Abstract

This paper presents an inverse daylighting model devoted to the design of building openings. The inverse daylighting model includes sky lighting as well as light reflected by surroundings, and therefore combines near-field and far-field light sources. Input data is a heterogeneous lighting distribution on indoor faces called “lighting intention”. Openings are considered as a set of intermediate anisotropic light sources. Therefore the geometric reconstruction problem is seen as a source emittance problem. A pin-hole model generates anisotropic light sources and computes light contribution on each indoor faces. An image metric evaluates the distance between this light contribution and lighting intention. Intermediate light sources which have the smallest distance are selected to be part of opening, and therefore define opening shape. This technique is intended to aid opening design in the early stage of architectural design. Our model is validated by test cases and illustrated by a case study in order to show the opening reconstruction process.


Keywords: Inverse lighting, Daylighting, Computer-Aided Design

1 Opening design problem

Designing forms and shapes from light data is a well-known problem in the computer graphics community. More precisely, the problem addressed in this paper is to compute building opening shape from indoor daylighting in buildings (Figure 1). We focus our work on opening design in order to aid architectural design. This work is a part of a computer-aided architectural design (CAAD) project which merges a visualization problem and a computer graphics (CG) problem. This project encompasses the expression of lighting intentions in the early stage of architectural design, and the use of these expressions as guidelines to design the building. Such an approach needs lighting intentions to be translated in scene lighting properties, and these lighting descriptions to be processed by an inverse model in order to obtain opening shapes.

The first problem, the expression of lighting intention by architects or lighting designers, is a visualization problem related to light perception. Lighting data (intensity, emittance, luminance, etc.) have been described with explicit lux amount [Costa et al. 1999], texture qualities [Moeck 2004], declarative modeling [Jolivet et al. 2002], implicit light sketching or textures [Kawai et al. 1993; Schoeneman et al. 1993; Siret 1996; Tourre et al. 2006] or pictures [Marschner and Greenberg 1997; Yu and Malik 1998]. We consider that lighting is expressed as graylevel textures, which represent illuminance value distribution on indoor faces.

The second problem, the processing of lighting intention, is more specifically addressed in this paper. Previous works can be classified following inverse problem type [Marschner and Greenberg 1997] according to whether the required element depends on the scene geometry - inverse geometry [Mahdavi and Berberidou-Kallikova 1995; Siret 1996], the reflectance properties of surfaces - inverse reflectance [Yu and Malik 1998; Kawai et al. 1993], or the position and intensity of light sources - inverse lighting [Costa et al. 1999; Jolivet et al. 2002; Schoeneman et al. 1993; Kawai et al. 1993]. For a complete review of inverse rendering problems, we refer to [Patow and Pueyo 2003; Patow and Pueyo 2005].

Opening design problem is a geometric recreation from daylighting intentions, and is addressed as an inverse geometry problem by [Mahdavi and Berberidou-Kallikova 1995; Siret 1996]. Nevertheless, lighting intention expression in these models is very limited and does not allow heterogeneous lighting distribution. We integrate lighting intention as graylevel light textures in our model. We propose to see this problem as an inverse lighting problem with anisotropic light sources.

An inverse daylighting model is introduced and uses an heterogeneous daylighting distribution to compute an opening shape layout. As we focus on daylighting, our model takes into account sky lighting as well as light reflected by surroundings. Potential opening areas are meshed in “opening elements” (Figure 1). An opening element is seen as an intermediate and anisotropic light source. A pin-hole model computes the lighting contribution of an opening element on indoor faces, through a rendering step using graphic card resources. An image metric is used to compare the designer’s lighting intention and the lighting contribution of an opening element. Finally, a binary segmentation of the opening element set
allows defining a raw opening shape. These shapes can be used by architects to design building opening.

In section 2, our approach is delineated to explain how we came from geometric reconstruction problem to anisotropic source emittance problem. Section 3 describes our inverse lighting model based on three steps: anisotropic source generation, lighting evaluation and opening element selection. Validation of this model is shown in section 4. Sections 5 & 6 present some test cases and a case study, before to conclude in section 7.

2 An opening focused approach

Our goal is to compute raw opening shapes from heterogeneous daylighting intentions. Daylighting is considered according to daylight factor formula with sun/sky component (SC), external reflected component (ERC) and internal reflected component (IRC). (Figure 2).

