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Accelerated Deterministic Simulation of X-ray Attenuation Using Graphics Hardware

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Abstract

In this paper, we propose a deterministic simulation of X-ray transmission imaging on graphics hardware. Only the directly transmitted photons are simulated, using the Beer-Lambert law. Our previous attempt to simulate X-ray attenuation from polygon meshes utilising the GPU showed significant increase of performance, with respect to a validated software implementation, without loss of accuracy. However, the simulations were restricted to monochromatic X-rays and finite point sources. We present here an extension to our method to perform physically more realistic simulations by taking into account polychromatic X-rays and focal spots causing blur.

Keywords: Three-Dimensional Graphics and Realism, Raytracing, Physical Sciences and Engineering, Physics.

1 Introduction

The simulation of the X-ray imaging process is extensively studied in the physics community and different physically-based simulation codes are available. For transmission imaging, when the Beer-Lambert attenuation law can be considered as a sufficient description, ray-tracing is often used as a fast alternative to Monte Carlo methods [1]. Physically-based simulations are however often performed on the CPU, and even with a fast ray-tracing algorithm, interactive frame rates cannot be achieved.

In [2], we demonstrated that X-ray attenuation from polygon meshes can be efficiently computed on the GPU using OpenGL and the OpenGL Shading Language (GLSL). Performance significantly increased without loss of accuracy. The method has been deployed into a medical simulator for training fluoroscopy (real-time X-ray images) guidance of needles [3]. It makes use of polygon meshes that are dynamically modified depending on the respiration cycle of the virtual patient. The simulations were however restricted to monochromatic X-ray beams (i.e. incident photons have the same energy) and finite point sources.

We have now extended the simulation pipeline to take into account focal spots that cause geometric unsharpness and polychromatic X-rays (i.e. incident photons have different energies).

2 Simulation Pipeline

The Beer-Lambert law relates the absorption of light to the properties of the material through which the light is travelling. For a polychromatic incident X-ray beam, it is:

$$N_{out}(E) = N_{in}(E) \exp\left(-\sum_{i=0}^{i<objs} \mu(E,i) L_p(i)\right) \tag{1}$$

with $N_{in}(E)$ the number of incident photons at energy E, $N_{out}(E)$ the number of transmitted photons at energy E. $objs$ is the total number of objects in the 3D scene. μ the linear attenuation coefficient (in cm^{-1}), which depends on: i) E, the energy of incident photons, and ii) the material properties of the object. $L_p(i)$ is the path length (in cm) of the ray in the i$^{\text{th}}$ object.

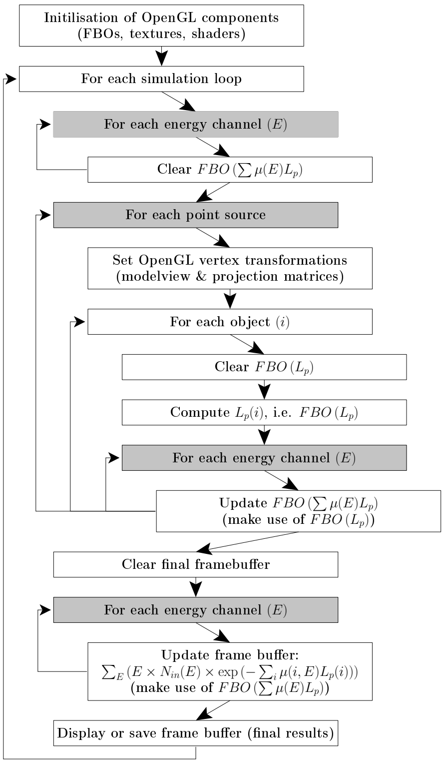


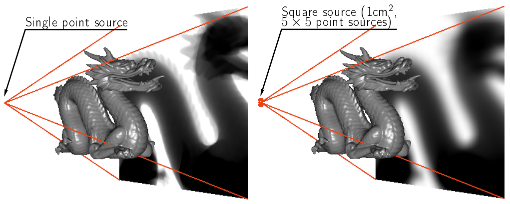
Figure 1: Simulation pipeline.

We adopted the algorithm presented by Freud *et al*[1] in [2]. This is used as the foundation of the present work. It makes use of a modified version of the Z-buffer, known as the L-buffer (for length buffer), to store the length of a ray crossing a given 3D object.

Additional loops (see gray boxes in Fig. 1) have been included in our simulation pipeline to implement Eq. 1. It is split into different rendering passes and uses frame buffer objects (FBOs) to store intermediate results (see [2] for details). Fig. 1 shows the full pipeline, taking into account the geometrical blur and polychromatic X-rays.

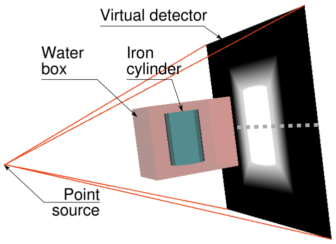
The shape of the source is modelled using a variable number of point sources (see Fig. 2 for examples). Each point is assigned a fraction of the total number of photons in the system.

