Hybrid Beam/Ray Tracing Simulation Method

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Summary
Beam tracing and ray tracing are well established acoustic simulation methods, based on geometric acoustics. Beam tracing offers the precision of the simulation at the cost of the computational complexity, while ray tracing excels with the performance and the flexibility but suffers from potential aliasing and non-detection errors. In this paper, we present the hybrid beam/ray tracing simulation method, that uses beam tracing for the first part of the room impulse response, and ray tracing for the later part of the room impulse response as well as for the simulation of diffuse reflections and diffraction. The geometry of reflective objects in the simulation is defined with irregular triangle networks instead of polygons. This is well suited for curved reflective surfaces found in ancient theatres and amphitheaters, as well as reflective bandshells often used in present day large outdoor performance spaces.

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1. Introduction

Beam tracing and ray tracing are acoustic simulation methods, often used in scientific and commercial applications. In this paper we propose the use of hybrid beam/ray tracing method, that would use best from both methods – accuracy from beam tracing, and speed and low computational demands from ray tracing. This paper is organized as follows: in the second chapter we present the review of related and previous work, in the third chapter we present the proposal of our hybrid method, and in the fourth chapter we give the brief conclusion.

2. Previous and related work

The simulation of wave propagation is an important tool used in engineering applications. It is used during the design phase by architects and designers, as well as in multimedia applications [1]. Light and sound waves are most often simulated, although wave simulations can be found in other areas [2]. Simulation of light propagation is often found in multimedia, especially since the last decade of the 20^{th} century, inspired by computer graphics in the entertainment world. Sound propagation simulations are also rapidly evolving during this period, and their application is predominantly in engineering - they are used for the design of acoustically important spaces. They can be used to calculate more accurate acoustic parameters than is possible using the classic Sabin and Eyring formulas. In the 21st century, acoustic simulations become ubiquitous part of the world of entertainment, and certain types of acoustic simulations can be performed in real time, interactively [3].
Mathematical methods used in optical and acoustic wave propagation simulations are similar, especially in the group of geometric methods. This fact is very useful, because certain algorithms that have occurred in one area can easily be applied in the other. Since visualization techniques have developed more rapidly, many algorithms and specialized hardware can be applied in acoustics as well.
The methods used to simulate wave propagation can be divided into two groups: numerical (FEM - finite element method, BEM - boundary element method ...) and geometric (virtual source method, ray tracing, beam tracing ...) [4]. Methods from the first group successfully simulate all relevant wave effects - refraction, diffraction, interference,

reflection and attenuation. The media is divided into small, finite elements, each of which is defined by its acoustic parameters. However, these methods are suitable for work only at low frequencies, and their efficiency is good only in simple geometries - they are mostly used for two-dimensional simulations, while a large processing power is needed [1, 5] required to simulate wave propagation in a three-dimensional space.

1.1. Geometric Simulation Methods

Geometric methods are less dependent on the wavelength, but they are not suitable for calculation at low frequencies when the wavelength has similar size as the room geometry. In this case, the rules for geometric wave propagation no longer apply. Geometric simulations are especially suitable for complex three-dimensional environments.

1.1.1. Virtual Source Method

The virtual source method is often used in acoustic simulations to calculate the impulse response of the room [4, 6]. In this method reflections are calculated by creating virtual, mirror image sources (Figure 1).

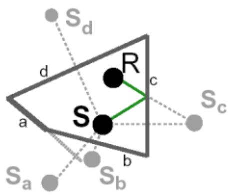

Figure 1. The virtual source method principle.

The multiple reflections are calculated so that virtual sources are re-mirrored around the room's reflective surfaces. The most important advantage of this method is its accuracy and completeness. With this method, all the sound paths can be found, as it examines all combinations of possible sound paths, or reflections. However, precisely because of the checking of all combinations, the complexity of the algorithm is:

$$O_{vs}(m^r) \tag{1}$$

where m is the number of room's reflective surfaces, and r is the highest order of reflection to be considered. Because of exponential complexity, the virtual source method can only be used for the calculation of early reflections. However, due to its accuracy, and because it is not subject to aliasing (as ray tracing method), it often is used in practice, mostly as hybrid algorithm. It is often combined with the ray tracing method.

1.1.2. Ray Tracing Method

In ray tracing method, rays are emitted from the sound source, with constant angle between two rays (Figure 2).

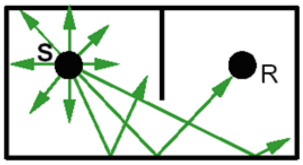

Figure 2. The ray tracing method principle.

