Reusable Radiosity Object

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Abstract

Because of the view independence and photo realistic image generation in diffuse environment, radiosity is suitable for an interactive walkthrough system. The drawback is time-consuming in form factor estimation, and furthermore, inserting, deleting or moving an object makes the whole costly rendering process repeat. To solve this problem, we encapsulate necessary information for form factor calculation and visibility estimation in each object, which is called a reusable radiosity object. Whenever a scene updates, the radiosity algorithm looks up the prestored information in each object, thus speeds up by two orders of magnitude. Besides, solution time based on cluster representatives is linear to the number of objects since each object is reusable, encapsulated with preprocessed data in every level of hierarchy. We also analyze the unregarded error on visibility estimation and propose a statistically optimal adaptive algorithm to maintain the same error for each link.

Keywords: Anisotropic visibility, Clustering, Hierarchical radiosity, Visibility error.

1. Introduction

Form factor calculation is always critical in radiosity. To speed up radiosity, we try to preprocess as much information needed for form factor computation as possible. The strategy is to save solution time at the cost of more storage space. There are two kinds of data, the effective area such as used in hemi-sphere method and the visibility between patches, can be preprocessed and stored in each object to significantly reduce form factor calculation overhead. We divide every object into 12 by 12 viewing directions around a sphere and store above two data for each corresponding direction. Whenever a form factor computation between two objects is needed, we find a suitable direction by table look-up among these 144 directions to retrieve information respectively. Moreover, whenever an object occludes others, the direction of a visibility testing ray is also taken as a reference among 144 directions to retrieve visibility hit probability prestored in that object. The advantage is to apply a table look-up method consistently in run time, and all objects with preprocessed data are reusable in any other application scenes.

This section introduces some fundamental concepts and experienced readers may skip. Then two issues in run time look-up are given first. We describe form factor estimation in section 2 and visibility estimation in section 3. The preprocessed parts are in section 4 and 5.

Form Factor and N-body Problem

The principle of hierarchical radiosity (HR) is inherited from Appel's algorithm for solving N-body problem [APPE 85]. Similar to the solution in N-body problem, i.e., the center of mass as a representative for a distant collection of nearby bodies, the acceleration of radiosity can be compared to that of N-body problem. In the original HR, Hanrahan used a disk with equivalent area as the representative for each element [HANR 91] because the form factor estimation by two disks is easy to obtain (see figure 3(a)). The form factor from a differential area to a disk shown in figure 1 can be approximated by the following equation [WALL 89] as figure 1,

$$F_{dA_j \to A} = \frac{\cos\theta_1 \cos\theta_2 r^2}{(h^2 + r^2)} \qquad (1)$$

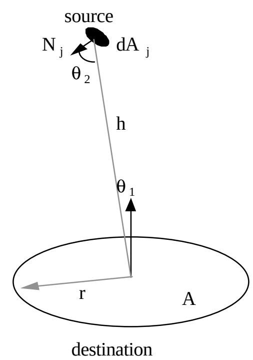


Figure 1. Configuration of form factor computation for differential area dA_j to disk A.

Consider the basic equation of the form factor,

$$F_{dA_i \to A_j} = \frac{\cos\theta_i \cos\theta_j}{s^2} dA_j dA_i \qquad (2)$$

In figure 2 The energy received by patch *dA* is equivalent to that by patch *dAcos* θ. This concept is appropriately proved by unit sphere method[MODE 93], which is one of the popular method for calculating form factor used in heat engineering.

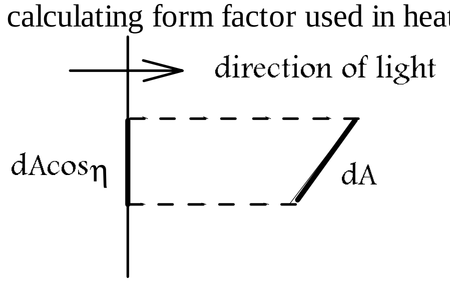


Figure 2. The effective area related to a direction of light.

