ROOM IMPULSE RESPONSE ESTIMATION USING SIGNED DISTANCE FUNCTONS

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ABSTRACT

Several algorithms and approaches for Room Impulse Response (RIR) estimation exist. To the best of the authors knowledge, there is no documentation of accuracy, speed or even the feasibility of using signed distance functions (SDFs) in combination with sphere tracing for this task. Here a proof of concept with a focus or real time performance is presented, that lacks many features such as frequency dependent absorption and scattering coefficients, arbitrary source and receiver directives etc. The results are shown and compared to real room impulse responses recorded by [1]. The implementation happens mostly inside a compute shader, an example application is provided in the framework `TouchDesigner`. The application as well as all generated data and `Jupyter Notebooks` can be found on this project's github repository at https://github.com/hrtlacek/rayMarchReverb.

1. INTRODUCTION

Sphere tracing [2] is extensively in the so called "demo scene" to render impressive 3D video demos via shaders in real time for decades. As a version of ray tracing that relies on the geometry being defined as so called signed distance functions (SDFs), it does not directly support the import of standard 3D Polygonal geometry. One of the advantages lies in the algorithm's potential improved speed in comparison to fixed-step ray tracing. SDFs describe implicit surfaces, via a function $f : \mathbb{R}^3 \rightarrow \mathbb{R}$. A function returns a negative value if the locus of the point is inside the geometry, a positive value if outside and 0 if on the surface. If defined carefully, the distance to the nearest surface is always known as the full geometry of the scene describes an ideally lipschitz continuous distance field in $\mathbb{R}^3$.

Since the distance to the nearest surface is always known, the step size of a ray tracing algorithm can be dynamically adjusted, resulting in fewer iterations along a ray, see Figure 1..

1.1. Previous Work

A lot of previous work exists both in the field of Ray/sphere tracing and RIR estimation. As shown in [3] and [1] there are numerous approaches for estimating RIRs. NVIDIA is working in the field of real time ray traced audio simulation NVIDIA VRWorks™ Audio (introduced with the Pascal GPU architecture)

[4] bidirectional ray tracing.

* Thanks to the predecessors for the templates

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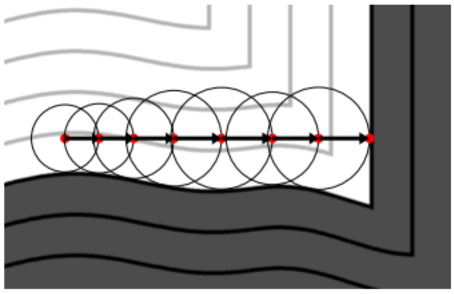


Figure 1: *Visualization of the sphere tracing algorithm in 2D. A ray is sent from the source (left) the right until it hits a surface, always moving the maximum distance as the SDF informs the tracing algorithm about the distance to nearest surface.*

RIR Estimation

[3] gives an overview of methods in use for RIR estimation.
image source method, wave based, ray tracing.

Sphere Tracing

Defining SDFs is an active field of research and there are several projects that aim at easier construction of SDFs and integration in 3D frameworks such as https://github.com/Flafla2/Generic-Raymarch-Unity and [5].

1.2. Motivation

The reasons why sphere tracing in a compute shader for RIR estimation has not been documented until now probably lie in the relatively new introduction of compute shaders as well as in the difficulty of creating SDFs(in comparison to using existing 3D /CAD models and import them to polygon based ray tracers).

1.2.1. Sphere tracing

As described above, ray tracing in general is in use. Sphere tracing has a number of advantages over ray tracing polygonal surfaces. It is "procedural" by default, since all geometry is defined by implicit surface equations. More over sphere tracing approximates cone tracing for reducing aliasing artifacts in the pixel domain[2], which in the audio domain, is considered to have advantages but is very time confusing in a non-SDF setup[3]. The deformation and rounding of geometry is possible in a very efficient way, which might offer an opportunity to approximate low-frequency response due to diffraction artifacts. Since geometry is not defined via vertizes and edges, there is no such thing as increasing the complexity of a shape in this way. Rounding a geometrical shape is a mere subtraction since it just shifts the rendering to another iso-surface, which is getting increasingly smooth as shown in 2. Depending on the construction of the geometry, this way, holes and cavities (such as in a diffusor) can also be made disappear for a low-frequency pass as shown in figure 3.

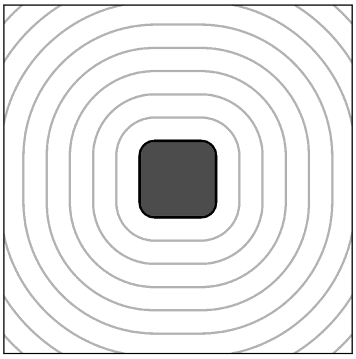
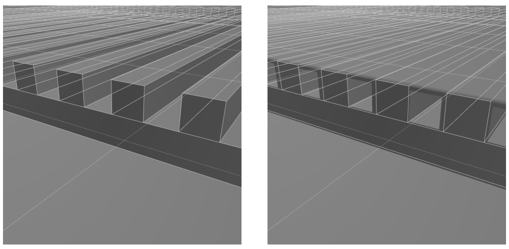


Figure 2: *rounding the box given in Equation 5 by subtraction of* 0.7.



