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Abstract: We address the main shortcomings of the voxel-based multi-bounce global illumination method of Chatelier and Malgouyres (2006), by introducing an iterated cached method which allows increasing sampling coarseness at each bounce for improved efficiency, and by introducing a ray-tracing based reconstruction process for a better final image quality. The result is a competitive accurate multi-bounce global illumination method with octree voxel-based irradiance caching.

1 INTRODUCTION

Comprehensive multi-bounce methods for global illumination have been extensively studied, and finding the right balance of speed vs accuracy is always painful. The most widely used approach consists in one step of coarse computation of a global illumination solution followed by a step of reconstruction by gathering the light by ray-tracing to provide good quality images.

In (Malgouyres, 2002) and (Chatelier and Malgouyres, 2006), a new to global illumination and a discretization of the diffuse illumination, based on voxel approximation of surfaces by voxels is proposed. The interest of the method is that visibility is determined in linear time with respect to the number of rays. Moreover, it directly provides a voxel-based irradiance lookup octree. However, the method presented in (Chatelier and Malgouyres, 2006) has two weaknesses: first, solid angle sampling is the same for each bounce, and in particular, direction sampling from light sources is insufficient while the cost of direction sampling after one or two bounces is very expensive. Second, no reconstruction process is presented and direct display of the voxel solution requires many voxels, which also increases the runtime.

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In this paper, we address these two shortcomings by proposing an iterated cached coarse global illumination solution, in which direction sampling decreases after each bounce, followed by a reconstruction phase based on light cuts (Walter et al., 2005). It results in a competitive accurate multi-bounce global illumination method with a voxel irradiance cache octree.

In section 2, we have presented previous work and outline the method of (Chatelier and Malgouyres, 2006). In Section 3, we present the iterated cached global illumination method, and in Section 4, we explain our reconstruction process. In Section 5, we present experimental results. Finally, in Section 6 we present some perspectives for future works.

2 PREVIOUS WORK

The most widely used global illumination techniques consist in a first phase of computation of a coarse solution, for example by photon mapping (Jensen, 1996), (Jensen, 1997), (Jensen, 2001). This method traces random rays from light sources, and at each intersection, traces a new random ray with a probability that depends on the *BRDF* according to russian roulette. Then, a second phase consists in a viewpoint-dependant ray-tracing for computing good quality images. Instant radiosity ((Keller, 1997)) was the first of such methods to be introduced. Other methods for final gather steps have been produced (Granier and Drettakis, 2004), (Arikan et al., 2005).

In all of these methods, determining visibility by ray-object intersection is a very important time cost factor. Attempts at getting rid of visibility problems altogether have been made (Dachsbacher et al., 2007), however at a cost of increased memory and reintroducing hierarchical radiosity difficult problems of refinement and meshing (Sillion and Puech, 1994). For accelerating the gather step, photon splatting (Lavignotte and Paulin, 2003), (Dachsbacher and Stamminger, 2006) can by used, but it neglects some occlusions for indirect light and uses rough approximations for speedup.

In (Chatelier and Malgouyres, 2006), a new global illumination approach is considered, with a cost which is linear with respect to the number of visibility rays. This is a promising result, but there are shortcomings. The goal of this paper is to provide solution to these, to obtain a competitive global illumination technique. Up to the end of this section, we outline the method of (Chatelier and Malgouyres, 2006).

In (Malgouyres, 2002), the (Lambertian) global illumination equation

$$B(x) = E(x) + \rho(x) \int_S B(y) \frac{\cos\theta}{\pi} d\overrightarrow{\sigma}$$

is discretized as

$$B(x) = E(x) + \rho(x) \sum_{\overrightarrow{\sigma} \in D} B(I(x, \overrightarrow{\sigma})) \frac{\cos\theta(x, I(x, \overrightarrow{\sigma}))}{\pi} \Delta\Omega(\overrightarrow{\sigma})$$

where x is now a voxel, D is a set of discrete directions in space, $I(x, \overrightarrow{\sigma})$ is the first point y viewed from x in the direction of $\overrightarrow{\sigma}$ (as in a ray-object intersection), and $\Delta\Omega(\overrightarrow{\sigma})$ is the fraction of a solid angle associated to the direction $\overrightarrow{\sigma}$. In (Chatelier and Malgouyres, 2006), a solution of the discrete equation is obtained with a linear complexity with respect to the number of rays. We remind the reader the main ideas of the method. More details can be found in (Chatelier and Malgouyres, 2006).

