (NN) classifier or support vector machine (SVM) (Duda et. al., 2001), to define different regions of Figure 4.14 according to their respective locations. Given a new input, we can first calculate its coordinate and then define its location through the trained classifier. After location information and intended audible sound frequency were obtained, it was easy to calculate the IID and ITD of the audible sound. This newly generated audible sound can be used to perceive more accurate spatial information compared with the original output of the electronic “Bat Ears”.

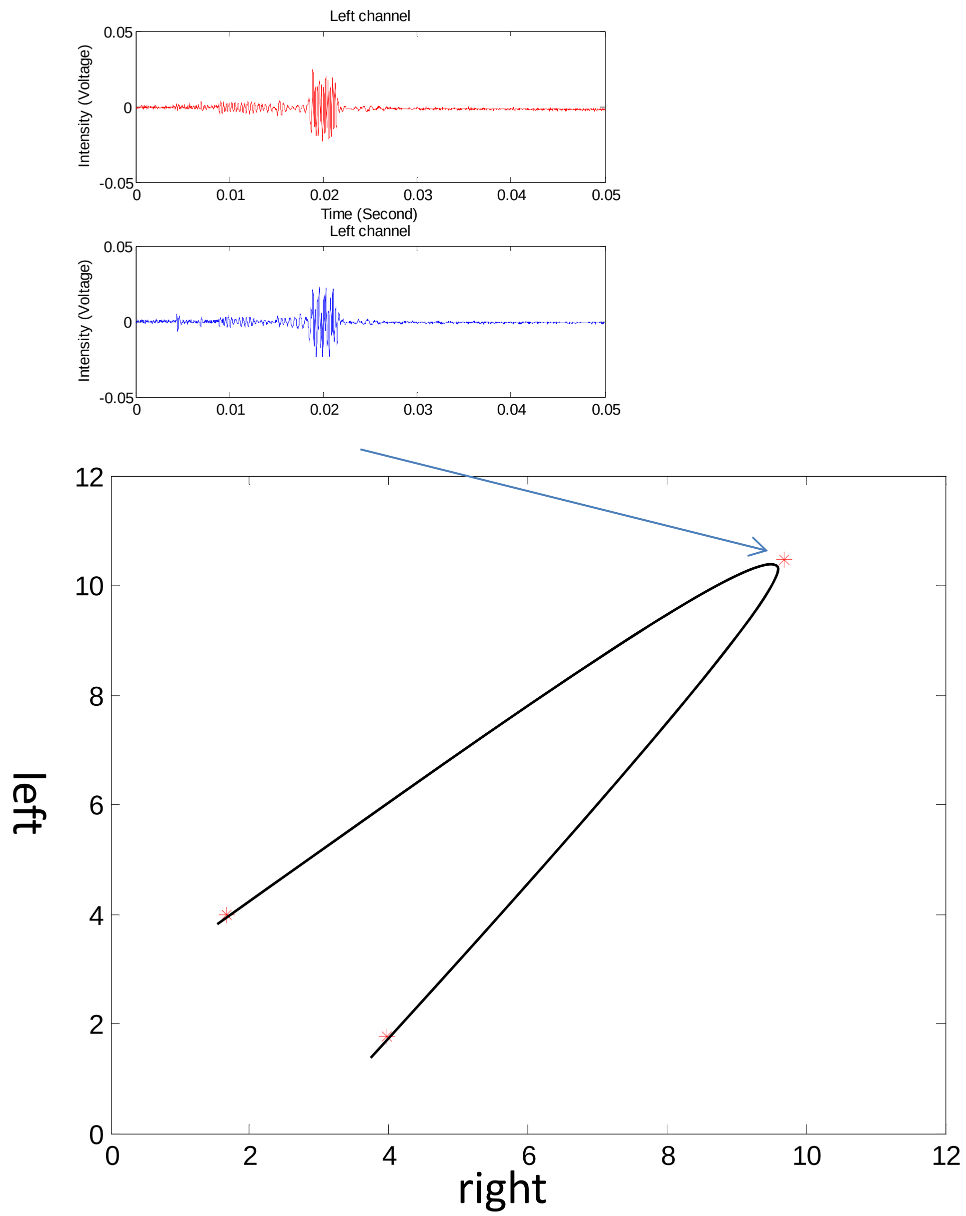


Figure 4.14 Coordinates of recording results for instances with azimuths of -15°, 0°, 15° (fixed size of 50x50 cm and distance of 2.5 m). Notice that the crosstalk signal is eliminated.

