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Implementation of improved 3D interpolation technique on HRIR models using PCA

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Abstract. Implementation of head-related impulse responses (HRIRs) in the present can be felt and experienced by most people. Three-dimension sound using HRIRs has been applied in various fields, such as voice virtualization, music, film, and also for video games. However, the amount of data available in the HRIR database required for 3D sound is substantial, hence making HRIR application more efficient even in computational systems that are limited in memory, requires a dimension reduction method for the HRIR data. This research used Principal Component Analysis (PCA) modelling method using HRTF PKU-IOA database. We analysed three interpolation techniques on the HRIR models; those are bilinear rectangular, bilinear triangular and tetrahedral interpolation technique. The best result of interpolation technique is by applying tetrahedral interpolation on PCA modelling of HRIR data, that has mean percentage error of 7.5034% from minimum phase HRIRs and spectral distortion of 4.7677 dB from magnitude HRTFs.

1. Introduction

Humans generally have the ability to know the direction of sound, this process is unique because humans can detect sound from many aspects, namely the distance from the top, bottom, front and also behind or from the sides of the human head just by using a pair of hearing devices. This unique process is called Head-Related Transfer Function (HRRF). The HRTF method outlines how a sound wave is filtered by reflection and also diffraction from the limbs of the human body i.e. head, body and earlobe before the sound wave reaches the inner ear.

Nowadays, the implementation of HRTF can be found in various fields such as voice virtualization, music, entertainment, and video games. This is implemented with the aim that humans can listen to artificial voices more naturally as the human auditory process on the original sound. HRTF itself has many source points of an originating or infinite sound, wherein practical systems only a certain amount of HRTF can be implemented, therefore HRTF data with the finite number is required, hence the use of Head-Related Impulse Response (HRIR) which has been measured under conditions has been controlled on a spherical or spherical surface, as well as a predetermined and measured azimuth angle and elevation angle from the human ear [1].

However, HRTF data has a high dimensionality that makes computing the data requires considerable resources and this can limit the performance of an application that uses real-time 3D audio [2]. In this research, we conduct the modelling using Principal Components Analysis (PCA) on HRTF database. PCA is a technique for reducing the dimensionality of a set of data destined for compression purposes

[3], by implementing the PCA method in HRTF, the dimensionality contained in the HRTF data set can be reduced but still has major variations remained in the data. The use of PCA can also reduce the amount of resources used for an individual HRIR implementation in an integrated circuit [4].

After pre-processing HRIRs in the PKU-IOA HRTF database into minimum phase HRIRs and magnitude HRTFs, three interpolation techniques were used directly on those data types in previous studies [5][6], namely bilinear triangular interpolation, bilinear rectangular interpolation and also tetrahedral interpolation. In this research, using PCA-reduced data sets from minimum phase HRIRs and magnitude HRTFs, we determined and compared these interpolation techniques to discover best interpolation technique out of those three interpolation techniques.

The rest of the paper is organized as follows. In Section 2, we discuss some basic concepts about PCA, HRIRs, PKU-IOA HRTF Database used, and interpolation techniques. Section 3 consists of the research method. Section 4 provides the results of the research and the discussion about them. The conclusion is explained in Section 5.

2. Literature review

In this section, some details of PCA, HRIRs, PKU-IOA HRTF Database used, and tetrahedral interpolation are explained.

2.1. Principal components analysis

Principal Components Analysis (PCA) is a technique that serves to simplify the observed variables by reducing their dimensions [3]. In addition, PCA is also called an easy technique to extract the required information from a large set of data [7]. The PCA technique is generally a data visualization technique, in which the data used has reduced dimension to make it easier to plot.

By using PCA, researchers can get an idea of reducing a large number of complex data blocks of important data. In this research, PCA calculations can be performed with Equation 1 [8],

 $X = pc_1 \cdot w_1 + pc_2 \cdot w_2 + pc_2 \cdot w_2 \dots + pc_i \cdot w_i$ (1)

where X is the initial input data or HRIR / HRTF data while the pc_j is the j-th principal component or the j-th basis vector [4]. The sum of the main components or principal components can be determined by looking at the total variance or variance described from all principal components over 90% [9] where the percentage of variance is the total distribution of variables from one principal component to the other principal component. The percentage of variance can also be used for estimating the dimensionality of a dataset [10].