The smaller the angle, the number of rays will be higher. This increases the accuracy of the simulation, but also slows down the time of the calculation. After generation, each ray is traced separately, in a way to ascertain whether there is an obstacle on its path. When a ray encounters an obstacle, it is reflected, and its tracking continues. The duration of tracking is usually limited by maximum number of reflections. The ray tracing method is computationally not very expensive:

$$O_{ray}(n \cdot r) \tag{2}$$

where n is the number of casted rays, and r is the highest order of reflection to be considered. While mirror image has exponential complexity (equation 1), the ray tracing has linear complexity.
To calculate the energy level at the receiver site, ray tracing uses a spherical detector, not a point one. If the ray touches or partially passes through such a spherical detector it is considered that the source has received it and that it contributes to the total energy and impulse response of the receiver. In ray tracing, other wave effects such as diffusion and diffraction can be implemented as an extension to the basic algorithm.
Besides its advantages, ray tracing has several shortcomings. Since a spherical detector is used for ray detection, an aliasing problem occurs. To overcome this larger number of rays can be cast, but then there is the danger of false multiple ray detection.
In practice, the ray tracing method is often used because of its speed and simplicity. However, in acoustics, it is often complemented by the virtual source method for early reflection calculation (to avoid aliasing) and with statistical methods for

calculating the late impulse response (to compensate for undetermined late reflections) [7].

1.1.3. Beam Tracing Method

The beam racing method began to develop later than the virtual sources and the ray tracing methods. In beam tracing the area around the source is divided into the finite number of beams in the form of cones or pyramids.

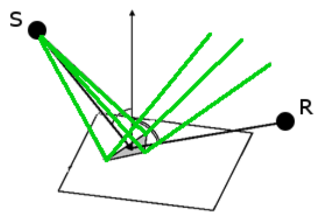

Figure 3. The beam tracing method principle.

Then the propagation of the beams is traced through the space, and when the beam encounters the reflective surface, its reflection is computed (Figure 3). Unlike rays, which are infinitely thin and require a specific volume (spherical) detector, beams have the final volume, and a point detector is used. If detection occurs, time and the acoustic wave intensity at the place of the receiver is calculated and added to impulse response.

Walsh et al. [8] and Heckbert and Hanrahan [9] have set the basics of the method as an improvement of the ray tracing method for the detection of hidden surfaces. In 1992, Maercke and Martin presented simulation names Epidaurus that used cones instead of rays. This change was an improvement over ray tracing, as it could use a point detector. However, although progress was evident, such a solution suffered from shortcomings – to cover the whole space the cones had to overlap each other, and the cone reflections did not adjust the shape of the reflective surfaces. The development continued in 1993, when Lewers used pyramid-shaped triangular beams instead of cones. In this way, the problem of cone overlap was solved - pyramidal beams filled the entire space around the source without overlapping. However, reflections were still not adaptable - in the case of reflections from the corners and small irregularities on the planes, the algorithm didn’t divide the reflected beam. The next step in developing the beam tracing method was made by Drum in 1997 with an adaptive beam tracking method [10]. The beam tracing method was extended with an adaptive reflection algorithm. Further contribution to the development of this method was provided by Funkouser et al., who in 2004 developed a beam tracing algorithm for interactive applications in architectural acoustics [11]. They successfully performed interactive , real-time sound auralization in office and city environment, using pre-processing of geometry, stationary sound sources, and the mobile listener. In addition to this interactive method, an important contribution of this work is also in the treatment of diffraction, which is simulated according to the geometrical theory of diffraction. Authors have shown that the diffraction in building and city acoustics, where there are a lot of sharp angles, makes a very important contribution to the fidelity of sound. Chandak and Lauterbach [12] in 2007 presented a method also developed for interactive applications, based on the beam tracing. In their method, beams do not adapt to the environment - their cross section is always quadratic. Authors call such a beam „frustum“. Where the beam encounters a reflective surface, that does not reflect the whole beam, it is divided into four equal parts, and the reflection is calculated for each of these parts. This method introduced a certain error, because the beam geometry does not exactly match the geometry of the environment. The advantage of this method was its speed. Laine et al. 2009 in their paper [13] gave an overview of another beam tracing algorithm designed for interactive applications. The algorithm only treats specular reflections, without diffraction, and for moderate complexity models gives good results. The development of interactive, real-time acoustic simulations continued [14-19] using spatial data structures, as well as parallelization for the simulation speedup.

