Digital Waveguide Mesh for Room Acoustic Modeling

Lauri Savioja and Tapio Lokki
Helsinki University of Technology
Telecommunications Software and Multimedia Laboratory
P.O.Box 5400, FIN-02015 HUT, FINLAND

Abstract

The two main approaches for room acoustic modeling are the wave-based and the ray-based techniques. In this paper we briefly overview the digital waveguide mesh method which is a wave-based model operating in the time domain. As a case study we show visualizations of edge diffraction modeled with the waveguide mesh technique. Some preliminary analysis of computational requirements for real-time auralizations are also presented, and the idea of frequency domain hybrid model is revisited.

1 Introduction

In real-time acoustic modeling the main emphasis has been on geometrical acoustics. This is not sufficient for authentic auralization due to lack of wave-based phenomena such as diffraction and interference. During the recent years the computational capabilities in an ordinary PC have grown enormously. Due to this it is not obvious anymore that all the wave-based methods are out of reach. These methods can be grossly divided into two categories. The ones operating in the time domain such as the FDTD (finite difference time domain), and the ones operating in the frequency domain such as FEM (finite element method) and BEM (boundary element method). At this point, we see the time domain approach to be much more appropriate for real-time acoustic rendering.

In this paper we briefly review one wave-based method, the digital waveguide mesh method and discuss its suitability for auralization at low frequencies. We have been developing this method since 1994, first for analysis of low frequency behavior of closed spaces such as listening rooms and loudspeaker enclosures. Nowadays the computation power has increased so much that the method is suitable also for larger spaces. In addition, the algorithm has improved a lot since its early days, and the technique is applicable in real cases.

In the campfire, we would like to have discussion on the position of wave-based modeling in the field of acoustic rendering both in real-time and in non-real-time simulations.

2 Digital Waveguide Mesh

The digital waveguide mesh is an extension of the one-dimensional digital waveguide technique [1, 2, 3]. The mesh can be used for simulation of two- and three-dimensional wave propagation in musical instruments and acoustic spaces. Mathematically it is very close to the finite difference methods. The original rectangular digital waveguide mesh algorithm suffers from direction-dependent dispersion. Alternative geometries, such as the triangular mesh, have been proposed to improve the performance of the mesh [4, 5]. Another choice to overcome this problem is use of multidimensional interpolation [3]. These techniques enhance the direction dependency problem, but there still remains dispersion. This dispersion error can be compensated to a certain degree by frequency warping, but in the case of real-time simulations, this is not possible with current algorithms [6, 3].
So far, the best solution for wave-based room acoustic modeling in the time domain, is the optimally interpolated three-dimensional digital waveguide mesh \[7\]. In this paper we still concentrate on the original 3D mesh.

2.1 Mesh Structure

A digital waveguide mesh is a regular array of discretely spaced 1-D digital waveguides arranged along each perpendicular dimension, interconnected at their intersections. A two-dimensional case is illustrated in Fig. 1. The resulting mesh of a 3-D space is a regular rectangular grid in which each node is connected to its six neighbors by unit delays \[8, 1, 3\].

The equations governing the mesh can be represented either by means of the nodes or by the means of the waveguides connecting the nodes. In this paper we apply the node approach. The difference equation for 3-D rectangular mesh is \[8\]

\[
p(n + 1, x, y, z) = \frac{1}{36} \left[ p(n, x + 1, y, z) + p(n, x - 1, y, z) + p(n, x, y + 1, z) + p(n, x, y - 1, z) + p(n, x, y, z + 1) + p(n, x, y, z - 1) - p(n - 1, x, y, z) \right]
\]

where \(p\) represents the sound pressure at a junction at time step \(n\), and \(x, y,\) and \(z\) are the coordinates of a node. This equation is equivalent to a difference equation derived from the Helmholtz equation by discretizing time and space. The update frequency of an \(N\)-dimensional mesh is:

\[
f_s = \frac{c\sqrt{N}}{\Delta x} \approx \frac{588.9}{\Delta x} Hz
\]

where \(c\) represents the speed of sound in the medium and \(\Delta x\) is the spatial sampling interval corresponding to the distance between two neighboring nodes. The approximate value stands for a typical room simulation \((c = 340 m/s, N = 3)\). That same frequency is also the sampling frequency of the resulting impulse response.

2.2 Computational Complexity

Let us consider the computational load by an example. If we study a room of size \(5m \times 10m \times 3m\) with grid spacing of 0.2m we have \(25 \times 50 \times 15 = 18750\) nodes. For each node six additions and one multiplication,
altogether seven operations, are required. This means that each time sample takes 131 250 instructions. With 0.2m grid spacing the sampling frequency will be 3kHz thus resulting in 386 MIPS (millions of instructions per second). The valid frequency range for auralizations depends on the application, but at most it is one fourth of the sampling rate. In this case the auralizations up to 750 Hz could be achieved with the given computational load. The load is still quite heavy, but we believe that in the near future it is possible to apply the technique in real-time at the low end of the frequency band.

3 Applications

In the following we describe a couple of application areas for the digital waveguide mesh.

3.1 Traditional Room Acoustic Modeling

So far we have concentrated in finding modes in a given space with the method. One interesting study has been carried out dealing with diffraction. In Fig. 2 there are a couple of visualizations of a stage house applied in the diffraction study. The sound source is on the stage and there are several listeners in the hall. In these visualizations a cross-section showing the sound pressure level at a given height are shown. In the campfire we will show these visualizations as animations.

3.2 Auralization

We haven’t made any auralizations yet with the method, but the first experiments will be done in the near future. To achieve realistic auralizations we need to make frequency domain hybrid renderer [9] in which the lowest end is calculated with the digital waveguide mesh and the upper end with our current DIVA system [10] which is based on the image-source method and artificial late reverberation.

4 Conclusions

In this paper we have discussed the digital waveguide mesh method. We believe that in the near future the room acoustic modeling techniques applied in auralization will include also some wave-based methods. Especially the ones operating in the time domain are interesting in this sense. Our goal is to develop a frequency domain hybrid in which we use both wave-based and ray-based methods to make realistic auralizations.

It would be nice to have some discussion in the campfire dealing with the future of the wave-based modeling methods.
References


