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Accurate and fast audio-realistic rendering of sounds in virtual environments

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Abstract— **In this paper we propose a novel method for real-time auralization of sounds in complex environments using visibility diagrams. The method accounts for both specular and diffracted reflections with receivers and sources that are free to move. Our solution concentrates in a pre-processing phase all the operations that can be conducted without knowledge of either source or receiver locations. In fact we pre-compute a set of visibility diagrams and diffracted beam trees. Once the source location is specified, we can determine the reflective beam trees through a simple lookup process on the visibility diagrams. The additional knowledge of the receiver location allows us to immediately generate all reflective and diffractive paths that link source and receiver.**

I. INTRODUCTION AND PREVIOUS WORK

The accurate determination of the paths that link source and receiver in a complex environment is a problem of crucial importance in many fields of application ranging from realistic sound rendering to prediction of multipath fading of wireless systems in indoor environments.

Several methods were proposed in the past decade for the fast determination of such paths. The first methods were inherited from computer graphics, such as image source method and ray tracing. Solutions based on the tracing of beams (bundles of rays) were later developed in order to overcome problems of spatial aliasing that are inherent of traditional ray tracing solutions. The effectiveness and the efficiency of beam tracing techniques was proven several times in the literature [2]), particularly when either the receiver or the source needs to move in the environment. The idea behind the beam tracing method is to follow the propagation of a beam (intended as bundle of acoustic rays) as it propagates from the source in the environment. In particular, the goal is to determine how it splits into new subbeams as it encounters reflective walls in the virtual environment. An iterative algorithm can be implemented in order to characterize this branching process. Branching information can be collected in a tree-like data structure called beam tree. An interesting aspect of beam tracing is that we do not have to recompute the beam tree when the receiver moves, as the information contained in the beam tree does not depend on the receiver's location. Once the receiver location is specified, the algorithm determines which beams contains it through a simple lookup of the beam trees. On the other hand, when the source moves a new beam tree needs to be constructed with the iterative branching algorithm. This operation can be computationally expensive.

A recent solution was proposed to overcome this limitation [1] in 2D non-convex environments (tall vertical walls). The idea behind this method is to compute the visibility information of the environment (reflectors) from an arbitrary point in space, which is equivalent to the visibility of a generic reflector from an arbitrary point on another generic reflector. This visibility computation can be performed in a pre-processing phase and stored in specific data structures (called visibility diagrams), one per reflective face of the walls. Once the source location is known, it is possible to iteratively construct the beam tree through a simple lookup of the preconstruted visibility diagrams. As soon as the receiver location is specified, the paths linking source and receiver can be found through lookup of the beam tree data structure.

In this paper we propose an extension of the visibility diagram approach, aimed at modeling reflections as well as diffraction phenomena. Diffraction is an acoustically relevant propagation phenomenon, particularly when dealing with complex (non-convex) environments. The literature is rich with physical models for evaluating and accounting for the diffracted field. Among them is the Uniform Theory of Diffraction (*UTD*), which is an extension of the Geometric Theory of Diffraction (*GTD*), which seems particularly suitable for our goals as it allows us to look at the diffraction phenomenon from a purely geometric standpoint.

We will show how the visibility diagram approach can be extended in order to accommodate diffractive phenomena at a very modest computational cost. The approach is can be applied to non-convex 2.5D environments (with vertical walls and horizontal floor and ceiling).

II. VISIBILITY DIAGRAMS

One key concept behind our work is the visibility diagram, which is a parameter-space representation of the visibility between reflectors. The visibility function of a reflector from an arbitrary viewpoint is here defined as a boolean function of the plenoptic space (the parametric space that describes a ray that departs from a generic point in space in an arbitrary direction). This function tells us whether or not the reflector will be visibile from that viewpoint while looking in the considered direction. A two-dimensional plenoptic space is thus described by three parametres: two for the viewpoint location and one for the viewing angle. Notice, however, that all points on a visual ray share the same value of the visibility function. This tells us that a plenoptic parametrization is, in

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fact, redundant. This fact is well known in applications of image-based rendering, where the plenoptic space is often replaced by a reduced-dimension space (see, for example, the Lumigraph [3]). In our case this dimensionality reduction can be easily achieved by considering only the viewpoints that lie on a reference section of the geometric space (a reference line in 2D environments and a reference plane in the 3D case). This section, in principle, can be chosen arbitrarily, as long as it does not lie on the reflector whose visibility we are evaluating. It is important to remember that the visibility function will be iteratively looked up for tracing beams in the geometric space, therefore it is important to choose the reference section in such a way to simplify this process. We will see that this can be achieved by making the reference section coincide with another reflector. This corresponds to defining the visibility *of* a reflector *from* another reflector. A complete evaluation of the environment visibility is thus given by the whole collection of visibility functions of all reflectors from all reflectors.

