Realistic Rendering and Computer Aided Lighting Design in Architecture.

I Fasse
J C Paul

CNRS/INRIA/INPL
University of Nancy.
INRIA – BP 101 F-54602
Villers-les-Nancy Cedex
FRANCE

This paper presents an application of realistic rendering to computer aided design in architecture. The application concerns lighting design of buildings. We describe a library of algorithms which allows the simulation of the light sources emittance, surfaces reflectance/transmittance, and light propagation laws. Our general algorithm can compute a physically based simulation of illumination in complex geometric models and offers the capability to change the inputs without recalculating the entire global physical solution. Since the solution is view independent, hardware graphic accelerations are then used to generate the images. Two industrial *experimentations have proved that our system can help designers to evaluate small iterations in the design, as well as compare global alternative solutions. Therefore, design quality improvement can be obtained while saving the costly full scale trials that are necessary when conventional methods are used.*

Keywords: computer aided design, computer graphics, synthesis images, architectural design, lighting engineering.

1 Introduction

Architectural lighting design, especially outdoor lighting design of architectural prestigious sites is a complicated work. To underline the architectural composition as well as take account of each detail, the management of a complex lighting system which can be composed of thousands of sources is required. Since rendering algorithms can provide realistic synthesis images now, we proposed to develop a graphic simulation software able to aid the designer to visualise a lighting project at its different design steps. We describe here a library of programs which allows the simulation of light sources emittance, surfaces reflectance/ transmittance, and light propagation laws. After a discussion about the lighting design (2), we present an overview of the software which has been developed for this kind of application (3). We then present, the main features of the general rendering algorithm. This algorithm computes a physically based simulation of the global illumination of the scene to be rendered (4). It allows us to calculate the light energy transfers between surfaces, even in complex geometric models, and with any spectral distribution (5). Moreover, the algorithm offers the capability to change the inputs without recalculating the entire solution (6). Finally, since the solution is view independent, hardware graphic accelerations are then used to generate images (7). As an illustration, a design process is presented, and results are discussed (8). Lastly, we conclude and present future work directions (9).

2 Illumination design

The illumination design process of building illumination, must be considered as an iterative and complicated process which yields to architectural, technical and physical problems. The example of the illumination of buildings like the "Cour Carree" of the Louvre Museum gives us a good illustration. The Louvre Museum is a prestigious architectural site, related to the architecture of the “French Renaissance”. The “Cour Carree”, primarily designed by Pierre Lescot in the reign of Francois 1er, is unique by its dimension and the homogeneity of its architecture. This square space is composed of three identical facades. Only the West aisle, giving access to the 'Cour Napoleon', differs in its style by the presence of low reliefs at the Attica and by the raised level of its central pavilion called 'Pavilion de l'horloge". For the "Cour Carree” illumination, early main goals were:

(1) to highlight the singularities of each floor, in particular the Italian richness of the Attica of the West aisle as well as the classicism of the false ground floor gallery,

(2) to respect the rhythm given by the vertical sequence of the double Corinthian columns,

(3) to highlight the low reliefs, garlands and friezes of the entablature, as well as the characters and ornaments of the Attica, without perturbing by shadowing effects the architectural lay-out.

2.1 A complicated work

Lighting such a prestigious architectural monument as the Cour Carree required much design work and costly full scale tests. This is related to the different problems or constraints encountered, depending on the light sources characteristics:

(a) the size, positioning and fixation of the different lighting systems must not disturb or damage the architecture of the facades,

(b) the light source orientation, based on the spatial intensity distribution, must be precisley determined, in order to avoid non-desired lighting projection effects,

(c) the light sources spectrums must guarantee a perfect rendering of the colour of the different materials or on the different space observing position:

(d) the global lighting design must be adapted to the different viewpoint locations according to the space organisation,

(e) direct light source visualisation and parasite glaring effects due to possible specular reflections, have to be avoided.

Concerning the "Cour Carree", the main difficulty has certainly been the imposed figure which consisted in obtaining a luminous rendering close to daylight effects, while respecting the will to enhance the architectural rhythm and particularities of each facade.

Artificial lighting has the feature of being able to present an other aspect of architecture, light coming from below gives a very different aspect from that of sky light. Artificial light develops volumes, stretches shadows and thus gives a magical atmosphere to architectural sites. However in the case of the Louvre Museum, such a lighting would destroy the architectural image of this famous worldreknown place. Commonly used lighting systems couldn't fit in this case:

(a) light sources fixed on the ground floor and cornices, illuminating the facades in an upward direction would tend to inverse the architecture, creating undesired artificial shadows,

(b) lighting facades from the other rooftops, in such a square space, would invariably dazzle the spectator, and create a lighting roof to this open space. For a conventional method, costly full scale trials remain the only worthwhile way to handle and circumvent (partially) all these technical and conceptual problems. Our idea is that realistic rendering could be applied, as a simulation tool, to aid for these kinds of problems.

The main advantage of the computer simulation is to be able to clearly identify these different problems, as well as to simulate step by step the whole lighting process. Where light designers couldn't handle such a lighting complexity (thousands of light sources involved in the whole lighting project), our idea was that the computer could deal with a multiplicity of architectural, technical and physical characteristics and so allow us to refine the whole lighting project on the base of intermediate solutions.