(a) *Normal Shape* (b) *After subtraction*

Figure 3: *The diffusor from scene 1 in [1] was reconstructed exactly(a). A subtraction of* 0.01 *from the distance function causes the holes to close(b).*

procedural by default deforming geometry

1.2.2. Implementation

It is possible to implement the chosen algorithm on the CPU and the GPU. A number of frameworks could be chosen for GPU accelerated computation such as OpenCL or NVIDIA CUDA. The choice of a shader has the advantage of being more operating system independent and hardware independent. Compute shaders (in contrast to fragment shaders) make it possible to write to arbitrary output locations which is necessary for generating the actual impulse response from the measurement of timings. Since they are available since OpenGL 4.3 (August 2012) / OpenGL ES 3.1 they are both aged enough to have received broad support in other frameworks and relatively new in respect to first publications about sphere tracing. Another reason for the choice of compute shaders is their simplicity. In comparison to CUDA and OpenCL, shaders are easier to write and the GLSL(Graphics Library Shading Language) is more widespread.

2. GENERATION OF SDFS

Only rather simplistic shapes where needed for this proof-of-concept. Mostly boxes are used and combined in various ways to achieve reflection areas, shoe-box scenes and the little more complex diffusor shape of scene 1 in [1]. A simple 3D box SDF with a size of R_xxR_yxR_z can be described by:

$$f(p_x, p_y, p_z) = \sqrt{c_0(p_x - R_x)^2 + c_0(p_y - R_y)^2 + c_0(p_z - R_z)^2} \quad (1)$$

where c_0 is just clipping at 0:

$$c_0(x) = max(x, 0) \quad (2)$$

which translates to GLSL conveniently:

```
float box(vec3 pos, vec3 R){
    return length(max(abs(pos) - R,0));
}
```

[2] gives a list mathematical definitions of many shapes and for example http://mercury.sexy/hg_sdf/ provides a rich and advanced library of shapes and operators that are ready to use for creation of more complex scenery.

3. SPHERE TRACING

For simplicity, deterministic equal-angle Ray Tracing is used in contrast to Monte Carlo or Equal Area Ray tracing (EART) [6]. Unidirectional ray tracing has been used, also for simplicity reasons, although [4] has shown that bidirectional ray tracing offers advantages. Since the classical sphere tracing algorithm was adapted, it was found to be simplest to consider the "camera" to be the receiver/microphone as it would receive light. It sends out rays that might hit the sound source, which acts as a receiver of rays. The sound source is chosen to be a sphere. Choosing a correct volume for the receiver is critical and using a constant size can introduce systematic errors [7], [3]. A number of models are available to compute the receiver Volume, V_r. Typically factors such as room volume, number of rays and the distance from source are used for this computation. As in [8], [3], and [9] the receiver was allowed to grow in volume. While [8] and [9] use time to as a factor to let the receiver grow, in this attempt the reflection count, k is used. Initially when a ray is sent, $k = 1$ and when it hits a surface, this counter is increased by one so the source grows by this factor. Instead of using time, the model provided in [3] is used and augmented with the k term:

$$V_r = k\omega d_{SR}\sqrt{\frac{4}{N}} \quad (3)$$

with

$$\omega = log_{10}V_{room} \quad (4)$$

where d_{SR} is the source-receiver distance, N is the number of initial rays and V_{room} is the volume of the room.

low frequency pass

4. GENERATION OF IMPULSE RESPONSE

Advantage of compute shader. Maybe introduce cascaded Lowpass.

All figures should be centred on the column (or page, if the figure spans both columns). Figure captions (in italic) should follow each figure and have the format given in Figure 4. Vectorial figures are preferred. For example when using `Matlab`, export using either Postscript or PDF format. Also, in order to provide a better readability, figure text font size should be at least identical to footnote font size. To do so using `Matlab`, use the `subplot` command before plotting. If bitmap figures are used, please make sure that the resolution is enough for print quality. Fig. 5 illustrates an example of a figure spanning two columns.