With reference to Figs. 1 and 2, the visibility of reflector 2 from reflector 1 can be expressed as a boolean function of two parameters q and $m = \tan\phi$. This function indicates whether a visual ray in position q on reflector 1 pointing in the direction ϕ passes through any point of reflector 2. Notice that the visibility region on the plane (m, q) corresponds to the dual of the reflector 2 with respect to a reference frame attached to reflector 1.

Let us consider the visibility diagram of reflector r_1 in Fig. 1, which describes how the other reflectors are seen from viewpoints on r_1. The first step consists of choosing a reference frame attached to r_1, which is normalized in such a way that r_1 will correspond to the segment (x_1, y_1), with $x_1 = 0$ and $-1 \leq y_1 \leq 1$. This choice allows us to delimit the parameter space to the reference strip corresponding to $-\infty \leq m \leq \infty$ and $-1 \leq q \leq 1$ (dual space of the reference reflector).

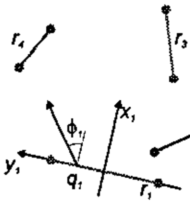

Fig. 1. 2D Environment to be used for the illustration of the visibility diagram construction process.

The rays departing from the reference segment and hitting the other segments correspond in the (m, q) space with visibility regions, for example the visibility region of s_2 is showed in Fig. 2.

Considering the dual space interpretation, the visibility regions of the various reflectors with respect to the reference one can be computed in closed form [1]. Notice, however, that the visibility regions of the various reflectors overlap in regions corresponding to visual rays that intersect more than one reflector. Figuring out which reflector occludes which corresponds to sorting out which regions overlaps which. This ordering operation can be performed very quickly by back-tracing one ray for each connected overlapping area. Once overlaps are all sorted out, the visibility of environment of Fig. 1 from reflector 1 is shown in Fig. 3.

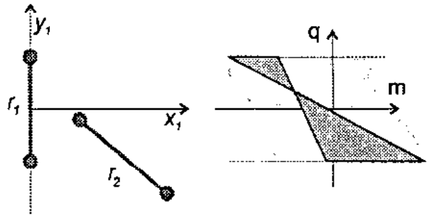

Fig. 2. Visibility region corresponding to segment s_2.

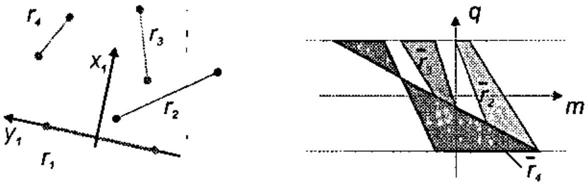

Fig. 3. Environment geometry (left-hand side) and visibility diagram of the s_1 segment. The visibility regions of the various reflectors are here shown with different colors.

Visibility diagrams can all be computed in a pre-analysis phase, and this information can be used for a fast construction of a beam tree and a fast determination of all geometric paths between source and receiver. As soon as the source location is specified, the initial beam departing from it will split into a number of sub-beams, each inciding on a different reflector. The reflected beams will then branch out again as they reach other reflectors. In order to trace all such reflections and branchings, we can implement an iterative process that involves looking up visibility information.

At the generic step of the branching process, a beam is characterized by a (real or virtual) source and that portion of a reflector that is "illuminated" by the beam (active portion of the reflector). The visibility from the active portion of the reflector can be readily obtained from the visibility of the whole reflector by narrowing the reference strip in the parameter space. Similarly, all the rays that depart from a source location correspond to a line on the visibility diagram (we recall that the parameter space of the visibility diagram is, in fact, the dual of the geometric space). The beam will thus be the intersection between the narrowed reference strip (illuminated portion of the reflector) and the dual line corresponding to the source (set of all visual rays that depart from the source's origin). In conclusion, in order to determine which reflectors the beam will encounter in its path after being reflected by r_i, we just need to determine the intersection between the dual of the source (a line) and the visibility regions of all the reflectors as seen from r_i.

Once the beam tree is constructed, all paths corresponding to a given receiver location can be readily found through a simple beam tree lookup as described in [1] and [2].