Since the patches shared the same projected area have the same form factor, we can calculate the equivalent patch by projecting the patches in the cluster onto the seeing plane. As the projected patch may be complicated, in figure 3(b), we use a disk with equivalent area as the representative to estimate its form factor. The premise is that the distance between the source and the destination must be far enough. The criterion of whether it is far enough will be discussed in section 2. Only the area for a given direction should be recorded in the object. Therefore, we use the point with angular equivalent area distribution as the representative of each cluster. Form factor calculation then can be replaced by fast table look-up with interpolation. Section 2 will give detailed description of the form factor estimation in run time, and section 4 describes its respective preprocess effort.

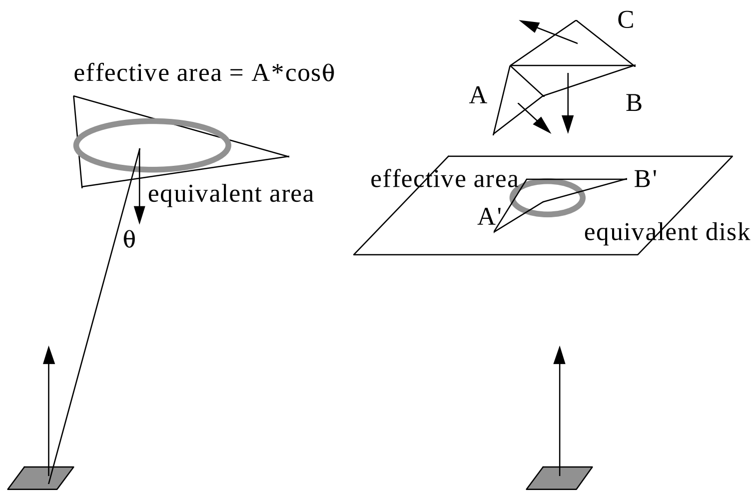


Figure 3. (a) Hanrahan's representative scheme (b) Our representative scheme

Visibility Acceleration

Visibility is also critical in the form factor calculation. It often wastes too much time on traversing trivial objects such as buttons on a telephone and the feature of a sculpture. Sillion proposed the feature-base error metric (FEBM) [SILL 95] to claim that it is unnecessary to estimate the shadows resulted from small objects. The philosophy of our visibility estimation is much the same as that of N-body problem. If a occluder between two patches (figure 6(a)) is small enough and a visibility testing ray hits the bounding volume of that occluder, a hit probability prestored in that occluder is used to determine the visibility. To determine the reasonable representative scattering volume of a occluder, our algorithm will traverse the clustering hierarchy and find a suitable volume to apply the statistical method. Therefore, when a occluder is processed, a suitable scattering volume replaces the original hierarchy to avoid redundant traversing on those detail small objects. The angular hit probability of each level of scattering volume is preprocessed to accelerate the visibility estimation. This algorithm is statistically correct and reduces the complexity significantly. Again, visibility determination can be replaced by table look-up with interpolation. Combined with the table look-up for angular equivalent area, we obtained two orders of magnitude speed-up in form factor calculation. Estimation in run time is detailed in section 3 and the preprocessed part is in section 5.

2. Acceleration of Form Factor Estimation

Figure 4 demonstrates the configuration of form factor estimation. To use the effective area as a representative, it is required that the distance between clusters over the radius of the cluster must be larger than a given threshold. The five-time rule provides a simple threshold and has been used in illumination engineering over one century. Thus, we first test if the geometrical constraints are satisfied. If not, we subdivide the larger cluster and repeat the procedure. Then we calculate the vector **d**, from source to the receiver in global coordinate system. To look up the effective area, we transform **d** to **d**', the vector in local reference frame of cluster 2. Vector **d**' is used to look up the effective area of cluster 2 for the interaction with cluster 1. In the same way, the effective area of cluster 1 can be obtained. We first store the area for the basis directions, in our case, 12%12 angular directions in a sphere were used. Then we can use the bivariate interpolation to get the effective area for any given direction. Finally, the form factor calculation between two disks is used to estimate the form factor between them. Figure 5 shows the configuration to calculate the analytical form factor between two parallel coaxial disks of radius R_1 and R_2. It can be easily proved using inside-sphere method [MODE 93].

