Pinhole Based Radiosity

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Uruguay:
180,000 km²
3,200,000 inhabitants
10,000,000 cows
20,000,000 sheep
Football: 2 world cups and 15 America cups

Universidad de la República:
160 years
100,000 students
20 schools

I work at:
Engineering School (Facultad de Ingeniería)
Computer Science Department (Instituto de Computación)
Goals of PBR

1. To solve the radiosity equation when natural light comes through an opening into a Lambertian scene (anisotropic emission, isotropic reflection).

2. To solve inverse lighting design problems.

3. To reduce the computational costs.
   - Memory
   - Time
Radiosity Equation

\[(I - RF)B = E\]

- \(B\): Radiosity value of each patch
- \(I\): identity matrix ; \(R\): diagonal matrix with the reflectance index of each patch ; \(F\): Rather dense matrix, \(F(i,j)\) contains the form factor between patches \(i,j\) ; \(E\): Emission value of each patch.
- \(F\) is usually a huge & dense matrices \((10^5 \times 10^5)\)
Inverse lighting problem

Lighting Intentions

- Minimal high light level at selected area
- Roof skylights: Set position, shape and emitting power
- Geometry restrictions: area size and symmetry
- Minimal light at the floors

minimize $f(x)$
subject to $c_i(x) \leq 0, \ i = 1 \ldots p$

Could be based on statistics
Inverse lighting algorithm

We use: Variable Neighborhood Search (VNS) as metaheuristic, and penalty/barrier methods to include constraints.
Speeding up the radiosity calculation: Light Coherence in Radiosity

[Baranoski et al. 1997], [Ashdown 2001], [Hasan 2007].
Speeding up the radiosity calculation: Low-Rank Radiosity (LRR)

Example for a Cornell box composed by 5632 patches:

Light coherence of the scene patches.

\[ \mathbf{RF} = \mathbf{UV}^T = \mathbf{V}^T \mathbf{U} \]

\( \mathbf{U}, \mathbf{V} \) are \( n \times k \), \( n \gg k \)
Speeding up the radiosity calculation: 
Low-Rank Radiosity (LRR)

The radiosity problem is transformed:

\[(I - RF)B = E \quad \rightarrow \quad (I - UV^T)\tilde{B} = E\]

and after Sherman-Morrison-Woodbury:

\[\tilde{B} = (I - UV^T)^{-1} E \quad \rightarrow \quad \tilde{B} = E + Y(V^T E)\]

**Pros:**
- \(O(nk)\) in memory and time (No Gauss-Seidel!!)
- Radiosity calculation of single patches.
**Speeding up the radiosity calculation: Statistical Radiosity**

\[
\mu_{W_A}(\tilde{B}(s)) = \left( \frac{\left( \left( 1_s^T W_A \right) Y \right) V^T}{\sum_{p \in s} W_A(p, p)} \right) E = mE
\]

\[
\sigma(\tilde{B}(s))^2 = \left( V^T E \right)^T \text{cov}_{W_A}(Y(s, :)) \left( V^T E \right)
\]

**Pros:**
- \( \mu \) is \( O(n) \) in memory and time.
- \( \sigma \) is \( O(k^2) \) in memory and \( O(n+e^2) \) in time. (\( e \) is the amount of patches belonging to the emitters)
- VNS can execute 500 radiosity calculations per second
Natural light without Lambertian diffuseors.
Modeling natural light with pinholes: Pinhole based radiosity (PBR)
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Modeling natural light with pinholes: Pinhole based radiosity (PBR)
A pinhole

\[(I-RF)B = E + GW\]  The first reflection is considered as emission
Modeling the pinhole with hemi-cubes
Correlation between hemi-cubes

Internal Hemi-cube \( (\mathbf{H}_j^I) \)

\[ (u,v) \]

\[ \mathcal{P}_i^I \]

External Hemi-cube \( (\mathbf{H}_j^E) \)

\[ (u,v) \]

\[ \mathcal{P}_i^E \]
From pinhole $j$ to patch $j$

• The calculation made for each pinhole is extended to consider the associated patch.