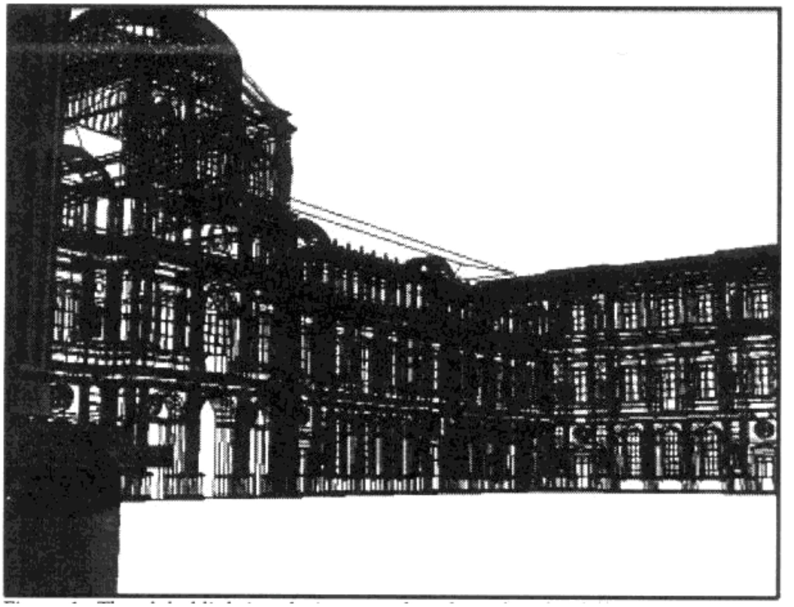

Figure 1: I he global lighting design must be adapted to the different positions of the visitors (different bottom-up viewing angles) and the 4 main paths to the "Cour Carree.

2.2 *An iterative process*

The solution for the "Cour Carree" illumination was finally to create a new lighting system allowing an ambient top-down lighting compatible with the daylight vision of the facade, reinforced punctually by bottom-up sources of low intensities to circumvent some deficiencies or to highlight some elements. To come to this solution, many full scale tests would have been Tout on different parts of the facades. In fact, every lighting effect has to be checked and each light source position and orientation then redefined. First, the ambient lighting system has been regulated, then the light sources highlighting the columns and bays have been turned on, and finally punctual light sources highlighting architectural details or attenuating shadows have to be set. Sources have been added, others removed or slightly moved, lamp intensifies adjusted, some turned on, some turned off, to finally lead to different local lighting solutions. For the "Cour Carree", to guarantee a perfect rendering of the colour of the stone and to obtain a top-down effect, the linear lighting system has been created from small bar reflectors using small halogen lamps. The bottom-up light sources are small round projectors made of dichroic halogen lamps. The capacity of all of these light sources (incandescent lamp intensities can be easily regulated) is to render various lighting atmospheres for each specific use of the space.

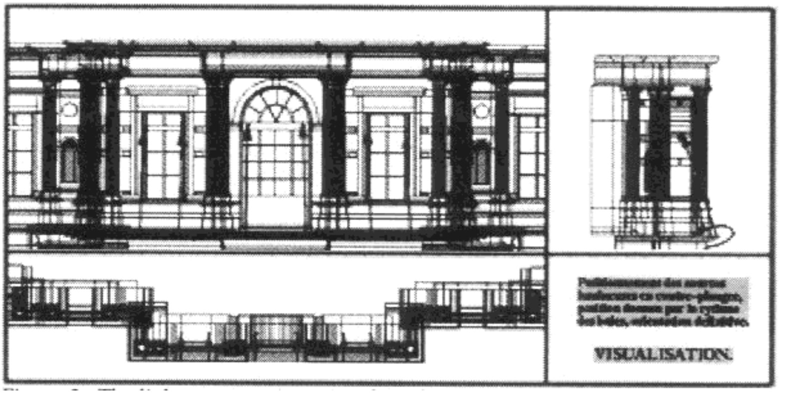

Figure 2: I he light source orientation, based on the intensity spatial distribution, must be precisely determined.

3 Software overview

Lighting simulation in architecture requires the creation of an extremely detailed 3D model. The architectural elements are often composed of complex forms. In the Louvre, for example, modelling was based on logical instructions and geometric constraints propagation. Moreover, as the number of geometric primitives is very large, modelling was based on a hierarchical data structure, in order to simplify the handling of the dataset. This data structure allowed us to group architectural elements into:

(a) alternative subsets of elements (bays, floors, assembly of elements according to axes of symmetry).

(b) simplified subsets (to represent the first floor of the 'Aile Sully, for instance, without the Corinthian columns, or according to a canonised representation of these columns).