Given a direction vector $(a,b,c) \in \mathbb{Z}^3$ with $a \geq b \geq c$, a notion of a $3D$ line has been proposed (Debled-Rennesson, 1995), as the set of points $(x,y,z) \in \mathbb{Z}^3$ such that

$$\mu \leq cx - az < \mu + \omega \text{ and } \mu' \leq bx - ay < \mu' + \omega'$$

where $\mu, \mu', \omega, \omega'$ are integers. Other cases can be deduced by symmetry. Let us denote by $\mathbb{Z}^3_*$ the set $\mathbb{Z}^3 \backslash \{(0,0,0)\}$. Given an integer vector $\overrightarrow{v} \in \mathbb{Z}^3_*$, the set $\mathbb{Z}^3$ can be partitioned into $3D$ discrete lines, whose direction vector is $\overrightarrow{v}$ (see Figure 1).

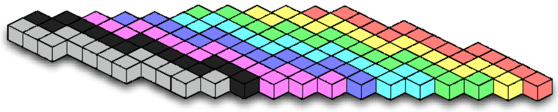


Figure 1: Partition of the space into parallel discrete lines

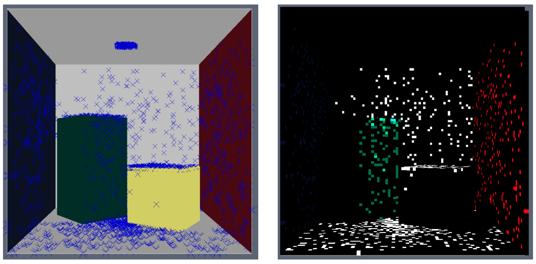
Moreover, given a voxel $x \in \mathbb{Z}^3$, finding out which $3D$ discrete line in the partition the point x belongs to can be done in constant time.

Now, to transfer energy from one voxel x to the first voxel y visible from x in a direction σ, for some finite set of sample directions σ, if we consider some fixed direction σ and a partition of the voxel space $\mathbb{Z}^3$ into discrete lines parallel to σ, then the voxels of the discretized surface (say mesh or implicit surface) that lie on the same discrete line can be arranged in an ordered list. In this ordered list, the first visible voxel is the next voxel in the list. So, once the lists are sorted, we can propagate the energy in linear time $O(N)$, where N is the number of voxels.

Now, the idea of the method is that by going over the set of all surface voxels in a lexicographic order (lexicographic orders are precomputed by radix sort), we can build all the sorted lists in linear time $O(N)$. We do this for each of the D sample directions and for each of the I Gauss-Seidel iteration, and we get a numerical solution of the global illumination equation in time $O(N \times I \times D)$.

3 SHOOTING FROM LIGHT SOURCES AND BOUNCE CACHE METHOD

Although the method of (Chatelier and Malgouyres, 2006) has a linear complexity with respect to the number of rays, one of its drawbacks is that it doesn't sample solid angles according to power importance. We consider small light sources which emit much light per unit of area, as we can find in many applications, first the voxel size needs to be small enough to approximate light source shapes, thus many voxels are required, and second, the solid angle sampling must be fine enough to avoid artifacts. A natural solution to this problem is the use of the raytracing instead of discrete shooting in this step. We proceed as follows: First we choose number of initial photons on light sources with the random normal distribution that depends on light power and area. The energy of each sample is equal to $\frac{\text{overall energy}}{\text{number of samples}}$. Then we shoot from each initial photon n rays into n directions, with energy equal to E/n. For each intersection point we



(a) Direct photons shooting (b) Initial voxel power

Figure 2: Photons shooting and voxels initialization

store the given energy and compute the corresponding irradiance. The set of indirect photons is used as initial voxel setup (the initial voxel irradiance is equal to the sum of the irradiance of the photons inside the voxel). We propagate this light using the linear voxel method of (Chatelier and Malgouyres, 2006).

After each bounce of Lambertian surface, the energy amount is reduced significantly, and is getting lower frequency (i.e. more smooth). We can use that property by using less directions at each intersection level, thus reducing the cost of multi-bounce simulation. At each bounce we propagate only the light that was created during previous shooting phase, summing all the light in a global accumulation cache after each iteration. We split computations into sets of independent i to $i+1$ bounces, and we use different (e.g. divided by 2 at each bounce) number of directions at each level. The algorithm can be sketched as follows:

- We shoot photons from light sources by raytracing at path length one (only first intersections).
- We sum the irradiance in the corresponding voxels and use the result as initialization of the linear method of (Chatelier and Malgouyres, 2006). We store this in *currentCache*.
- for each iteration

  we propagate *currentCache* and store new values into *CachePlus*

  we add the energy from *CachePlus* to *GlobalCache*

  we swap *CachePlus* and *currentCache*

  we clear *CachePlus*

4 RECONSTRUCTION METHOD

We present two approaches to light gathering for voxel-based global illumination: one similar to instant radiosity (Keller, 1997) and one based on lightcuts (Walter et al., 2005).