5. RESULTS

compare to [1] compare to [10] compare to ROOMSIM

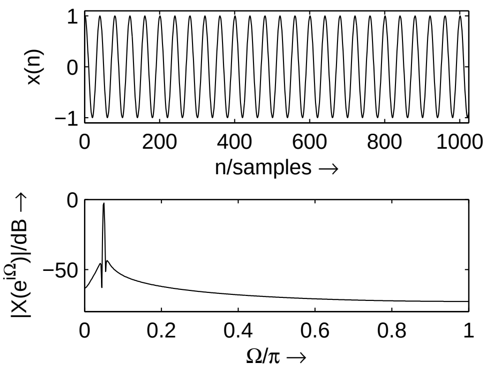


Figure 4: *Sinusoid in time and frequency domain. Short captions are centred, long captions (more than 1 line) are justified.*

5.1. Tables

As for figures, all tables should be centered on the column (or page, if the table spans both columns). Table captions should be in italic, precede each table and have the format given in Table 1.

Table 1: *Basic trigonometric values.*

angle (θ, rad)	$\sin\theta$
$\frac{\pi}{2}$	1
π	0
$\frac{3\pi}{2}$	-1
2π	0

5.2. Equations

Equations should be placed on separate lines and numbered:

$$X(e^{j\Omega}) = \sum_{n=0}^{N-1} x(n)e^{-j\Omega n} \tag{5}$$

where the sequence $x(n)$ in equation (5) is a windowed frame:

$$x(n) = s(n)w(n) \tag{6}$$

with a window function $w(n)$.

5.3. Page Numbers

Page numbers will be added to the document in the postprocessing stage, so *please leave the numbering as is*, that is, the first page will start at page DAFX-1 and the last page, at most, will have to be DAFX-8.

5.4. References

5.4.1. Reference Format

The reference format is the standard IEEE one. We recommend to use BibTeX to create the reference list.

6. CONCLUSIONS

This template can be found on the conference website. For changing the number of author affiliations (1 to 4), uncomment the corresponding regions in the template `tex` file. Please, submit full-length papers (max. 8 pages both oral and poster presentations). Submission is fully electronic and automated through the Conference Web Submission System. DO NOT send us papers directly by e-mail.

7. ACKNOWLEDGMENTS

Many thanks to the great number of anonymous reviewers!

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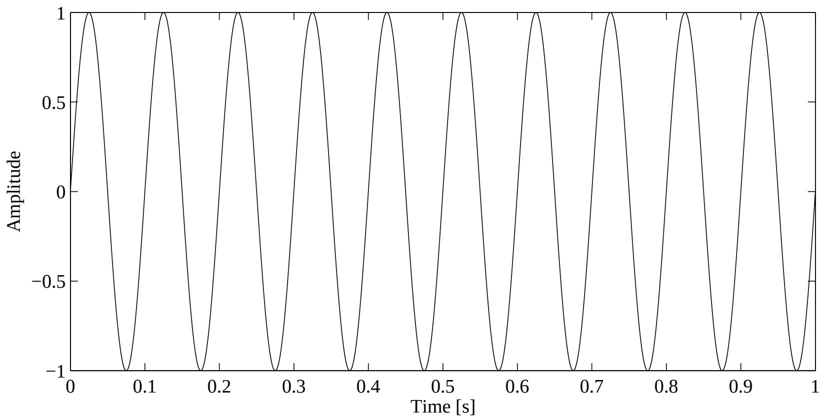

Figure 5: *A figure spanning two columns, as mentioned in Sec. .*

Table 2: *Basic trigonometric values, spanning two columns.*

angle (θ, rad)	$\sin\theta$	$\cos\theta$	$(\sin\theta)/2$	$(\cos\theta)/2$	$(\sin\theta)/3$	$(\cos\theta)/3$
$\frac{\pi}{2}$	1	0	$1/2$	0	$1/3$	0
π	0	-1	0	$-1/2$	0	$-1/3$
$\frac{3\pi}{2}$	-1	0	$-1/2$	0	$-1/3$	0
2π	0	1	0	$1/2$	0	$1/3$

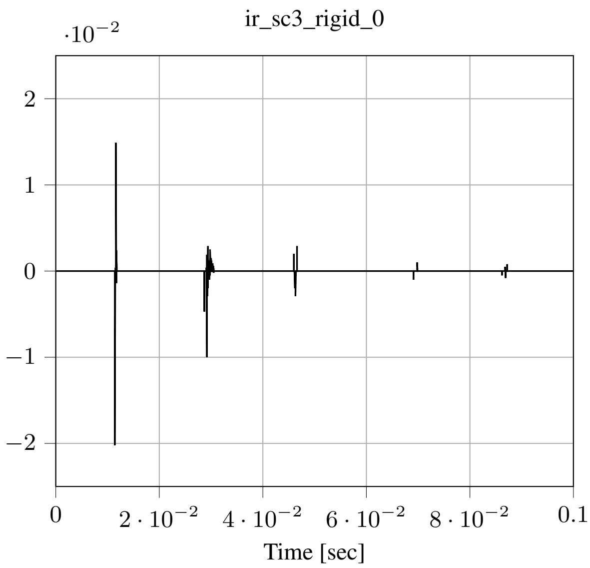

Figure 6: A PGF histogram from `matplotlib`.

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9. APPENDIX: MARGIN CHECK

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