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Skeleton based importance sampling for path tracing

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Abstract

When working with large and complex scenes, situations arise where light flux takes complex paths to reach the observer. In such cases, traditional stochastic algorithms, like ray tracing algorithms, will have difficulties to compute noise-free images. Our present research aims to solve this problem using the 3d scene skeleton as a coarse representation. Indeed, curvilinear skeletons can be used to find light paths with higher energy. This article presents our research to use these skeletons for any ray tracing algorithm, allowing a knowledge-based choice when choosing light paths. Our method adds little computation time while producing a more accurate image.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Raytracing

1. Introduction

In complex 3D scenes, notably in dark areas, a ray of light can bounce multiple times before reaching the camera. In that case, global illumination algorithms are mandatory in order to obtain a photorealistic image. Such algorithms must solve the rendering equation and commonly, use a stochastic numerical Monte Carlo approach. Many variants have been presented from pure path tracing to bidirectional ray tracing [LW93], Metropolis Light Transport [VG97] or photon mapping [Jen96].

In such methods, on points where illumination has to be computed, the hemisphere is sampled in order to retrieve the incoming luminance. Usually, these algorithms use the BRDF to perform importance sampling. It means that the sampling of the hemisphere, and so the direction of the incoming rays, will be chosen primarily on the areas where the BRDF is strong. While this idea is good for well lighted surfaces, it can be proved wrong in dark areas, where we should orient rays towards the main incoming light direction. Figure 1.a shows several view paths in a scene where light is far from the camera. It is clear that in such case, it is inefficient to follow the BRDF.

Following the main light flux is not new since the Bidirectional Ray Tracing [LW93] tries to connect camera paths to light paths. MLT [VG97] also seeks for brighter light paths, through mutations. In photon mapping, previous researches have focused on the camera for importance sampling like Importons or even progressive photon mapping [PP98, HOJ08]. Our work is complementary to these approaches since they can use our importance sampling strategy on each light bounce. The technique of Fan et al. [FCcL05] is more sophisticated since it couples photon mapping to metropolis mutation and allows the user to manually select interesting rays. Our method is fully automatic and does not need any manual intervention. Metropolis Instant Radiosity [SIP07] rely on the same strategy but focuses on radiosity and virtual point light. Our work is inspired by this technique but adapted to ray tracing approach. Importance sampling on the MLT [HH10] has also been pro-

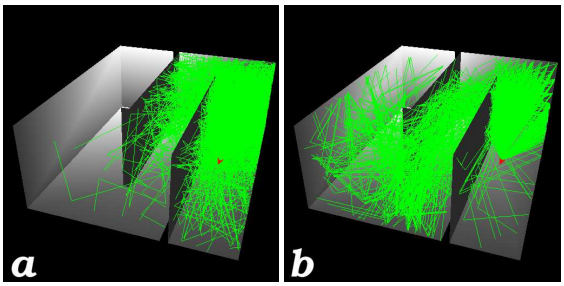

Figure 1: *Some of the rays (green) generated by a 5 bounces max path tracing, using in (a) classic importance sampling following BRDF, and in (b) our skeleton based approach. Camera is shown in red.*

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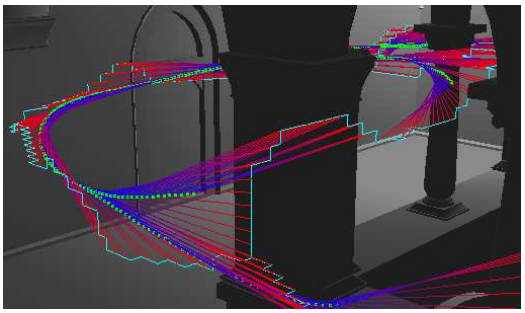

Figure 2: *In light blue, the skeleton. At each skeleton node, a vector is drawn (red to blue ended with a green dot) towards important points.*

posed and can introduce any user-defined importance sampling strategy such as ours.