4.1 Random Sample Voxels

Our first reconstruction is inspired from instant radiosity (Keller, 1997). Of course, the principle must be substantially adapted to voxels. The intensity of the voxels is proportional to their radiosity as obtained in the output of the method of (Chatelier and Malgouyres, 2006) improved by the iterated cached method. However, in order to reduce the number of point lights, and to take into account the nature of radiosity (power per unit of steradian per unit of area) we select the voxels *randomly* according to a probability proportional to their *area*, as defined below, and multiplied by a solid angle.

The area of a voxel is the sum for all boundary voxel of an object of the dot product of the normal to the faces of the voxel with the normal to the underlying surface.

$$\Delta A(x) = \sum_{y \in N_6(x) \cap \overline{O}} \overrightarrow{xy}.\overrightarrow{N} \qquad (1)$$

So, we make a raytracing phase by tracing rays from the viewpoint through the pixels. For each pixel, we compute the ray hit point I that we must shade. In order to shade the hit point I, we use the sample voxels y, randomly selected with probability proportional to $\Delta A(y)$, as point light sources with light contribution:

$$C_y(I) = B(y)\frac{\cos\theta(I,y)\cos\theta(y,I)}{||I-y||^2}V(I,y) \qquad (2)$$

In fact, we select two random samples sets of voxels by monte-carlo sampling. We can use progressive raytracing that allows the user to get approximate results after a few seconds. This method generated nice images, but its complexity is dependent on $O(n)$ where n is number of virtual point lights.

4.2 Reconstruction Based on Lightcuts

In order to reduce the dominant reconstruction cost, we use the lightcuts method (Walter et al., 2005). This method enables us to render massive (thousands to millions) number of point lights in a reasonable (sublinear) time. The only drawback is a small pixel potential error value (determined by a user-set parameter, e.g. 2%) . A cluster is a set of point light sources which are approximated by a single representative light source. A common lightcut tree, the nodes of which are clusters, is created which unifies illumination and enables transparent tradeoffs between adequate components. During the reconstruction process, at a ray hit point, the largest clusters compatible with

	Scene 1	Scene 2
Antialiasing	off	on
number of triangles	1,176	67,462
number of voxels	108,455	22,615
Light path length	4	6
Voxel directions	146	256
Primary photons	650	4000
Direct photons	200	256
Continuous Rays	87,913,202	184,834,570
Discrete Rays	26,637,785	10,146,637
Rays/sec (continuous)	140,819	68,983
Rays/sec (discrete)	5,122,651	5,176,855
Propagation Time	6.1 sec	4.15 sec
Linear method Time	5.2 sec	1.96 sec
Reconstruction Time	624.3 sec	2679.27 sec
Overall Time	630.5 sec	2684.43 sec

Table 1: Statistics for Scene 1

the error criterion is selected, and summed to obtain the irradiance value. This method allows us, instead of using a random sample of voxels, to consider all the voxels. This simplifies the voxel selection process, at a cost of constructing lightcuts trees.

Our implementation of lightcuts is based on (Miksik, 2007). We divide direct and indirect virtual light points and create separate trees, and combine them in a root node as described in (Miksik, 2007). The direct tree is based on light source photons and the first irradiance cache (for direct light) of the method of Section 3. The indirect tree is based on the indirect accumulation voxel cache.

5 RESULTS

Tests were done on *PC* with Intel Core 2 Duo 6300 (1.86GHz). Only one core was used (single thread with Widows Vista).

The first test compares the method with a reference solution computed by path tracing. In Figure 3, a quality comparison with other classical methods is provided. The results shows that the method is accurate and without noise. We computed path-tracing at a constant rate samples per pixel (50) thus the time is sometimes better, but the noise is strongly visible. This test shows that the method is accurate.

In Table 1, we can see the statistics for runtime. The ratio of number of rays per seconds for continuous rays (KD-tree accelerated ray-object intersection) and discrete rays in 2.75%, For Scene 2, the ratio of number of rays per seconds for continuous rays and discrete rays in 1.33%. This result shows the relevance of the discrete linear method, even more so for complex scenes. Moreover, the discrete number of rays per seconds is little dependant on the scene complexity.

In (Hasan et al., 2007) Hasan et al. render similar views of the Sponza atrium in about 8s, but we can not compare that directly since it uses hardware acceleration vs our fully software single thread based raytracer, Moreover we used area light to simulate day light, which is slower than a single ray sunlight. Quality of the image of (Hasan et al., 2007) may be also lower since it uses the same set of lights for whole image, contrary to the lightcuts which selects lights adaptatively.

(a) Scene 1: Polygonal scene with 1.176 triangles. Shooting and multicache methods combined are 6.1 sec. The reconstructions phase lasted 630 sec. We used 108,455 voxels and 146 directions.

