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Individual head-related impulse response measurement system with 3D scanning of pinnae

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Abstract

Head-related impulse responses (HRIRs) in the time domain, or head-related transfer functions (HRTFs) in the frequency domain, characterize the transmission between a sound source and the eardrums of a subject. They are different for each ear, angle of incidence, and also vary from person to person due to the anatomical differences. Individual measurement of HRIRs become required for applications where precise simulation of the acoustic scene is necessary, such as virtual auditory environments, and for validation of HRTF personalization methods. This presentation describes a HRIR measurement system, which uses as excitation signal logarithmic sine sweep or binary sequences known as Golay codes. The system also has a 3D scanner mounted over detachable holders that captures the digital models of the pinnae as a mesh. The results of measurements carried out in a head and torso simulator with soft pinnae are presented.

Keywords: HRIR, HRTF, measurement system, 3D scanning of pinnae

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1 Introduction

The sound waves that arrive to the eardrums of a person carry information that a human being uses to localize a source in space accurately [1]–[3]. Many of the cues involved in localization are generated by the interaction between the sound and the body of the listener. All information in these transformations produced by this interaction are present in the head-related impulse responses (HRIRs) in the time domain, or in the head-related transfer functions (HRTFs) in the frequency domain. Thus, they are different for each ear, angle of incidence, and also vary from person to person due to the anatomical differences. Digital filters based on these measurements constitute the principal signal processing used for implementing binaural auditory displays. The HRIR characterizes the transformation of sound from a specific source location to the listener's ears in the free-field.

The HRIRs often have notable differences between subjects. It has been found that these anthropometric differences between individuals can have serious perceptual implications [1], [4]. If the set of HRIRs used to model the listener are themselves (individual HRIRs), the source is perceived more compactly, external, well-defined and in a specific position in space, being more precise its localization than if the HRIRs belonged to another individual (generic HRIRs). That is to say, in order to experience an authentic auditory perception of space, the subject must hear sounds filtered with a set of HRIRs obtained from his own head [5].

Therefore HRIRs individual measurements become necessary for applications where a precise simulation of the acoustic scene is required, such as virtual auditory environments, and for validation of HRTF personalization methods. For example, these measurements become important for to use in improving the AVRS auditory display, developed in the CINTRA [6], [7].

Essentially, there are two methods for acquirement of HRIRs [8], direct method and reciprocal method [9]. The HRIR measurement system presented here was designed for the direct method, which means, that binaural microphones are placed into the subject’s ear canal and there is an excitation signal coming from the loudspeaker.

It is also interesting to know the dimensions of relevant anthropometric measurements of the listener, as in the case of the pinnae. These parameters are helpful for simulations and for to use them in methods of HRTF personalization, that is, to adapt a set of measured HRTFs to any subject [10]–[12].

In this paper the prototype of an individual HRIR measurement system is presented, which consist of a graduated supporting arc with a mobile loudspeaker, binaural microphones, a chair equipped with headrest, and a measurement software. The system also allows three-dimensional scan of the pinnae using the same supporting arc.

2 Measurement and scanning system

2.1 Supporting arc

The supporting arc of the measurement system is used to mount the mobile loudspeaker or the 3D scanner that digitizes the pinnae (Figure 1). Both the loudspeaker and the scanner are mounted over detachable holders. It was designed to minimize their influence on the sound field, and, during the process of measuring, supports are covered with absorbent material.

(a) (b)

Figure 1: (a) Setup for measurement of individual HRIRs. (b) Setup for 3D scanning of pinnae.

A radius of 0.80 m was chosen for the arc, which it is graduated with the angles of azimuth and elevation. First, measurements are performed on the front hemisphere, and then the chair is rotated to measure the posterior hemisphere. The person should sit in the middle of the arc. The chair is equipped with headrest to keep the subject's head stable during measurement.

2.2 Individual HRIR measurement

The set of HRIRs are obtained by measuring the impulse response between a sound source and both eardrums of a listener, in an acoustically treated chamber (free of reflections). The subject is located in the center of the sphere, and miniature binaural microphones Brüel & Kjaer 4101 placed at the entrance of both ear canals are used as input transducers, and a 4" two-way loudspeaker Pioneer TS-G1040 is used as sound source (through an amplifier). The desired frequency range was reduced to a range between 200 Hz and 16 kHz.

