Optimized Local Pass using Importance Sampling

Wolfgang STÜRZLINGER

GUP, Johannes Kepler University Linz
Altenbergerstraße 69, A-4040 Linz, Austria/Europe
Tel.: +43 732 2468 9228, Fax: +43 732 2468 9496
Internet: stuerzlinger@gup.uni-linz.ac.at

Abstract

Recent approaches to realistic image synthesis split the rendering process into two passes. The first pass calculates an approximate global illumination solution, the second produces an image of high quality (from a user selected view point) using the solution obtained in the first pass by applying the local illumination model to each surface point visible through each pixel.

This paper presents two new methods to compute the local illumination quickly. Instead of recalculating form factors and visibilities the information computed by a hierarchical radiosity solution algorithm is reused. The image generation time is reduced significantly by using stochastic methods.

Key Words: image generation, local illumination, local pass.

1 Introduction

The light leaving a surface is determined by the incoming light and by the material properties of the surface - as described by the local illumination model. The problem is how to accurately calculate the light reaching the surface which in turn is determined by the light emitted by all other surfaces, the scene geometry and occlusion.

An approximation to the light leaving all surfaces is calculated by global illumination methods which simulate the distribution of light in an environment. Light emitted by a light source is either absorbed by the hit surfaces or reflected to other surfaces and so on. By discretizing the environment into patches (i.e. planar polygons) and by restricting the scene to diffuse surfaces an equation system can be formulated which describes the mutual influence of patches onto each other. Solving this system gives the emitted light (the radiosity) for each patch. For an image of the environment the polygons are rendered from a user selected view point with hidden surfaces removed. However, the chosen patch size limits the quality of the approximation and leads to artifacts in the final image. These artifacts are due to an interpolation of radiosity values at inappropriate places or over unacceptably large areas as neither the final view point nor the image resolution are known at this stage. For an overview of global illumination methods see Cohen et al. [CW93] or Sillion et al. [SP94].

As every patch can interact with every other patch the cost of computing a global illumination solution appears to be $O(n^2)$. But groups of patches widely separated in space might reasonably have their interaction represented by a single number without introducing significant error. This idea is used in the hierarchical radiosity (HR) method [HSA91] which calculates a solution to the global illumination problem in less time. The patches are organized into a hierarchy where upper nodes represent groups of patches with the radiosity averaged. The hierarchical refinement algorithm constructs links for every non-zero transfer of light energy between the nodes of this tree. An interaction between widely separated patches can then be represented by a link between the two respective nodes of the tree. The solution process transfers light energy using the links and distributes this energy up and down in the tree.

This first HR algorithm created a tree for every surface, thereby creating $O(s^2 + n)$ links where s is the number of surfaces and n the number of patches. A later work [SAG94] improved the running time to $O(s \log s + n)$ and the number of links to $O(s + n)$ by clustering all patches using a bounding volume hierarchy.

Rendering the hierarchical radiosity solution still produces images with artifacts. The most prominent errors are caused by the discontinuities in the illumination at shadow boundaries. Lischinski et al. [LTG93] subdivided the mesh along those lines to produce more accurate results.

More correct images are obtained by a so called local pass. First the surface point visible through each pixel is determined, then the light leaving the surface at this point is calculated from the incident illumination (using the results of the global illumination solution) and the material properties. Approaches based on traditional radiosity algorithms have to recompute visibilities and form factors to all patches. The hierarchical radiosity method stores this information as links. The incident illumination can be computed quickly by following the links.

This paper presents two new methods for quickly computing the local illumination of a surface point using the results of a HR algorithm. Instead of following all links and recomputing all visibilities and form factors stochastic methods are used to reduce the computational effort.

After a brief overview of the local pass and previous work, the new methods are discussed following the presentation of Lischinski et al. [LTG93]. The last section concludes with results and directions for further research.

2 Local Pass: Local Illumination at Each Pixel

The local pass method evaluates the local illumination model at each surface point visible through the pixels of an image. This allows to compute high quality images from an approximate global illumination solution and avoids the artifacts of the discretized global illumination solution.

A picture is generated by finding the surface point x visible at each pixel and obtaining the colour of this pixel by computing the irradiance of x and applying the local illumination model.