(b) Scene 2: Sponza atrium. Highly textured scene with 67,462 triangles. We used huge area light to simulate day light. Shooting and multicache methods combined lasted 4.15 sec. We used 22,615 voxels and 256 directions.

Figure 4: Test scenes.

6 CONCLUSION AND FUTURE WORK

Our results show that our voxel based method can be competitive and accurate for precise multi-bounce global illumination. It provides very large numbers of rays per seconds for discrete rays, which make the technique promising. To improve the method, we could possibly find a method with linear complexity with respect to the number of rays for the reconstruction process also, which could result in dramatic reduction of the reconstruction time, which is the dominant term. Then, a GPGPU acceleration for the discrete linear method could result in a very low-time propagation phase, and should be considered. The current version of the method works only for Lambertian material, and a method for general BRDF's should be developed, by storing a more complex representation of outgoing light in voxels. Finally, we could find a method for fast animation by enabling to add an object into the scene without recomputing the whole solution by the use of antiradiance (Christensen and Batali, 2004).

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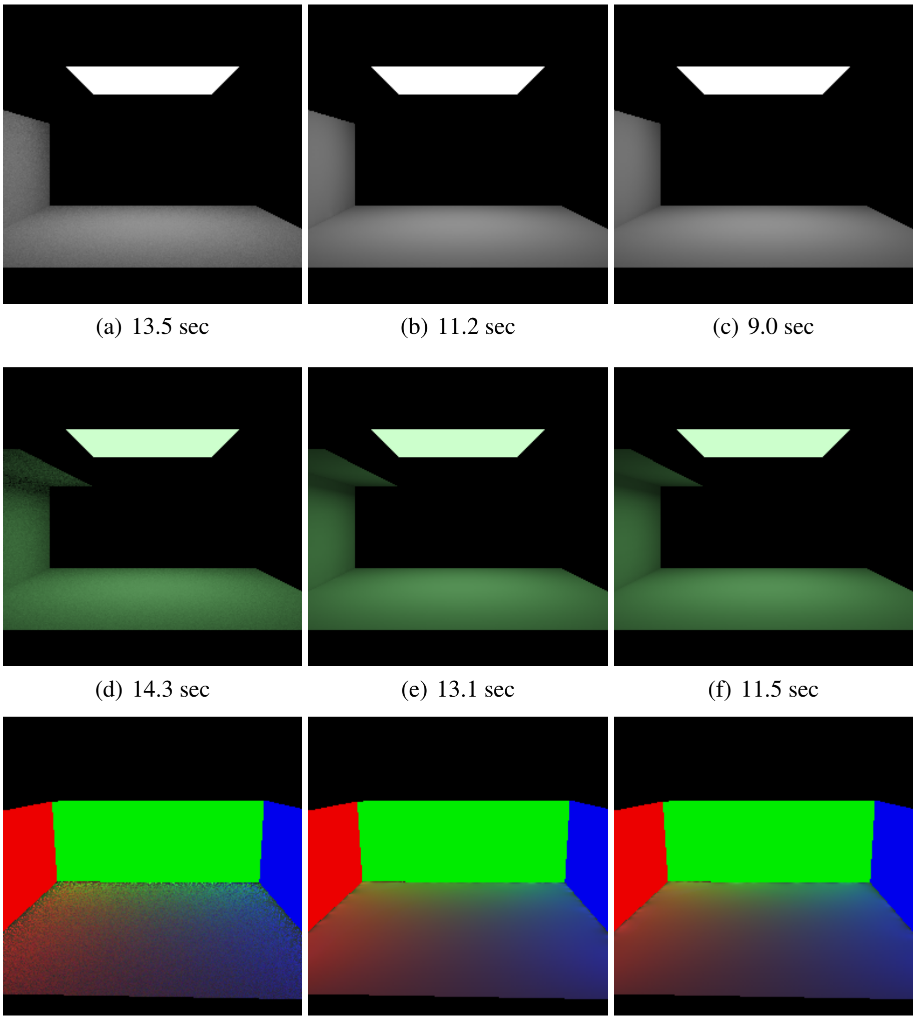

(a) 13.5 sec (b) 11.2 sec (c) 9.0 sec

(d) 14.3 sec (e) 13.1 sec (f) 11.5 sec

(g) 18.0 sec (h) 20.6 sec (i) 21.0 sec

Figure 3: Comparison tests. the left column was computed by monte carlo path tracing (50 samples per pixel), the middle column is photon mapping with lightcuts for reconstruction, and the right column is the voxel-based method with lightcut reconstruction. All pictures were computed using 1600 direct photons. We used 1600 indirect photons for photon mapping. We used 128 directions in the linear voxel propagation, and 2 iterations. The discretization resolution was $64 \times 64 \times 64$ voxels.