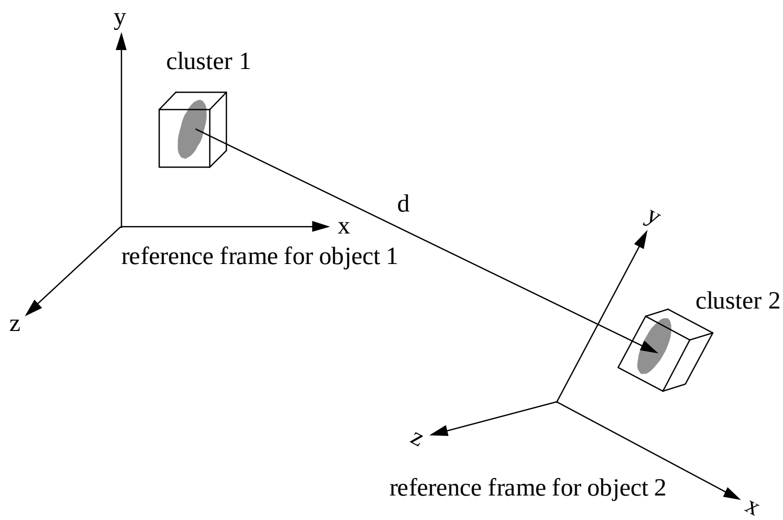
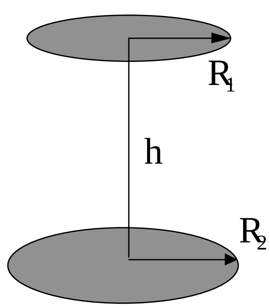


Figure 4. Configuration to estimate the form factor between two clusters.



$$R_1 = \frac{r_1}{h} \quad R_2 = \frac{r_2}{h}$$

$$X = 1 + \frac{1 + R_2^2}{R_1^2}$$

$$F_{1-2} = \frac{1}{2}\left[X - \sqrt{X^2 - 4\left(\frac{R_2}{R_1}\right)^2} \right]$$

Figure 5. The configuration to estimate the form factor of two coaxial disks.

3. Adaptive Visibility Estimation Algorithm

In figure 6, an arbitrary point on S shoots a ray R_i to an arbitrary point on D. R_i is defined as 1 if no occluder on the ray and 0 otherwise. The visibility can be defined as

$$Y = \frac{1}{m}\sum_{i=1}^{m} R_i \qquad (3)$$

where Y is a binomial random variable and m is the number of trials. Expected value and variance of random variable with binomial distribution is shown in equation 4,

$$E(Y) = \bar{v}$$
$$V(Y) = \sigma^2 = \frac{\bar{v}(1-\bar{v})}{m} \qquad (4)$$

where $\bar{v}$ is the quantity that the process tries to estimate the exact visibility between S and D.

