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Visualizing the Phonon Map

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Abstract

In this work we present several visualization approaches for analyzing acoustic behavior inside a room. Our methods are based on the results of the phonon tracing algorithm. For a simulated phonon map we examine the influence of the room surfaces on the wave fronts during their propagation from the sound source. Our visualization is based on individual phonon and surface representations as well as scattered data interpolation. Additionally, an observation of acoustic behavior at different positions inside the room using colored and deformed spheres is possible.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Raytracing I.6.3 [Simulation and Modeling]: Applications

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1. Introduction

When designing a concert hall, a theater or a class room, in addition to the visual effect the acoustic aspect is very important. Nowadays, computer-based simulations of acoustic behavior inside a room are available [Kro68, Kul84, Vor89, FCE*98, KJM04, BDM*05]. The question comes up for an appropriate visual representation of the simulation results.

Stettner et. al. [SG89] visualize room acoustic quality properties such as clarity or spatial impression by use of specific icons. Furthermore, they color the room boundaries according to the pressure level. Khoury et. al. [KFW98] represent the sound pressure levels inside the room by means of color maps. Additionally, the authors analyze the precedence effect (or "law of the first wavefront") by using iso surfaces. Funkhouser et. al. [FCE*98] use visualization of source points, receiver points, pyramidal beams, reverberation path etc. in order to understand and evaluate their acoustic modeling method. The system also provides the presentation of power, clarity etc. A couple of commercial systems [ODE, CAT, Bos] provide some tools for visualizing computed acoustic metrics. In [BDM*05] we have visualized the spacial propagation of particles called phonons from the sound source using spheres colored according to their energy spectra.

Our work concentrates on the presentation of the simulation results of our phonon tracing algorithm [BDM*05]. Here, we introduce various approaches for visualizing the phonon map. First, we represent the individual phonons on their positions at the room surfaces colored according to their energy spectra. This method provides insight how the room influences the spread sound waves. In order to observe the propagation of different wave fronts for the first few reflections, we visualize them as deformed surfaces. For the visualization of late reflections and a time dependent look at the phonon map, scattered data interpolation is used. For the representation of acoustic behavior at a certain listener position, we use colored spheres deformed according to the received sound.

The remainder of our paper is arranged as follows. In the next section we will give a short description of the phonon tracing algorithm. In section 3 we will present our visualization approaches and provide examples. Then we will discuss our results in the last section.

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2. Phonon Tracing

Photon mapping [Jen96] is often used for rendering photorealistic images, supplementing uni-directional raytracing by a variety of visual effects, like color bleeding and caustics. We adopt a similar approach to the simulation of sound, named phonon tracing [BDM*05], which is summarized in the following.

2.1. Problem specification.

Our simulation algorithm requires the following input information:

- position of sound source s
- emission distribution E of sound source
- one or more listener positions l_i
- a triangulated scene with tagged material m_j
- an absorption function $\alpha_j : \Omega \mapsto (0,1]$ for each material
- an acoustic BRDF for each material (if applicable)
- an energy threshhold ε for terminating the phonon paths

The output of our approach is a FIR filter f_i for each listener's position l_i corresponding to the impulse response with respect to the sound source and the phonon-map containing for each phonon the energy spectrum e_p, the traversed distance d_p, the phonon's position p_p at the reflection point, its outgoing direction v_p, number of reflections n_p, and the material m_p at the current reflection.
Our simulation algorithm contains two steps, the *phonon tracing* step constructs the phonon map, and the *phonon collection and filtering* step collects the phonon's contribution to a FIR filter for every listener position.

2.2. Phonon tracing.

Every phonon p emitted from the sound source carries the following information:

- an energy spectrum $e_p : \Omega \mapsto \mathbb{R}^+$
- the distance d_p traversed from the source
- the phonon's current position p_p
- the normalized outgoing direction v_p