The incident beam is split into discrete energy channels. A 3D texture is now attached to the FBO used to store $\sum \mu(i,E)L_p(i)$. Each slice of the 3D texture corresponds to an energy channel (E). To produce the final image, the total amount of energy received by each pixel is computed (see Fig. 3 for an example).

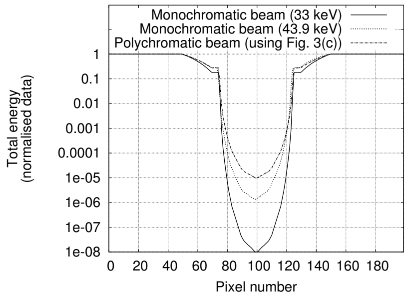


(a) Using a point source. (b) Using a square source.

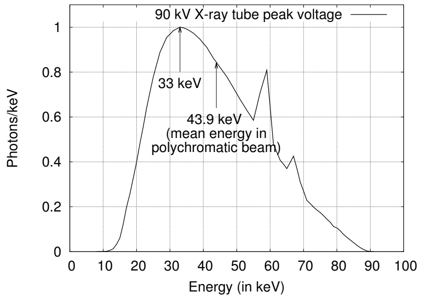
Figure 2: Simulations with different X-ray source shapes.



(a) Set up.



(b) Profiles (dashed line in Fig. 3(a)).



(c) Polychromatic beam spectrum.

Figure 3: Incidence of the beam spectrum.

3 Conclusion

X-ray transmission images can be fully simulated on the GPU, by using the Beer-Lambert law with polychromatism and taking into account the shape of the source. Additional loops have been added to the simulation pipeline and the computation cost proportionally increases depending on the number of source points and energy channels. This is a useful development to improve the level of realism in simulations, when both speed and accuracy have to be retained.

References

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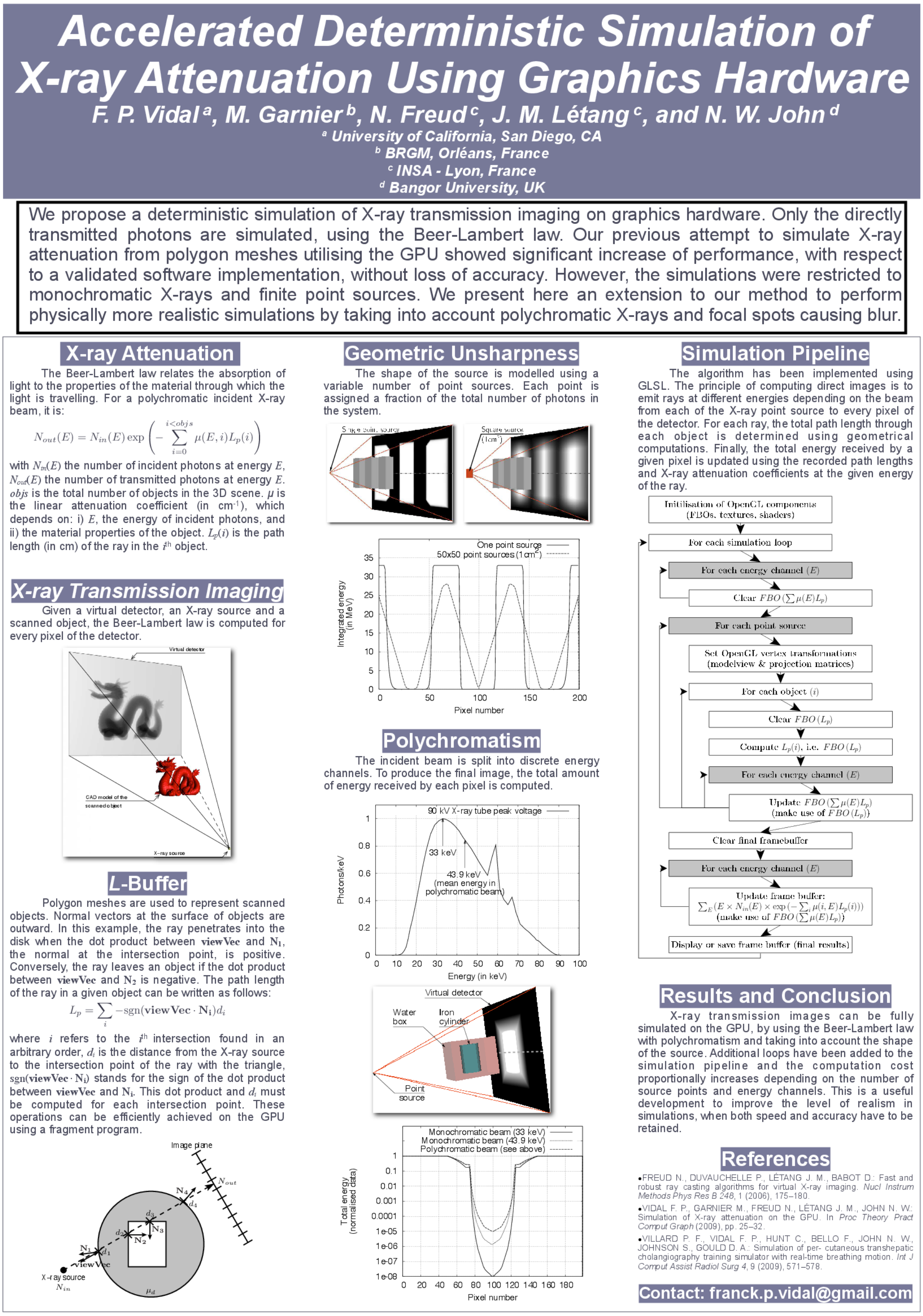

