Extending Geometrical Acoustics to Highly Detailed Architectural Environments

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EXTENDING GEOMETRICAL ACOUSTICS TO HIGHLY DETAILED ARCHITECTURAL ENVIRONMENTS

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ABSTRACT

Geometrical acoustics (GA) is a widely used approximation for simulating sound propagation in virtual 3D environments. However, GA is a high-frequency approximation and therefore very detailed models, containing features small compared to audible wavelengths, may fall outside its validity domain. Including finer geometrical details might actually degrade the quality of the simulation, as supported by a number of previous studies. Furthermore, the cost of running GA-based simulations significantly increases with the geometrical complexity.
In this paper, we propose an extension to GA for highly detailed environments. In particular, we pre-compute a representation of the scattering behavior off complex geometry using finite element techniques. We then use this representation within classical GA frameworks, such as radiosity or ray-casting, to compute impulse responses and auralize the corresponding acoustical effects.

INTRODUCTION

Geometrical acoustics (GA) is one of the most widespread approaches in architectural acoustic modeling. GA is a high-frequency approximation that models sound propagation along ray-paths. The propagation paths can be constructed using techniques such as ray or beam tracing [18, 12] using spatial data structures (e.g., BSP trees) to maximize efficiency. However, the geometrical models used for architectural acoustic simulation tend to be of low complexity. Experimental studies have shown that low-resolution models might be more appropriate to evaluate acoustical criteria with GA approaches [21], which is somewhat counter-intuitive. In interactive GA applications, the reflection of sound rays is usually modeled as purely specular assuming the size of the surfaces is large compared to the wavelength, which is often not the case in practice. In off-line acoustical simulations, additional lambertian or "glossy" reflections [14, 7, 31, 3] have been classically used to approximate scattering off complex surfaces, which are usually replaced by a flat proxy geometry. Recent works have been devoted to level-of-detail (LOD) approaches for GA [16, 30, 23] but to our knowledge no general simplification scheme that preserves the correct scattering properties has been proposed to date.
The goal of our work is to compute scattering from very complex geometry, such as highly tesselated CAD-CAM models or those acquired through scanning techniques. We introduce a framework that can be used to approximate first-order scattering effects off arbitrary complex surfaces and pre-compute corresponding filters. These filters can be re-used within classical GA simulators. Our approach brings an alternative solution to the problem of surface-simplification. Below, we review existing approaches which can be used to improve classical GA models.

Edge diffraction models

GA simulations can be enhanced by introducing diffraction effects from wedges [19] in order to avoid audible discontinuities when the source or a strong reflection path becomes occluded from the receiver [26]. As all GA models, the geometrical theory of diffraction (GTD) assumes edges to be large compared to the wavelength. Increasing geometrical complexity would imply using smaller primitives and eventually would fall outside the validity domain of GA. Thus, it is unclear how classical GA+GTD approaches could apply to more detailed scenes. Other approaches, such as the Biot-Tolstoy-Medwin model [22, 17, 8] can be used to accurately compute the impulse response due to scattering from finite-sized wedges in time-domain. However, due to its computational complexity it has found limited use in practical applications.

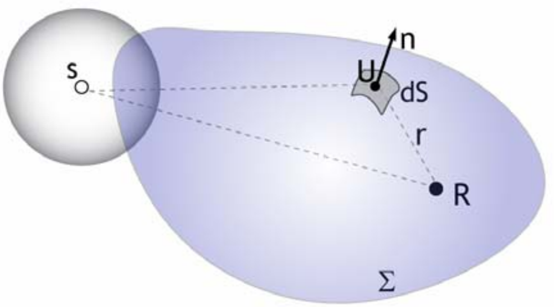


Figure 1.- Notations for the Kirchhoff-Helmholtz theorem. S and R denote the source resp. receiver.