Our absorption and energy functions α_j are represented by $n_e = 10$ coefficients associated with the frequencies $40, 80, 160, ..., 20480$ Hz. The basis functions for the energy spectrum are wavelets adding up to a unit impulse. Every phonon is composed of different frequencies, which is more efficient than tracing a single phonon for each individual frequency band.
Phonons are emitted from the source s according to the emission probability distribution E and have at starting point a unit energy spectrum $e_{p,i} = 1$ $(i = 1, ..., n_e)$. At the intersection of the phonon ray with the scene, the phonon direction d_p is reflected with respect to the surface normal and the absorbed energy is subtracted according to the local material m_j, and the distance d_p is set to the traversed distance. The phonon is fixed at the intersection point, contributing to a global phonon map.
If the maximal energy of the phonon exceeds the energy threshold, i.e. $max\{e_{p,i}\}_{i=1}^{n_e} > \varepsilon$, the next phonon re-uses the path and energy of the preceding one, saving computation time. It is started at the current position with respect to the outgoing direction d_p and contributes to the phonon map at the next surface intersection. If the threshold is not exceeded and a minimum number of reflections have been computed, then a new phonon is started from the source. After a prescribed number n_p of phonons have contributed on the global phonon map, the tracing is terminated. The phonon map is written to a file for further visualization purposes.

2.3. Phonon collection and filtering.

The remaining task of the phonon tracing method is collecting the phonon's contribution to a FIR filter f for every listener's position l. This filter corresponds to the impulse response from the source, recorded at l, such that convolution with an anechoic signal, reproduces the perceived signal.
In the case of uniform absorption for all frequencies, the contribution of a phonon visible from the listener is simply a scaled, translated unit impulse (Dirac). The Dirac is shifted by the time elapsed between emission and reception of a phonon and scaled by the phonon's energy $e_{p,i}$ multiplied by a gaussian weighting the distance of the ray to the listener. In classical acoustic raytracing [Kro68, Kul84], a sphere is used to collect rays at listener position. Using a gaussian, however, provides much smoother filters, since more phonon rays contribute to the filter, weighted by their shortest distance.
In the more general case of frequency dependent absorption, the unit impulse is subdivided into wavelets representing the individual frequency bands. The filter becomes then a sum of this wavelets scaled by $e_{p,i}$ and shifted by the elapsed time. In our implementation we use 10 frequency bands and absorption coefficients for the frequencies $\omega_i = 20 \cdot 2^i$ Hz $(i = 1, ..., 10)$. We construct band-pass filters in spectral domain by means of cosine functions in order to obtain quickly decaying wavelets. The wavelets are achieved by inverse Fourier Transform.
Description of our phonon tracing algorithm, especially filter design, can be read in more detail in [BDM*05].

3. Visualization Methods

The phonon map characterizes the acoustic behaviour of a scene considering the location of a specific sound source. It consists of the reverberations of a unit pulse, coming from different directions with different time delays and specific energy distributions. How can we visualize this complex information?

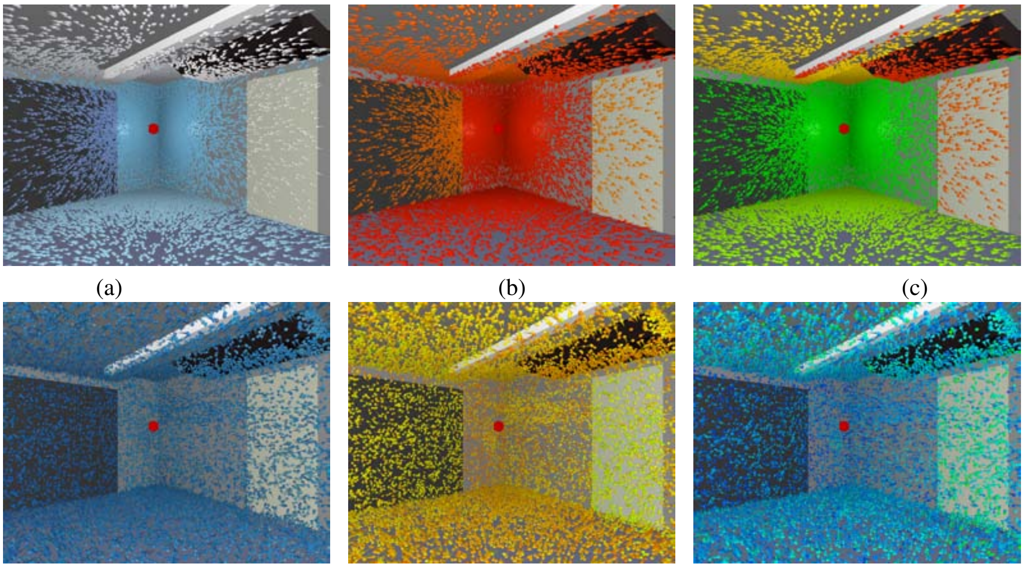


Figure 1: *Visualization of particular phonons. First (a) and fourth (d) reflection color coded using the overall frequency spectrum. First (b, c) and fourth (e, f) reflection color coded using the frequency band at 160 Hz and at 10240 Hz, respectively.*