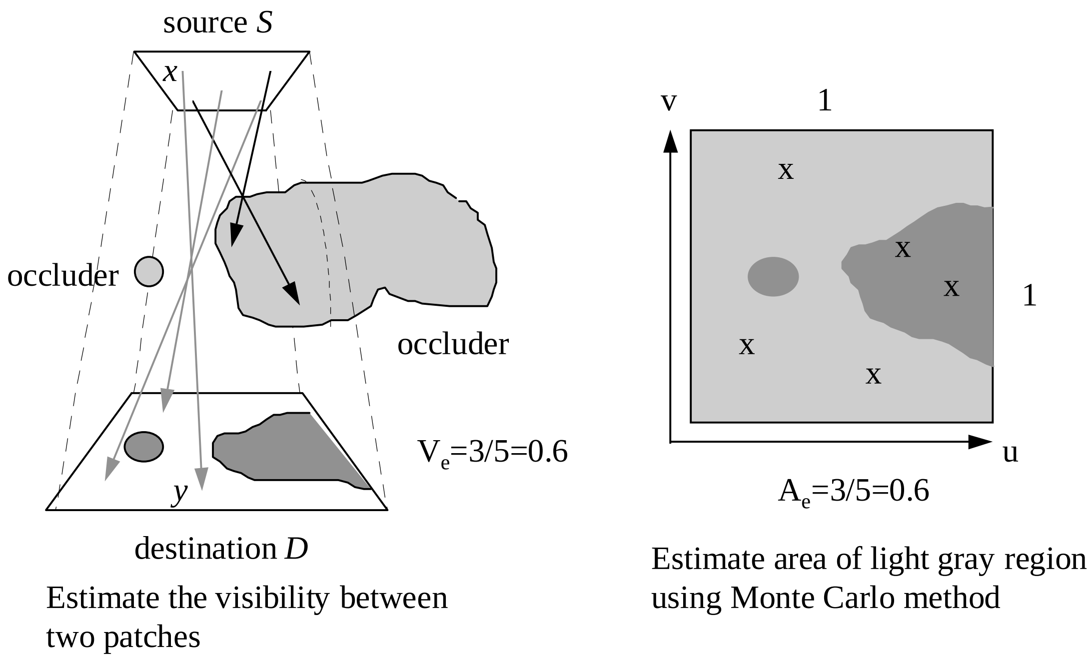


Figure 6. The analogy of visibility estimation and area estimation using Monte Carlo analysis.

The adaptive algorithm initially shoots 16 rays from randomly selected points on S to those randomly selected on D and exam if $V(Y)$ is small enough. The algorithm will shoot successively 25, 36, ..., 144 rays until $V(Y)$ is smaller than a threshold. The procedure below illustrates how this can be achieved.

```
float VisibilityEstimationWithStandardDeviation(float σ)  // σ is the tolerable standard deviation
begin
  repeat
      get the number of necessary trials at next iteration m;        // it can be predefined
      do m more experiments and then get the new estimation v;
      standard deviation=sqrt(v(1-v)/m);
  until (standard deviation<σ or number of total trials exceed the defined limit);
  return v;
end
```

Finally, we add the concept of feature-base error metric [SILL 95] into the visibility estimation. When the volume is fine enough or the potential missing area (volume's projected area*(1-hit_probability)) is small enough, we use a dice with hit probability to determine if the ray hit the object. There are many clusters with hit probability 1.0 since we project all the object, not just primitives in cluster. Therefore, we can immediately return the result, INVISIBLE. Equivalently, we use the filtered version when the approximation is good enough. Another efficient approach is to return the hit probability without further testing the object when the volume is too fine or missing area is tolerable. Therefore, the feature-base error metric (FBEM) error should be low.

4. Clustering and Angular Equivalent Area Preprocessing for Table Look-up

We define a cluster as a mass of triangles. Therefore, the hierarchy of the scene can be illustrated in figure 7. Note that the cluster may contain only one triangle, that is to say, a triangle is a cluster itself. The objects are specified by the user and every object is precompiled using model compiler. For each object, the first step of model compiling is to build its HBV tree. The HBV tree is used to accelerate the ray query.

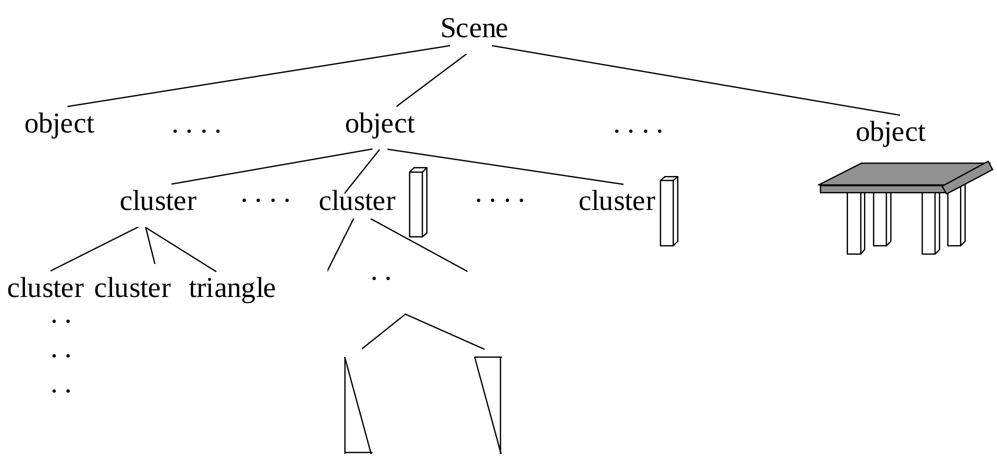


Figure 7. Hierarchy of the scene. Scene is composed with objects. Object is also a cluster itself. A cluster is collection of triangles and contains at least one triangle. Children of cluster are also clusters. The cluster containing only one triangle is called leaf.

