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Nama	:	Dr. Hugeng, S.T., M.T.
Program Studi	:	Sistem Komputer
Jabatan	:	Dosen
Tugas yang diberikan	:	Menulis dan mengirimkan karya ilmiah untuk dipublikasikan pada International Journal of Technology FTUI, e-ISSN:2087-2100, dengan judul "Implementation of 3D HRTF Interpolation in Synthesizing Virtual 3D Moving Sound"
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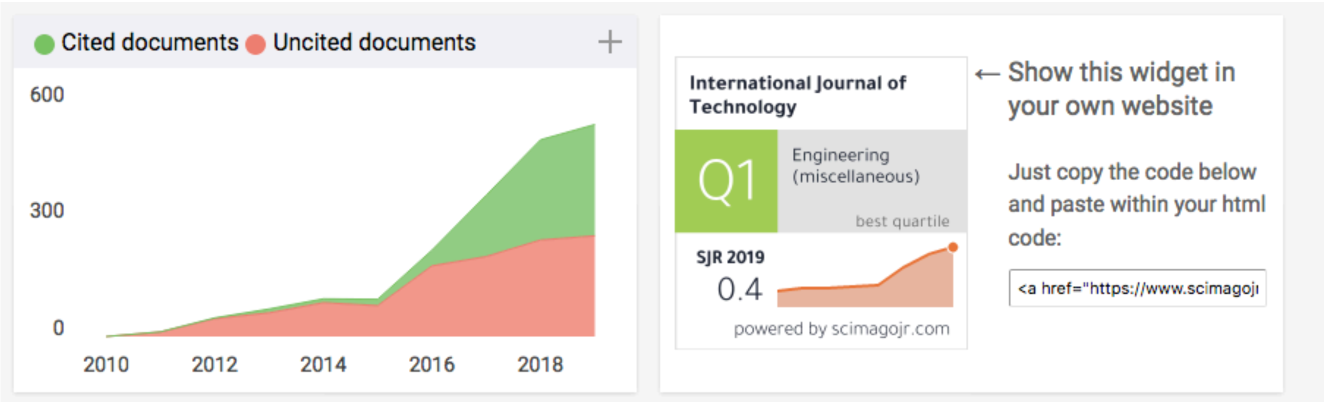
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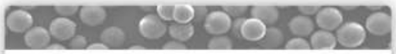


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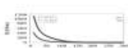


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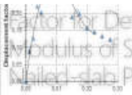

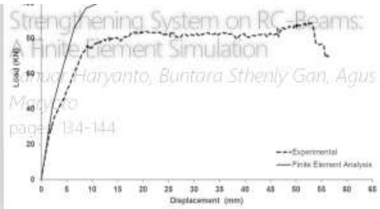

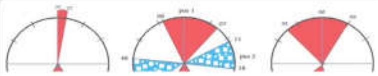

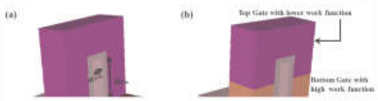

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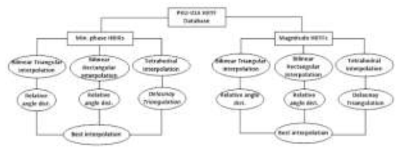
Implementation of 3D HRTF Interpolation in Synthesizing Virtual 3D Moving Sound