Chapter V Discussion

In this chapter, we discuss about the recording results, the online study result, and the matching study result in the previous section.

5.1. About the recording results

With the recording results, we note that there was a slight intensity difference with the crosstalk signal of all recording results. This difference was mainly caused by the depletion of the battery voltage, which would affect the function of voltage amplifiers in the electronic “Bat Ears”.

To overcome this problem, it is recommended to adopt durable batteries to power the electronic “Bat Ears”.

5.2. About the online study results

In the present study, both the two experimental circuits have shown their effectiveness for eliminating the crosstalk signal. In the future, two concerns can be addressed to further improve the effectiveness of these two circuits. One is to use 16-bit MCU to improve the output accuracy of the proposed circuits, which initially used 8-bit MCU. The other is to use one battery to power both the electronic “Bat Ears” and the newly proposed circuits. This can eliminate the affect of battery differences between the electronic “Bat Ears” and the newly developed circuits.

Moreover, we may further investigate the effectiveness of the two experimental circuits via subject test, i.e., compare the effectiveness of the electronic “Bat Ears” implanted with newly developed circuits against the original electronic “Bat Ears” though the use of blind people. For example, we could test the subjects’ (wearing the two versions of electronic “Bat Ears”) localization accuracy when the obstacle is put in different locations.

5.3. About the matching results

In the present study, we presented an implicit method to construct a matching relationship between the audible sound and the output of the electronic “Bat Ears”. However, we did not realize it in an online setting. In the future, this concern could be addressed to make the user perceive the echoed ultrasound like the echoed sound. This will further improve the performance of the electronic “Bat Ears”.

Chapter VI Conclusion

In this thesis, we studied the output properties of the electronic “Bat Ears” and conducted both offline and online studies to eliminate the crosstalk between the transmitter module and receiver modules. We also presented a method to construct a matching relationship between the output of the electronic “Bat Ears” and the theoretical audible sound.

6.1. Significance of the present study

We recorded and analyzed the output of the electronic “Bat Ears” with different obstacle sizes, distances, and azimuths and found that the echo signal showed different characteristics under different recording conditions. With a fixed location (i.e., distance and azimuth), the bigger the obstacle size was, the stronger the echo signal; with a fixed obstacle size and azimuth, the nearer the distance was, the stronger the echo signal; and with fixed obstacle size and distance, the echo signals of the two channels had the same intensity when the obstacle was in the center, while the left (right) channel echo signal was stronger than the right (left) channel when the obstacle was in the left (right). In addition, we found that the crosstalk signal had a fairly stable waveform in all recordings. Thus it was reasonable to directly subtract it from the output of the electronic “Bat Ears”.

In the offline study, we simulated two different methods to eliminate the crosstalk signal in the output of the electronic “Bat Ears”. One method used the recording result of the obstacle-free case as the reference for subtracting crosstalk signal in the present time cycle, while the other used the crosstalk signal of the last time cycle. Simulation results showed that both these two methods can decrease the effect of crosstalk signal and the second method, which used the crosstalk signal of the last cycle, can achieve better results than the first.

In the online study, an experimental circuit was designed to eliminate crosstalk signal in an online setting. In addition, an enhanced version of the experimental circuit, which has the potential to yield even better results, was also discussed.