Authors extended the beam tracing algorithm with refraction (BTR), by calculating not only the reflection, but also the refraction of sound [20]. The BTR has been implemented as adaptive, meaning that the beams are split on discontinuities. In BTR, surfaces are not defined by polygons, but by triangles, forming irregular triangle networks (TIN). In BTR, the scene is made up of media (polyhedra) and discontinuities (surfaces) between them. At discontinuities, as in reality, the reflection and refraction of the sound wave occurs. Thus, when encountering an obstacle, one part of the sound energy passes through it, and is traced through new medium. Using BTR one can simulate the sound propagation in non-homogenous environments, through several different media.

3. Hybrid beam/ray tracing method

We used BTR also for simulation of room acoustics. In such a simulation, we disregarded the refraction, discontinuities became reflecting surfaces, and there was only one media – air. Complex and irregular room geometry was not a problem, since reflecting surfaces were defined by TIN. But when we used BTR for room acoustics we stumbled on the obstacle of computational complexity. We discovered that simulating high order reflections with beam tracing seriously increases the complexity of the simulation.

3.1 Complexity

In the case of virtual sources method, the computational complexity increases exponentially with the complexity of the geometry, because all surfaces must be taken into consideration to check the validity of all possible virtual sources (Equation 1). In ray tracing all geometric operations involved are performed per ray, meaning that for reflection of a ray one must calculate how would a line reflect from a plane. Complexity of ray tracing linearly depends on the order of reflections (Equation 2).
On the contrast, a beam is defined by three bounding rays, so to calculate the reflection of a beam one must calculate the reflection of three lines from a plane. This means that beam tracing complexity is higher than ray tracing complexity by the factor of three.

$$O_{beam}(3 \cdot n \cdot r) \qquad (3)$$

where n is the number of beams emitted from the source, and r is the order of reflections.
If the beam tracing is performed with adapting to the surrounding geometry, the complexity increases even further, because the beam is divided when it encounters more than one triangle of the reflective TIN. Ray intersects the reflective surface in a single point, which always belongs to only one of the triangles of the surface TIN. So, the result of the reflection is always only one ray. On the other hand, the beam intersects the reflective surface TIN forming a triangular section. In general, that triangular section is composed of several triangles of the surface TIN. The adaptive beam tracing algorithm then divides the incoming beam in as many beams as there are triangles composing the section. This means that an incoming beam results in several reflected beams, so with each reflection the number of beams grows. For example, in Figure 4 the incoming beam *ABC* encounters two triangles of the reflective TIN and will be divided into two reflected beams.

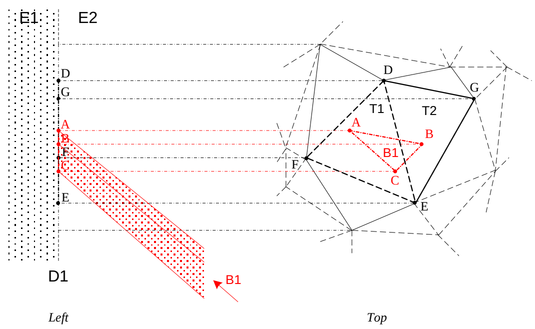

Figure 4. Beam ABC encounters multiple reflective triangles.

To assess the complexity of such a beam division, we must consider what happens with initial beams. Initial beams cover the whole space around the source, and (if the room is concave) hit all triangles that form the room's reflective surface TIN. Since the beams divide when they hit several triangles, the initial beams would be divided into at least m beams, where m is the number of triangles of the room's TIN. When these reflected beams reflect again they would in second iteration repeat the same process. They would divide into at least m beams. This process repeats r times, where r is the maximum order of reflections calculated. Since a beam doesn't hit room's TIN in a way that its boundaries perfectly match the TIN's triangle boundaries, at each reflection the number of divided beams would be greater than m, by a constant k.

$$O_{beam,adaptive}(3 \cdot r \cdot m \cdot k^{r}) \qquad (4)$$

where r is the order of the reflections, m is the number of triangles in room's TIN and k is the factor of beam division. In equation 4 we didn't use the number of emitted beams n as it is in general much lower than the number of triangles m. We empirically determined factor k by performing several room acoustic simulations. Mean value of k was 1.5.
The typical reverberation time of a general-purpose auditorium is about 2s. During this time sound in air travels approximately 700m. If the size of a multi-purpose hall is 20m, then to calculate all

reflections that fall into the reverberation time window, one must calculate reflections up to 35th order. The ray tracing complexity would now be $O(3.5{\cdot}10^5)$ (if 10.000 rays are used for tracing), while the complexity of the adaptive beam tracing would be $O(3.1{\cdot}10^9)$ (for typical value of k=1.5, and if the TIN of the multi-purpose hall has 700 triangles).