2.2. Head-Related Impulse Response

Head-related impulse response (HRIR) is a technique that works by capturing changes in sound waves generated from the sound source to the human eardrum. Humans have different HRIRs for each right and left ear. HRIR of each human ear depend on position of sound source which has an elevation angle (ϕ) and azimuth angle (θ). Therefore, it is necessary to find the HRIRs of both human ears to synthesize binaural signals from a mono sound source originating from a certain point [7].

All HRTF data come from the Fourier transform of HRIRs. HRIR is an impulse response in the time domain of the human eardrum that performs the sound filtering coming on the eardrum [4]. HRIR data are measured in predetermined state, which meant that the predetermined state was the state where the elevation angle (φ) and the azimuth angle (θ) were dotted toward the human ear. Among a limited number of practical systems, estimating a pair of HRIRs from an unknown source requires an interpolation technique [1].

2.3. PKU-IOA HRTF database

PKU-IOA HRTF database is a high-resolution spatial HRTF database. This database contains HRIRs obtained from Knowles Electronics Mannequin for Acoustics Research (KEMAR) mannequin with a number of 6,344 spatial points. The PKU-IOA HRTF database has varied data wherein this data has a range of 20 to 160 cm, an elevation angle from -40 ° to 90° with a jump of 10°, as well as a full azimuth

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angle from 0° to 360° with a jump of 5° [11]. HRIR at each point in this database has 2,048 samples with double data type, where the first 1,024 samples are HRIR for left ear and 1,024 next samples are HRIR for right ear for a particular point. This database uses a sampling rate of 65,536 Hz of HRIRs.

2.4. Tetrahedral interpolation

Interpolation is a method for finding new data points within a certain range of discrete data sets, interpolation is required in HRIR data processing, interpolation serves to estimate HRIR at any desired point.

The tetrahedral interpolation is an interpolation that uses 4 points on the horizontal and vertical plane (azimuth and elevation) and the distance from the point sought where the four points form a quadrangle space [5]. The geometry shape of the tetrahedral interpolation space can be seen in Figure 1.



Based on [13], calculations of tetrahedral interpolation can be done with Equation 2.

$$X = g_1 A + g_2 B + g_3 C + g_4 D \tag{2}$$

where X is the preferred HRTF value, whereas A, B, C and D are the points forming a tetrahedral shape that covers the X or the sought HRTF value and g1, g2, g3 and g4 are barycentric coordinates from point X, Barycentric Coordinates itself can be used as an interpolation weight. To find HRTF value at X with the following terms.

$$\sum_{i=1}^{4} g_i = 1 \tag{3}$$

By subtracting D from Equation 2, we will get,

$$\vec{X} - D = [g_1 \, g_2 \, g_3]T \tag{4}$$

where T is

$$T = \begin{bmatrix} A - D \\ B - D \\ C - D \end{bmatrix}$$
(5)

From Equation 4, the final form of the equation to find the weights is as follows,

$$[g_1 \ g_2 \ g_3] = (X - D)T^{-1} \tag{6}$$

The value of g4 can be obtained the following equation,

$$g_4 = 1 - g_1 - g_2 - g_3 \tag{7}$$

Tetrahedral interpolation itself can only be performed if there are at least HRIR data on 2 different distances. Thus tetrahedral interpolation can not be tested using data from CIPIC HRTF Database, because that database only has HRIR data on one distance only.

3. Research method

The HRIR data used for this research is PKU-IOA HRTF, from the database the original HRIR data are retrieved and then pre-processed the data to get the minimum phase HRIRs and magnitude HRTFs. Calculation on real cepstrum of original HRIRs is applied to get the minimum phase HRIRs while the



magnitude HRTF is obtained by performing Fourier transform on the original HRIR data, after that PCA modelling is applied to both data types to reduce the dimensions of the data.