Hugeng Hugeng, Jovan Anggara, Dadang Gunawan

Abstract: 3D sound is a new trend in various media, such as movies, video games, and musicals. Interpolated head-related transfer functions (HRTFs) are a key factor in its production, due to real-time system limitations in storing measured HRTFs. In addition, the interpolation of HRTFs can reduce the need to measure a large amount of HRTFs and the associated effort. In this research, we used the PKU-IOA HRTF Database and covered three interpolation techniques, namely bilinear rectangular, bilinear triangular, and tetrahedral. Bilinear interpolations can be used to compute weights in interpolating measured HRTFs in a linear fashion, with respect to azimuth and elevation angles. Such interpolations have been proposed for three measurement points that form a triangle or for four measurement points that form a rectangle, surrounding the HRTF at a desired point. These geometrical approaches compute weights from a distance of the desired point from each measurement point. Tetrahedral interpolation, meanwhile, is a technique for HRTF measurements in 3D (i.e. azimuth, elevation, and distance) using barycentric weights. Based on our experiments, 3D tetrahedral interpolation results in the best average mean square error (MSE) of 3.72% for minimum phase head related impulse responses (HRIRs) and best average spectral distortion (SD) of 2.79 dB for magnitude HRTFs, compared to 2D bilinear interpolations (i.e. rectangular and triangular interpolation). Regarding the latter, bilinear rectangular interpolation generally performs better than the triangular variety. Additionally, the use of minimum phase HRIRs as input data results in more optimal interpolated data than magnitude HRTFs. We therefore propose an optimal framework for obtaining estimated HRIRs by interpolating minimum phase HRIRs using tetrahedral interpolation. Such HRIRs have been simulated to produce virtual 3D moving sound in a horizontal plane with a difference of 2.5° of azimuth angle. The simulated moving sound that is heard moves naturally in a clockwise direction from an azimuth angle of 0° to 360°.



Keywords: Bilinear interpolation; HRIR interpolation; HRTF interpolation; Tetrahedral interpolation

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IMPLEMENTATION OF 3D HRTF INTERPOLATION IN SYNTHESIZING VIRTUAL 3D MOVING SOUND

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ABSTRACT

3D sound is a new trend in various media, such as movies, video games, and musicals. Interpolated head-related transfer functions (HRTFs) are a key factor in its production, due to real-time system limitations in storing measured HRTFs. In addition, the interpolation of HRTFs can reduce the need to measure a large amount of HRTFs and the associated effort. In this research, we used the PKU-IOA HRTF Database and covered three interpolation techniques, namely bilinear rectangular, bilinear triangular, and tetrahedral. Bilinear interpolations can be used to compute weights in interpolating measured HRTFs in a linear fashion, with respect to azimuth and elevation angles. Such interpolations have been proposed for three measurement points that form a triangle or for four measurement points that form a rectangle, surrounding the HRTF at a desired point. These geometrical approaches compute weights from a distance of the desired point from each measurement point. Tetrahedral interpolation, meanwhile, is a technique for HRTF measurements in 3D (i.e. azimuth, elevation, and distance) using barycentric weights. Based on our experiments, 3D tetrahedral interpolation results in the best average mean square error (MSE) of 3.72% for minimum phase head related impulse responses (HRIRs) and best average spectral distortion (SD) of 2.79 dB for magnitude HRTFs, compared to 2D bilinear interpolations (i.e. rectangular and triangular interpolation). Regarding the latter, bilinear rectangular interpolation generally performs better than the triangular variety. Additionally, the use of minimum phase HRIRs as input data results in more optimal interpolated data than magnitude HRTFs. We therefore propose an optimal framework for obtaining estimated HRIRs by interpolating minimum phase HRIRs using tetrahedral interpolation. Such HRIRs have been simulated to produce virtual 3D moving sound in a horizontal plane with a difference of 2.5^o of azimuth angle. The simulated moving sound that is heard moves naturally in a clockwise direction from an azimuth angle of 0^o to 360^o.

Keywords: Bilinear interpolation; HRIR interpolation; HRTF interpolation; Tetrahedral interpolation

1. INTRODUCTION

Sound is one of the key components of anyone's life, allowing us to tell what is happening around us through our ears. Sound is also one of the most effective means of communication. Every person, except those who are auditorily or vocally impaired, can use sound to talk with

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others. Communication aside, sound can also be used as an entertainment media, such as in music.