Psychophysics experiments told us that human could perceive only a single source of sound when two successive sounds that spatially separated with each other (Good MD and Gilkey, 1996) (i.e., the interference effect mentioned previously). After the elimination of the crosstalk we expect that the “Bat Ears” would improve the echolocation of the ultrasound source, though psychophysical experiments have to be executed to justify the claim.

In the matching study, the different attenuation properties of ultrasound and audible sound were analyzed, and a method to construct a matching relationship between theoretical audible sound and the output of the electronic “Bat Ears” was presented. The results obtained in the present study would be able to provide a database for the future exploration to find out a conversion from ultrasound propagation to the sound propagation in an online setting. With the conversion, we would be able to perceive the echoed ultrasound like the echoed sound, so that we could localize the echoed sound source with our existing calculation circuits in our brain (Rayleigh, 1907; Wang and Brown, 2006).

6.2. Limitations and future work

There are several limitations in the studies presented in this thesis.

First, because the “Bat Ears” were battery-powered, the intensity of the recording results decreased as consumption of the battery increased. This phenomenon affected the effectiveness of the offline and online studies. We recommend that future works adopt more durable batteries to power the electronic “Bat Ears”.

Second, because the AT89C51 is an 8-bit controller, it constrained the output accuracy of the proposed circuits, which affected the effectiveness of the online study. We recommend the use of a 16-bit controller to address this problem in future works.

Third, because we did not realize the matching study in an online setting, we would like to address this concern to further enhance the performance of electronic “Bat Ears” in the future.

Fourth, we would like to compare the improved electronic “Bat Ears” against the original electronic “Bat Ears” via subject test, i.e., test them with blind people, to demonstrate the effectiveness of the newly developed electronic “Bat Ears”.

Fifth, we would be interested in testing electronic “Bat Ears” and the enhanced version with obstacles of irregular shapes and sizes or testing the electronic “Bat Ears” with multiple obstacles. This study will be helpful for the practical application of electronic “Bat Ears”.

Finally, it is also meaningful to compare the performance of electronic “Bat Ears” when solely IID, solely ITD, or both the IID and ITD are used. Meanwhile, test the different frequency ranges in humans to see which they perform best is also a meaningful work for electronic “Bat Ears”.

Reference

Bensaoula S, Boulebtateche B, Bedda M (2006) Electronic device for blind mobility aid. Journal of Engineering and Applied Sciences 1(4): 514-522.

Boudreau JC, Tsuchitani C (1968) Binaural interaction in the cat superior olive S segment. Journal of Neurophysiology 31:442-454.

Bousbia-Salah M, Fezari M (2007) A navigation tool for blind people. In: Tarek S, editor, Innovations and Advanced Techniques in Computer and Information Sciences and Engineering.

Burkhard MD, Sachs RM (1974) Anthroponetric manikin for acoustic research. Journal of the Acoustical Society of America 58(1):214-222.

Caird D, Klinke R (1983) Processing of binaural stimuli by cat superior olivary complex neurons. Experimental Brain Research 52:385-399.

Carr CE, Konishi M (1988) Axonal delay lines for time measurement in the owl's brainstem. Proceedings of the National Academy of Sciences 85:8311–8315.

De Volder AG, Catalan-Ahumada M, Robert A, Bol A, Labar D, Coppens A, Michel C, Veraart C (1999) Changes in occipital cortex activity in early blind humans using a sensory substitution device. Brain Research 826(1): 128-134.

Domnitz RH, Colburn HS (1977) Lateral position and interaural discrimination. Journal of the Acoustical Society of America 61:1586-1598.

Duda RO, Hart PE, Stork DG (2001) Pattern Classification, New York: John Wiley & Sons, ISBN: 0-471-05669-3.

Farcy R, Leroux R, Jucha A, Damaschini R, Grégoire C, Zogaghi A (2006) Electronic travel aids and electronic orientation aids for blind people: technical, rehabilitation and everyday life point of view. Conference and Workshop on Assistive Technologies for People with Vision and Hearing Impairments Technology for Inclusion.

Gardner B, Martin K (1994) HRTF measurements of a KEMAR dummy-head microphone. Technical Report 280, MIT Media Lab, Perceptual Computing Group.