Three interpolation techniques are applied to both data, that is bilinear rectangular interpolation, bilinear triangular [12] and tetrahedral interpolation [13] and finally, the results of interpolation data are analysed using mean square error (MSE) parameter for the minimum phase HRIRs while magnitude HRTF data are analysed using spectral distortion (SD) parameter [5]. The research scheme can be seen in Figure 2. From the analysis, we could attain the best interpolation technique for models of minimum phase HRIR and also the best interpolation technique for models of magnitude HRTF.



Figure 2. Block diagram of research method

4. Results and discussion

4.1. PCA variances

Information in Table 1 is the results of PCA modelling performed on minimum phase HRIRs and magnitude HRTFs, it can be seen that ten principal components (PCs) or main components are taken from the initial dataset where the variance is the distribution of variables from each PC resulting from PCA modelling on the original pre-processed data.

Principal	Variance of Minimum	Variance of Magnitude
Component	Phase HRIRs (%)	HRTFs (%)
PC1	51.33	71.45
PC2	10.97	6.36
PC3	7.43	4.86
PC4	6.67	3.75
PC5	4.71	2.70
PC6	2.67	1.82
PC7	2.27	1.49
PC8	1.88	1.0
PC9	1.44	0.85
PC10	1.13	0.69
Total	90.5	94.9

 Table 1. Variance of each PC from pre-processed HRIRs data

In this research, PCA modelling performed on the minimum phase HRIRs is conducted by ten PCs, that it includes a cumulative variance of 90.5%; and on the magnitude HRTFs by taking the same number of PCs as the minimum phase HRIRs, it includes the cumulative variance of 94.9%. In this case, both data can be explained adequately only by using 10 principal components Then, the data can be reconstructed back into original observation data with the same amount of data as original observation by using new variables that are produced or reduced from the PCA method.

4.2. Interpolation results

Table 2 shows that after applying modelling using PCA, bilinear triangular interpolation resulted in the worst average MSE of models of minimum phase HRIR in the value of 8.9897% and the worst average SD of models of magnitude HRTF in the value of 4.7932 dB. On the other hand, tetrahedral interpolation shows the best performance with average MSE of 7.5034% and average SD of 4.7677 dB. These results are in line with our previous work in [5][6][14]. But tetrahedral interpolation needs Delaunay triangulation [15] to be performed first and needs data from two adjacent distances thus making it more complex than the other two interpolation techniques.

As seen also from Table 2 that the average value of MSE of models of minimum phase HRIR and SD of models of magnitude HRTF from bilinear rectangular interpolation are better than those of bilinear triangular interpolation because the interpolated data are not located in the middle of interpolation data in the bilinear triangular interpolation. However, bilinear triangular interpolation itself has an advantage that it only needs three reference points while the bilinear rectangular interpolation needs four reference points.

	Interpolation Technique			
Performance Parameter	Biliniear Rectangular	Bilinear Triangular	Tetrahedral	
Average MSE of models of minimum phase HRIR	8.6052%	8.9897%	7.5034%	
Average SD of models of magnitude HRTF	4.7772 dB	4.7932 dB	4.7677 dB	

	Table 2. Average	value of l	MSE and	SD of	PCA	modelling
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5. Conclusion

Based on this research, the average of MSE and SD are obtained from the three interpolation techniques on PCA models. Tetrahedral interpolation technique which needs data in 3D space, has the lowest average MSE and SD compared to the other two interpolations, with average MSE and SD value of 7.5034% and 4.7677 dB, respectively.

Compared to [5], the average value of MSE and SD of each interpolation technique are increased from the interpolation result that did not apply PCA modelling or directly interpolated from minimum phase HRIRs and magnitude HRTFs. Although the average error is worse by using PCA modelling, but interpolation of models of minimum phase HRIR is still promising to be implemented in a DSP board to reproduce 3D sound because of the simplicity and dimensions reduction of PCA models.

Acknowledgments

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