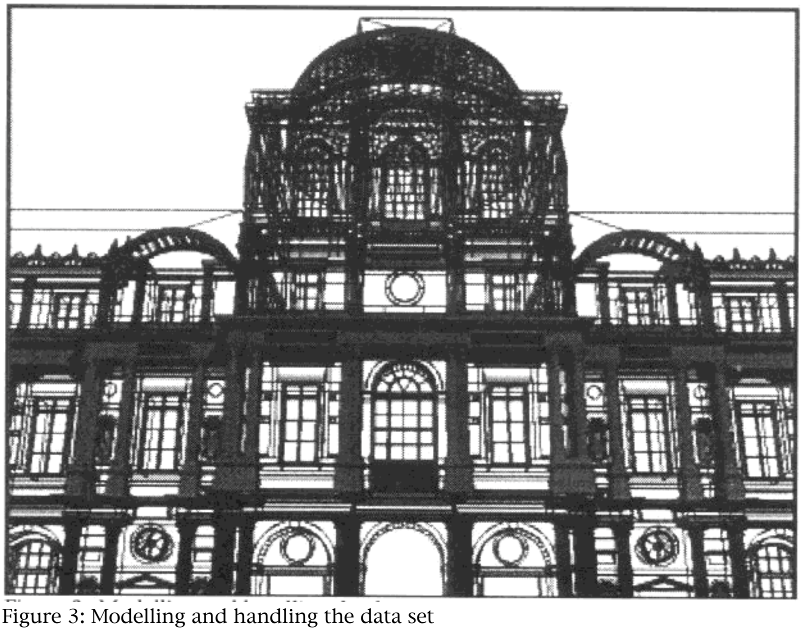

Figure 3: Modelling and handling the data set

Moreover such a specific data structure will facilitate the exact location of light sources in the 3D environment and allow better control of the whole lighting network. The aims of the simulation software were to help the designer at the first step of design to select light sources specified by their spectrum and spatial intensity distribution, test their effect on different materials applied to spherical or planar surfaces, define light sources and place them in the 3D model according to a 3D position and orientation. For the first step of the design, efficient algorithms allow us to rapidly visualise light source positions, the spotlight field angles, beam overlaps but also allow us to rapidly detect parasite effects due to specular reflections on windows for example. Moreover, they must give us primary ideas of the lighting project on parts or on the whole data base of the building. At this stage of the lighting process, direct illumination calculations are sufficient to rapidly render the major lighting assumptions that are an overview of the light and shadow repartitions and volume perceptions.

Then, in order to appreciate the subtle nuances of illumination, the simulation must be more accurately physically based, and not only take account light emanating from light sources but also light reflected on every surface. At this stage of the design, the designer needs to verify with a high degree of accuracy, whether a given brightness has been preserved, or if shadows have been attenuated, before adding or changing a light source, for example.

Finally, according to the iterative process of design, the software allows the designer to interact directly with the system, that is, to change light source attributes or locations, to generate images from several view points, and to offer walk-through capabilities. The resulting images can be either a photo-realistic representation of these simulations, or a transcription of numerical calculations as intensity and lux calculations. These two kinds of representations allow the light designer to check and verify his lighting assumptions. Realistic images will accurately transcript the lighting effects while iso-lux false colour images will give him an idea of energy values used to verify if main lighting rules have been respected. For comfort and security, the luminance values must not exceed a certain level. Also, an illumination with the same luminance on various facades cancels the Perception of space and volume. Glaring effects can also be generated when the intensity of light sources is too high.

4 Modelling light

4.1 Light sources emittance

The assumption of point light sources, which is commonly used in image synthesis, cannot be accepted in the lighting design, application, since sophisticated light sources emittance has to be simulated (except when small light sources are used, such as dichroic lamps). In order to compute the direct illumination of an extended light source (that is a linear or a surfacique one) in a given environment, we assume that the spatial energy distribution is known at each point of the interface (the surface from which the light leaves the source) of this light source.

In order to take into account arbitrary distributions, we model the geometry of the light sources (reflector, lamp) and simulate the luminous energy transfers occuring in the source [DP95]. This method leads to the solution of the radiance equation in a spatial subdomain (inside the source), and then computes the energy distribution of an interface. This interface corresponds either to the real optic of the light or a virtual one, and is specified by its reflectance and its transmittance. The problem then consists of solving the following equation, at every point of the optic of the light and at the virtual one:

$$L_\lambda(x,\omega_{x_{out}}) = L^0_\lambda(x,\omega_{x_{out}}) + \int_{\Gamma_s \cup \mu_s} (\rho_\lambda(x,\omega_{x_{in}},\omega_{x_{out}}) + \tau_\lambda(x,\omega_{x_{in}},\omega_{x_{out}})) L_\lambda(x_s,\omega_{x_{s_{out}}}) g(x_s,x) dx_s \quad (1)$$

where :

- Γ_s : the set of surfaces defining the source's interior (reflector, lamp ...),
- L^0_λ : the self-emitted radiance leaving x in direction $\omega_{x_{out}}$,
- τ_λ : the bidirectional transmittance function at point x,
- g : the geometrical term between x_s and x.

In the case where the interface is virtual, the properties of this interface at a point x_s are given by :

$$\rho_\lambda(x_s,\omega_{x_{s_{in}}},\omega_{x_{s_{out}}}) = 0$$

$$\tau_\lambda(x_s,\omega_{x_{s_{in}}},\omega_{x_{s_{out}}}) = \begin{cases} 1 & \text{if} \quad \omega_{x_{s_{in}}} = -\omega_{x_{s_{out}}} \\ 0 & \text{else} \end{cases}$$

In order to compute the solution of the equation (1), we use the finite element method with this projection formula :

$$L_\lambda(x,\omega) = \sum_j \sum_k \alpha_{\lambda,jk} \gamma_j(x) \psi_k(\omega) \quad (2)$$

where :

- $\gamma_j(x)$: a basis function depending on the position
- $\psi_k(\omega)$: a basis function depending on the direction.

Using this projection formula, we obtain a linear system of equations from equation equation (1) that permits us to compute the coefficients that appear in equation (2) at each point of the mesh.

When these coefficients are defined, we can compute the energy distribution at each point of the interface, and use this energy distribution to compute the direct light energy arriving on a surface.

4.2 Surface reflectance/transmittance

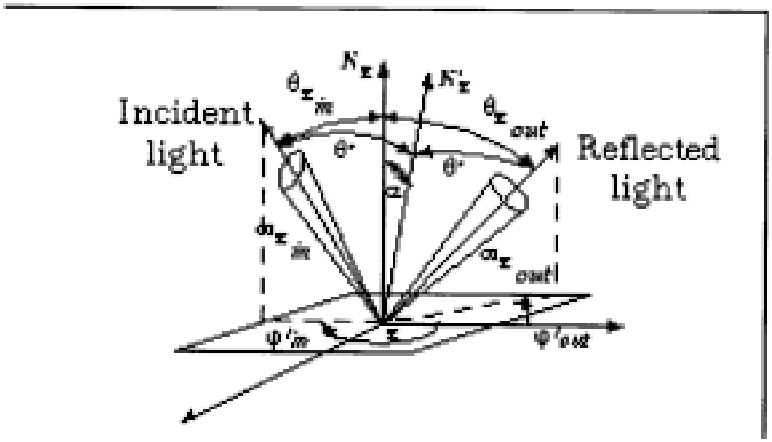

Figure 4 Bidirectional reflection distributions function.