In the modern world, sound is frequently used in various technologies. All kinds of smartphones, laptops, PCs, and various other gadgets use sound, for communication, entertainment, or a range of other purposes. All computers use head-related transfer function (HRTF) so that the sounds they produce can be heard in 3D by human ears. HRTF describes how a sound from a certain point is heard by our ears. Every sound source point has a different pair of HRTFs. Amongst these, there is an optimum pair of HRTFs that produces sound that comes from every direction clearly. This is commonly applied in game development, so that the player can pick up the various sounds in the game.

To obtain an HRTF at a certain sound source point, the interpolation of several adjacent HRTFs is required. This can reduce the necessary HRTF measurements, as well as decreasing the amount of HRTF data, thereby using less storage. Several interpolation techniques, including all or most measurement points, have been proposed, such as those using spherical splines or rational state-space interpolation. Hartung et al. (1999) compared various algorithms for HRTF interpolation. Interpolation in the frequency domain, using spherical splines, yields superior results to those garnered by that in the time domain. The quality of interpolation can be improved if the transfer functions are smoothed in the frequency domain. Keyrouz and Diepold (2008) stated that in order to obtain a realistic synthesis of a moving sound source and changes in listener position in real-time virtual auditory spaces, a dense grid of HRTFs is needed for interpolation. They proposed an interpolation algorithm based on a block Loewner matrix to avoid the results caused by dynamic changes in HRTFs. Although these approaches have great potential for returning estimates of HRTFs that are more accurate than what is garnered by the methods that use few HRTF measurements for interpolation, they entail a higher cost of computation. The computation complexity of an interpolation algorithm has become a key obstacle when creating virtual moving sources, as well as when many sources and/or room reflections are reproduced simultaneously, or when the reproduction is performed in a device that has low computation power, as in a cellular phone. In a real-time system, interpolation must be performed quickly; however, despite the increase in speed, the result should not ultimately be affected. For this reason, the algorithm used should be efficient and use as little memory as possible (Freeland et al., 2004).

In this research, three interpolation techniques were analyzed: bilinear triangular interpolation, bilinear rectangular interpolation, and tetrahedral interpolation. We created a program that could execute these three methods using the same HRTF database, before conveniently determining which was best out of the three interpolations. Unlike in the studies of Ajdler et al. (2005), Freeland et al. (2004), and Gamper (2013a), we did not propose a new interpolation technique. Instead, we analyzed the performance of these three techniques by estimating two HRTF data types, namely minimum phase head related impulse responses (HRIRs) and magnitude HRTFs, using the same database; that is, the PKU-IOA HRTF Database. The results of our research show that tetrahedral interpolation was the best approach for estimating HRIRs' minimum phase. Hence, our proposed framework constitutes the interpolation of HRTFs using HRIRs' minimum phase as input data and the tetrahedral interpolation technique with Delaunay triangulation (de Berg et al., 2008). We also describe the problems and difficulties occurring with each tested technique, as per de Sousa and Queiroz (2009).

2. ALGORITHM OVERVIEW

In this research, we built a program that was able to interpolate HRTFs using Matlab. As mentioned, the interpolation techniques applied were bilinear triangular interpolation, bilinear rectangular interpolation, and tetrahedral interpolation. Each of these were tested on data from the PKU-IOA HRTF Database. This database has HRIRs on several points. HRTF can be obtained by performing Fourier Transform on HRIR. The interpolation techniques were tested by interpolating HRTF/HRIR on points that had value in the database. Data obtained from interpolation were compared with the originals by calculating the spectral distortion (SD) for HRTF and mean square error (MSE) for HRIR.

Besides SD and MSE, each technique had certain parameters such as the amount of reference points needed, computing complexity, and whether there were HRTF or HRIR data in three dimensions.

2.1. Head-related Transfer Function

HRTF is a function that describes how ears pick up a sound from a certain point. Both ears have different HRTFs, each at a certain point; this is caused by the elevation angle ϕ and azimuth angle θ, which are different for each ear. HRTF catches all physical signals for source localization. Once the HRTF for the right and left ear is known, we can synthesize the accurate binaural signal from a mono sound source.