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We propose a deterministic simulation of X-ray transmission imaging on graphics hardware. Only the directly transmitted photons are simulated, using the Beer-Lambert law. Our previous attempt to simulate X-ray attenuation from polygon meshes utilising the GPU showed significant increase of performance, with respect to a validated software implementation, without loss of accuracy. However, the simulations were restricted to monochromatic X-rays and finite point sources. We present here an extension to our method to perform physically more realistic simulations by taking into account polychromatic X-rays and focal spots causing blur.

X-ray Attenuation

The Beer-Lambert law relates the absorption of light to the properties of the material through which the light is travelling. For a polychromatic incident X-ray beam, it is:

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with $N_{in}(E)$ the number of incident photons at energy E, $N_{out}(E)$ the number of transmitted photons at energy E. $objs$ is the total number of objects in the 3D scene. μ is the linear attenuation coefficient (in cm^{-1}), which depends on: i) E, the energy of incident photons, and ii) the material properties of the object. $L_p(i)$ is the path length (in cm) of the ray in the i^{th} object.

X-ray Transmission Imaging

Given a virtual detector, an X-ray source and a scanned object, the Beer-Lambert law is computed for every pixel of the detector.

L-Buffer

Polygon meshes are used to represent scanned objects. Normal vectors at the surface of objects are outward. In this example, the ray penetrates into the disk when the dot product between $\mathbf{viewVec}$ and $\mathbf{N_1}$, the normal at the intersection point, is positive. Conversely, the ray leaves an object if the dot product between $\mathbf{viewVec}$ and $\mathbf{N_2}$ is negative. The path length of the ray in a given object can be written as follows:

$$L_p = \sum_i -\mathrm{sgn}(\mathbf{viewVec}\cdot\mathbf{N_i})d_i$$

where i refers to the i^{th} intersection found in an arbitrary order, d_i is the distance from the X-ray source to the intersection point of the ray with the triangle, $\mathrm{sgn}(\mathbf{viewVec}\cdot\mathbf{N_i})$ stands for the sign of the dot product between $\mathbf{viewVec}$ and $\mathbf{N_i}$. This dot product and d_i must be computed for each intersection point. These operations can be efficiently achieved on the GPU using a fragment program.

Geometric Unsharpness

The shape of the source is modelled using a variable number of point sources. Each point is assigned a fraction of the total number of photons in the system.

Polychromatism

The incident beam is split into discrete energy channels. To produce the final image, the total amount of energy received by each pixel is computed.

Simulation Pipeline

The algorithm has been implemented using GLSL. The principle of computing direct images is to emit rays at different energies depending on the beam from each of the X-ray point source to every pixel of the detector. For each ray, the total path length through each object is determined using geometrical computations. Finally, the total energy received by a given pixel is updated using the recorded path lengths and X-ray attenuation coefficients at the given energy of the ray.

Initilisation of OpenGL components (FBOs, textures, shaders)

For each simulation loop

For each energy channel (E)

Clear $FBO\,(\sum\mu(E)L_p)$

For each point source

Set OpenGL vertex transformations (modelview & projection matrices)

For each object (i)

Clear $FBO\,(L_p)$

Compute $L_p(i)$, i.e. $FBO\,(L_p)$

For each energy channel (E)

Update $FBO\,(\sum\mu(E)L_p)$ (make use of $FBO\,(L_p)$)

Clear final framebuffer

For each energy channel (E)

Update frame buffer: $\sum_E(E\times N_{in}(E)\times\exp(-\sum_i\mu(i,E)L_p(i)))$ (make use of $FBO\,(\sum\mu(E)L_p)$)

Display or save frame buffer (final results)

Results and Conclusion

X-ray transmission images can be fully simulated on the GPU, by using the Beer-Lambert law with polychromatism and taking into account the shape of the source. Additional loops have been added to the simulation pipeline and the computation cost proportionally increases depending on the number of source points and energy channels. This is a useful development to improve the level of realism in simulations, when both speed and accuracy have to be retained.

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Figure 4: Poster presented at Eurographics 2010, Norrköping, Sweden, May 3–7, 2010.