The properties of the light reflected or transmitted by a material are affected by its sub-atomic structure. One part of the light ray is directly reflected by the surface of the material. The other part penetrates the material and propagates within the top layers before being re-emitted. The resulting reflected /transmitted light energy has therefore a spatial and a spectral distribution depending on the incoming light rays direction and spectral characteristics, as well as the material characteristics.

These distributions are quantified by the bidirectional reflectance/ transmittance distribution function (brdf/btdf), which is defined by:

$$\rho_\lambda(x, \omega_{x_{in}}, \omega_{x_{out}}) = \frac{L(x, \omega_{x_{out}})}{L(x, \omega_{x_{in}}) \cos\theta_{x_{in}} d\omega_{x_{in}}} \qquad (3)$$

where :

$L(x, \omega_{x_{out}})$: the reflected/transmitted radiance in the direction $(x, \omega_{x_{out}})$,

$L(x, \omega_{x_{in}}) \cos\theta_{x_{in}} d\omega_{x_{in}}$: the differential irradiance from the incident direction $(x, \omega_{x_{in}})$.

He et al. proposed a brdf model based on the electromagnetic waves propagation laws, where the brdf is define by:

$$\rho_\lambda = \rho_{\lambda,d} + \rho_{\lambda,sp} + \rho_{\lambda,sl} \qquad (4)$$

where :

$\rho_{\lambda,d}$: the diffuse component,

$\rho_{\lambda,sp}$: the specular peak component,

$\rho_{\lambda,sl}$: the specular lobe component.

The roughness of the material affects both the specular lobe component and the specular peak component. As the roughness decreases, the specular lobe decreases too, and the specular peak tends to dominate. For very small roughnesses, the lobe is small in comparison with the peak, and the specular peak component is represented by a delta function. Otherwise, the lobe is dominant, and is accurately computed by an infinite sum of exponential terms. The diffuse term is the result of sub-surface interactions, and is hardly calculable on physical basis. However, an easy approximation based on Fresnels reflection model is usually used.

Some of the main problems m using these theoretical models for a real complex case of global illumination are the storage and computing costs (for a complex scene which can contain millions of polygons, themselves meshed in small elements (patches), the luminance has to be stored for each element and for every direction).

In order to take account the radiance properties of materials of existing buildings, Ward [War92] proposed a system based on reflectance measurements. The calculation of the characteristics of a reflected ray are quite fast, but the method requires the storage of the values of the luminance for each patch using Gaussian functions:

$$\rho_\lambda(x, \omega_{x_{in}}, \omega_{x_{out}}) = \frac{\rho_{\lambda,d}}{\pi} + \rho_{\lambda,s} \cdot \frac{1}{\sqrt{\cos\theta_{x_{in}} \cos\theta_{x_{out}}}} \frac{\exp(-\tan^2(\alpha/\sigma_a^2))}{4\pi\sigma_a^2} \qquad (5)$$

where :

σ_a : the standard deviation (RMS) of the surface slope,

$\rho_{\lambda,d}, \rho_{\lambda,s}$: the diffuse and specular reflectance coefficients,

α : the angle between the surface normal and the bisector of the viewing and the lighting directions.

Even a few parameters still requires still significant storage cost, when the geometrical model is very large. So, in general we only consider the diffuse component (Fresnel Factor) of the material reflectance. This is not detrimental for the design assistance of Classical Architecture but is an important restriction with regards to the realistic rendering of materials.

4.3 Modelling the light propagation

The propagation of light within an environment, in the absence of participatory media, can be formulated by the radiance equation:

$$L_\lambda(x', \omega_{x'_{out}}) = L_\lambda^e(x', \omega_{x'_{out}}) + \int_{\omega_{x'_{in}}} \rho_\lambda(x', \omega_{x'_{in}}, \omega_{x'_{out}}) L_\lambda(x, \omega_{x'_{in}}) \cos\theta'_{in} d\omega'_{in} \quad (6)$$

where :

$L_\lambda(x', \omega_{x'_{out}})$: the radiance leaving x' along $\omega_{x'_{out}}$,
$L_\lambda^e(x', \omega_{x'_{out}})$: the self emittance radiance leaving x' along $\omega_{x'_{in}}$,
$L_\lambda(x, \omega_{x'_{in}})$: the radiance leaving x along $\omega_{x'_{in}}$,
$\rho_\lambda(x', \omega_{x'_{in}}, \omega_{x'_{out}})$: the bidirectional reflectance distribution function,
$\omega_{x'_{in}}$ and $\omega_{x'_{out}}$: the solid angle subtended at point x' by A and by A'' respectively,

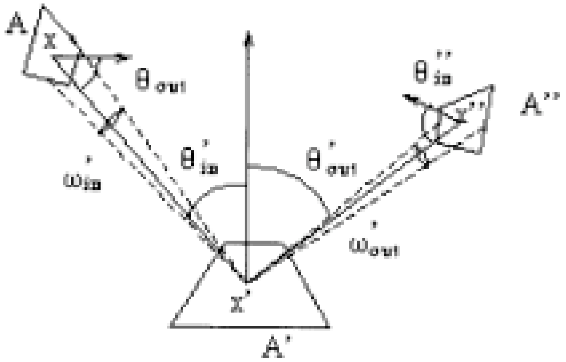

Figure 5 : Radiance

We may reparametrize this equation to yield:

$$L_\lambda(x', x'') = L_\lambda^e(x', x'') + \int_A \rho_\lambda(x, x', x'') L_\lambda(x, x') G(x, x') dx \quad (7)$$

where :

$$G(x, x') dx = \frac{\cos\theta_{out} \cos\theta'_{in}}{|x - x'|^2} v(x, x') \quad (8)$$

where :

$v(x, x')$: is 1 if points x and x' are mutually visible and 0 otherwise.