Sky is an extended, heterogeneous and dynamic source [Mahdavi and Berberidou-Kalikova 1995; Siret 1996] which influences surrounding lighting, which in turn influences indoor lighting ambiance. As SC lighting and ERC lighting mainly depend on opening properties, we add SC and ERC features to our inverse daylighting model in order to compute building openings. Internal interreflections are put aside in this paper, nevertheless we keep in mind that we will have to integrate IRC in our model. As our model encompasses skylight (SC) and reflections from the external built environment (ERC), we deal with light coming from the outside into the indoor space.

The inverse lighting simulation computes opening shape from lighting properties. This is an inverse geometry problem as we are looking for scene geometry. However this geometry defines also daylight source visibility, so this problem could be seen as an inverse lighting problem, source positioning or emittance research. Therefore this problem is not clearly identified in the inverse rendering framework as an inverse geometry problem or an inverse lighting problem.

In addressing this problem as an inverse geometry problem, we face a large solution space as opening can be of any size, shape and number. Getting back to an inverse lighting problem, we have to choose between the source positioning problem and the emittance problem. In the source positioning problem, the source position also determines source emittance. Here we face a double problem which is very difficult to solve. If we address this problem like an emittance problem, we get back to one problem. This approach forces us to fix source position, and therefore it becomes a manageable problem. We propose in the next section a source emittance approach based on pin-hole model and image distance measurement to compute raw opening solutions.

3 Inverse daylighting model

The opening face is meshed into n opening elements. Each opening element brings its own lighting contribution coming from skylight (SC) and surrounding reflected light (ERC) (Figure 3). As this lighting contribution is different according to light direction, an opening element is considered as an anisotropic light source. The SC + ERC lighting on indoor faces of several opening elements can be computed as a linear combination of their lighting contributions.

Our method is divided in three steps:

- Generation of light coming through each opening element.
- Evaluation of each opening element according to its light contribution to indoor lighting.
- Selection of an opening element subset in order to create an opening shape which produces lighting close to lighting intention.

3.1 Opening element light generation

Lighting contribution of each opening element is computed with a pin-hole model in order to obtain lighting from skylight SC and surrounding reflected light ERC (Figure 3).

Actually, lighting contribution of an opening element can be computed with any rendering technique. Radiosity techniques are not adapted to compute lighting through tiny opening elements. A ray-casting technique could be used too, but the adaption of ray-casting engine to fit our needs is much more important than our model implementation.

As a virtual camera is used, we compute lighting contribution thanks to GPU in an easy-to-implement way. Our model can be seen as a kind of hemi-cube [Cohen and Greenberg 1985] centered on opening element which allows to compute light field, and adapted to convex volumes.
We consider a room of the building being designed as a camera, the room itself is the dark room, openings are camera optics and the outdoor environment is the object to photograph. The outdoor environment is the sky vault, surrounding buildings and streets. Indoor direct lighting without inter-reflections can be seen as a picture of the outdoor. In the inverse process, indoor lighting becomes the lighting intention provided by the designer. Therefore the problem is to find out the camera properties i.e. opening properties of the building being designed (Figure 4).

![Figure 4: Inverse day lighting based on pin-hole model.](image)

Each sky patch, respectively surrounding building patch, can supply SC lighting ($E_{SC}$), respectively ERC lighting ($E_{ERC}$), through an opening element to indoor faces. Our problem is to compute $E_{SC}$ and $E_{ERC}$ of each outdoor patch, and more precisely their illuminance value and lighted area position, shape and size.

### 3.1.1 Illuminance equations

An opening element acts as a filter between outdoor and indoor spaces. A part of light received by an opening element from an outdoor patch is transmitted to indoor space. If an opening element is seen as a light source, this transmitted light is considered as "emitted" by the opening element on indoor faces.

The lighting simulation tool we use, Solene [Miguet and Groleau 2002], gives sky luminance and surrounding building exitance. Therefore, we set a relation between the sky patch luminance $L$ and the indoor illuminance $E_{SC}$, through a relation between the luminous flux $\Phi_e$ received by an opening element and the luminous flux $\Phi_r$ emitted by an opening element. $E_{ERC}$ is obtained from the former relation which is modified to set up a relation between the environment patch exitance $M$ and the indoor illuminance $E_{ERC}$.

The luminous flux $\Phi_r$ received by an opening element can be expressed following the luminance $L$ of sky patch on this opening element.

$$\Phi_r = \int_S L \cdot \Omega_r \cdot \cos \beta \ dS \quad (1)$$

with $\Omega_r$ the solid angle containing luminous flux $\Phi_r$, $\beta$ the angle between opening element normal and direction from opening element to sky patch and $S$ the opening element surface.