Initially, each triangle forms a cluster itself. The next step of clustering is to group the similar clusters into a larger one. The similarity of clusters is defined according to the factors that affect form factor computation. It includes proximity, orientation, reflectivity, aspect ratio and homogeneity in size.

Then, we calculate the angular equivalent area distribution for each cluster as its representative. The spherical inverse mapping [HAIN 89] is used to convert the polar coordinate system into the planar coordinate system as figure 8. We uniformly subdivide the u-v space in figure 8 into 12%12 blocks, each corresponds to a angular equivalent area.

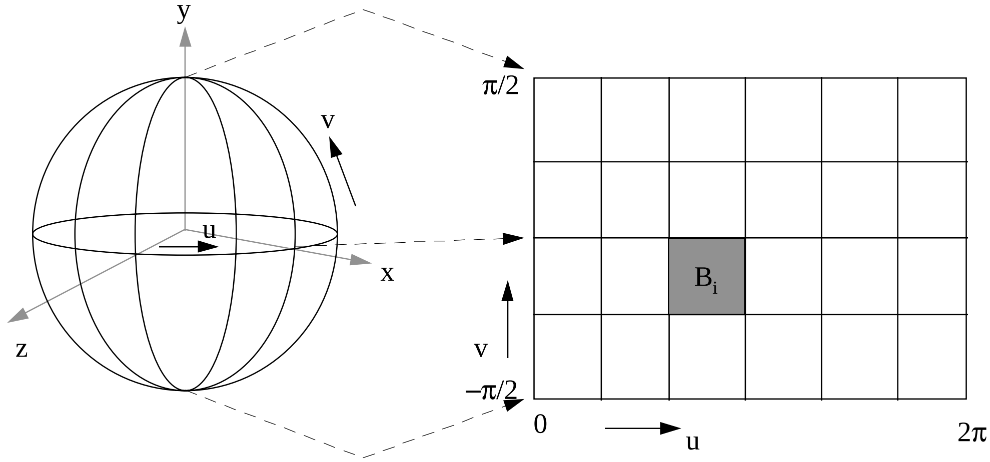


Figure 8. Spherical inverse mapping [HAIN 89]. One thing to note is that u-axis corresponds to the longitude ranged from 0 to 2π and v-axis corresponds to the latitude ranged from $-\pi/2$ to $\pi/2$.

5. Visibility Preprocessing for Table Look-up

We describe an algorithm to construct the multi-resolution visibility representative of objects. This algorithm follows two concepts, HBV and anisotropic scattering volume.

First, the bounding volume hierarchy of object is considered. We take the hierarchy bounding volume as an approximation of the object. It is similar to construct an object using blocks. If one uses fine blocks, one can construct an object better than using coarse blocks. However, the objects constructed with coarse and fine blocks look almost the same when one sees them at a long distance. Therefore, HBV provides a not bad multi-resolution hierarchy of the object.

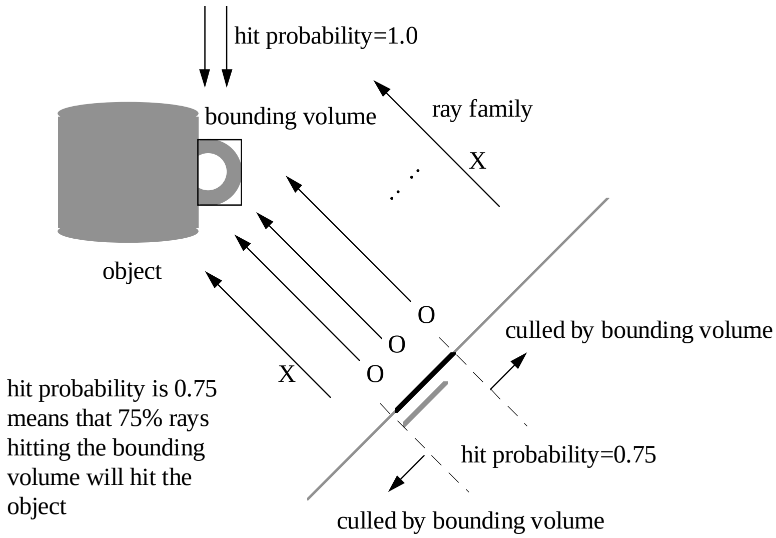


Figure 9. The configuration of calculating hit probability as extinction coefficient, which shows that the hit probability varies as the angular hit direction changes. An O means the ray hit the volume and an X misses the volume. All the rays missing the volume are culled by the HBV test.