This equation can be significantly simplified if we assume that all surfaces within the environment are perfectly lambertian diffuse reflectors. Thus, the brdf is independent of the incoming and outgoing directions and can be taken out from under the integral. More importantly, the outgoing radiance for a lambertian surface is the same in all directions. This leads to even more dramatic simplification and allows to rewrite the equation as follows:

$$b_\lambda(x') = b_\lambda(x') + \rho_d(x') \int_A b(x) G(x, x') d(x) \quad (9)$$

This equation which is known as the Radiosity Equation, expresses the conservation of light energy at all points in space.

5 Computing radiosity

5.1 Computing radiosity in complex environments

Computing a full and exact solution to the Radiosity Equation requires either finding the exact fonctionnal form of the radiosity across each surface, or computing the radiosity values for an infinite number of surface points. In order to compute an appropriate discrete solution, we mesh the geometrical model and then project the radiosity function (b(x)) using a projection method.

The problem can be then reformulated as following :

$$b(x) \simeq \hat{b}(x) = \sum_{i=1}^{n} b_i N_i(x)$$

where $\hat{b}(x)$ is the approximate solution of the radiosity function.

Independent of the basis set $(N_i(x))$ chosen (constant basis, polynomial basis), the approximation scheme yields always to a linear system of the form :

$$b_i = b_i^e + \sum_{i=1}^{N} k_{ij} b_j, \quad \text{where } k_{ij} = \rho_i G_{ij}$$

N is the number of mesh elements.
Written in its compact form, the linear system become :

$$(M - F)\,\vec{b} = \vec{b^e}$$

If the radiosity function is approximated using constant basis functions, area terms can be divided out, and M is simply the identity matrix. Thus, the linear system of equations looks like:

$$(I - F)\,\vec{b} = \vec{b^e}$$

Various iterative methods can be used to solve the linear system of equations. However, since each iteration takes 0(n) operations, the full iteration takes 0(nxn). Moreover, the number of interactions to compute, requires costly form factor and visibility calculations.

Managing the computational complexity of the radiosity algorithm is therefore an important challenge, since architectural models are generally composed of millions of polygons. Fortunately, in most of the architectural models, only a small number of surfaces see each other. Therefore, using a global visibility algorithm can be an effective strategy for reducing the number of interactions needed to compute a radiosity solution. In such cases, the interaction matrix has many zero coefficients. If the location of these coefficients is known, then less form factors need to be computed. Teller and al. have described [TS91J, visibility algorithms that pre-process polygon databases in order to accelerate visibility determination during illumination calculations.

We have extended the visibility algorithm to various geometrical heuristics in respect of admissible partitioning rules. Assume an environment composed of n elements and decomposed into m subregions or sub-domains, an admissible partitioning P must satisfy the following criteria

1. $S = \cup_{i=1}^{m} \Omega_i$: must be satisfied to guarantee that all surfaces are taken into account.
2. minimal visibility between two sub-domains Ω_i and Ω_j if $i \neq j$. The minimal visibility ensures that the underlying form-factor matrix has a block structure where block zero coefficients are identified.

Then, admissible partitioning allows to sparse the interaction matrix and identify the non-zero interactions.

The matrix solution is computed with a Southwell relaxation method. This numerical solving method consists of computing each value of the radiosity values vector b by one column of the interaction matrix [I-F]. This method corresponds to the physical intuition of the shooting process described by Cohen in [CC WG88] . Taking advantage of a physically based heuristics, this method allows the computation of the matrix coefficients on the fly, and accelerates the convergence of the linear system.

5.2 Computing radiosity for any spectral distributions

Radiosity algorithms allow the computation of the interaction of light within an environment for any wavelength across the visible spectrum. Practically, conventional radiosity algorithm uses a set of samples at discrete wavelengths as the primary colour space [Mey88] . This involves selecting specific wavelengths at which to sample the reflection and emission spectrum, performing the radiosity solution at each sample wavelength and then reconstructing the spectrum, or directly converting them to CIE XYZ colour space, and then to monitor RGB. Meyers sampling method consists of using Gaussian quadratures for evaluating the integrals. However, since the colour matching functions are not strictly positive over the whole integration domain, the wavelength

samples are not always contained in this domain. Furthermore, the Gaussian quadrature method assumes that the spectrum to integrate is continuous. Consequently, for light source spectrums with emission peaks or materials with discontinuous spectrums, the colours calculated by this method are not correct. The only way to minimise the error is to use a large number of samples.

Another approach proposed by Peercy [Pee93], is to project both the spectral distribution of light sources and the reflectance of materials into a set of basis functions. This approach has a great advantage when dealing with rather smooth spectrums, because they can be approximated by a few basis functions and only small errors occur in the calculation of the tristimulus values. However, in the particular case of discontinuous spectrums, some problems may be encountered with his approach. The choice of the set of basis functions may not be adequate, can be very time consuming, and the errors in the calculation may dramatically grow since the least square method is used to find these functions.

The following method, detailed in [DMPC94], permits the handling of such spectrums. This approach is based on a pre-calculation, which allows the simplification of the integral as a simple weighted sum over a set of wavelength. The value of the integral is then given by:

$$\int_{visible\ domain} E(\lambda)W(\lambda)d\lambda \approx \sum_{i=0}^{n} H_i E(\lambda_i)$$

where :

- $E(\lambda)$: the spectral energy distribution,
- $W(\lambda)$: the weighting function (a colour matching function),
- λ_i : the sample wavelengths,
- H_i : the results of the pre-calculation.