Good MD, Gilkey RH (1996) Sound localization in noise: The effect of signal-to-noise ratio. Journal of the Acoustical Society of America 99(2):1108-1117.

He J, Pan G, He J, Chan CCH (2005) An electronic device for helping the vision impaired to walk and identify obstacles. China Patent: 200520109184.1.

Hershkowitz RM, Durlach NI (1969) Interaural time and amplitude jnds for a 500-hz tone. Journal of the Acoustical Society of America 46:1464-1467.

Horchler AD, Reeve RE, Webb BH, Quinn RD (2003) Robot phonotaxis in the wild: a biologically inspired approach to outdoor sound localization. 11th International Conference on Advanced Robotics (ICAR'03).

Horiuchi T, Hynna KM (2001) Spike-based VLSI modeling of the ILD system in the echolocating bat. Neural Networks (Special Issue on Spiking Neurons in Neuroscience and Technology) 14: 755-762.

Ihara I (2008) Ultrasonic sensing: fundamentals and its applications to nondestructive evaluation. In: Mukhopadhyay SC, Huang RYM, editors. Sensors Advancements in Modeling. Design Issues, Fabrication and Practical Applications. Lecture Notes in Electrical Engineering 21:287-305.

Kay L (2000) Auditory perception of objects by blind persons, using a bioacoustic high resolution air sonar. Journal of Acoustic Society of America 107(6): 3266-3275.

Kažys R, Mažeika L, Tumšys O (2000) Experimental investigation of performance of the binaural sonar. Ultragarsas (Ultrasound) Kaunas: Technologija 1(42): 29.

Kažys R, Mažeika L, Tumšys O (2002) The experimental investigation of spatial resolution of ultrasonic coordinate meter. Ultragarsas (Ultrasound) 1 (42): 31-33.

Kuc R (1996) Fusing binaural sonar information for object recognition. Proceedings IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems 727-735.

Kuhn GF (1977) Model for the interaural time differences in the azimuthal plane. The Journal of the Acoustical Society of America 62:157-167.

Kuwada S, Batra R, Fitzpatrick DC (1997) Neural processing of binaural temporal cues. In: Gilkey RH, Anderson TR, editors, Binaural and Spatial Hearing in Real and Virtual Environments, chapter 20: 399-425.

Lewinger W, Watson M, Roger Q (2006) Obstacle avoidance behavior for a biologically-inspired mobile robot using binaural ultrasonic sensors. Proceedings of the IEEE International Conference on Intelligent Robots and Systems.

Lund HH, Webb B, Hallam J (1998) Physical and temporal scaling considerations in a robot model of cricket calling song preference. Artificial Life 4: 95-107.

McAlpine D, Jiang D, Palmer AR (1996) Interaural delay sensitivity and the classification of low best-frequency binaural responses in the inferior colliculus of the guinea pig. Hearing Research 97:136-152.

Moita F, Lopes AC, Nunes U (2007) A fast firing binaural system for ultrasonic pattern recognition. Journal of Intelligent and Robotic Systems 50(2): 141-162.

Mwakibinga T, Lee J (2005) Altitude control of an unmanned aerial vehicle using a binaural bat echolocation system. RITE Technical Reports.

Pan AW, He J (2002) Electronic “bat ears” for vision impaired. China patent: 01255716.1.

Peremans H, Reijniers J (2005) The CIRCE head: a biomimetic sonar system. Artificial Neural Networks: Biological Inspirations - ICANN 3696:283-288.

Pinho C, Ferreira JF, Bessière P, Dias J (2008) A bayesian binaural system for 3D sound-source localization. Proceedings of the 2008 International Conference on Cognitive Systems.

Rayleigh L (1907) On our perception of sound direction. Philosophical Magazine 13:214-232.

Rose JL (1999) Ultrasonic waves in solid media. Cambridge University Press, Cambridge.