III. DIFFRACTIVE BEAM TREES

In this Section we show how the above data structure can be used to account for phenomena of diffraction as well. The Uniform Theory of Diffraction envisions the diffracted field as generated by a secondary source located on the edge of a wall that occludes the line of visibility between source and receiver. Notice, however, that the diffracted field turns out to be less relevant when source and receiver are in direct visibility. In the next sections we will refer to the *wedge* as a structure where two or more walls will converge in a single edge. If the angular opening of the wedge is smaller than π and both receiver and source fall inside the wedge, the direct signal will be present. The very first phase of the proposed algorithm will detect the diffracting wedges in the considered environment. The algorithm then generates one beam tree per diffracting wedge. With reference to Fig. 4, the beam tree will departfrom the diffracting wedge in such a way to scan only the two regions marked as **I** and **II**, where source and receiver are not necessarily in conditions of mutual visibility.

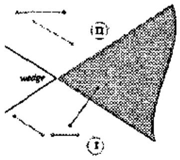

Fig. 4. When the source and the receiver fall outside regions **I** and **II**, the risulting diffraction is non-relevant. The diffractive beam trees will thus cover regions **I** and **II** only.

The number of levels of the diffractive beam trees is indeed to be specified in a different fashion compared with reflective beam trees, for reasons of relevance and computational load. The virtual source will be placed on the edge of each wedge, the first step consists of looking up the visibility diagrams of both segments forming the wedge, with outward orientation. The dual of such beams correspond to a segment on each one of the visibility diagrams of the wedge sides. By scanning such segments along the visibility diagrams we immediately determine all the visible reflectors of the above beams, which allows us to determine their branching.

Adopting the geometric space in such a way that the reference reflector will end-up on the vertical axis between -1 and 1, the source will be represented by a horizontal line that intersects the vertical axis either in position 1 or -1. The diffracted beam trees are thus semi-infinite portions of such lines. The segments obtained by the intersection of such lines with the visibility diagrams represent the diffracted beams. In Fig. 5 we can see the construction of the first-level beams corresponding to the above-described configuration. The beams that will branchout of that will be determined through the same procedure explained in [1]. Diffractive beam trees can be evaluated in a pre-processing phase, as they do not need source and receiver to be specified in order to follow the propagation from wedge to reflectors.

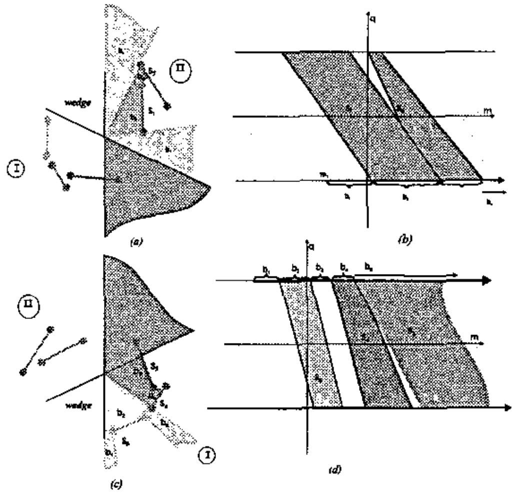

Fig. 5. Diffracted beam trees departing from a wedge.

Once determined the diffracted paths, we need to render the diffracted field. A simple way to do so consists of computing the UTD filter on the fly. In alternative we can choose to give up some of the accuracy offered by the UTD in exchange of some computational efficiency. This can be a convenient choice when dealing with applications of virtual acoustics where it is more important to produce a convincing acoustic rendering rather than than a physically accurate one. A simple method of this sort is based on a double interpolation process. During the pre-computation phase we record the complex-value of the diffracted field at the origin of the beam ("penumbra area") and in proximity of the wall of the shadow region. This operation is done by placing the source at eight angles in the angular range in which the beam tree spans and for eight frequencies between 0 and 3 kHz. The source-wedge and receiver-wedge distances are assumed to be the average of the half-distances between wedge and unoccluded walls. We use this information in the calculation phase as follows: we check that source and receiver fall both in the considered beam tree: we then compute the complex-value of penumbra and shadow-zone as linear interpolation of nearest values in the pre-computed structure. The interpolation is angle-based. Given the position of receiver, we use a linear angle-based interpolation between the half-light value and shadow value of the diffracted filter to find the value of the diffracting filter at the frequencies that we are considering. An inverse Fourier transform is then performed to derive the required filter.