3.1. Visualizing Phonons on Surfaces

The first method we have implemented to examine the phonon map is the visualization of certain phonons at their position inside the given scene. Each phonon is rendered as a sphere and is colored according to its spectral energy. We provide the option to consider all frequency bands in total or each of them separately, whereas we consider 10 frequency bands associated with the frequencies $40, 80, 160, ..., 20480$ Hz. In the first case the spheres are color coded by using the RGB components, such that red corresponds to the average of $e_{p,8}, ..., e_{p,10}$ (5120, 10240, 20480 Hz), green corresponds to the average of $e_{p,5}, ...e_{p,7}$ (640, 1280, 2560 Hz), and blue to the average of $e_{p,1}, ..., e_{p,4}$ (40, 80, 160, 320 Hz).

In the second case, considering only one frequency band, we color coded the energy of this frequency band using the HSV model. We interpolate the color of the spheres between red (full energy) and blue (energy equals zero) corresponding to the energy $e_{p,i}$ of the i-th frequency band. In order to show the phonons outgoing direction v_p we render a cone whose peak is rotated towards v_p. The color of the cone corresponds to the phonons energy, too.

Since the number of phonons in the phonon map is large we render only phonons with a given number of reflections n_p simultaneously. With this approach we examine how the surfaces of the considered scene affect the overall acoustic of the room. The phonon map contains for each phonon the number of reflections n_p, so we display only those phonons with a certain number of reflections, visualizing their frequency spectrum and outgoing direction.

Figure 1 shows an example of this visualization approach. The phonon map consists of one million phonons. In figures 1 (a) and (d) the overall frequency spectrum of the phonons after one and four reflections, respectively, is depicted using the RGB components. As we can see in figure 1 (a) the walls, the bottom and the canvas absorb high frequencies better than low frequencies(bluish color), whereas the door, for example, reflects all frequencies equally. After four reflections at the scene surfaces we can observe a shift towards lower frequencies. The representation using the RGB model shows an average of the energy spectrum at low, middle and high frequencies. Sliding through the frequency bands we can observe the absorption for each individual frequency band. Figure 1 (b, e) shows the energy at 160 Hz and figure 1 (c, f) at 10240 Hz after one and four reflections, respectively. As we can see, after four reflections there are about 75% of the energy of the phonons at 160 Hz, whereas the energy at 10240 Hz is nearly completely absorbed by the room. By depicting the outgoing direction we can guess which object the phonon will hit next.

3.2. Wave Front Visualization

In this section we describe an approach visualizing wave fronts reflected at the room surfaces by use of triangulated surfaces. In order to build these surfaces we need to know which phonons belong to a common wave front. Therefore we subdivide the phonons in clusters of equal history, such that phonons in the same cluster satisfy the following criteria:

- equal numbers of reflections n_p

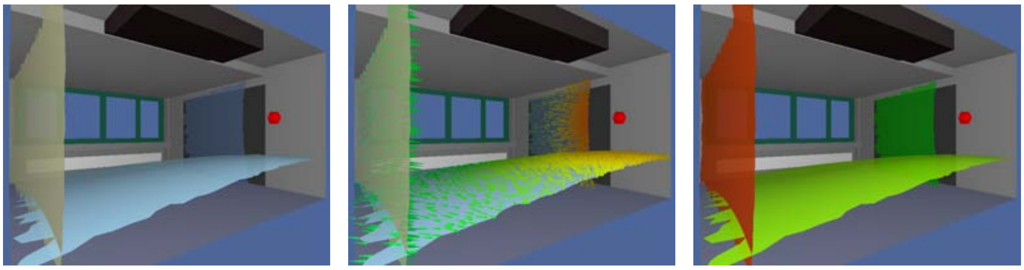

(a) (b) (c)