The pre-calculation relies upon the segmentation of the wavelength domain which corresponds to visible light. This segmentation algorithm analyses the spectral energy distribution of the light sources (emittance) and the reflectance distribution of the materials used in the scene, in order to obtain a set of wavelength intervals Si over which the continuity constraint is respected. These intervals are obtained by building the set of wavelengths corresponding to the irregularities (characterised by a strong variation of the gradient of a spectral distribution). By sorting this set, we obtain the boundaries of the intervals Si. In order to reduce the number of samples over each interval, only the non-zero part of each interval are kept.

In order to minimise the errors, two integration techniques are used, depending on the interval. If the interval corresponds to an emission peak, that is, if its width is small (about 5 nm or 10 nm), the trapezoidal method is used. This is justified by the fact that the spectral data supplied by the manufacturers is in the order of or 10 nm. For the other cases, sharp variations do not exist in the spectrum, so the Gaussian quadrature method is used. This gives a better approximation with only a few sample points.

6 Controlling the simulation

In order to facilitate the exact location of the light sources in the virtual model, a specific data structure is used for both the geometric model and the lighting system. The environment is split into hierarchical subsets of primitives which are related to a local coordinate system. This makes further positioning of the light sources and the localisation of their aim much easier, since each of them is expressed in the appropriate local coordinate system.

Changing the radiosity inputs without recomputing the entire solution is then an important challenge to help the study of various lighting design versions, or to simulate dynamic lighting scripts. To overcome this problem, the light sources are linked together in different subsets to allow for a better control of the whole lighting network. Consequently, different sets of light sources can be connected to rheostats, for example to control separately the top-down and the bottom-up lighting system. Without such a model, it would be hardly possible for the designer to drive this many, light sources.

Once these light source groups are defined, the designer should be able to change the intensity of these groups, in order to visualise in short time an image of the new solution with the radiosity inter-reflections. One way to resolve this problem is to assume that:

1. the global network of light sources C is split into subsets $C_i, 1 \leq i \leq L$, with the restriction that $C_i \cap C_j = \emptyset$ if $i \neq j$.
2. the intensity of a group of light sources C_i varies linearly, that is : $e = \alpha e_{max}$, where e_{max} is the maximum intensity emitted by C_i.

Then, the radiosity solution $\vec{B}^k_{max}$ (associated with e_{max}) for each subset C_k is computed independently. So that, when the intensity of the subsets C_k varies by α_k respectively, the final radiosity solution $\vec{B}$ is a linear combination of $\vec{B}^k_{max}$:

$$\vec{B} = \sum_{k=1}^{L} \alpha_k \vec{B}^k_{max} \tag{10}$$

The proof of this equation is shown in [PDW95]. This means that no more radiosity iterations need to be performed, but a linear combination of the pre-computed solutions for the different light networks is enough to obtain an exact image of the new lighting design.

When the photometric attributes of a light source (intensity, spectral or spatial distribution, aim position) have to be changed, it is quite easy to update the radiosities in the scene [PSV9O] In this case, the only change to be made to the original radiosity method is to propagate to all the patches the difference of the energy emitted by this source. Furthermore, as the location of the source does not change, the visibility problem is not affected, so every visibility pre-process can be reused. The form-factors are affected only in the particular case of the modification of the aim. Even in this case, the new form-factors are updated in a short time, because the visibility does not change. In any case, the extra processing time required with this method corresponds to the time needed for propagating the energy of one source only. If the scene contains many sources, it is obvious that this method is much faster than beginning the radiosity process from scratch, which means reshooting all the light sources (Plates 1-2-3).

If the location of a light source changes, the form-factors between this source and some patches are modified, and the light energy shot toward a particular patch is also changed. Furthermore, this movement implies in most cases a change in the visibility of this source toward the scene, and if a visibility pre-process has been done, it can hardly be reused. In this case, the easiest way to update the radiosity of the scene is to switch off the light source, and to turn a new one on. Another way is to re-shoot its energy based on the form-factor changes, that is, to re-shoot the difference of the radiosity contribution from the old geometry versus the new one. Note that it corresponds to the incremental form-factor method proposed in [Che90], restricted here to the re-propagation of the emissivity of the light source. In the worst case, it corresponds to shooting two light sources, and in this case also, the speedup is great, compared to restarting the radiosity algorithm.

7 From solution to image

The radiosity solution is an independent view solution. Then hardware graphic acceleration allows fast rendering to display mesh stored luminances. If the architectural model is composed of specular surfaces, once the view independent solution has been computed in a first pass, a simple ray-tracing pass is used in a second pass [SAWG91], supply the view dependent portion and create the final image. When rays encounter surfaces, the intensity contributed by the specular reflectance function is obtain by recursively following reflected, as in conventional ray tracing.

8 Illustrations and results

The rendering system presented here, has been experimented for both the lighting design of the Louvre Museum in Paris (Plate 4-5) and Place Stanislas in Nancy (Plates 6-7). Both geometrical models contain more than million polygons (that is 5 billion patches). For the “Cour Carree" of the Louvre Museum, 3000 light sources were modelled, grouped for each facade into 18 networks. For the Place Stanislas, some 1420 light sources were modelled, grouped for each building into six networks. The spectral distributions are smooth for the dichroic halogen sources, but in the case of fluorescent lamps such as the pink ones (pink filter) use for the Place Stanislas lighting, the spectrums are discontinuous. We used our wavelength domain segmentation method to achieve the right colours. All images were calculated on a SGI Onyx bi-processors with 128Mb of main memory. Each processor is a Mips R8000 driven at 75Mhz. Results are presented in Plates and Videotape added to this paper.