The measurements are determined for different discrete positions on a spherical surface (Figure 2). The origin of the spherical coordinate system is the intersection of three planes: the horizontal or azimuthal plane, parallel to the floor, which contains an imaginary line connecting both ears; the median plane, which divides the head into right-left symmetrically; and the frontal plane, perpendicular to the previous two and divided into front-behind the subject. Each position is defined by the azimuth θ and elevation Φ angles.

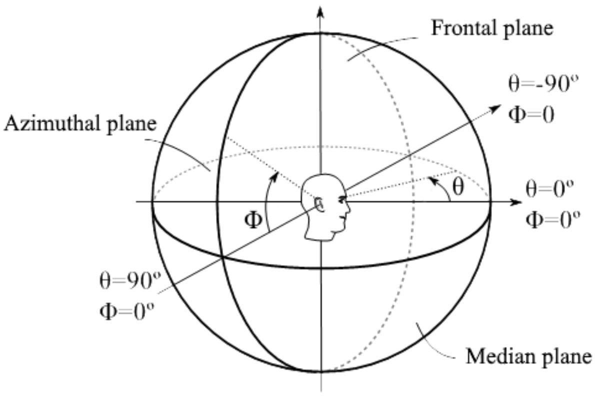


Figure 2: Spherical coordinate system

According to Blauert [1], a HRTF in free-field for a given position $H(\theta, \Phi, f)$ is defined as the ratio between the sound pressure measured at a point of the ear canal to said position $p(\theta, \Phi, f)$, and the sound pressure measured at a reference point corresponding to the center of the subject's head $p_0(f)$ (center of coordinate system), when it is absent.

$$H(\theta, \Phi, f) = \frac{p(\theta, \Phi, f)}{p_0(f)} \tag{1}$$

If both captures are made using the same measurement chain (microphones, loudspeakers, amplifiers, etc.), the influence of the system will be negligible.

In recent years, indirect measurement HRIR methods such as: maximum-length sequences [13], logarithmic sine sweep [14], [15] and binary sequences known as Golay codes [16], [17] have become more important. Basically they consist in exciting the system with signals that have particular characteristics (rather than an impulsive signal) and then post-process the response to obtain the impulse response. They allow greater control of product distortion measurement and a substantial improvement in signal-to-noise ratio.

2.2.1 Software system

The software for the measurement system was developed using the NI LabVIEW platform. The diagram of the measurement system is presented in Figure 3.

The software is responsible for constructing the excitation signals (so far implemented logarithmic sine sweeps and Golay codes) and reproducing them by the audio interface (E-MU 0404 USB 2.0). It is also responsible for capturing the signals from wireless acquisition module (National Instruments NI 9234), which are obtained from the binaural microphones located at the entrance of both ear canals.

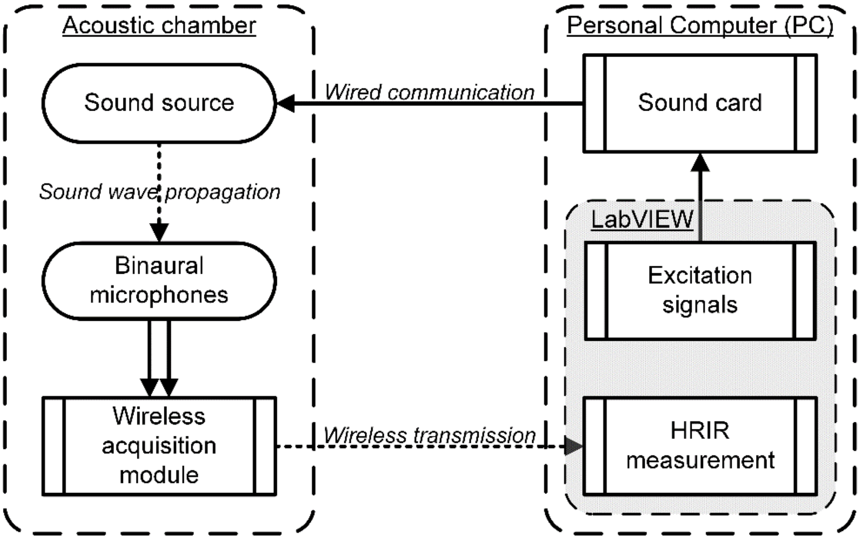


Figure 3: Measurement system diagram

These responses are post-processed to obtain audio files with individual HRIR for both ears with a length of 256 samples. Furthermore, to increase the signal to noise ratio, the system provides the possibility of an averaging several measurements for the same position.