Figure 2: *Clustered wave front. (a) first reflection color coded using the overall frequency spectrum. (b) Traversed distance represented by use of cones. (c) first reflection color coded using the frequency band at 10240 Hz.*

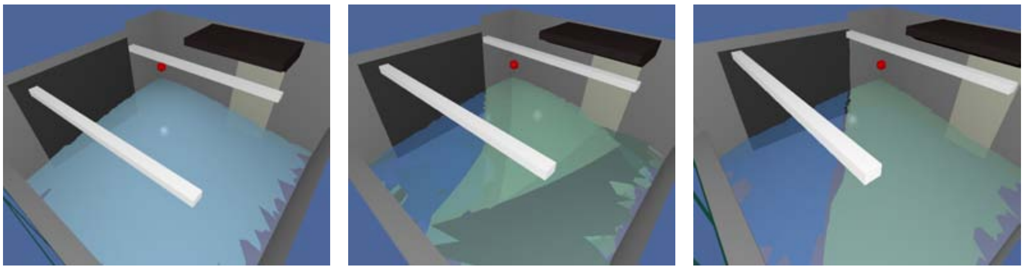

(a) (b) (c)

Figure 3: *Clustered wave fronts. First (a) and second (b) reflections at the bottom. (c) Second reflections at the bottom reflected before at the wall and powerwall, respectively.*

- and for each reflection:
  - equal material indices m_p (same object of the scene)
  - equal surface normals n at the reflection position

Consequently all phonons inside a cluster have equal energy spectra.

In order to build the cluster we need to trace the phonons back to the sound source and compare their histories. This is not a difficult task since the phonon p_i re-uses the path and energy of the preceding one (see section 2). For the same reason we can easily compute the normal of the surface hit by p_i as:

$$n = \begin{cases} v_{p_i} - (p_{p_i} - s)/\|v_{p_i} - (p_{p_i} - s)\| & \text{if } n_{p_i} = 1 \\ v_{p_i} - v_{p_{i-1}}/\|v_{p_i} - v_{p_{i-1}}\| & \text{else} \end{cases} \quad (1)$$

where s is the position of the sound source. The material index m_p is stored in the phonon map.

We can construct the surface of the wave front comming from the sound source as a convex hull of phonons on the unit sphere and obtain the neighborhood relationship of particular phonons. This relation does not change in time for a set of phonons in the same cluster, so the polygonal representation of the wave front must be calculated only once. For the construction of the convex hull on the unit sphere providing a Delaunay-triangulation we use the CGAL library [CGA]. The wave front surfaces reflected at the objects inside the considered room are built by keeping only triangles of the initial wave front whose vertices (phonons) reside in the according cluster. Figure 4 shows the wave front coming from the source. Where it hits the canvas, for example (figure 4 (b)), the faces that now belong to the wave front of the reflection at the canvas are separated from the initial surface.

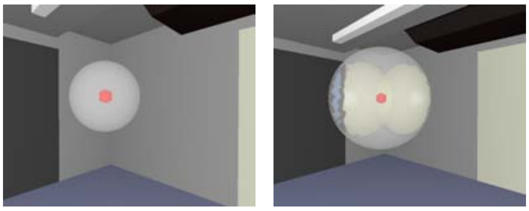

(a) (b)

Figure 4: *Wave front traversed from the sound source (a), separated after reflections (b).*

Now we can render the resulting surfaces for visualization of the wave fronts reflected from the scene objects. To illustrate where the wave front hits the object first and in which direction it propagates we use the phonons traversed distances d_p to deform the surface. First, we determine the maximum traversed distance d_{max} of all phonons inside the cluster. Then, we render the phonons (which are the triangle vertices of the wave front surface) in an offset from the according scene surface:

$$p_p \leftarrow p_p + (1 - \frac{d_p}{d_{max}}) \cdot n \tag{2}$$

where n is the scene surface normal. This way, the offset between the original surface and the visualized wave front is at most one unit. We color coded the wave front surfaces according to the energy spectra of corresponding phonons. Depend on whether we want to examine all frequency bands in common or each of them separately we use the RGB model or the HSV model as described in the previous section. Furthermore, we set the surface transparency according to the average energy of the wave front.