None of the previous algorithms search for a complete inventory of the interesting paths between the camera and a light. Our method does by retrieving the topology of the scene and computing explicitly these paths to get the main streams of light. To obtain a direction following these streams, we compute a curvilinear skeleton of the scene using an efficient and robust discrete geometry algorithm. Once done, we perform an importance sampling regarding this direction. It gives better directionality of the rays as illustrated on figure 1.b. The contribution of our paper is, on one hand, to propose an efficient algorithm for recovering the curvilinear skeleton of a 3D scene, and on the other hand, to use this skeleton to make a proper importance sampling when solving the rendering equation. Since we affect only importance sampling, our technique can be used on any kind of ray tracing approach like path tracing, photon mapping or even bidirectional path tracing.

2. Skeletonization

A skeleton of an object X is a subset of points of X that possesses the same *topology* of X, that is, in 3d, the same number of connected components, holes and cavities. Moreover, a skeleton of X should be centered in X and at most two-dimensional. Some works on skeletonization focus on obtaining a skeleton which *looks like* the object : in this case, the difficulty lies in obtaining a skeleton devoided of spurious elements, which can be seen as noise.

Recent works on skeletonization use the cubical complex framework in order to obtain robust skeletons [BC06]. We use the skeletonization method presented in [CC09], which takes as input a voxel object and produces a thin and centered cubical complex skeleton. We modified the algorithm in order to only keep 1d elements in the output, thus producing a curvilinear skeleton.

The skeleton is filtered using our technique explained in [Cha10], which requires no user input: during the skeletonization, we calculate the lifespan of each point of the object (the number of iterations necessary to remove a point from the skeleton). We also compute for each point p of the object, the size of the biggest ball included in the object and containing p (called opening value of p). The filtering consists in keeping, during skeletonization, all points whose lifespan is superior to their opening value. This provides a noise robust skeleton relevant of the object visual aspect.

3. Our method

3.1. Overview

Our method defines a new importance sampling for choosing a new direction when light bounces on surfaces. Instead of relying on the BRDF, we seek a direction towards lit parts of the scene. We restrict presently to indoor scenes lit by a single light, but handling several lights might not be an issue, since we need only to select randomly, for each primary ray, a light source to reach. Our method follows four steps, the last one being the only used during the ray tracing pass :

1. make a relatively coarse voxelization of our scene.
2. skeletonize this 3D representation.
3. compute importance direction on this skeleton.
4. use the resulting skeleton and the voxelization to perform the importance sampling

3.2. Voxelization and skeletonization

The 3d scene is voxelized using Patrick Min's Binvox software, which implements [NT03]. The part of the scene considered as the object, and voxelized, is the propagation medium of the light (typically, the complementary of what is usually considered as the object of the scene). The finer the resolution of the grid is, the more geometrical and topological information of the original scene are contained in the output.

The voxel scene is then skeletonized, using the scene's lights and, optionnaly, camera as the constraint set of the skeletonizaton algorithm: this way, the output skeleton has branches passing by these elements. Using a simple propagation algorithm, we compute, for each voxel of the scene, the position of the closest point of the skeleton and store it (using a geodesic distance - a distance constrained to stay inside the object).

3.3. Computation of importance points

The curvilinear skeleton computed on step 2 can be seen as a graph - each vertex is a node connected to its neighbor vertex in the skeleton - where it is easy to compute shortest paths from the camera to any light. Note that if none of a light's photons can reach the camera, no shortest path exists between the camera and the light. Therefore, it is detected

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Scene	Memory overhead	p_{skel}	grid resolution	pre. time
Corridor	18 MB	4	93x205x250	13s
Sponza	130 MB	1	210x308x500	30s

Table 1: *Memory overhead, grid resolution, p_{skel} and precomputation time in both Sponza (fig. 4 right) and Corridor (fig. 3 and 4 left) scenes*

Scene	fig.3	fig.4 far left	fig.4 far right
MSE 100	145 / 57	301 / 156	881 / 826
MSE 40	434 / 260	924 / 628	2678 / 2570

Table 2: *Timing(s) to reach an MSE of 100 and 40 against reference images. In each cell, the left number is for the standard path tracing, the right one our method*

during this step and the light can be safely removed from the light list. This gives us a Litmus Test as defined in [PP98].