In addition, it is necessary to consider that the HRIR obtained may contain some reflections from the surfaces of the measuring room and some elements close to the microphones. However, the entire HRIR is contained in the first 2 ms of the measurement [18]. In order to remove these unwanted reflections, the HRIR is processed with a modified Hann window where the maximum window value corresponds to the maximum impulse response value.

The estimated measurement time per position (with averaging) is about 12 s.

2.3 3D scanning of pinnae

The supporting arc allows exchanging the loudspeaker for the portable optical 3D scanner and to use the same structure for scanning the pinnae. The scanner used is a Sense 3D of 3D Systems Inc., which has a spatial resolution of 0.9 mm @ 0.5 m. Scanning both pinnae takes less than ten minutes and is performed by scanning each ear horizontally and vertically, with smooth movements.

It is necessary to note that, due to the inaccessibility of some areas of scanning, there are small "gaps" in the raw data [19]. This issue is solved by a smoothing and compensated in a post-processing stage.

Because the pinna 3D models contain full information on its anatomical structure, it is possible to extract anthropometric parameters used in the literature or explore new parameters that may be related to the HRTFs [20], [21]. To perform this extraction of information, a software for parametric measurement and for design of mechanical models can be used, for example, FreeCAD or Solidworks.

3 Results

As a proof of concept the individual HRIRs of a head and torso simulator (HATS) Brüel & Kjær 4128-C with right (DZ-9769) and left (DZ-9770) soft pinnae were measured. A dummy head offer the advantage that the subject under test does not move itself and can be precisely positioned.

Binaural microphones Brüel & Kjær 4101 inserted at the entrance of both ear canals are used (Figure 4).They were at a height of 1.20 m above the ground.

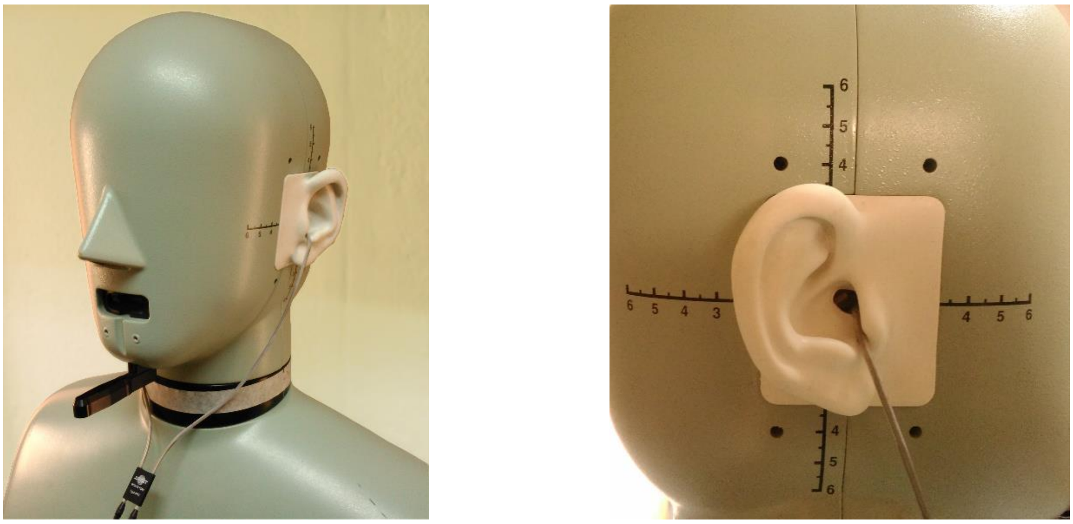


Figure 4: HATS Brüel & Kjær 4128-C with binaural microphones Brüel & Kjær 4101

The measurements were carried out in a silent chamber (acoustically treated) of CINTRA, which is 4.20 m long, 3.80 m wide and 2.60 m high. The reverberation time of the room is ~170 ms in the middle frequencies and the background noise is ~17 dBA SPL. To minimize reflections, the floor and the support elements are covered with absorbent material.