For better clarifying the propagation direction of the wave fronts and the traversed distance, we provide the option to draw colored cones at the position of the phonons. The peaks of these cones are rotated towards the phonons outgoing directions. Their color corresponds to the traversed distance and is calculated by use of the HSV model as follows:

$$(1-\alpha) \cdot H_{red} \; + \; \alpha \cdot H_{blue} \text{ with } \alpha = \frac{d_p}{l_{max} \cdot n_p} \tag{3}$$

where l_{max} is the maximum distance of the scene. In this case red corresponds to $d_p = 0$ and blue to the maximum possible distance depending on number of reflections n_p. Using the above equation for color mapping the cones we can compare the traversed distance of wave fronts reflecting at different objects for a given number of reflections. Since displaying all wave front surfaces becomes complex, our implementation provides the alternative to select wave fronts by number of reflections, material(object) or history.

Figures 2 and 3 show examples of the described visualization approach. The red colored sphere in the corner of the room represents the sound source. Figure 2 depicts the wavefronts of first reflections comming from the bottom, the wall and the canvas. In image 2 (a) and (b) we see the wave fronts color coded using the RGB model and overall frequency spectrum as described above. We can see that the bottom and the canvas predominantly absorb more high frequency, whereas the wall absorbs more low frequencies. Figure 2 (c) shows the wave front surfaces color coded by use of HSV model and the frequency band at 10240 Hz. This frequency band is absorbed by the canvas and bottom, but is reflected almost completely by the wall.

The surfaces are deformed according to the traversed distance of the phonons belonging to the clusters. Here, we can observe where the wavefronts hit the room surfaces first and in which direction they will further spread. A representation of the traversed distance by use of colored cones (figure 2 (b)) shows that the wave front propagated from the sound source hit the canvas and the bottom before the wall.

Figure 3 presents the wave front reflecting at the bottom the first (a) and the second time (b,c). Since reflections comming from all objects inside the scene can overlap (fig. 3 (b)) we provide the option to select different wavefronts. In figure 3 (c) we see the second reflection at the bottom reflected first at the wall and the canvas, respectively. In this picture we can observe how the energy spectrum of the wave front changes and how it is split during the reflections at the room surfaces. This way we can examine the interacton of the single objects inside the room.

Since the wave front traversed from the sound source is splitted after each reflection, the visualization approach described in this section is applicable only to the first few reflections.

3.3. Scattered Data Interpolation

At higher reflection orders, the clusters become smaller and smaller, until they contain only a single phonon. In the following we develop a visualization method for the entire phonon map based on scattered-data interpolation.

The goal of the interpolation is to get a continuous representation of the emitted energy on the surfaces of the scene. First of all it is used to visualize phonons not belonging to the early reflections of wavefronts, because these cannot be visualized as cluster surfaces due to the increasing fragmentation. Rather than visualizing individual reflections, we look at the phonon map from a different viewpoint, namely discrete timesteps, i.e. "show the energy emitted from the floor at 50 msec". This allows us to look at the change in energy comming from a surface over time.

The interpolation is done for the energy and pathlength of the phonons. The direction is neglected, since it is not important for the visualization due to scattering.

We use an inverse distance weighted method with a modified version of the Franke-Little [Nie93] weight function which uses variable radii rather than a fixed one depending on a given number of phonons which need to be considered.

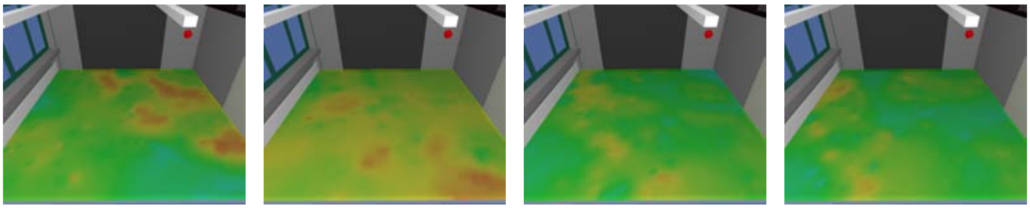
$$\begin{aligned} F(x,y) &:= \textstyle\sum_{k=1}^{m} \frac{w_k(x,y)\cdot f(x_k,y_k)}{\sum_{k=1}^{n} w_k(x,y)} \\ w_k(x,y) &:= \left(\frac{(R-d_k)_+}{R\cdot d_k}\right)^2 \\ (R-d_k)_+ &:= \begin{cases} R-d_k & R \geq d_k \\ 0 & R < d_k \end{cases} \end{aligned} \tag{4}$$