HRTF has four variables, three of which are coordinate space variables, and frequency. On the spherical coordinate, if the sound source has a distance greater than one meter, that source is in the far field and HRTF falls off inversely with range. Most HRTF measurements are done in the far field, which reduces the HRTF to a function of azimuth, elevation, and frequency.

2.2. Interpolation Techniques

Interpolation is a method of searching for a value in a certain point that lies within at least two other points for which the values are known. The interpolation of HRTF is necessary to reduce HRTFs' measurement and the storage needed to store the individual measured HRTFs.

2.2.1. Bilinear rectangular interpolation

Bilinear interpolation is an interpolation that uses a set of nearby points on the vertical or horizontal plane from the point at which the value will be searched. In bilinear rectangular interpolation, four points are used as references, forming a rectangular shape. Meanwhile, in bilinear triangular interpolation, three points are used as references, forming a triangular shape. Calculation for bilinear rectangular interpolation follows the following equation (Freeland et al., 2004):

$$\hat{h} = (1-C_\theta)(1-C_\phi)h_a + C_\theta(1-C_\phi)h_b + C_\theta C_\phi h_c + (1-C_\theta)C_\phi h_d \tag{1}$$

where θ is azimuth angle and ϕ is elevation angle; C_θ and C_ϕ refer to Equations 2 and 3 below respectively:

$$C_\theta = \frac{c_\theta}{\theta_{grid}} = \frac{\theta \operatorname{mod}(\theta_{grid})}{\theta_{grid}} \tag{2}$$

$$C_\phi = \frac{c_\phi}{\phi_{grid}} = \frac{\phi \operatorname{mod}(\phi_{grid})}{\phi_{grid}}\,. \tag{3}$$

In Figure 1, h_a, h_b, h_c, and h_d are the four adjacent HRTFs from the target HRTF $\hat{h}$, which has already been available from a database. These points are used as reference points for interpolation calculation. Figure 1 also explains how to attain the values for C_θ and C_ϕ.

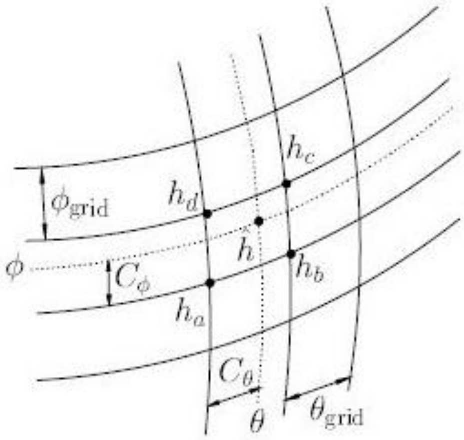

Figure 1 Graphical interpretation of bilinear rectangular interpolation (Freeland et al., 2004)

2.2.2. Bilinear triangular interpolation

Bilinear rectangular interpolation requires four points as references, while bilinear triangular interpolation only requires three. The interpolated HRTF can be calculated by following Equation 4 below:

$$H_P = w_A H_A + w_B H_B + w_C H_C \tag{4}$$

where w_A, w_B, and w_C are weights for interpolation calculation as follows:

$$w_A + w_B + w_C = 1 \tag{5}$$

H_P is the target HRTF, whose values are to be found by interpolating the adjacent HRTFs, H_A, H_B, and H_C. These are measured HRTFs, which are given by a database and used as references in estimating target HRTF. By referring to Figures 2 and 3, W_C and W_B can be obtained via these equations:

$$w_C = \frac{\Delta\phi}{\Delta\phi_{grid}} \tag{6}$$

$$w_B = \frac{\Delta\theta}{\Delta\theta_{grid}} \tag{7}$$

Figure 2 shows a graphical interpretation of bilinear triangular interpolation, while Figure 3 shows angular distances to obtain the weights.