As an example, measurements are reported for four positions: the sound source located in front of the subject (0º, 0º), the source facing the right ear (+90º, 0º), the source facing the left ear (-90º, 0º), and the source behind the subject (+180º, 0º).

In the left column of Figure 5 the HRIRs measured can be observed (blue for the left ear and red for the right ear), while the right column shows the corresponding HRTFs.

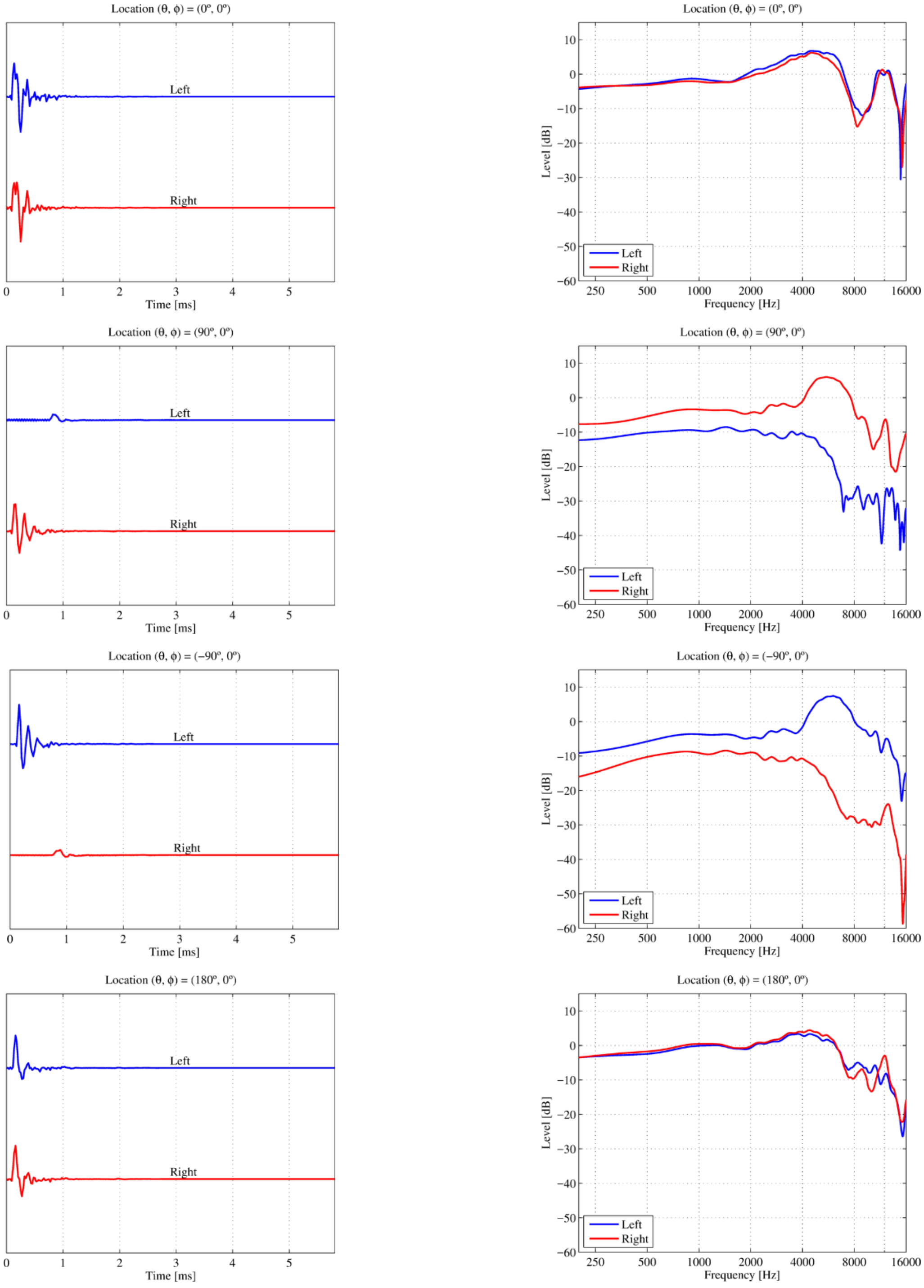
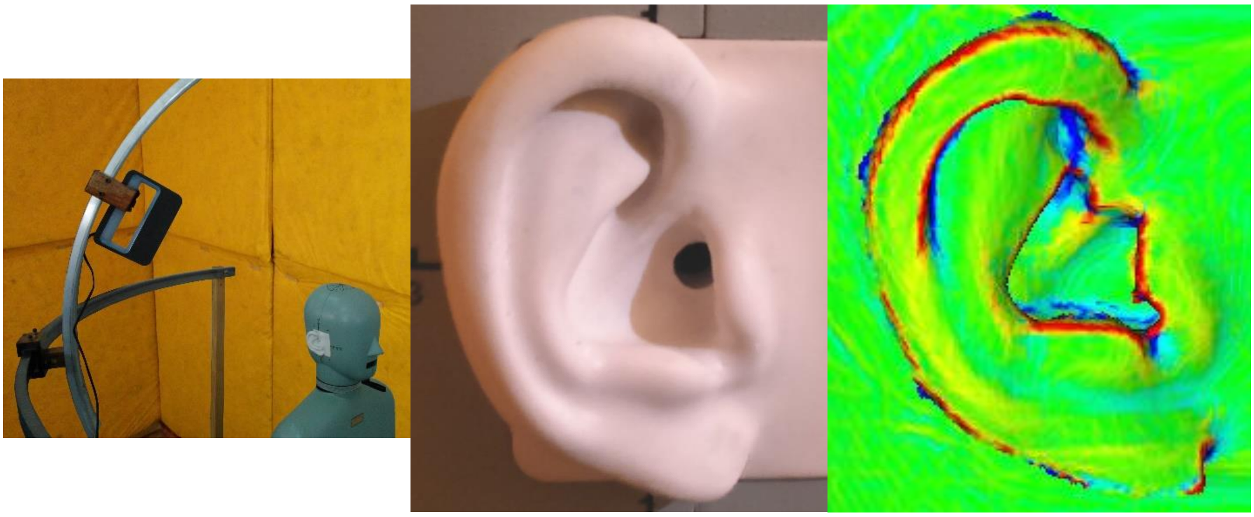