with $d_k = \sqrt{(x-x_k)^2 + (y-y_k)^2}$ and R being the distance to the k-th nearest phonon. It is guaranteed, that a value for each point can be calculated.

Depending on what to visualize, different kinds of phonons are used for the interpolation, i.e. all phonons which are reflected at least 5 times or all phonons present on a surface for a certain timestep.

The interpolation results are color coded corresponding to section 3.1. This means using RGB color when visualizing the whole frequency spectrum and HSV for distinct frequency bands.

As mentioned before, the interpolation is used to visualize late reflections ($n_p \geq 4$). Therefore the energy of all phonons

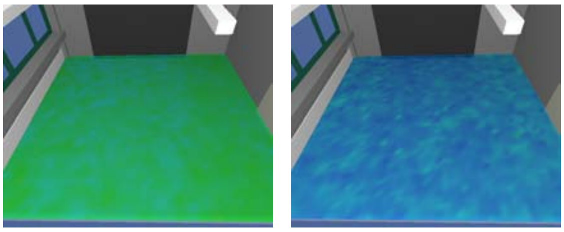


(a) (b) (c) (d)

Figure 7: *Energy on the floor at timesteps 20-23 msec for the 160Hz band.*

reflected at least n times is used to calculate the energy for the whole surface.

It can be seen in figure 5 that the result is an energy distribution for the whole surface of an object. In this case figure 5 shows the energy after the 5th (a) and 10th (b) reflection on the floor for the 2560Hz band. Comparing (a) and (b) it can be seen that after the 10th reflection (d) the energy for the 2560Hz band is quite low (bluish colors) compared to the 5th reflection (b).



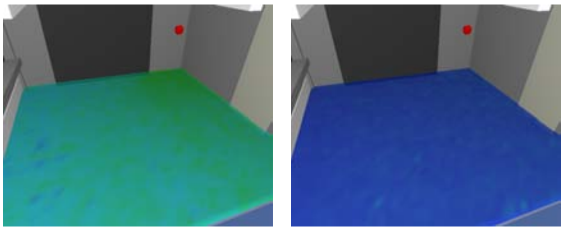
(a) (b)

Figure 5: *Energy on the floor after the 5th (a) and 10th (c) reflection for the 2560Hz band.*

When visualizing the phonon map with respect to time, it is possible to look at a time span (i.e. 0-50 msec) or distinct time steps (i.e. 15 msec). Figure 6 shows the average energy between 0-49 (a) and 50-100 (b) msec for the 20480Hz band. Comparing the first (a) and second (b) 50 msec after the unit pulse the difference in energy for the 20480Hz band is clearly visible. For the first 50 msec the main emission of energy in the 20480Hz band comes from right under the sound source (green color) as for the second 50 msec there is almost zero energy on the whole floor (blue color).

An example for distinct time steps is given in figure 7 (a-d), where the change in emitted energy for the 160Hz band is shown at 20(a), 21(b), 22(c) and 23(d) msec.

Having dealt with the visualization of the phonon map on the surface in the last sections, the next section will provide information about the received energy at distinct listener positions throughout the room.



(a) (b)

Figure 6: *Average energy between 0-49 (a) and 50-100 (b) msec for the 20480Hz band.*