Rose JE, Gross NB, Geisler CD, Hind JE (1966) Some neural mechanisms in the inferior colliculus of the cat which may be relevant to localization of a sound source. Journal of Neurophysiology 29:288-314.

Schroeder MR (1977) New viewpoints in binaural interactions. In: Evans EF and Wilson JP, editors. Psychophysics and Physiology of Hearing 455-467.

Shamma SA, Shen N, Gopalaswamy P (1989) Binaural processing without neural delays. The Journal of the Acoustical Society of America, 86:987-1006.

Shaw EAG (1997) Acoustical features of the human external ear. In: Gilkey RH and Anderson TR, editors. Binaural and Spatial Hearing in Real and Virtual Environments, chapter 2:25-47.

Shi R, Horiuchi T (2004) A VLSI model of the bat lateral superior olive for azimuthal echolocation. Proceedings of the 2004 International Symposium on Circuits and Systems (ISCAS'04).

Stanford, TR, Kuwada S, Batra R (1992) A comparison of the interaural time sensitivity of neurons in the inferior colliculus and thalamus of the unanesthetized rabbit. The Journal of Neuroscience 12: 3200-3216.

Su MC, Chen CY, Su SY, Chou CH, Hsiu HF, Wang YC (2001) A portable communication aid for deaf-blind people. IEE Computing and Control Engineering Journal 12(1): 37-43

Thurston RN, Pierce AD (Eds.) (1999) Ultrasonic instruments and devices I&II. Academic Press, San Diego.

Wang DL, Brown GJ (Eds.) (2006) Computational auditory scene analysis: Principles, algorithms, and applications. IEEE Press / Wiley-Interscience.

Wightman FL, Kistler DJ (1989a) Headphone simulation of free-field listening. I: Stimulus synthesis. Journal of the Acoustical Society of America 85:858-867.

Wightman FL, Kistler DJ (1989b) Headphone simulation of free-field listening. II: Psychophysical validation. Journal of the Acoustical Society of America 87:868-878.

Wightman FL, Kistler DJ (1997) Factors affecting the relative salience of sound localization cues. In: Gilkey RH, Anderson TR, editors. Binaural and Spatial Hearing in Real and Virtual Environments 1-23.

Yin TCT, Kuwada S (1984) Neuronal mechanisms of binaural interaction. In: Edelman GM, Gall WE, Cowan WM, editors. Dynamic Aspects of

Neocortical Function 263-313.

Young SR, Rubel EW (1983) Frequency-specific projections of individual neurons in chick brainstem auditory nuclei. The Journal of Neuroscience 3:1373-1378.

Appendix A: The schematic diagram of electronic "Bat Ears"