Finite element methods

Finite element methods (FEM) are numerical solutions to the wave (Helmholtz) equation and associated boundary conditions. They are classically solved in frequency domain by subdividing the environment into small elements (voxels) but alternative time-domain formulations can also be used [25]. Of special interest is the Green surface integral formulation. Using this formulation, the pressure solution P(R) to the Helmholtz equation can be obtained using an arbitrary surface Σ surrounding the receiver R [13]:

$$P(R) = P_0(R) - \int_{\Sigma} \left(P(U)\nabla G(U,R) - G(U,R)\nabla P(U)\right) \cdot \mathbf{d}S, \qquad (1)$$

where **dS** = **n**dS (**n** unit vector) and G(U,R) = $-e^{ikr}/4\pi r$ is the Green function corresponding to the propagation of a spherical wavefront in free-field (see Figure 1). Po(R) is the free-field pressure emitted by the source and the integral term, often called diffracted field, is the solution of the homogeneous Helmholtz equation associated with the boundary conditions on the surfaces of the environment. This surface integral is also called the Helmholtz-Kirchhoff integral theorem. The Green surface formulation serves as a basis for boundary element methods (BEM) techniques. In this case, Σ corresponds to the surfaces of the environment. BEM methods can account for full scattering effects in a unified way and are widely used to compute reference solutions. However, edge-length for surface elements must typically be smaller than 1/4th of the wavelength. This makes such approaches very time-consuming at high frequencies or for large-scale problems. They also require carefully-designed meshes with uniform elements to limit errors in the solution. They are thus hard to use with most 3D models, particularly those acquired through scanning.

The Kirchhoff approximation

The Kirchhoff approximation (KA) can be seen as a hybrid strategy between GA and wave acoustics [13]. It is based on Eq. 1 but imposes P(U) = Po(U) and ∇P(U) = ∇Po(U) on the “illuminated” side of the surfaces (visible to the source) and P(U) = ∇P(U) = 0 on the “shadowed” side. As a result, P(R) can be computed by a direct integration but surfaces facing away from the sound source will not contribute to the solution. Neglecting the contribution from occluded surfaces and higher-order scattering is the major source of error in the KA. As a result, the approximation will degrade at very low frequencies as the scattered component becomes more important in the regions occluded from the source. The KA will also lead to inaccurate results when second-order occlusions/reflections become prominent. Several studies have shown that it can introduce significant errors in the computed scattering from simple flat or randomly-rough surfaces when compared to reference solutions [15, 29, 20, 5]. In particular, errors were found to be more important at grazing angles and near-field from the surface. However, some of these studies also used additional far field approximations which might also contribute to the observed errors. As stated in [29, 10], further work is still required to evaluate the validity of the KA which is still not well established even today. Despite these limitations, the KA has been widely used to solve scattering/occlusion problems in acoustics [24, 4, 5, 27, 11, 10]. In [24] it was shown that the KA can be used to simulate impulse response of first-order reflection/diffraction off rigid panels with good agreement to measured responses. In this paper, we evaluate whether the KA can be efficiently used to compute scattering effects off arbitrary complex geometries.

THE KIRCHOFF APPROXIMATION IN ARCHITECTURAL ACOUSTICS

To use the KA for complex architectural acoustics problems, we evaluate the surface integral on all geometry visible from the sound source. This integral can be computed in software using ray-casting but it also maps very well to modern graphics hardware leading to a very efficient implementation. For more information and implementation details, we refer the reader to [28].
To evaluate our approach, we computed scattering filters for large-scale real-world situations and compared them directly to corresponding recordings taken in the field. Example audio files can be found at: http://www-sop.inria.fr/reves/projects/InstantScattering.
A first interesting example is the Kukulkan temple, a Maya staircase-pyramid located in Chichén Itzá, Mexico (Figure 2 left). The stairs of this pyramid act as a sound diffraction grating. They reflect a particular chirped echo which has been the object of a number of studies [9, 1]. For additional information, please see http://www.ocasa.org/MayanPyramid.htm.
We modeled a 856 polygons virtual replica of the pyramid, on which we applied our scattering algorithm. We used the same model for all frequencies without frequency-dependent adaptation of the tessellation. We computed a full-bandwidth (0-22KHz) transfer function in 2.45 Hz increments (8192 frequencies) in 92 sec. on a Pentium 4 3.4GHz workstation with a GeForce 8800 GTX graphics processor. We applied the obtained filter to the handclap used in the on-site recording available at the above URL. Figure 2 (right) compares the result of our simulation to the recording. Although the recording contains significant environmental noise, the comparison shows that our algorithm convincingly captures the chirped echo from the stairs.