Our idea is then to compute, for each skeleton node, the main direction that rays must follow in order to reach the light as soon as possible. For each skeleton node n, we scan the shortest path from light to n (information precomputed for all nodes with a shortest path algorithm) and select the first sequence of nodes which are visible from n. We associate to n the barycenter of this group, and call it *the importance point*. In figure 2, we represent, for each node, normalized directions towards these points.

3.4. Importance sampling

Finally, we rely on the skeleton and the importance points to perform an efficient importance sampling. First, if a point is directly lighted or is specular, we use the standard BRDF sampling. Otherwise, we perform our skeleton based sampling using the following method. Based on the precomputation performed on the 3D grid at step 2., we are able to find, in constant time, the nearest skeleton node of the current point and retrieve the importance point computed at step 3. We then compute the importance direction as the normalized vector between the current position and this importance point. If this direction goes below the surface, we come back to classical BRDF sampling. Finally, we generate a direction on the unit hemisphere proportional to a cosine raised to power p_{skel}, which is the influence rate of our skeleton based sampling : the higher p_{skel} is, the more "oriented" towards the light source the paths will be.

4. Results and discussion

For comparison purposes, all renderings have been done with the same ray tracer, Embree, implemented by Intel on a laptop with a Quad Core processors i7 at 1.6GHz and 3.8GB of RAM. Images are tone mapped using simple gamma correction function with varying exposures. Sponza scene is the courtesy of Crytek. Table 1 provides some technical details.

Figure 3 compares our method with the path tracing algorithm using BRDF importance sampling. We converge faster except for some speckles. Figure 4 shows several examples, indicating Mean Square Error (MSE) against reference images computed with 65536 samples per pixel. The worst case scenario is the view of Sponza where some part is lit and some remains in shadow but are close to lit areas. Even in that case, we perform correctly and are even better on dark parts, as can be seen in the blue squares. Regarding timing, we add up to 25 percent to the cost of traditional path tracing for the same number of rays, but we converge faster, as shown on table 2.

However, using the topology of the 3D scene for importance sampling created some drawbacks. The first one being speckles or 'fire flies' that appear since we use a power cosine function. Therefore, the stronger the strength p_{skel} is, the more there are speckles. We plan to remove speckles using morphological operators in a post processing step. Our second drawback is the lack of color bleeding in the dark areas. Indeed, near lit areas, we focus too much on the main stream of light and neglect neighbouring surfaces. This is mainly due to the binary decision of following the BRDF or the stream light direction. If we blend the two sampling approaches, we will get this interreflection back. Moreover, the strength p_{skel} will be adaptatively chosen to be small near direct lighting areas, and strong far away.

The assumption that the single shortest path towards light follows the mean stream of light can be proved wrong, but is quite accurate in most of the cases. Moreover, this path is only used as a hint for the choice of a random direction. To enhance accuracy, we plan to work on weighting these paths according to a coarse estimate of light in areas along them.

5. Conclusion and future works

This ongoing research on skeleton based importance sampling allows to converge faster to reference image. This technique proves useful in dark areas, where light is not easily reachable, while still efficient in lit areas. Future works will focus on blending BRDF sampling to skeleton based sampling, on removing speckles and on tuning improved strategies in the computation of direction towards lit areas.