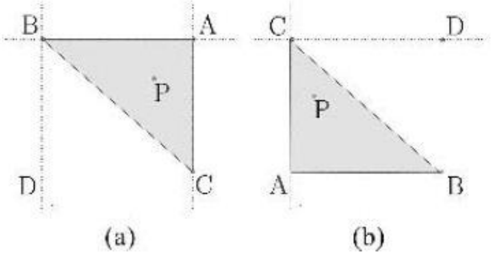

Figure 2 Graphical interpretation of bilinear triangular interpolation (Freeland et al., 2004)

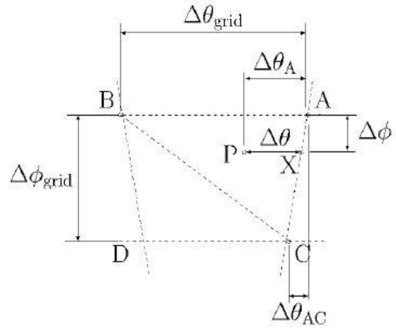

Figure 3 Angular distances to obtain w_A, w_B, and w_C (Freeland et al., 2004)

2.2.3. Tetrahedral interpolation

An interpolated HRTF can be obtained from three measurement points that form a triangle enclosing the target source position. This approach can be extended to include the target source distance through direct interpolation of HRTF measurements obtained at various distances. Tetrahedral interpolation is a kind of three-dimensional interpolation, based on finding four measurement points forming a tetrahedron that encloses the target position.

Delaunay triangulation (DT) can be used to determine a set of points in 2D that are grouped into non-overlapping triangles. It is optimum that these triangles are nearly equiangular when used for interpolation. DT is the best approach in this sense, as it maximizes the minimum angle of the generated triangles. DT creates triangles such that the circumcircle of each contains no other points. In 3D, DT results in a tetrahedral such that the circumsphere of each tetrahedron contains no other points. Figure 4 shows a graphical interpretation of tetrahedral interpolation. As can be seen from this figure, X is the position of the target HRTF, while A, B, C, and D are positions of given measured HRTFs from different source distances. Any target point, X, inside the tetrahedron can be calculated as a linear combination of the vertices, as shown by Equation 8:

$$\mathbf{X} = g_1\mathbf{A} + g_2\mathbf{B} + g_3\mathbf{C} + g_4\mathbf{D}, \quad (8)$$

where g_i are scalar weights that add up to one.

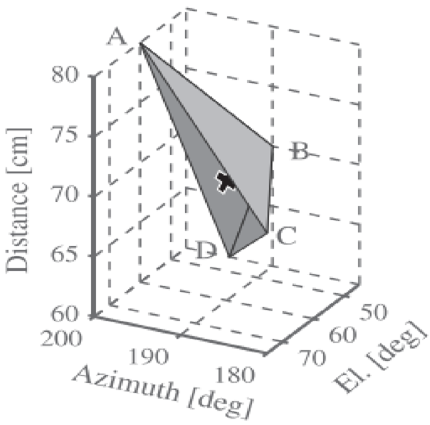

Figure 4 Graphical interpretation of tetrahedral interpolation (Gamper, 2013a)

The weights g_i are the barycentric coordinates of point **X**. To estimate the target HRTF $\hat{\mathbf{H}}_x$ at point **X** as the weighted sum of the HRTFs, $\mathbf{H}_i$, measured at A, B, C, and D, we can use the barycentric coordinates as interpolation weights, as follows:

$$\hat{\mathbf{H}}_x = \sum_{i-1}^{4} g_i\mathbf{H}_i \quad (9)$$

Reducing both sides of Equation 8 with **D** yields:

$$\mathbf{X} - \mathbf{D} = [g_1\ g_2\ g_3]\ \mathbf{T}, \quad (10)$$

Where:

$$\mathbf{T} = \begin{bmatrix} \mathbf{A} - \mathbf{D} \\ \mathbf{B} - \mathbf{D} \\ \mathbf{C} - \mathbf{D} \end{bmatrix} \quad (11)$$

By rearranging Equation 10, the weights of g_1, g_2, and g_3, can be obtained via:

$$[g_1\ g_2\ g_3] = (\mathbf{X} - \mathbf{D})\ \mathbf{T}^{-1}. \quad (12)$$

The other weight, g_4, can be calculated by:

$$g_4 = 1 - g_1 - g_2 - g_3. \quad (13)$$

Note that **T** depends solely on the geometry of the tetrahedron and is independent of the desired source position, **X**. Therefore, $\mathbf{T}^{-1}$ can be pre-calculated for all tetrahedra during initialization and stored in memory.