IV. VALIDATION RESULTS

In order to validate the algorithm proposed in the previous section, we conducted an acquisition campaign in a real environment made of two rooms connected by a door, and we simulated the acoustic rendering of a virtual environment with the same geometric and reflective characteristics. We placed a source (a directional speaker) in a fixed location in space and we acquired the signal with an omnidirectional measurement microphone in a tightly sampled grid of locations within the whole environment while the speaker produced a pseudo-random binary signal. This allowed us to use the MLS method [4] for measuring the impulse response of the room in the various locations (by computing the cross-correlation between the acquired signal and the MLS original sequence). In order to remove the impact of the acquisition and the output devices (D/A converter, speaker, microphone and A/D converter) we applied a deconvolution process (using the first arrival in free propagation conditions). In order to avoid 50 Hz power supply interferences, we also used a notch filter.

Once the impulse response was derived for each one of the locations of the microphone, we derived a number of parameters. Many of them required the computation of the Scröder integral of the impulse response $h(t)$, defined as

$$I(\tau) = \frac{\int_{\tau}^{\infty} h^2(t)\, dt}{\int_{-\infty}^{\infty} h^2(t)\, dt}$$

In this paper we only show two of them:

- Early Decay Time (EDT): time that it takes the Schröder integral to go down -10 dB.
- Center Time: first momentum of the energy of the impulse response.

Fig. 6 shows the EDT of the acquired response (top), simulated with (center) and without (bottom) diffraction. As we can see, the diffraction better improves the approximation a great deal. Fig.7 compares the center time of the acquired response (top), simulated with (center) and without (bottom) diffraction. Also in this case the inclusion of diffraction results in a far better approximation of reality.

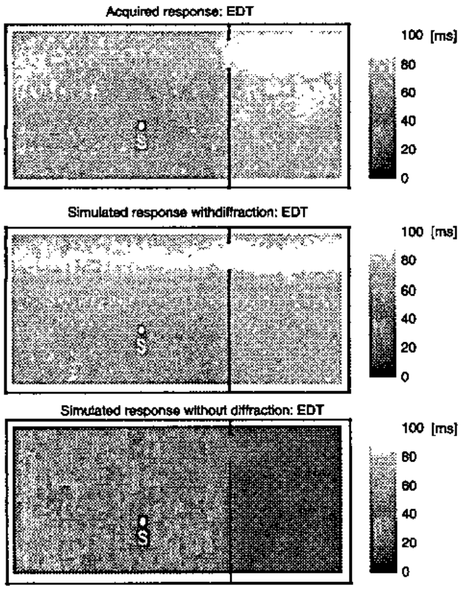

Fig. 6. EDT of the acquired response (top), simulated response with (center) and without (bottom) diffraction.

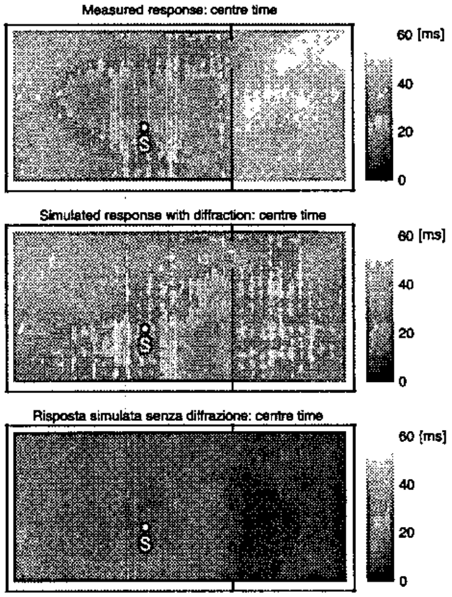

Fig. 7. Center time of the acquired response (top), simulated with (center) and without (bottom) diffraction.

V. CONCLUSIONS AND FUTURE WORK

In this paper we proposed a fast algorithm for generating the beam trees that are needed for modeling reflections as well as diffraction phenomena in 2D complex environment and we validated the approach through a comparison with real acquisitions. The method, in fact, has been implemented in such a way to model also reflections on the floor and the ceiling under the assumption that such surfaces be perpendicular to the vertical walls.

In the actual simulation algorithm, only a level of diffraction was included. One possible improvement of the current work could be the connection of diffractive beam trees in order to account for multi-diffraction paths.

We are currently working on a 3D version of the fast beam tracing approach based on visibility function, which includes reflection, diffraction and diffusion.

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