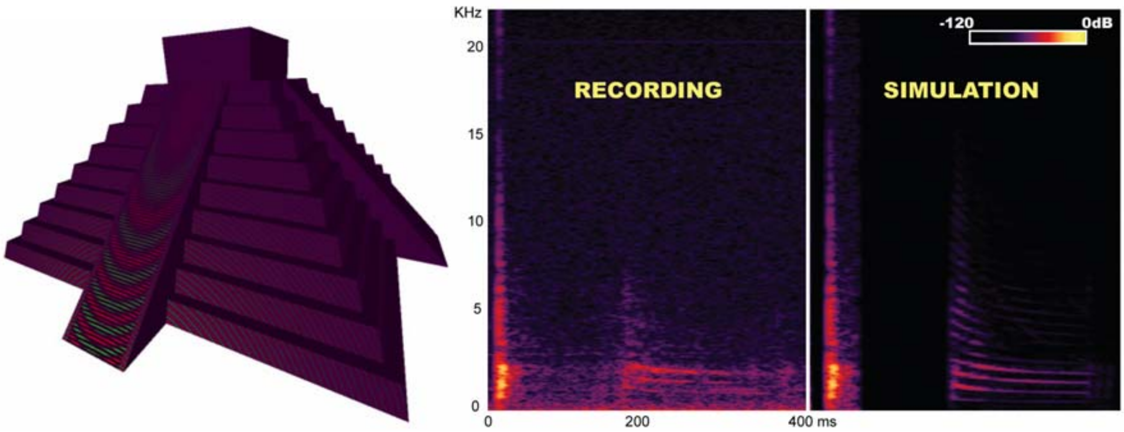


Figure 2.- Left: Visualization of the scattering terms on the surface of a model of the Kukulkan temple for a 500Hz wave. The sound source is 15 meters in front of the stairs. Right: Comparison between spectrograms of a simulation and an on-site recording for the Kukulkan temple. The simulated response is convolved by the handclap of the original recording.

Application to a complex range-scanned model

Our second, more challenging example models the scattering off the façade of the Duomo on the Piazza dei Miracoli in Pisa, Italy, also famous for its leaning bell-tower. We used a detailed model of the cathedral obtained from time-of-flight laser scanning (Figure 3 left) and containing 13 million triangles (a resolution of about 2 cm). Figure 3 (right) compares a simulation with an on-site recording of a handclap. The approach gives satisfying results although some components are missing, probably due to higher-order scattering or reflections from the ground (which was not acquired). The computing time for the solution is similar to the one of our pyramid example since we can calculate all geometrical information once (e.g., position of visible surface samples and normals) and re-use it for all frequencies. Creating the necessary renderings required only 2 additional seconds using our graphics hardware.

INTEGRATION WITH GEOMETRICAL ACOUSTICS ENGINES

In this section, we propose two solutions in order to integrate our KA-based approach into current GA simulators. First, the approach can be used to simplify complex geometry by introducing details as textures on a flat approximate geometry, as used in graphics rendering. Second, scattering filters from complex geometry can be pre-computed and stored in order to be directly used within classical GA frameworks.

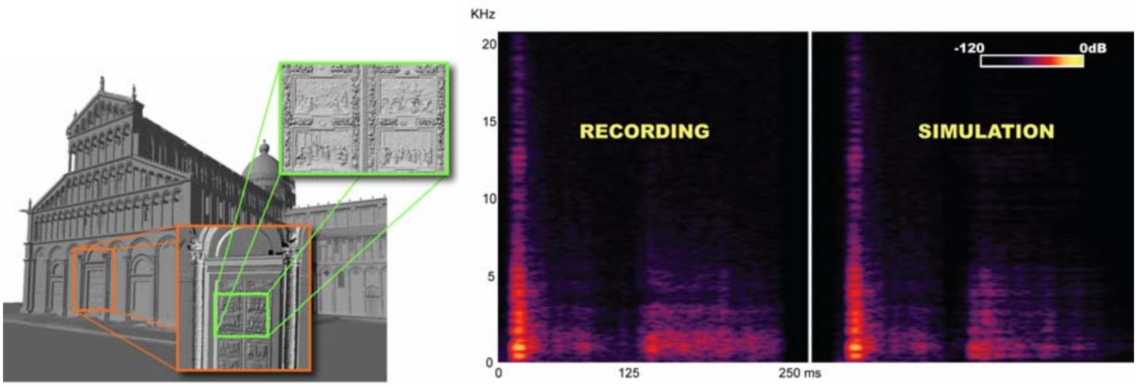


Figure 3.- Left: A 3D model of the scanned façade of the Duomo in Pisa, Italy and close-ups on surface detail. Right: Comparison between spectrograms of a simulation and an on-site recording. The simulated response is convolved by the handclap of the original recording.