• The extension to the patch works properly when:

\[
\frac{\text{diameter of } j}{\text{distance}(i, j)} \ll 1
\]

- Elements of external environment are far enough to avoid large “circles of confusion”.
From pinhole $j$ to patch $j$

$$G(i,j) = R(i) \frac{A(j)}{A(i)} \left( \sum_{(u,v) \in \mathcal{A}_i} \Delta F(u,v)H_j^E(u,v) \right)$$

- $G(i,j)$ is the amount of natural light coming through $j$ that is reflected in patch $i$.
- $G$ is a $n \times W$ matrix.
- It depends on:
  - $R(i)$: Reflection coefficient of $i$
  - $A(j)/A(i)$: Ratio between the areas of $j$ and $i$.
  - $\left( \sum \cdots \right)$: Radiosity received at patch $j$. 

\[ (1 - RF)B = E + GW \]

- \( G(i,j) \) is the light coming through \( j \) that is reflected in patch \( i \).
- \( E \) refers to other light sources (artificial light sources).

\( W(j) = 1 \) when \( j \) belongs to the opening,

otherwise \( W(j) = 0 \)
But using Low Rank Radiosity, we have:

\[
(I - RF)B = E + GW
\]

Then:

\[
M = (I - RF)^{-1} \approx (I + YV^T) = \tilde{M}
\]

\[
\tilde{B} = (I + YV^T)(GW + E) = \tilde{N}W + Y(V^TE) + E
\]

where

\[
\tilde{N} = G + Y(V^TG) \quad \tilde{N} \text{ is } n \times \overline{W}
\]
When there are not other light sources \((E=0)\) the radiosity equation is simplified to:

\[
\tilde{B} = \tilde{N}W + Y(V^TE) + E
\]

When there are not other light sources \((E=0)\):

\[
\tilde{B} = \tilde{N}W
\]

\[
\tilde{N} = G + Y(V^T G) \quad \tilde{N} \text{ is } n \times \overline{W}
\]
Experimental Results:
Single Pinhole in the roof
Experimental Results: Single Pinhole in the roof

Exterior hemicube

First Reflection

Interior hemicube

Final Radiosity
Experimental Results:
PBR compared with other Ray-based method

PBR takes 0.1s to generate this image

RBM takes several minutes to generate this image
Optimize red surfaces $s_1$ $s_2$.
Subject to constraints in the emitters $L_1$ $L_2$
Experimental Results: Inverse Lighting

Maximize $\mu_A(B(s1))$

Maximize $\mu_A(B(s2))$

About 1000 iterations per second in each VNS optimization process. Solutions after 10000 iterations.
Experimental Results: Inverse Lighting

- About 400 iterations per second in each VNS optimization process.
- Solutions after 50000 iterations.

Mathematical expressions:

\[
\begin{align*}
\text{max } \sigma_A(C(s)) & \\
\text{min } \sigma_A(C(s)) & \\
\text{min } \sigma_A(C(s)) & \quad \text{s.t. } \mu_A(C(s)) > \mu_{\text{min}}
\end{align*}
\]
• **Related to Pinhole:**
  – Inverse lighting problems considering thousands of skies.
  – Extend pinhole method to non Lambertian artificial lights.

• **Other lines of work:**
  – Better (Faster, bounded error) factorization methods $RF \approx UV^T$
  – Inverse Lighting Problem using Photon Mapping instead of Radiosity linear systems.
Current work: Inverse lighting problems using PBR & UDI (3650 skies)

The shape and position of several rectangles defines the shape of the opening.
Current work: Inverse lighting problems using PBR & UDI (3650 skies)

Optimization through VNS, 15000 windows are evaluated, for each one there is a PBR process that is calculated for 3650 skies.

15000 evaluations takes about 25 mins for 8 sensors and 45 mins for 24 sensors.
Current work: Inverse lighting problems using PBR & UDI (3650 skies)
**Current work:** Using PBR to modelize non-Lambertian artificial lights.

Set of pinholes can be used to approximate artificial light emitters.
Current work: “Hierarchical Factorization” to find fast a good factorization of RF.
Current work: Inverse lighting based on Photon Mapping (no linear equation)

- Photons are emitted by light sources, with bounces & absorption on surfaces.
- Few photons ($10^5$) are enough for inverse lighting.
- Scenes with $10^5$ poligons evaluated in 1/10 second.
- Nvidia: Optix - Graphics Cards
Current work: Inverse lighting based on Photon Mapping (no linear systems)

• Why Photon mapping in inverse lighting? Because allows to:
  – work with Non-Lambertian surfaces
  – modify the reflection properties of surfaces for free
  – modify the geometry without expensive pre-computation

• Warning!!: stochastic optimization
Thanks!! Questions?

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