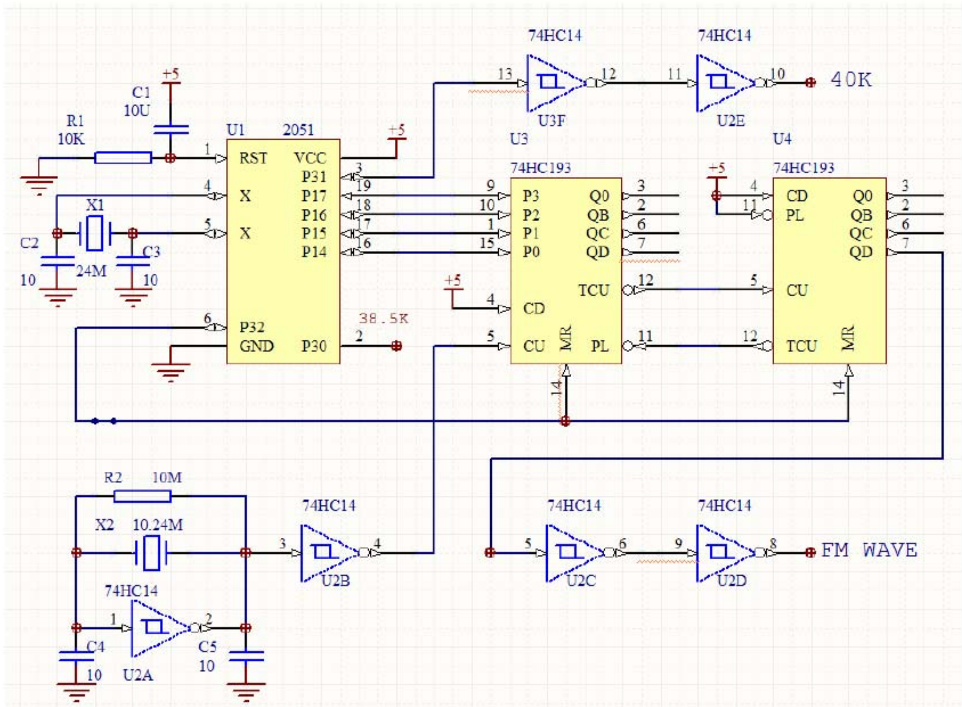


Figure A1 The schematic diagram for the transmitter of the electronic "Bat Ears". AT89C2051 is the controller for generating the 40 kHz ultrasound. The two 74HC193s are used to generating the FM signal which are useful demodulating the echo signals.

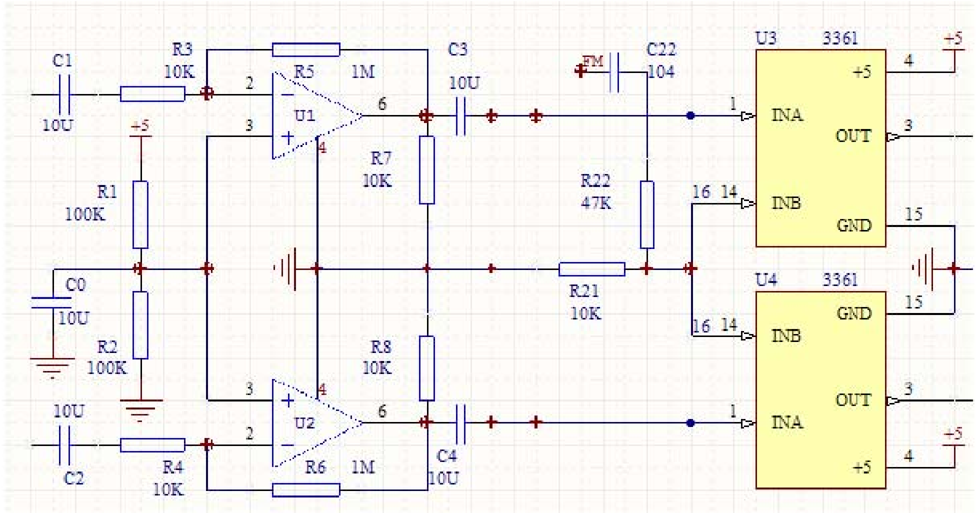


Figure A2 The schematic diagram for the receiver of the electronic "Bat Ears". (Part I) U1 and U2 are two amplifiers (OP27) for the left and right channel echo signals respectively. 3361 is the multiplier for multiply the echo signal and FM signal.