9 Conclusion and future works

We have presented in this paper an application of realistic rendering to lighting design in architectural environments. Based on a physical simulation, generated images give a precise idea of the design, but they still require high computational costs and memory storage. Managing the complexity of the illumination computations and improving the control of the simulation are the most important challenges to be achieved in order to make this realistic rendering application (in a CAD context) more tractable. Our future works are aimed towards these goals and concern: Domain Decomposition methods (and Parallel Algorithms), incremental computation numerical methods, and real-time rendering.

10 Acknowledgement

The authors wish to thank "Electricite de France' Company for its technical and financial support.

11 References

[CCWG88] M.F. Cohen, S.E. Chen, JR. Wallace, and D.P. Greenberg. A progressive refinement approach to fast radiosity image generation. In J. Dill, editor, Computer Graphics (Siggraph'88 proc.), pages 75-84, August 1988.

[Che9U] S.E. Chen. Incremental Radiosity: An extension of progressive radiosity to an interactive image synthesis system. In F. Baskett, editor, Computer
Graphics (Siggraph'90 proc.), volume 24, pages 135-144, August 1990.

[DMPC94] P.M. Deville, S. Merzouk, D. Cazier, and J.C. Paul. Spectral data modeling for lighting applications. The International Journal of The

Eurographics Association, Computer Graphics Forum, 13(3):97-106, September 1994. Blackwell Publishers. Oslo, Norway.

[DP95] P.M. Deville, and J.C. Paul. An accurate modeling of light sources for image synthesis. In Proceeding of the International Workshop on Rendering Eurographics'95, pages 107-115, June 1995.

[HTSG91] X.D. He, K.E. Torrance, F.X. Sillion, and D.P. Greenberg. A comprehensive physical model for light reflection. In T.W. Sederberg, editor, Computer Graphics (Siggraph91 proc.), volume 25, pages 175-186, July 1991.

[Mey 88] G.W. Meyer. Wavelength selection for synthetic image generation. Computer Vision, Graphics and Image Processing, 41:57-79,1988.

[DPW95] J.C. Paul, P.M. Deville, and C. Winkler. Modeling radiative properties of light sources and surfaces. The Journal of Visualisation and Computer Animation, 1995. to be published.

[Pee93] M.S. Peercy. Linear color representations for full spectral rendering. In J.T. Kajiwa, editor, Computer Graphics (Siggraph93 proc.), Annual Conference Series, pages 191-198, August 93.

[PSV9O] C. PUECH, F.X. Sillion, and C. Vedel. Improving interaction with radiosity-based lighting simulation programs. In R. Riesenfeld and C. Sequin, editors,

Computer Graphics (Symposium90 on Interactive 3D Graphics), volume 24, pages 51-57, March 1990.

[SAWG91] F.X. Sillion, J.R. Arvo, S.H. Westin, and D.P. Greenberg. A global illumination solution for general reflectance distributions. In T.W. Sederberg, editor, Computer Graphics (Siggraph'91 proc.), volume 25, pages 187-196, July 1991.

[TS91] J.S. Teller and C.H. Sequin. Visibility preprocessing for interactive walkthroughs. In T.W. Sederberg, editor, Computer Graphics (Siggraph91 proc.), volume 25, pages 61-69, July 1991.

[War92] G.J. Ward. Measuring and modeling anisotropic reflection. In E.E. Catmull, editor, Computer Graphics (Siggraph92 proc.), volume 26, pages 265-272, July 1992

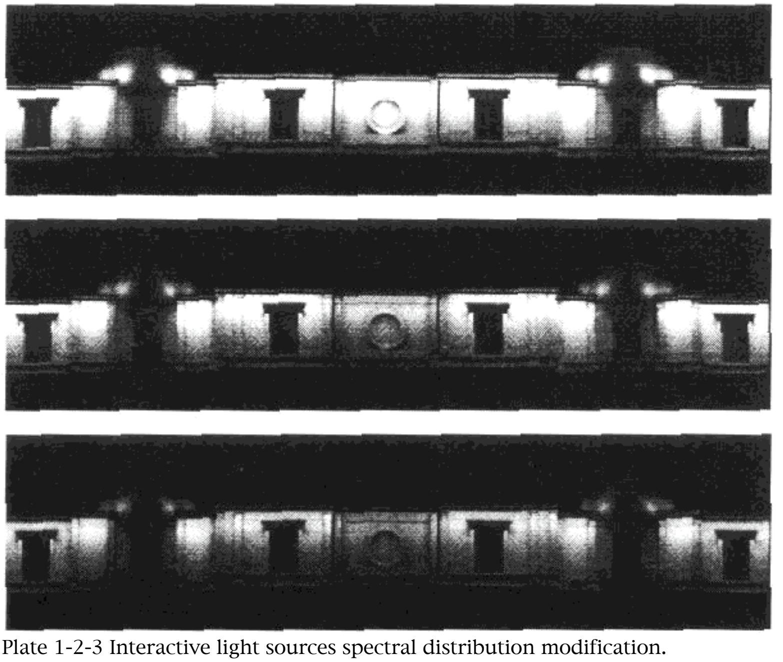

Plate 1-2-3 Interactive light sources spectral distribution modification.