Scatter-preserving geometrical simplification

The surface integral approach of the KA offers the possibility to leverage level-of-detail schemes originally developed for graphics rendering [6]. In this section, we propose a strategy combining normal mapping with displacement correction to model complex surface detail for acoustic scattering calculations. Displacement surfaces [2] use textures to encode fine-grain surface detail which can be used at rendering time by a software ray-tracer or with the graphics hardware. To avoid costly ray-intersections with complex geometry, we propose a simpler approach that accounts for the correct propagation delay but omits accurate visibility calculations. To remove the contribution of back-facing fragments, which should not be contributing to the integral, we use an additional weighting term defined as $-\mathbf{v}.\mathbf{n}$, where $\mathbf{v}$ is the direction from the 3D location to the sound source and $\mathbf{n}$ is the surface normal. To evaluate our approach, we created several 4x4 meter surface samples from displacement textures. The amplitude of displacement was 0.5 meters. Figure 4 shows example surfaces and scattering impulse responses calculated with true displaced geometry. In this case, source and microphone were directly above the center of the surface respectively 10 and 20 meters away. We also created corresponding normal maps from the displaced geometry and performed a scattering calculation using a flat proxy surface with our displacement-corrected normal mapping and standard normal mapping only. Figure 4 compares the different results. As can be seen, normal maps without displacement correction result in very little difference compared to a flat surface. This demonstrates the importance of the interference phenomena which are paramount in modeling the proper scattering effect. Our displacement-corrected normal mapping results in a much better approximation. We also evaluated our simplification technique at oblique incidence. As can be seen in Figure 5, errors are more significant due to self occlusions but our approximation remains acceptable.

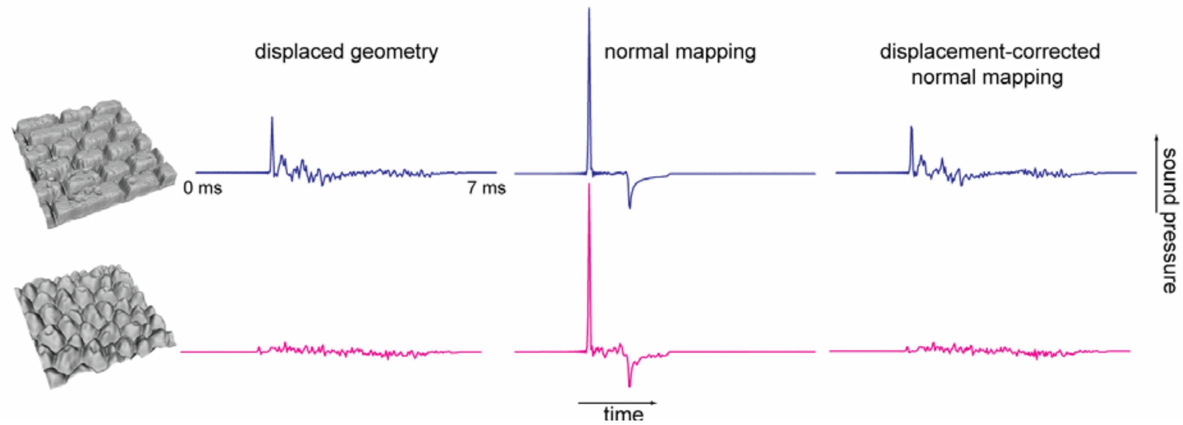


Figure 4.- Comparison of true displaced geometry with a proxy flat quadrilateral enhanced with normal-map only or combined normal/displacement maps. Source and receiver are respectively 10 and 20 m directly above the center of the face. Note how the normal-map alone has little effect on the obtained response.