3. EXPERIMENTAL METHOD

As is known, tetrahedral interpolation can only be performed using HRTFs datasets from various spheres (at different distances from the center of the human head), such as the PKU-IOA HRTF Database.

3.1. PKU-IOA HRTF Database

This is an HRTF database that has been released to the public and can be downloaded at http://www.cis.pku.edu.cn/auditory/Staff/Dr.Qu.files/Qu-HRTF-Database.html (Qu et al., 2009). The database contains HRIRs measured using the KEMAR (Knowles Electronics Mannequin for Acoustics Research) mannequin. It has data on 6,344 points, with distances from 20–160 cm, elevation from -40–90^o, and azimuth from 0–360^o.

The database contains data on various distances: 20 cm, 30 cm, 40 cm, 50 cm, 75 cm, 100 cm, 130 cm, and 160 cm. Meanwhile, for elevation, it contains data with elevations from -40–90^o, at intervals of 10^o. For azimuth, the angles range from 0–360^o; however the step depends on the elevation, with constraints as follows:

a. On elevation -40–50^o, the azimuth step is 5^o;
b. On elevation 60^o, the azimuth step is 10^o;
c. On elevation 70^o, the azimuth step is 15^o;
d. On elevation 80^o, the azimuth step is 30^o;
e. On elevation 90^o, the azimuth step is 360^o.

On each point, the database has data with the size of 2,048 numbers, with the data type being double. The first 1,024 samples are HRIR for left ear, while the remaining 1,024 are HRIR for the right ear. This database uses a sampling rate of 65,536 Hz.

3.2. Research Method

This research was performed by applying several optimal interpolation techniques to HRTFs. These were elaborated and tested conveniently on the same HRTF database using the same performance parameters. We used the PKU-IOA HRTF Database, consisting of 6,344 HRIRs for one ear of a KEMAR mannequin. Based on our previous research (Hugeng et al., 2010), we used minimum phase HRIRs and magnitude HRTFs as input data types of HRTFs for the explored techniques. These techniques were bilinear triangular interpolation with relative angle distance, bilinear rectangular interpolation with relative angle distance, and tetrahedral interpolation with DT. Using a combination of the three techniques and two types of input data, we aimed to find the best interpolation for application to a certain HRTF data type. The block diagram of our research is shown in Figure 5.