2.1 Local Illumination Model

The local illumination model describes the relationship between the irradiance H of a point x (the “incoming” light) and the reflected light. For the diffuse case the radiosity B equals the irradiance multiplied by the reflectivity of the surface plus its emission:

$$B(x) = E(x) + \rho(x) H(x) \tag{1}$$

where E is the emission and ρ is the reflectivity of x’s surface. The incoming light for a point x is given by

$$H(x) = \frac{1}{\pi} \int_{\Omega} B(\vec{\omega}) \cos\Theta \, d\vec{\omega} \tag{2}$$

which integrates the radiosity B coming from all possible directions $\vec{\omega}$ on the hemisphere Ω weighted by the cosine of the angle Θ between $\vec{\omega}$ and the normal vector of x’s surface. The radiosity coming from each direction $B(\vec{\omega})$ is calculated from the surface point y visible in the direction $\vec{\omega}$ and its radiosity $B(y)$ obtained from a previous global illumination solution.

The emitted radiance of a fully visible polygon A with constant radiosity B towards a point x is (see e.g. [BRW89]):

$$H(x, A) = B(A) \cdot \underbrace{\frac{1}{2\pi} \sum_{a \in A} N \cdot \Gamma_a}_{FF(x, A)} \tag{3}$$

where a are the edges of the polygon and N is the normal vector of x's surface. Γ_a is the vector normal to the plane defined by x and the edge a and length equal to the angle γ_a (see figure 1). The geometry dependent term in equation (3) is also called the form factor $FF(x,A)$.

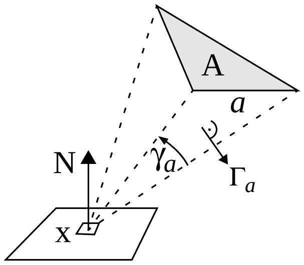

Figure 1: Geometry for form factor of a polygon

General scenes consist of several polygons and occlusion must be taken into account. Let $A^{vis(x)}$ be the part(s) of A visible from x. One way to compute the irradiance $H(x)$ is:

$$H(x) = \sum_{A} B(A) \cdot FF(x, A^{vis(x)}) \tag{4}$$

The visible parts of all polygons can be identified by projection methods [SS95]. A computationally cheaper alternative is to cast a number of rays from x to the polygon in order to estimate the visibility $Vis(x,A)$ by the ratio of unblocked rays to the total number of rays.

2.2 Local Pass

The local pass method evaluates the local illumination model at each surface point visible through the pixels of an image.

Rushmeier [Rush88] describes a two-pass approach in which the first pass consists of a constant element radiosity solution computed using the progressive refinement algorithm. During the rendering pass the hemisphere integral is evaluated using Monte Carlo methods. The direct illumination (illumination from primary light sources) is calculated for each pixel, because of its dominant contribution to the illumination for most pixels. Random rays are used to compute an approximation to the local illumination. Shirley [Shir94] describes a similar approach but uses a full path tracing method to evaluate the indirect illumination.

A different approach was presented by Shirley [Shir91], where only the direct illumination is computed using stochastic methods. The indirect illumination is interpolated from the mesh. Kok et al. [KJ92] describe a generalization of this approach in which illumination due to the most significant secondary reflectors as well as the emitters is recomputed during rendering, based on information gathered during the radiosity pass.

Reichert [Reic92] calculates the local illumination for a point x by calculating the form factor and visibility to each element and summing up the contributions. This method is quite costly as all elements have to be processed for every pixel.

The RADIANCE System [Ward94] computes a global illumination solution by caching irradiance samples in the scene, instead of using a progressive refinement algorithm. The indirect illumination is computed by interpolating the irradiance of nearby samples, if appropriate. Otherwise new irradiance samples are created by stochastic sampling.

All above methods (except [Ward94]) use the results of a progressive refinement radiosity algorithm. As it is impractical to store all form factors and visibilities which were computed by the algorithm, a local pass method cannot take advantage of previously computed information.

Lischinski et al. [LTG93] use a hierarchical radiosity solution to compute the local illumination for each pixel. His approach is discussed below.

3 Optimized Local Pass

The complexity of a brute force local pass is proportional to the number of pixels times the cost of computing the local illumination. All approaches based on non-hierarchical solutions have to recompute form factors and visibilities of other patches, as it is impractical to store information for all potential $O(n^2)$ interactions. A hierarchical refinement algorithm constructs links for every transfer of light energy between patches. The algorithm creates only $O(n)$ links. The existence of a link signifies that a patch has an non-zero influence onto another. This knowledge can be reused for the computation of local illumination.

Lischinski et al. [LTG93] compute the local illumination of a surface point x by following all the links and summing up the contributions. As the links express area-to-area interactions the results are averaged over the area of the patch. To compute more precise results some or all of the participating terms can be recomputed. Lischinski presents four methods which are discussed here for comparison purposes:

Method A: The simplest approach is to use the radiance stored at the hierarchy leaf that contains x. This method has no further overhead. The accuracy of the resulting value equals the accuracy of the global pass solution.