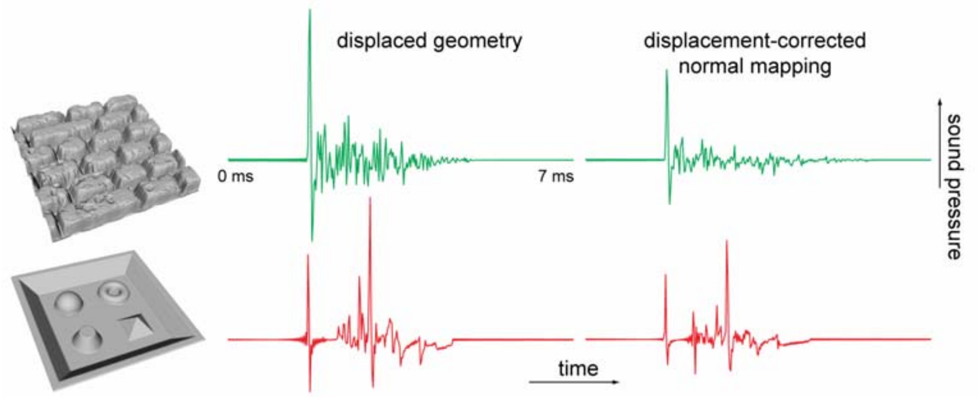
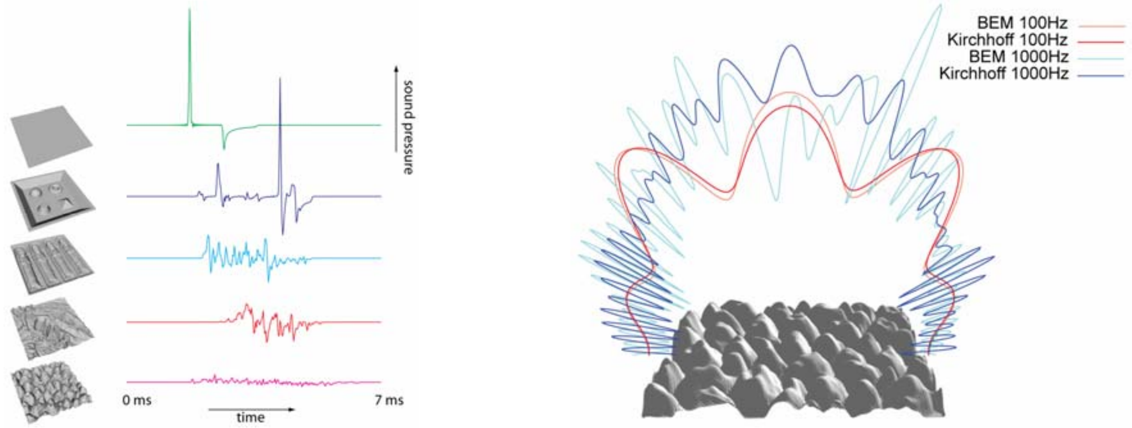


Figure 5.- Comparison between displaced geometry and a combined normal+displacement map computed with the source and receiver respectively at 60° and 45 ° incidence relative to the surface normal and 5m away from the center of the face. The surface sample is 4x4m.

Using complex scattering filters with GA engines

We believe our approach can be used to enhance GA simulations with realistic pre-computed surface scattering functions or filters similar to Figures 5 and 6. For instance, the filters could be convolved along the propagation paths obtained with an image-source/beam-tracing technique. However, such an approach would fail at modeling energy transfers in non-specular directions. Hence, the approach would probably better suit a radiosity framework to account for more diffuse transfer between surfaces. In this context, our approach could also be used to compute the impulse response of the form-factors when obstacles are present between surface patches.



(a) (b)

Figure 6.- (a) Responses from different 4×4m surface samples. Each surface is composed of 131072 triangles and generated from displacement maps. Note the secondary scattering component due to the finite extent of the flat surface on the top row (green curve) and the increasingly "diffusing" nature of the surfaces from top to bottom. (b) Scattering patterns for a detailed surface. The figure compares sound pressure levels in a plane medial to the surface obtained by BEM and our approximation. Source is 5m directly above the center of the face and the pressure is plotted at a distance of 10m.

CONCLUSIONS

In this paper, we proposed the first study aiming at computing early sound scattering off very detailed geometry as an alternative to using simplified models. We show that the Kirchhoff approximation (KA) is a good framework for the efficient implementation of a scattering integral which can be accelerated with commodity graphics hardware. Our approach shows for the first time that the KA can be used to compute scattering filters for detailed architectural models and offers a viable solution extending current GA techniques. It also provides the basis for geometrical simplification schemes preserving correct scattering properties of complex surfaces.

In the future, we plan to conduct further validation tests in order to assess the accuracy of our approach compared to traditional GA frameworks. Of special interest is also the perceptual evaluation of complex scattering effects in order to assess which level of accuracy is required for auralization. Although it remains an approximation to the physically-accurate solution, we believe that no other approach could currently offer a similar trade-off between accuracy and computing-time on our examples.

Acknowledgements
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