The luminous flux $\Phi_e$ emitted by an opening element can be expressed following the illuminance $E_{SC}$ of indoor lighted area $A$.

$$\Phi_e = \frac{E_{SC} \cdot \Omega_e \cdot d^2}{\cos \alpha} \quad (2)$$

with $\Omega_e$ the solid angle containing luminous flux $\Phi_e$, $\alpha$ the angle between indoor lighted area normal and direction from indoor lighted area to opening element and $d$ the distance between opening element and indoor lighted area.

Then, by replacing the distance $l$ by the distance $d$ between opening element and the face containing indoor lighted area ($A$) $d = l \cdot \cos \alpha$, we have:

$$\Phi_e = \frac{E_{SC} \cdot \Omega_e \cdot d^2}{\cos^3 \alpha} \quad (3)$$

The luminous flux $\Phi_e$ is transmitted, reflected or absorbed according to, respectively, transmittance, reflectance or absorptance of opening element. The luminous flux $\Phi_e$ emitted by the opening element is equal to the flux transmitted by the opening element:

$$\Phi_e = \Phi_r \cdot \tau \quad (4)$$

with $\tau$ the transmittance of opening element.

Therefore, the indoor illuminance $E_{SC}$ can be expressed following the luminance $L$, by replacing $\Phi_r$ and $\Phi_e$ in equation 4:

$$E_{SC} = \int_S \frac{L \cdot \Omega_r \cdot \cos^3 \alpha \cdot \cos \beta \cdot \tau}{\Omega_e \cdot d^2} \ dS \quad (5)$$

Under the assumption that there are no refraction or diffraction effects, then $\Omega_e = \Omega_r$ (Figure 5).

$$E_{SC} = \int_S \frac{L \cdot \cos^3 \alpha \cdot \cos \beta \cdot \tau}{d^2} \ dS \quad (6)$$

![Figure 5: Illustration of equation 6.](image)

Lighting coming from the environment $E_{ERC}$ is obtained from equation 5, modified to set a relation between environment patch emittance $M$ and $E_{ERC}$: We consider all external reflections with Lambert’s law ($M = \pi \cdot L$):

$$E_{ERC} = \int_S \frac{M \cdot \cos^3 \alpha \cdot \cos \beta \cdot \tau}{d^2 \cdot \pi} \ dS \quad (7)$$

### 3.1.2 Position, size and shape of illuminated area

Now we know the lighting contribution value of an outdoor patch into indoor space through an opening element. We have to compute position, size and shape of the indoor lighted area $A$ with a projection of the solid angle $\Omega_e$ on the lighted face. A picture of the outdoor scene from opening element centre represents lighting passing through this opening element into indoor space.

We use the power of graphic cards to achieve this perspective projection, in order to compute in one shot the light contribution of all
outdoor patches through one opening element on one face. With this approach based on a perspective projection, we avoid a time consuming meshing of indoor faces to compute position, size and shape of illuminated area.

Our model is created by combining the pin-hole model and illuminance equations in order to take into account simultaneously near-field and far-field light sources. The process of anisotropic source generation is summarized below:

- A camera is placed at the opening element centre, and calibrated to look towards an indoor face, parallel to face normal and its field of view is adjusted in order to see all the indoor face.
- Illuminance values, $E_{SC}$ or $E_{ERC}$, are computed and mapped on their corresponding outdoor source patch (Figure 6).
- Camera is rotated towards the outdoor scene, and a fast scene rendering is computed.
- Resulting image is convolved according to opening element size and shape, and then clipped to match indoor face position, size and shape.
- Finally the image, which represents indoor lighting, is mapped on indoor face or stored for future use.

![Figure 6: Mapping of illuminance values on environment and projection on an indoor face.](image)

Opening elements are considered without thickness and have a binary behavior: opacity or transparency. Therefore we are looking for which opening elements have to be transparent, so that their summed lighting contribution is close to designer’s lighting intentions.

### 3.2 Opening element evaluation

The opening element evaluation determines the interest of light brought by an opening element in order to generate the desired lighting. This evaluation quantifies the pertinence of an opening element with a comparison between lighting brought by an opening element and lighting intention.