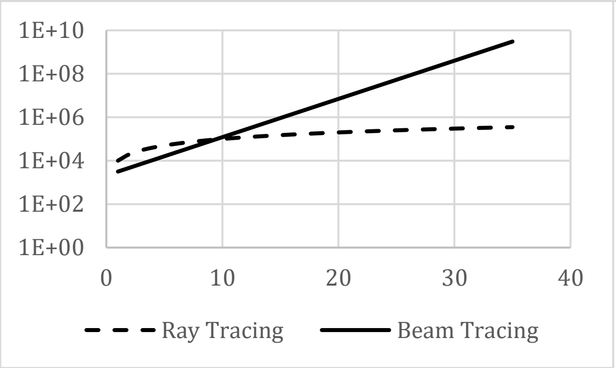

Figure 5. Complexity of ray and beam tracing depending on the order of reflections.

This means that if the calculation of room impulse response with ray tracing would last for 10 seconds, the same calculation with the beam tracing would almost 28 hours. Such an exponential increase in complexity prevents the beam tracing algorithm to be a practical solution for the simulation of room acoustics.

3.2 Hybrid beam/ray tracing

While using our BTR algorithm we have noticed another effect that occurs for high order of reflections. Adaptive beam tracing divides the beam at each reflection according to the reflective surface geometry, causing the beam to become thinner at every division. At high order of reflections, the beams are so thin that they are more like rays. Also, since the sound intensity decreases with the propagation and at each reflection, the high order reflection beams have significantly less energy than the beams with lower order of reflections. Also, late reflections, which are represented by high order reflection beams, are not so important to the overall sound impression as early reflections.

Because of all the facts we mentioned above, we changed the beam tracing algorithm, so we calculate high order reflections as rays and not as beams. This greatly reduces the complexity of the simulation. Also, since late reflections are less significant and contribute with lower energy than the early ones, the potential errors that ray tracing introduces are not so prominent and can thus be neglected. In this way the beam tracing algorithm becomes the hybrid beam/ray tracing algorithm. Similar hybrid approach has already been used for image sources/ray tracing hybrid algorithm, in simulations such as Odeon [21], but to our knowledge has not been until now applied to the beam tracing.

The beam tracing complexity surpasses the ray tracing already after few reflections (Figure 5.). This is the moment when we make the transition from beam to ray tracing. In such a configuration the beam tracing precisely renders the early reverberation, and then switches to ray tracing, keeping the complexity rather low, and calculating the late reverberation with still acceptable precision of ray tracing.

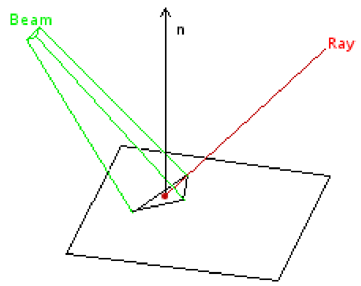

Figure 6. Transition from beam to ray tracing.

The transition from beam to ray tracing is done in a way that the incoming beam reflects as one outgoing ray, propagating from the barycenter of the section of the beam and the reflecting surface (Figure 6). With the outgoing ray we store the information about the energy it carries as well as about the equivalent radius, that enables us to later use the sphere detector of the right size.

3.3 Diffuse reflections and diffraction

To have realistic results, the room acoustic simulation must calculate not only the specular reflections, but also the diffuse reflections and the diffraction of the sound. It is not an easy task to simulate this phenomena with the beam tracing method, so we intend to use the ray tracing for these two phenomena. The diffusion would be simulated by taking away a portion of energy from the specular beam reflections and creating secondary diffuse sources at the point of the barycenter of the reflected specular beam. The diffraction would be simulated according to the geometrical theory of diffraction, by detecting the diffraction paths, and using ray tracing to calculate the sound created by diffraction.

4. Conclusions

In this paper we presented the hybrid beam/ray tracing method, currently at an early stage of the development. This hybrid method enables the beam tracing to be used without the problem of high computational complexity. Triangular beams are traced up to the certain reflection order, and subsequently transformed to rays and traced on. The ray tracing would also be used for the simulation of diffuse reflections and diffraction of sound. Upon completing the development of the method, we plan to thoroughly test its performance and accuracy. We expect this method to be flexible and suitable not only for classical room acoustic simulation, but also to enable the simulation of complex, semi-open acoustical environments such as ancient theatres and amphitheaters, as well as outdoor performance spaces with reflective bandshells.

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