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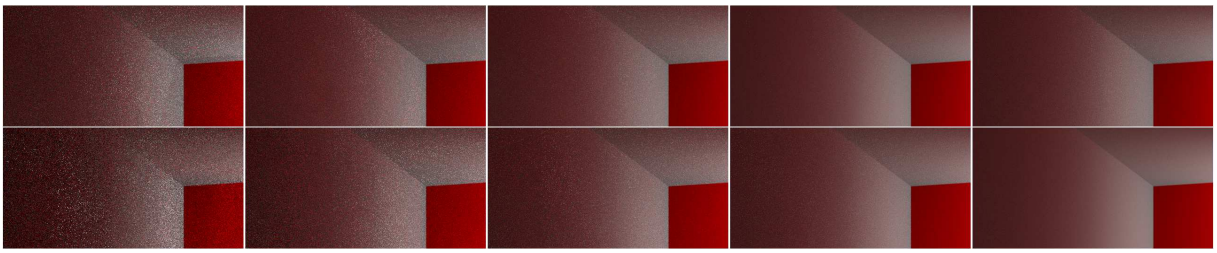

Figure 3: *Images showing an extract from a same scene with raising numbers of samples per pixel of 32, 128, 512 and 2048. On the first four columns, the top row shows images from our method while bottom row shows the ones from path tracing using BRDF importance sampling. The last column shows, on the top, the image obtained by our method for an MSE of 20, and, on the bottom, the reference image.*

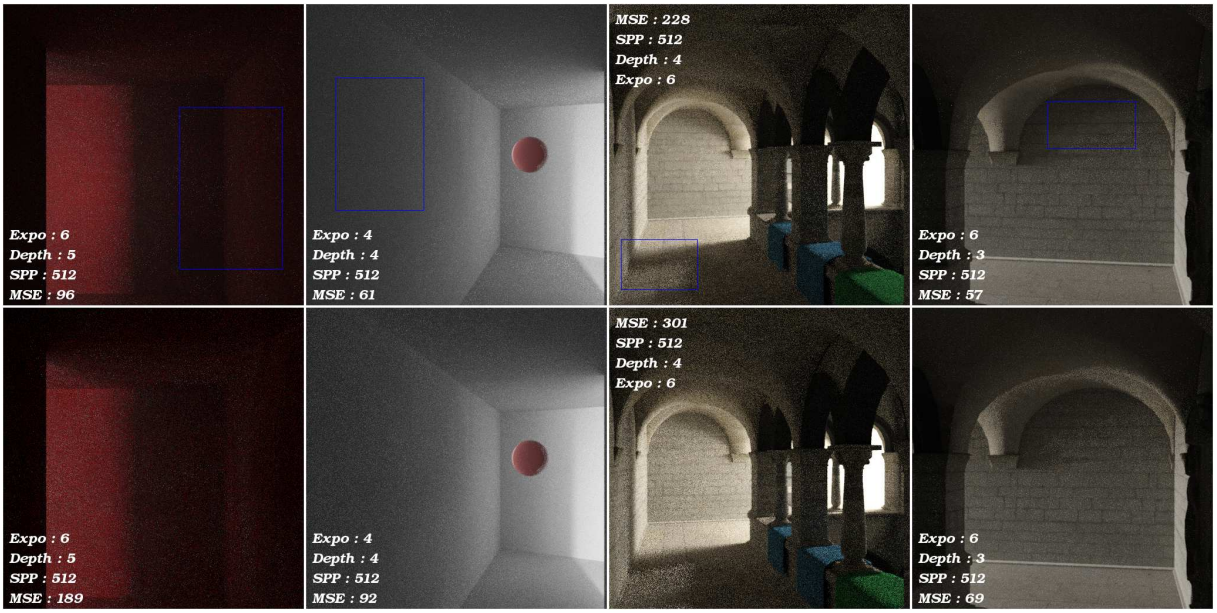

Figure 4: *Four different views using, on the top row, our method and, on the bottom row, the classical path tracing. Blue squares highlight areas where our method perform better. Exposure, samples per pixel, ray depth and MSE are indicated on the pictures.*

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