Method B: Each link stores the unoccluded form factor from the centre of the hierarchy leaf to the corresponding source, as well as the visibility factor. To obtain a more accurate value the form factor from the point x to each source can be recomputed. Multiplying this value with the stored visibility yields a more accurate result.

Method C: The next logical step is to recompute the visibility from the point x to each source. Due to the cost of solving the visibility problem exactly, this approach is quite costly. The only remaining error is now the inaccuracy of the global illumination solution due to the discretization of the environment into patches.

Method D: To reduce the cost, visibility is recomputed only for primary light sources. This is justified by the fact that primary sources are typically responsible for the most noticeable changes in illumination, i.e. responsible for the most noticeable shadow boundaries.

Instead of recomputing all visibilities or only the primary light source visibilities, the information supplied by the links can be used to recompute visibilities only if the contribution of a link is significant, as a far away light source has almost no influence on the illumination of a given patch.

Method E: This approach follows methods C as presented above. But instead of recomputing all visibilities, a stochastic method is used to reduce the cost.

The radiosity value stored at the patch is an approximation to the true value of a point x on the patch. More precise it has been computed and can be recomputed by summing the contributions of all links by weighting the source's radiosity of each link by the respective form factor and visibility factor.

The radiosity value of the patch can be used to determine the potential relative contribution of each link. This in turn can be used to determine visibilities only as precise as indicated by this contribution. A link with a strong contribution merits an exact visibility computation, whereas a link to a relatively dark patch needs almost or no visibility re-computation at all. To avoid systematic errors we have chosen to use importance sampling to determine the number of rays to cast to a light source (see e.g. the Stochastic Ray Method [NPTN95]). A discrete cumulative distribution function F for the contribution of the links C_i is defined by:

$$F_j = \frac{\sum_{i=1}^{j} C_i}{\sum_{i=1}^{N} C_i} \tag{5}$$

The stored radiosity of a patch is used as denominator for this expression. The numerator can be calculated incrementally while iterating through the links.

An advantage of this approach is that the total number of rays N for the sampling can be the same for each sampling point x. As the cost of the visibility computation overshadows the cost of the other computations the number of rays influences the time for the local pass almost linearly.

Method F: Analysing the performance of method E shows that many rays are used to determine visibility between fully visible patches. This happens when the stored visibility of a link is one (i.e. fully visible) and no other patch is situated between the linked patches. The contribution of the link is then potentially high and a proportional number of rays is used to determine the visibility, which is not necessary.

If shaft culling [HW91] has been used as a speed up technique during the global illumination solution it can be easily determined if two patches are mutually fully visible. This information can easily be stored as a flag for each link.

This flag can be used to classify the links of a patch into two sets:

1. All links with predetermined full visibility. Clearly it is not necessary to recompute visibilities for this set.
2. All other links. A point x on the patch may see nothing, some part or everything of the source patch pointed to by the link, therefore it is necessary to compute the visibility. These links occur along the shadow boundaries caused by the source patch.

The contributions of links of the first set are computed with method B above - only the form factor is recomputed. The links of the second set are handled as in method E - stochastic sampling is used to determine the visibility. The denominator of equation (5) has to be calculated in advance.

The advantage of this method is that the computational effort is concentrated where the global illumination solution is inaccuracte - along shadow boundaries. Both new methods are summarized as pseudocode in figure 2 (for pseudocode for Methods A-D see [LTG93]).

4 Implementation and Results

The current implementation of the local pass method runs on a Silicon Graphics workstation. The results shown were obtained with a scene consisting of 2461 polygons (see figure 3). The hierarchical global illumination solution took 2513 second to compute and produced approximately 30000 links. A comparison of the run times for methods A to F for the generation of an 512x512 image is given in table 1. The image produced by method E has some minor flaws along the shadow boundaries, as few or no rays were used there to recompute visibilities. The result of Method F is practically identical to the result of method C.

```
Spectrum Shade(Node n, Point x)
    if ShadeMethod is E
        total = node.rad
    else if ShadeMethod is F
        total = 0
        for all node.links do
            if not link.fully_visible
                total += link.source.radiosity * link.ff * link.visibility
    rad = 0
    for all node.links do
        ff = FormFactor(x,link.source)
        num_rays = 0
        if (ShadeMethod is E) or (ShadeMethod is F and not link.fully_visible)
            determine num_rays using equation 5 with total as denominator
        v = Visibility(x,link.source,num_rays)
        rad += ff * v * link.source.radiosity
    return rad

Real Visibility(Point x, link Link, int num_rays)
    if num_rays != 0
        v = 0
        for i = 1 to num_rays
            v += VisibilityRay(x,link.source) / num_rays
    else
        v = link.visibility
return v
```