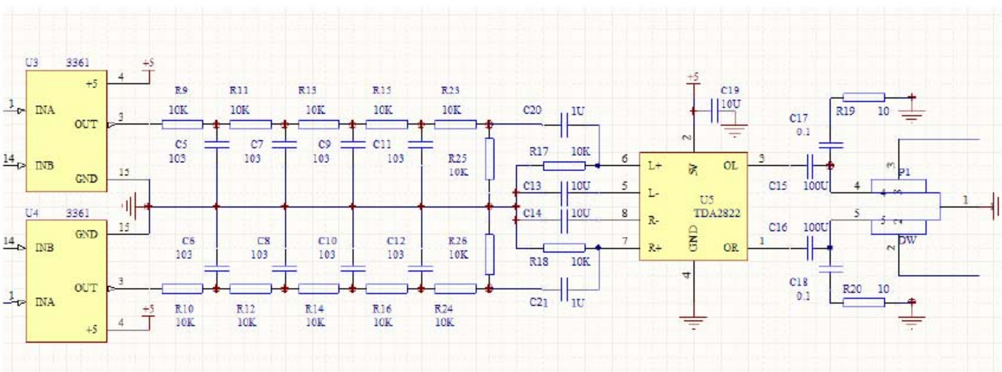


Figure A3 The schematic diagram for the receiver of the electronic "Bat Ears". (Part II) Resistors and capacitor constitute a low pass filter network to extract the expected low frequency signals.

Appendix B: MATLAB code for transforming the table of hex type format

```
clear all
[Y,FS,NBITS,OPTS]=wavread('data.wav');
[m,n]=size(Y);
m=m-1;
m=m/FS;
i=FS/10*1:1:FS/10*2.4;
i=i(1:2:end);
figure;
subplot(2,1,1);
mean_Y=mean(Y(i,1));
Y(i,1)=Y(i,1)-mean_Y;
plot(i/FS,Y(i,1),'r-');
table=['00H, ';'01H, ';'02H, ';'03H, ';'04H, ';'05H, ';'06H, ';'07H, ';'08H, ';'09H, ';'0AH, ';'0BH, ';'0CH, ';'0DH, ';'0EH, ';'0FH, ';...
    '10H, ';'11H, ';'12H, ';'13H, ';'14H, ';'15H, ';'16H, ';'17H, ';'18H, ';'19H, ';'1AH, ';'1BH, ';'1CH, ';'1DH, ';'1EH, ';'1FH, ';...
    '20H, ';'21H, ';'22H, ';'23H, ';'24H, ';'25H, ';'26H, ';'27H, ';'28H, ';'29H, ';'2AH, ';'2BH, ';'2CH, ';'2DH, ';'2EH, ';'2FH, ';...
    '30H, ';'31H, ';'32H, ';'33H, ';'34H, ';'35H, ';'36H, ';'37H, ';'38H, ';'39H, ';'3AH, ';'3BH, ';'3CH, ';'3DH, ';'3EH, ';'3FH, ';...
    '40H, ';'41H, ';'42H, ';'43H, ';'44H, ';'45H, ';'46H, ';'47H, ';'48H, ';'49H, ';'4AH, ';'4BH, ';'4CH, ';'4DH, ';'4EH, ';'4FH, ';...
    '50H, ';'51H, ';'52H, ';'53H, ';'54H, ';'55H, ';'56H, ';'57H, ';'58H, ';'59H, ';'5AH, ';'5BH, ';'5CH, ';'5DH, ';'5EH, ';'5FH, ';...
    '60H, ';'61H, ';'62H, ';'63H, ';'64H, ';'65H, ';'66H, ';'67H, ';'68H, ';'69H, ';'6AH, ';'6BH, ';'6CH, ';'6DH, ';'6EH, ';'6FH, ';...
    '70H, ';'71H, ';'72H, ';'73H, ';'74H, ';'75H, ';'76H, ';'77H, ';'78H, ';'79H, ';'7AH, ';'7BH, ';'7CH, ';'7DH, ';'7EH, ';'7FH, ';...
    '80H, ';'81H, ';'82H, ';'83H, ';'84H, ';'85H, ';'86H, ';'87H, ';'88H, ';'89H, ';'8AH, ';'8BH, ';'8CH, ';'8DH, ';'8EH, ';'8FH, ';...
    '90H, ';'91H, ';'92H, ';'93H, ';'94H, ';'95H, ';'96H, ';'97H, ';'98H, ';'99H, ';'9AH, ';'9BH, ';'9CH, ';'9DH, ';'9EH, ';'9FH, ';...
```

```
'0A0H,';'0A1H,';'0A2H,';'0A3H,';'0A4H,';'0A5H,';'0A6H,';'0A7H,';'
0A8H,';'0A9H,';'0AAH,';'0ABH,';'0ACH,';'0ADH,';'0AEH,';'0AFH,';...
'0B0H,';'0B1H,';'0B2H,';'0B3H,';'0B4H,';'0B5H,';'0B6H,';'0B7H,';'
0B8H,';'0B9H,';'0BAH,';'0BBH,';'0BCH,';'0BDH,';'0BEH,';'0BFH,';..
.'0C0H,';'0C1H,';'0C2H,';'0C3H,';'0C4H,';'0C5H,';'0C6H,';'0C7H,';
'0C8H,';'0C9H,';'0CAH,';'0CBH,';'0CCH,';'0CDH,';'0CEH,';'0CFH,';.
..'0D0H,';'0D1H,';'0D2H,';'0D3H,';'0D4H,';'0D5H,';'0D6H,';'0D7H,'
;'0D8H,';'0D9H,';'0DAH,';'0DBH,';'0DCH,';'0DDH,';'0DEH,';'0DFH,';
...'0E0H,';'0E1H,';'0E2H,';'0E3H,';'0E4H,';'0E5H,';'0E6H,';'0E7H,
';'0E8H,';'0E9H,';'0EAH,';'0EBH,';'0ECH,';'0EDH,';'0EEH,';'0EFH,'
;...
'0F0H,';'0F1H,';'0F2H,';'0F3H,';'0F4H,';'0F5H,';'0F6H,';'0F7H,';'
0F8H,';'0F9H,';'0FAH,';'0FBH,';'0FCH,';'0FDH,';'0EEH,';'0FFH,';..
.
   ];
%  axis([0 0.1 mean_Y-0.02 mean_Y+0.05]);
subplot(2,1,2);
mean_Y=mean(Y(i,2));
Y(i,2)=Y(i,2)-mean_Y;
Y(i,2)=Y(i,2)/(max(Y(i,2)))*2.5;
plot(i/FS,Y(i,2),'b-');


DATA=Y(i,2);
len=length(DATA);
DATA2=cell(1,len);
for i=1:len
   index=floor((DATA(i)+2.5)/0.0195);
   DATA2{1,i}=table(index,:);
end
m=floor(len/8);
all_table=[];
for i=1:m
   temp_table=['DB
',DATA2{1,(i-1)*8+1},DATA2{1,(i-1)*8+2},DATA2{1,(i-1)*8+3},DATA2{
1,(i-1)*8+4},DATA2{1,(i-1)*8+5},DATA2{1,(i-1)*8+6},DATA2{1,(i-1)*
8+7},DATA2{1,(i-1)*8+8}];
   all_table=[all_table;temp_table];
end
```