#### 3.2.1 Image distance

Lighting is represented by light distribution on a surface and considered as an image. The image metric used is based on mean squared error (MSE). MSE respects properties of symmetry, separation and triangular inequalities, and can be used to define a distance [Zhou et al. 2002]. Opening element evaluation is based on a distance measure between lighting intention $E^{int}$ and light contribution of an opening element $E^{op}$. The image of squared error $\Delta E_f$ is computed on each indoor face $f$:

$$\Delta E_f = \left| E^{int}_f - E^{op}_f \right|^2$$

with $E^{int}_f$ the lighting intention on face $f$ and $E^{op}_f$ the light contribution of an opening element on face $f$.

Two descriptors are extracted from the histogram of squared error image: mean $\overline{\Delta E}$ and standard deviation $\sigma_{\Delta E}$. MSE represents the difference in lighting quantity and standard deviation of squared error represents difference between overall lighting shapes.

$\overline{\Delta E}$ and $\sigma_{\Delta E}$ are added for all faces, and this sum shows if lighting brought by one opening element can contribute to reach the desired light. Distance between lighting intention on all faces $E^{int}$ and light contribution of one opening element on all faces $E^{op}$ is:

$$d(E^{int}, E^{op}) = \sum_{f=1}^{n} w_f \left( a \cdot \Delta E_f + b \cdot \sigma_{\Delta E_f} \right)$$

with $n$ the number of indoor faces, $w_f$ the face $f$ weight, $\Delta E_f$ the squared error image of face $f$ and $a$ and $b$ weight factors of mean $\overline{\Delta E_f}$ and standard deviation $\sigma_{\Delta E_f}$, respectively.

Figure 7 shows, on the left, the lighting contribution of an opening element, on the middle, the lighting intention and on the right, the error between both.

![Figure 7: (left) Opening element lighting (middle) Lighting intention (right) Error image $|E^{int}_f - E^{op}_f|$](image)

#### 3.2.2 Evaluation map

Descriptors are extracted from the former image comparison in order to generate an evaluation map. Values computed at the evaluation step are attributed to each corresponding opening element and coded in graylevel scale. The opening element set associated to their values constitutes the evaluation map of the opening face related to one indoor face. The more an opening element is dark, the more the evaluation is good, and therefore suitable to produce the desired lighting. As an example, in Figure 8, opening element evaluation of opening face, on the right side, according to a given lighting on indoor face, on the back side, produces an evaluation map. Evaluation maps of opening face according to indoor faces (floor, sides, back and ceiling) are displayed separately. The designer can choose each indoor face weight, $w_f$ in equation 9, in order to compose a global evaluation map.
3.3 Opening element selection

The evaluation map is considered as input data at the selection step. The problem is to know how we have to select opening elements in order to produce an opening shape. The solution is intended to be a starting point for an architect designing the actual opening.

We are looking for an opening element subset $Sel$ which has minimal descriptor values. An automatic selection method computes a threshold value $t$ in order to reach light quantity needed in daylighting intention. All opening elements which descriptor value less than $t$ are selected.

$$Sel = \{ op \in OP, E_{op} < t \}$$  \hspace{1cm} (10)

with $Sel$ the selected opening element set, $OP$ the opening element set, $E_{op}$ the descriptor value of the opening element $op$ and $t$ the threshold.

From this descriptor value, a binary segmentation of the evaluation map is automatically performed and displayed. Therefore the designer can immediately appreciate the theoretical opening shape that has been created. (Figure 9). The associated daylighting is immediately computed from light contributions of selected opening elements, and displayed in user interface. The interactive selection interface allows the designer to tune threshold value in order to modify light quantity and opening shape.

5 Test case with a north-facing room

This test case shows how our inverse lighting model reconstructs an opening from a given lighting distribution produced by an original opening. The situation is a room with a north opening face located in an east-west street ($47^\circ$ N) (Figure 13). North opening face is chosen in order to show that all sky lighting ($SC$) is taken into account, and not only sunlighting.

Sky luminance is set at noon on September 21 under a clear sky. A direct daylighting simulation is computed with Solene [Miguet and Groleau 2002] to get original light distribution in the tested room. Light distributions of five indoor faces (top, bottom, left, right and back) are put in our inverse lighting model and considered as lighting intentions.
Mean square value descriptor and standard deviation descriptor are equally weighted on the evaluation maps (b in Figures 16 & 17). Interactive selection method is used with values between 25% to 40% of maximum descriptor value.