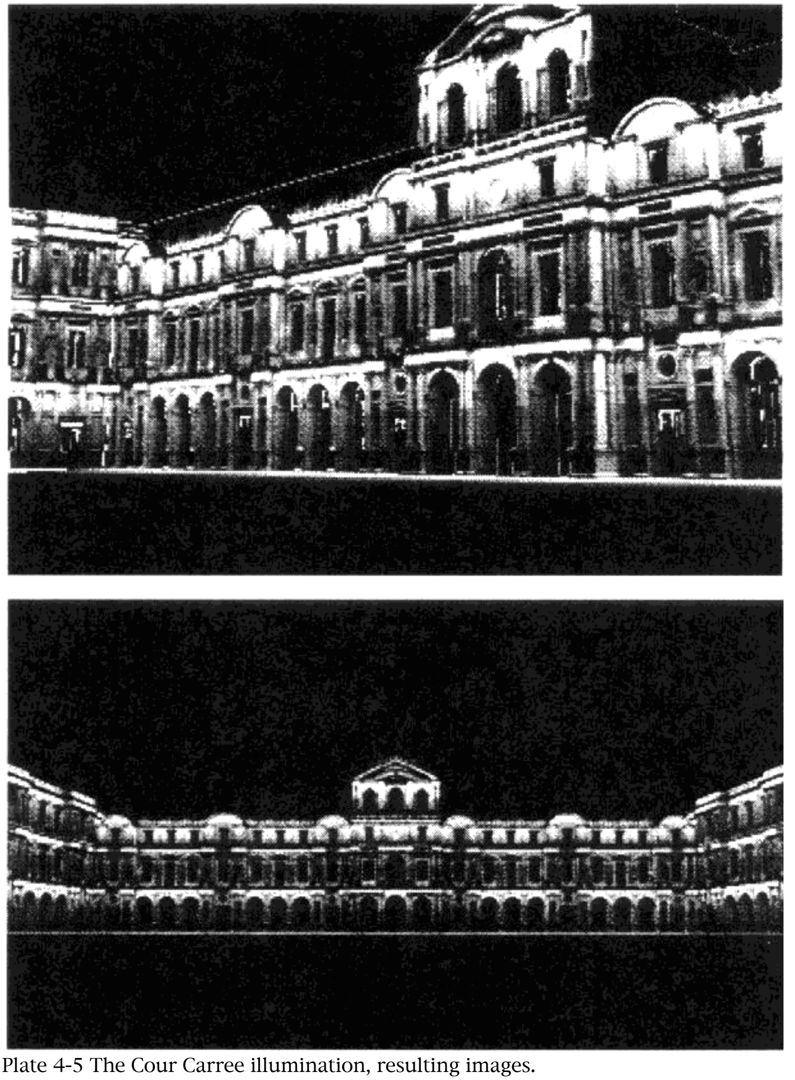

Plate 4-5 The Cour Carree illumination, resulting images.

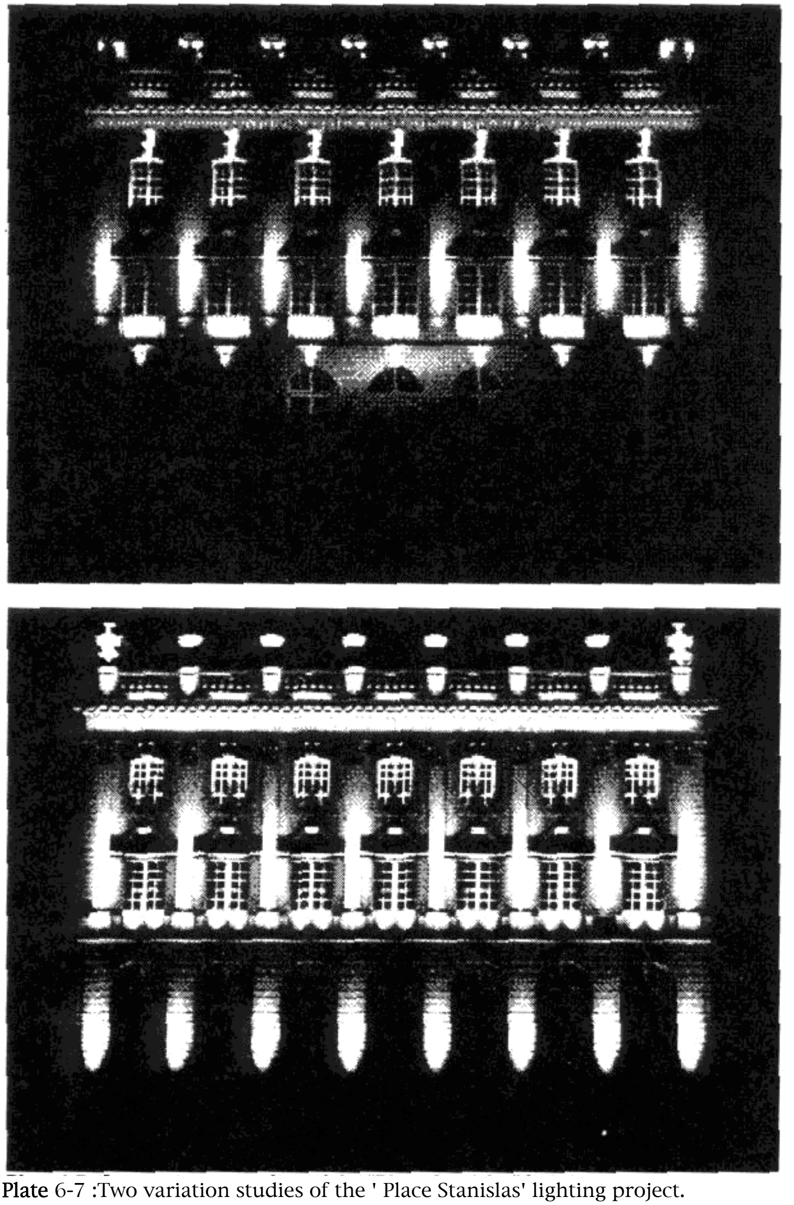

Plate 6-7 :Two variation studies of the ' Place Stanislas' lighting project.