Appendix C: Assembly language code for controlling the electronic “Bat Ears”.

Notice: this is just a short version for reference.

```
CLR P3.2 ;使复位脚无效
MOV P1,#00H
START:    MOV R0,#078H ;设置刚开始的循环次数
;
;             SETB P3.2            ;使计数器复位
;3ms 内产生 40khz 的信号，之后关断
LOOP:     CLR P3.1               ;产生正反信号
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP;10 个 nop
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP;10 个 nop
```

```
NOP
NOP
NOP
NOP;总共 25 个 nop

SETB P3.1
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP;10 个 NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP;10 个 NOP
NOP
NOP;总共 21 个 nop
NOP
DJNZ R0,LOOP
ORL P3,#02H         ;置 P3.1 无效
;2.5ms 内产生 40khz 的信号，之后关断
;中间空闲 1 毫秒
            MOV R0,#14H         ;空耗 3960 个机时
```

```
IDLE1:    MOV R1,#062H
IDLE2:    NOP
          DJNZ R1,IDLE2
          DJNZ R0,IDLE1
;         CLR P3.2            ;使复位脚无效
;中间空闲 2 毫秒
          SETB P3.0
          NOP
          NOP
          NOP
          NOP
          NOP
          NOP
          NOP
          NOP
          NOP
          NOP
          NOP
          CLR P3.0            ;给后级的同步脉冲
```