The test case process is summarized in Figure 14. Original opening shape is compared with the evaluation map and the reconstructed opening shape obtained at the selection step. The designer can propose several interpretations of the reconstructed opening shape. A forward lighting simulation is then computed with the interpreted opening shape in order to compare the result with the original light distribution.

When only the sky is considered as a light source (SC lighting), the ceiling receives no direct light at all and therefore only the floor and three walls are considered. We show opening reconstruction results for horizontal opening with SC lighting, and cross shape opening with SC and SC + ERC lightings (c in Figures 15, 16 & 17).

The horizontal opening reconstruction with the SC lighting is not so far from the original horizontal opening and therefore produces a lighting which matches initial intentions (Figure 15).

The cross-shaped opening reconstruction with the SC lighting misses the top part of the cross (Figure 16). Since the sky is the only light source, the ceiling is not lighted. The inverse lighting process depends on other faces and highest opening elements bring a very diffuse light to these faces. Therefore the top part of cross is not necessary to reproduce lighting given as an intention.

The cross-shaped opening reconstruction with the SC + ERC lighting gets the higher part of the cross. The ERC lighting brings useful lighting data specifically on ceiling and allows retrieving a cross shape (Figure 17). Nevertheless we note this map is less accurate than the previous one because the SC + ERC lighting is more diffuse than the SC lighting on all indoor faces.

The last opening reconstruction is interpreted from an architectural point of view as a diamond-shaped opening. A light simulation is computed with Solene [Miguet and Groleau 2002] in order to compare original illuminance values from cross-shaped opening and those from diamond-shaped opening (Figure 18).

These results are computed with our prototype implemented in JAVA on Intel Core 2 Duo computer with 2 Gb RAM and Quadro FX 550 graphic card. J3D, Swing and Java Advanced Imaging libraries are used to manage respectively 3D, user interface and image comparison.

The test scene contains an opening face with 1024 patches, 5 indoor faces and an environment (sky and street) with more than 10,000 patches. Execution times are approximatively 1 hour for generation.
step, with one third for image input/output, 20 minutes for evaluation step and few seconds for selection step. Memory used during execution is about 500 Mb, with 300 Mb dedicated to projection images from generation step.

6 Case study

We asked an architect to express some lighting intentions in a simple volume as a sketch (Figure 19). This sketch was scanned, clipped and projected in order to get indoor face lighting as textures. These textures were integrated in our model with design interface (Figure 20). Our inverse model computed an evaluation map, and the architect interpreted it to design his own opening. Lighting produced by this final opening was confronted to original intention.

Light source generation was computed under clear sky with SC and ERC lighting at noon on September 21st. Source evaluations were performed with standard deviation $\sigma_{AE}$. Evaluation maps related to each indoor face were computed and displayed in selection interface (Figure 21). The designer can tune indoor face weight to adjust his intention through vertical cursors under each indoor face. The global evaluation map is immediately computed following indoor face weights, and displayed.

Sources are selected thanks to segmentation cursor (Figure 22). As the cursor moves, opening shape is drawn by opening element selection, and the room is interactively relighted. Segmentation cursor minimum and maximum are respectively the best and the worst evaluation values. Therefore, this cursor can be seen as a tolerance value: the more the designer gives a high value with this cursor, the more he has to accept to be far from his original intention.

This theoretical solution was translated into opening shape by an the architect in three ways according to his sensibility. A lighting simulation with Solene was computed from the first interpretation in order to compare illuminance values with original lighting intentions (Figure 23). As we can see on these figures, lighting produced by the first opening interpretation brings more light in the bottom right corner, although it does not match exactly the original lighting intention. Nevertheless, the idea behind this intention “one corner in shadow and one corner in light” is respected.

7 Conclusion and Further works

Our main contribution is an inverse lighting model which takes into account daylighting with sun/sky and external reflected components ($SC + ERC$). We show that an inverse geometry problem for opening design, can be seen as an inverse lighting problem. Our inverse
lighting model integrates anisotropic light sources, and is able to reconstruct openings from heterogeneous lighting distribution in a simple room. A model implementation has been tested by an architect who used it to draw some sketches. Therefore results produced by this inverse lighting model can be an aid to architectural design for sketching opening.

Where further works are concerned, we look for integration of interreflections, lighting color and several times of the day. We also need to demonstrate that our model scales to realistic scenes and is able to handle several openings in order to be useful for architects. The integration of this method in a CAAD tool will allow the designer to experiment computer-aided “design by ambience intention” in order to explore his own architectural solutions from the theoretical ones proposed by our inverse daylighting model.

References