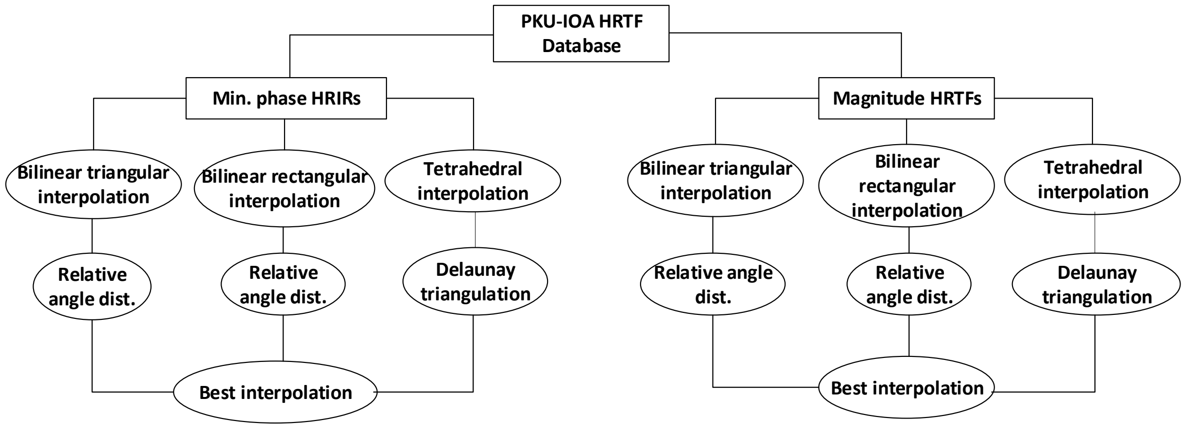

Figure 5 Block diagram of research method

For both bilinear interpolations, we used parameter azimuth-elevation, distance-elevation, and distance-azimuth for interpolation. For parameter azimuth-elevation, we used the HRIRs data on a sphere with distance of 75 cm, where a target HRIR was estimated from adjacent HRIRs with different azimuths and elevations on the same sphere. For parameter distance-elevation, target HRIRs were on the sphere with distance of 75 cm, whereas interpolating HRIRs came from the same elevation but from adjacent spheres, with distances of 50 cm and 100 cm. Similarly, for parameter distance-azimuth, we interpolated target HRIRs on the sphere with distance of 75 cm, by using HRIRs that came from the same azimuth but from two spheres with distances of 50 cm and 100 cm. For tetrahedral interpolation, the target HRIRs were on the sphere with distance of 75 cm, whereas the interpolating HRIRs that formed tetrahedra came from spheres with distances of 50 cm and 100 cm.

3.3. Performance Parameters for Interpolation

Most researchers around the world who model and interpolate HRTFs use MSE and SD to measure the performance of their interpolation techniques. MSE, e(ϕ,θ), is usually used to compare the estimated/interpolated HRIR, $\hat{h}$(ϕ,θ), to the original HRIR, h(ϕ,θ), as denoted by Equation 14 below:

$$e(\emptyset,\Theta) = 100\% \text{ x} \frac{\left|\left|h(\emptyset,\Theta) - \hat{h}(\emptyset,\Theta)\right|\right|^2}{||h(\emptyset,\Theta)||^2} \tag{14}$$

where (ϕ,θ) is the position of sound source of HRIR with elevation ϕ and azimuth θ.

In the meantime, SD is actually the root MSE between log-magnitude HRTF from measurement and estimated log-magnitude HRTF. SD is defined as:

$$\text{SD} = \sqrt{\frac{1}{K}\sum_{k=1}^{K}\left[20.\,log_{10}\frac{|H(k)|}{|\hat{H}(k)|}\right]^2} \text{ [dB]}, \tag{15}$$

where K is the number of frequency components, |H(k)| is magnitude HRTF from measurement, and $|\hat{H}(k)|$ is the estimated magnitude HRTF.

4. RESULTS AND DISCUSSION

Initially, the complexities of the explored interpolation techniques were compared. Table 1 indicates the complexity of each approach. As for reference points, the triangular method required only three, whereas the other two needed four. From the complexity point of view, the tetrahedral pathway was the most complex with a value of $O(n) + O(n^{(d-1)/p})$, while the other two only had a complexity of O(n). Finally, tetrahedral interpolation requires the presence of 3D HRIR data. If the latter is not present, it cannot be executed. The other two techniques do not need the presence of 3D data to be executed.

Table 1 Complexity of each interpolation technique

Interpolation technique	# Reference points	Complexity	3D data needed
Bilinear rectangular interpolation	4 points	O(n)	No
Bilinear triangular interpolation	3 points	O(n)	No
Tetrahedral interpolation	4 points	$O(n) + O(n^{(d-1)/p})$	Yes

The experimental results of the applied interpolation techniques can be seen in Table 2.