Figure 5: HRIRs (left column) and HRTFs (right column) for left (blue) and right (red) ear. Four location are showed: (0º, 0º), (+90º, 0º), (-90º, 0º) and (+180º, 0º).

Then scans were performed for both ears. Figure 6 shows the scanning process: the 3D scanning setup (Figure 6a), the right pinna of HATS (Figure 6b), and the 3D model obtained after the scanning (Figure 6c).



(a) **(b)** **(c)**

Figure 6: (a) Scanning setup. (b) Right pinna of HATS. (c) 3D scanned model of right pinna.

To make measurements of anthropometric parameters from 3D scanned model a post-processing (smoothing and compensation) was performed. Preliminary findings suggest that, in the 3D model of the Figure 6c, an error below 1 mm was obtained in the pinna height with respect to the information provided by the manufacturer.

4 Conclusions

In this paper the development of a prototype of individual HRIR measurement system with 3D scanning of pinnae is presented.

The system can capture HRIRs using logarithmic sine sweeps or Golay codes as excitation signals, which significantly improve the signal-to-noise ratio measurement. To further enhance this relationship, the system allows averaging a predetermined number of measurements for a position. The estimated measurement time per position (with averaging) is about 12 s. The supporting arc has a radius of 0.80 m and was designed to minimize their influence on the sound field. During the process of measuring, supports are covered with absorbent material.

The system also has a 3D scanner mounted over detachable holders in the same supporting arc, which captures the digital models of the pinnae as a digital mesh.

Results of HRIRs measurements of a HATS Brüel & Kjær 4128-C in four particular positions were presented: the sound source located in front of the subject, the source directly facing the right ear, the source directly facing the left ear, and the source behind the subject. These first measurements showed good agreement with other measurements.

In addition, 3D models of the pinnae are made using an optical scanner mounted on the same setup. Scanning both ears takes less than ten minutes. With these digital models it is possible to extract anthropometric parameters used in the literature or explore new parameters that may be related to the HRTFs. Errors below 1 mm were obtained in the pinna height.

As regards future work, it is necessary to improve the measurement time of a set of HRTFs by adding more loudspeakers, as well as adapting the software. Furthermore, these measurements will be performed in individuals to establish patterns between HRIRs and anatomical features of the pinna.

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