Secondly, we use extinction coefficient for each volume to avoid getting trap into the small features of the object. To break the isotropic assumption, we calculate the angular extinction coefficient distribution. For calculating the angular extinction coefficient, we have two parameters, longitude and latitude. That is, we have a family of rays with the same direction and different origins. The extinction coefficient of the volume at given direction is defined to be the conditional probability that the family of rays hit the object given they hit the bounding volume. Figure 9 shows the configuration of calculating hit probability. The computation of the angular hit probability is similar to the procedure used to calculating the angular effective area in section 4. One thing to note is that not only the primitives in the cluster but all primitives in an object are projected.

6. Results

A model compiler is built on an SGI Indigo^2 Extreme graphics workstation. Our test case consists of twelve objects in one room (color plate 5) and is compiled using the model compiler. The preprocessing time spent for the objects ranges from about one hour in the case of Beethoven to several minutes for the chair model. Total time for all objects is nearly four hours. However, the model compiling time should be taken as the modeling time since the object files are reusable.

6.1 Results of Adaptive Optimal Visibility Algorithm

To test the performance of adaptive visibility algorithm, an experiment has been conducted. As a comparison, we estimate the visibility by shooting fixed number of rays or adaptive number of rays. The estimation time using fixed 256%256 rays is used as a reference. Then, we compare the result of different algorithms against the reference. We test them with two models, a ball and a chair. Table 1 shows the results with two measures: root mean square (RMS) error and signal to noise ratio (SNR) in picture quality. The comparison reveals that the adaptive algorithm can achieve high accuracy with less rays.

methods	fixed 16	fixed 64	fixed 81	fixed 144	**adaptive**	fixed 256
number of rays	4096	16384	20736	36864	8764	65536
RMS error	0.029937	0.019598	0.017158	0.014656	0.014777	reference
SNR	28.58	32.26	33.41	34.78	34.71	reference

N=16 for the ball model

methods	fixed 16	fixed 64	fixed 81	fixed 144	**adaptive**	fixed 256
number of rays	16384	65536	82944	147456	39246	262144
RMS error	0.035836	0.021453	0.017146	0.015403	0.016318	reference
SNR	28.03	32.48	34.43	35.36	34.86	reference

N=32 for the chair model

Table 1. Comparison of adaptive visibility estimation algorithm and original algorithm.

6.2 Results of Reusable Radiosity Object Method

We compare the original hierarchical and our reusable radiosity object method on the model 'readingroom'(color plate 1 and 2). The total elapsed time is 99.28 seconds on SUN Sparc-10 workstation with 32 MB memory. The detailed comparisons are listed below.

algorithm	timing (sec)	resulted triangles	resulted links
hierarchical	7693.33	6550	419614
reusable radiosity object method	99.24	6199	42952

Table 2. Comparisons between hierarchical radiosity and reusable radiosity object method, using a model in color plate 3 and 4.

For further testing of our reusable radiosity object method, models shown in color plate 5 are used and results in color plate 3 and 4.

7. Conclusions

In this paper, we demonstrate the feasibility of reusable radiosity objects, from which the solution time of radiosity is greatly reduced by two orders of magnitude.

We first get rid of the patch-to-patch form factor calculation overhead by grouping patches into clusters, then solve this problem using the principle of N-body problem with a rule of thumb, the five-time rule. Both the effective area and the visibility problems in form factor computation are solved based on the same concept of N-body problem. Furthermore, the ways of representing these two important data are consistent, prestored in 12 by 12 directions, and encapsulated in each cluster. These objects can be inserted, deleted or moved in any other scene very conveniently and efficiently.

A speed-up by two orders of magnitude in radiosity can be easily achieved because table look-up is much faster. Significantly more storage space is needed for preprocessed results. However, we think it is worthwhile since the storage costs less and less.

We also propose an adaptive algorithm to maintain the same visibility estimation error for each link. A multi-resolution visibility hierarchy is built for faster but statistically accurate visibility. A statistically optimal adaptive approach can guarantee an acceptable shadow effect and costs fewer testing rays.

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