Table 2 Experimental results from the three interpolation techniques

	Interpolation: Bilinear	Rectangular	Triangular	Tetrahedral
Az. – Elev.	MSE HRIR min ph.	7.1341%	7.2644%	3.7231%
	SD HRTF min ph.	3.6507 dB	3.7428 dB	2.7959 dB
	SD HRTF interpol.	3.7258 dB	3.7705 dB	2.7852 dB
Dist. – Elev.	MSE HRIR min ph.	7.6942%	9.5197%	3.7231%
	SD HRTF min ph.	3.7431 dB	4.0284 dB	2.7959 dB
	SD HRTF interpol.	4.0715 dB	4.1288 dB	2.7852 dB
Dist. – Az.	MSE HRIR min ph.	4.3363%	9.5197%	3.7231%
	SD HRTF min ph.	2.8246 dB	4.0284 dB	2.7959 dB
	SD HRTF interpol.	2.8598 dB	4.1288 dB	2.7852 dB

From the three kinds of parameters to determine the interpolating HRIRs for bilinear, rectangular, and triangular interpolation, as explained in Section 3.3 (i.e. azimuth-elevation, distance-elevation, and distance-azimuth), we found that interpolating minimum phase HRIRs and magnitude HRTFs using parameter distance-azimuth yielded the best results, which are least average MSE and least average SD. However, out of the 2D interpolation techniques, bilinear rectangular interpolation, on average, resulted in more optimal MSE and SD than bilinear triangular interpolation. This result may stem from the fact that contributions were balanced among four HRTFs in different positions with the same two azimuths and elevations, as can be seen in Figure 1. Our previous work (Hugeng et al., 2015) showed that linear interpolation between two HRTFs in a straight line with the same elevation angles performs better than that between two HRTFs with the same azimuth angles. In bilinear triangular interpolation, a target HRTF is located between two HRTFs in the hypotenuse of a right triangle. Therefore, both HRTFs contribute more dominantly than another HRTF. As we know, the positions of two HRTFs in the hypotenuse have different azimuth and elevation angles.

As seen from our experiment shown in Table 2, tetrahedral interpolation with 3D property provided the best average MSE of 3.72% when estimating minimum phase HRIRs and the best average SD of 2.79 dB when estimating magnitude HRTFs. In addition, it may be observed from Table 2 that the use of minimum phase HRIRs in general gives more optimal interpolation performance than that of magnitude HRTFs, as can be seen from the comparison of the SD HRTF minimum phase and SD HRTF interpolation in each case. The former is calculated from magnitude HRTFs of interpolated minimum phase HRIRs, while the latter is calculated from interpolated magnitude HRTFs. The calculation of SD HRTF minimum phase is intended to compare the interpolation of minimum phase HRIRs in the time domain and that of magnitude HRTFs in the frequency domain.

Our result from using tetrahedral interpolation with minimum phase HRIRs as input data, and SD HRTF minimum phase of 2.7959 dB, is comparable with that of tetrahedral interpolation with magnitude HRTFs as input data (Gamper, 2013a) and SD HRTF interpolation of 2.7852 dB. The framework proposed here is to interpolate measured HRTFs in 3D, namely azimuth, elevation, and distance, using tetrahedral interpolation with minimum phase HRIRs as its input and barycentric weights. A tetrahedral mesh is then generated via DT and searched via an adjacency walk. This method makes the framework robust, due to the irregular positions and computational efficiency of the measured HRTFs. The framework can be seen in the third path from the left in Figure 5.

Estimated HRIRs using tetrahedral interpolation have been simulated to produce virtual 3D moving sound in a horizontal plane with a difference of 2.5^o of azimuth angle. The simulated moving sound that is heard naturally moves in a clockwise direction from azimuth angles of 0-360^o.

5. CONCLUSION

In this work, an optimal framework for obtaining estimated HRIRs, by interpolating minimum phase HRIRs using tetrahedral interpolation, was proposed. An objective evaluation showed that optimal interpolated HRIRs were provided by tetrahedral interpolation with minimum phase HRIRs as its input, rather than by deploying magnitude HRTFs as its input. There were also extremely close similarities between interpolated and measured HRTFs. A subjective listening test for the simulated virtual 3D moving sound showed that the sound heard naturally moving around the horizontal plane was intended in the design.

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