INITIAL TECHNOLOGY REVIEW
SPATIAL EFFECTS:
BINAURAL SIMULATION OF SOUND SOURCE MOTION

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ABSTRACT

This report considers the technology needed to achieve binaural simulation of sound source motion based on a single-channel audio input. To do so will require an understanding of Interaural Time Differences, Interaural Level Differences, spectral cues, falloff with distance and the Doppler Effect. Binaural reproduction will be discussed as well as the outline of a simple simulation setup.

1. INTRODUCTION

Spatial hearing is an important part of our day to day experience, yet without a deeper investigation it is not initially obvious how it functions. The human hearing system has an incredible ability to localise a sound source, especially when it is in motion. In order to be able to simulate such sound source motion, it is first important to understand how our spatial hearing operates.

Firstly we must be able to understand how we can localize static sounds. Interaural Time Differences and Interaural Level Differences are known as the strong cues as they play the most important roles in determining the location of a sound source. Secondary to these are spectral cues that help in discerning the difference between front and back as well as up and down. These spectral differences occur due to the way the head, torso and pinnae reflect and absorb sound before it reaches the inner ear. Head Related Transfer Functions can be used to simulate the response of these cues. It is also important to consider that a sound source further away appears quieter than if it were close by. This is accounted for by the inverse distance law. Additionally, when we are considering a sound source in motion we must appreciated the shift in frequencies that occurs, known as the Doppler Effect.

Spatial audio is often reproduced using loudspeakers (for example, the use of 5.1 surround sound in DVD movies); however this report will focus on binaural reproduction over headphones. Finally, an overview of a simple sound source motion example is presented which brings together the discussed topics.

2. SPATIAL HEARING

2.1. Interaural Time Difference

Depending on the location of a sound source relative to the observer and the position of the head, the sound may reach one ear before the other. Although the difference will be in the order of less than a millisecond, the brain is able to use this information to help localize the sound source. This difference is known as the Interaural Time Differences (ITD).

2.2. Interaural Level Difference

Similarly, a sound source will appear to have different levels as perceived at the left and right ear. This is due to the distance between the ears as well as the fact that the head acts as a filter. This difference is known as the Interaural Level Differences (ILD).

2.3. Spectral Cues

Spectral cues also play an important role in sound localization. Certain frequencies will be filtered differently before entering the inner ear. This is due to the way the head, torso and pinnae absorb and reflect sound before they enter the ear. These differences are important for the brain to decide whether a sound may be coming from in front or behind, above or below.

This information can be represented in the frequency domain by the Head Related Transfer Functions (HRTF). HRTFs vary with sound source as well as shape of pinnae, head and torso.

HRTFs are based on Head Related Impulse Responses (HRIR) which are determined experimentally using human subjects or dummy recording heads. The method used to determine the impulse responses mean that they not only represent spectral cues but also information about ITD and ILD. A pair of HRIRs for two ears can be then used to synthesise a binaural sound that seems to come from a particular point in space. The perceived accuracy of the result depends on how well the HRIR dataset matches the characteristics of the listener’s own ears, head and torso.

3. ACOUSTIC MODELLING

3.1. Falloff for Distance

When the sound source is located further away from the observer it will appear quieter due to a reduced sound pressure when compared to when the sound source is near to the observer. In the free field, sound pressure obeys the inverse distance law:

$$\frac{p_1}{p_2} = \frac{r_2}{r_1} \qquad (1)$$

Where $\boldsymbol{p}$ is the sound pressure and $\boldsymbol{r}$ is the distance between sound source and observer at locations 1 and 2 as indicated.

This falloff must be modelled as the sound source moves past the observer in order for a realistic effect to be achieved.

3.2. The Doppler Effect

The Doppler Effect is a further cue that is present when there is a radial component to the relative motion between sound source and observer. The greater the radial velocity, the greater the shift in frequency heard by the observed.

For a stationary observer and moving sound source, the Doppler Effect is calculated using the mathematical formula:

$$\boldsymbol{f_d} = \boldsymbol{f_s}\left(\mathbf{1} + \frac{\boldsymbol{v_s}}{\boldsymbol{c}}\right) \tag{2}$$

Where $\boldsymbol{v_s}$ is the he radial component of the relative motion between the observer and sound source (see Figure 1), $\boldsymbol{c}$ is the speed of sound, $\boldsymbol{f_s}$ is the frequency of the sound source and $\boldsymbol{f_d}$ is the apparent frequency of the sound source for the observer.