3.4. Listener-based Visualization

The approaches described above visualize the phonon map considering the surfaces of the room and their acoustic properties. In this section we present a visualization method depicting the received energy at a listener position. With this approach we can detect from which direction the most energy reaches the listener and visualize the energy spectrum. For this purpose we render a triangulated sphere deformed according to the weighted phonons received at the listener position. The phonons are collected using the collection step described in section 2. For each phonon which contributes to the total energy at the listener position, we first calculate the intersection point $p_{intersec}$ of the ray from the center c_s of the sphere to the phonons postion p_p with the sphere. We increase then the energy e_{sp} and the displacement $disp_{sp}$ of the point sp of the intersected triangle with minimal distance to $p_{intersec}$ as follows:

$$\begin{aligned} e_{sp} &\leftarrow e_{sp} + fac \cdot \begin{pmatrix} (e_{p,8}+e_{p,9}+e_{p,10})/3 \\ (e_{p,5}+e_{p,6}+e_{p,7})/3 \\ (e_{p,1}+e_{p,2}+e_{p,3}+e_{p,4})/4 \end{pmatrix} \\ disp_{sp} &\leftarrow disp_{sp} + fac \cdot \tfrac{1}{10}\textstyle\sum_{i=1}^{10} e_{p,i} \end{aligned} \tag{5}$$

$e_{sp} \in \mathbb{R}^3$, $disp_{sp} \in \mathbb{R}$ if we consider all frequency bands and

$$\begin{aligned} e_{sp} &\leftarrow e_{sp} + fac \cdot e_{p,i} \\ disp_{sp} &\leftarrow disp_{sp} + fac \cdot e_{p,i} \end{aligned} \tag{6}$$

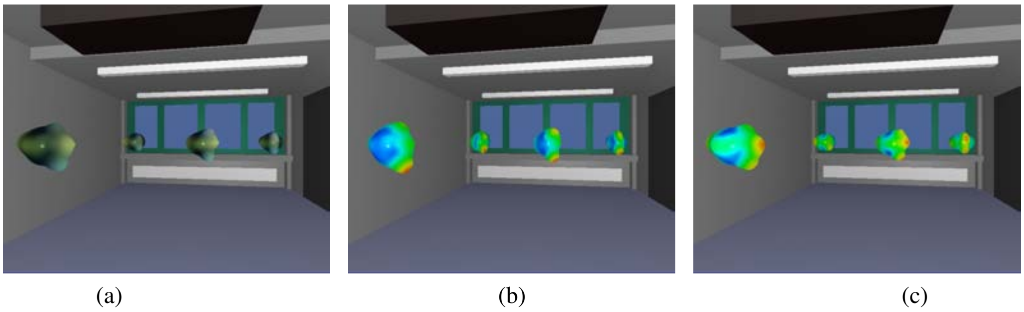


Figure 8: *Deformed spheres representation at four listener positions. (a) color coded using the overall frequency spectrum (b) by 80 Hz and (c) by 1280 Hz.*

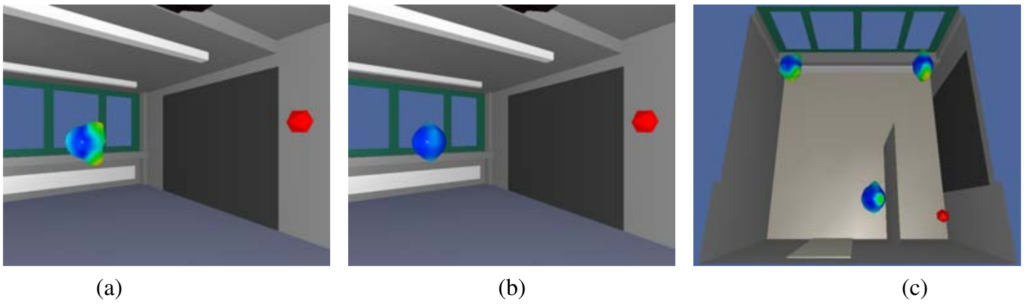


Figure 9: *Deformed spheres representation at 80 Hz collected before (a) and after (b) 50 msec at one listener position. Deformed spheres representation at 5120 Hz at three position in a room with a separating wall with total absorption (c).*

$e_{sp} \in \mathbb{R}$, $disp_{sp} \in \mathbb{R}$ if we look at a certain frequency band. Thereby fac is the gaussian distance described in section 2. In order to smooth the sphere representation we increase the energy of the points sp_j around sp if $arccos(\langle c_s - sp_j, c_s - sp\rangle) < \alpha$ for a given angle α as follows:

$$\begin{array}{rcl} e_{sp_j} & = & w \cdot e_{sp} \text{ where} \\ w & = & 1-(arccos(\langle c_s - sp_j, c_s - sp\rangle)/\alpha) \end{array} \tag{7}$$