Figure 2: Optimized local pass pseudocode

Figure 3: Sample scene

Method	A	B	C	D	E	F
time in sec	176	847	3937	982	1050	1130
shadow rays/pixel	0	0	213	16	16	16

Table 1: Statistics for Local Pass Methods

5 Conclusion and Further Extensions

Two methods were presented to speed up the the local pass. Instead of recomputing information already calculated during the hierarchical global illumination pass, this information is reused if appropriate. The image generation time is reduced significantly by using stochastic methods. An interesting property of the presented method is that the performance is compareable with standard raytracing with area light sources as an almost constant number of rays is shot for each pixel.

Currently the system does not use error bounds for the calculation of local illumination. If the hierarchical solution has been computed using the techniques presented by Lischinski et al. [LSG94] the calculated bounds can also be used to generate more exact images.

6 References

[BRW89] D. R. Baum, H. E. Rushmeier, and J. M. Winget, *“Improving radiosity solutions through the use of analytically determined form-factors”*, Computer Graphics (SIGGRAPH 89), pp. 325-334, July 1989.

[CS94] K. Chiu, P. Shirley, *“Rendering, Complexity, and Perception”*, Proceedings of the 5th Eurographics Rendering Workshop (Darmstadt), pp. 19-34, June 1994.

[CW93] M. F. Cohen, J. R. Wallace, *“Radiosity and Realistic Image Synthesis”*, Academic Press, 1993.

[HW91] E. A. Haines, J. R. Wallace, *“Shaft Culling for Efficient Ray Traced Radiosity”*, Proceedings of the 2nd Eurographics Rendering Workshop (Barcelona), 1991.

[HSA91] P. Hanrahan, D. Salzman, L. Aupperle, *“A Rapid Hierarcical Radiosity Algorithm”*, Computer Graphics (SIGGRAPH 91), pp. 197-206, July 1991.

[KJ92] A. J. F. Kok, F. W. Jansen, *“Adaptive Sampling of Area Light Sources in Ray Tracing including Diffuse Interreflection”*, Computer Graphics Forum (Eurographics 92), vol. 11, no. 3, pp. 289-298, Sept. 1992.

[LTG93] D. Lischinski, F. Tampieri, D. P. Greenberg, *“Combining Hierarchical Radiosity and Discontinuity Meshing“*, Computer Graphics (SIGGRAPH 93), pp. 199-208, Aug. 1993.

[LSG94] D. Lischinski, B.Smits, D. P. Greenberg, *“Bounds and Error Estimates for Radiosity “*, Computer Graphics (SIGGRAPH 94), pp. 67-74, July 1994.

[NPTN95] L. Neumann, W. Purgathofer, R. F. Tobler, A. Neumann, P. Elias, M. Feda, X. Pueyo, *“The Stochastic Ray Method for Radiosity”*, Proceedings of the 6th Eurographics Rendering Workshop (Dublin), pp. 195-206, June 1995.

[Reic92] M. C. Reichert, *“A two-pass radiosity method driven by lights and viewer position”*, Master’s thesis, Program of Computer Graphics, Cornell University, Jan. 1992.

[Rush88] H. E. Rushmeier, *“Realistic Image Synthesis for Scenes with Radiatively Participating Media”*, Ph.D. thesis, Cornell University, 1988.

[Shir91] P. Shirley, *“Physically Based Lighting Calculations for Computer Graphics”*, Ph.D. thesis, University of Illinois at Urbana-Champain, 1991.

[Shir94] P. Shirley, *“Hybrid Radiosity/Monte Carlo Methods”*, Siggraph 94 Advanced Radiosity Course. July 1994.

[SAG94] B. Smits, J. Arvo, D. Greenberg, *“A Clustering Algorithm for Radiosity in Complex Environments”*, Computer Graphics (SIGGRAPH 94), pp. 435-442, July 1994.

[SC94] P. Shirley, K. Chiu, *“Notes on Adaptive Quadrature on the Hemisphere”*, Technical Report TR-411, Dept. of Computer Science, Indiana University, 1994.

[SP94] F. X. Sillion, and C. Puech, *“Radiosity and Global Illumination”*, Morgan Kaufmann Publishers, 1994.

[SS95] G. Schaufler, W. Stürzlinger, *“Exact and Error Bounded Approximations of Local Illumination”*, Compugraphics 95 (Alvor, Portugal), Dec. 1995.

[Ward94] G. J. Ward, *“The RADIANCE Lighting Simulation and Rendering System”*, Computer Graphics (SIGGRAPH 94), pp. 459-472, July 1994.