The sound source may produce a range of frequencies so we consider the coefficient of frequency since all frequencies are affected linearly:

$$\boldsymbol{F} = \frac{\boldsymbol{f_d}}{\boldsymbol{f_s}} \tag{3}$$

Where $\boldsymbol{F}$ is the frequency coefficient.

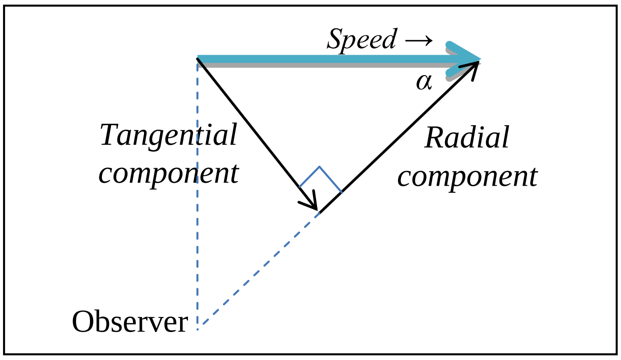

Figure 1. *Radial component of velocity of sound source relative to observer.*

To achieve the best spatial effect, the Doppler shift needs to be calculated individually for the left and right ear since the radial component of velocity is effected by the fact the ears are separated (by the interaural distance).

4. BINAURAL SOUND REPRODUCTION

Unlike when listening to sound reproduced over loudspeakers, a binaural reproduction over headphones offers the ability to control the signal being given to each ear individually. Loudness and relative distance of sound source can be varied independently by manipulating the ipsilateral gain and contralateral attenuation. It is important to note that the sound data processed by the HRTF will not only be different from the original source data but there will also be difference between the channels of the two-channel output. This two-channel output is precisely what is needed for binaural reproduction and each can be sent directly to the left and right channels of channels of a pair of headphones respectively allowing for the listener to observe the simulated spatial effect.

5. STRAIGHT LINE MOTION SIMULATION

In some situations, it is desired to simulate the motion of a sound source in a straight line as it passes in front of the observer, for example, the sound of siren as it an ambulance drives past. Figure 2 shows the setup of a simulation that attempts to model the sound source motion as it passes from left to right in front of the observer.

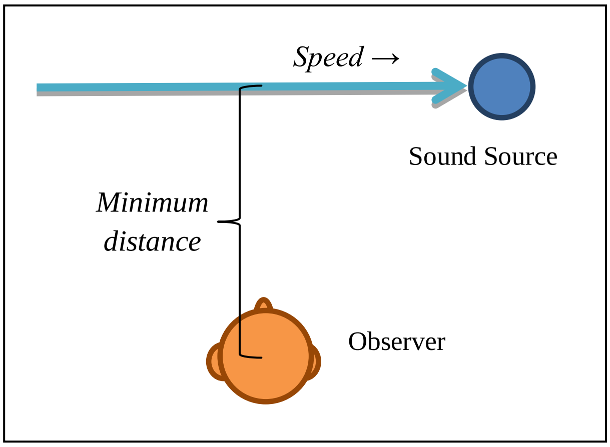

Figure 2. *Straight line motion of sound source simulation configuration.*

Required inputs are the single-channel input sound file, the desired speed of the sound source and the minimum distance as it passes in front of the observer. To achieve a convincing result, the simulation must account for ITD, ILD, spectral cues, distance falloff and the Doppler Effect.

6. DISCUSSION

There are limitations to the above simulation due to simplifications made. Firstly, considering the sound source to move in a straight line and at a constant speed removes the complex motion that may otherwise occur in reality.

Secondly, the simulation is assumed to take place in the free field and there is therefore no attempt to incorporate any artificial reverberations that would have otherwise given the simulation additional realism when correctly implemented.

Additionally, since the simulation models the sound source as a simple point source there is no consideration of sound source directivity and any additional spatial cues to do with the size and shape of the source.

7. CONCLUSION

The modelling of acoustics as well as a number of spatial cues can be used to simulate the motion of a sound source which can be reproduced binaurally for use over headphones.

More robust models will be able to accommodate complex motion and consider the dimensional characteristics and directivity of the sound source. The most demanding challenge, however, is the consideration of the dynamic changes in reverberation that would occur as the sound source moves within a space. It can be appreciated that the Doppler Effect must not only be applied to the direct sound but also the reflections that reach the observer.

8. REFERENCES

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