Afterwards, we normalize the energy and the displacement of the sphere points. Therefore we determine the maximal displacement $disp_{max}$ and energy e_{max} (in all three components) of all points. Then we normalize these values:

$$\begin{array}{rcl} e_{sp_j} & \leftarrow & \frac{e_{sp_j}}{e_{max}} \\ disp_{sp_j} & \leftarrow & \frac{disp_{sp_j}}{disp_{max}} \end{array} \tag{8}$$

In order to consider occlusion of the listener position, we scale the energy values of the sphere points sp_j as follows:

$$\begin{array}{rcl} e_{sp_j} & \leftarrow & e_{sp_j} \cdot \frac{n'_{ph}}{n_{ph}} \\ disp_{sp_j} & \leftarrow & disp_{sp_j} \cdot \frac{n'_{ph}}{n_{ph}} \end{array} \tag{9}$$

where n_{ph} is the number of phonons in the phonon map and n'_{ph} the number of phonons which are seen from the listener. Now after the calculation of the displacement factors and energy at each point of the sphere we can deform and paint the spheres at given listener positions. The new position of the point sp_j results in:

$$sp_j \leftarrow sp_j + disp_{sp_j} \cdot \frac{c_s - sp_j}{\|c_s - sp_j\|} \tag{10}$$

The color of the sphere points is calculated by use of the RGB (for overall frequency spectrum) or the HSV (certain frequency band) model as mentioned in the previous sections. For assessing purpose of the acoustic quality at a listener position it is important to know at which time the reflections arrive at the listener. For this reason we add the feasibility to determine the lower and upper time limits for phonon selection.

The following figures present the results of the introduced visualization approach. Figure 8 (a) show spheres at four positions in the considered room. The energy is collected over the entire time interval. The spheres are deformed and color mapped by using the overall energy spectrum. As we can see that the most energy of low frequencies arrives at the listener from the bottom and the ceiling, since they do not absorb low frequencies. Whereas middle and high frequencies reach the listener from the walls. Considering the energy at 80 Hz (figure 8 (b)) and at 1280 Hz (figure 8 (c)) we can observe that most part of the energy at 80 Hz reflects at the bottom and ceiling, and at 1280 Hz most part is reflected at the walls.

The depicted spheres in figure 9 (a) and (b) are deformed and color coded using the energy at 80 Hz of phonons that reached the listener position before and after 50 msec, respectively. We can observe that the whole energy of the reflections at the room surfaces arrives the listener before 50 msec. In this way we can compare the amount of early to late reflections.

Figure 9 (c) shows a room with a separating wall with total absorption. This wall prevents most reflections from the surfaces on the left side of the room to the right side and vice versa. We placed a listener position behind the wall and two in the corners of the room. We visualize the spheres for the frequency band at 5120 Hz. As we can see, no reflections are received from the separating wall and only few reflections reach the listener from the left and right room surfaces.

4. Discussion

In this work we have presented various visualization approaches for analyzing acoustic behavior inside a room by use of the phonon map resulting from our phonon tracing algorithm. First of all we visualized the single phonons as color coded spheres. The advantages of this approach is the simplicity of the technique and the direct visibility of the material influence on the sound traversed from the source. A huge drawback is the lack of connectivity information between the phonons. This is overcome by our second approach, the visualization of wave fronts. Additionally this method is a natural representation of the propagation of sound. Due to increasing fragmentation, this method can only be used for the first few reflections. Also there is only limited time dependency. To visualize the reverberations of higher order at the scene surfaces and to include the time dependency in the visualization, we used scattered data interpolation. At the moment, we restricted this method to the surface representation and neglect the direction of the particular phonons. In these three presented methods we disregarded the situation at certain listener positions. Therefore we introduced the listener-based visualization approach. This technique allows a time dependent view on the received energy on a certain listener position.

In total, these approaches give a general idea over the acoustic behavior inside the considered scene which can be derived from the phonon map. Further work has to be done in the area of interpolation to incorporate the outgoing direction of the phonons so that it can be used in the simulation process. For a better assessment of hearing experience it would be favorable to look at the different acoustic metrics at the listener positions, as well.

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