Realistic Image Synthesis

Environment Map Lighting and Precomputed Radiance Transfer

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Overview

• Today
  – Why rendering with natural lighting is important?
  – Example environment map sampling algorithms
  – Video Environment Maps
  – Precomputed Radiance Transfer (PRT)

• Next lectures
  – Perception and Image quality Metrics
  – Perception-based rendering
  – High Dynamic Range Imaging
  – Tone mapping
Scene Lighting

- **Virtual light source selection and placement**
  - Tedious manual process requiring many rendering iterations to obtain good visual effects
  - Difficult to get rid of “CG look”

- **Human visual system (HVS) is focused on the object recognition and tend to discount illuminant**
  - Separation of illumination and reflectance in incoming lighting to the human eye retina is an ill-posed problem
  - Some implicit assumptions concerning the scene lighting are required to factor out the illumination
Build-in Assumptions

- Presumption of light from above
- Preference for “ground” as opposed to “ceiling” surfaces
- Preference for convex rather than concave forms
  - Hollow mask illusion:
    - [http://www.michaelbach.de/ot/fcs_hollow-face/index.html](http://www.michaelbach.de/ot/fcs_hollow-face/index.html)
Rendering with Natural Lighting

- **Experimental results [Dror, Fleming, Adelson]**
  - Under real world lighting the ability to discern even subtle differences in the object appearance is much better than under typical CG lighting

- **Even simple geometry illuminated by captured lighting looks very convincing**
  - Snapshots from Paul Debevec movie
Material properties recognition: illumination type plays an important role
Material properties recognition: illumination consistency is less important
Psychophysical experiment with human subjects:
Ward reflectance model parameters manipulation (specular reflectance and roughness) to get match in appearance for two different illumination conditions
Rendering with Natural Lighting

Figure 11. Spheres rendered under each of the synthetic illuminations used in the matching experiment. Each illumination was designed to have some key properties in common with real-world illuminations, but otherwise to have atypical statistics. If subjects’ stored assumptions about illuminations are infringed, performance should be impaired. It should be noted that perceived surface reflectance is less clear for these spheres than for those in Figure 9, with the possible exception of (c), which was rendered in a world featuring a single extended rectangular source.
Rendering with Natural Lighting

Matching experiment

Figure 6. Example stimuli from the surface reflectance matching task. Subjects adjusted the reflectance properties of the Match sphere until it appeared to be made of the same material as the Test sphere, despite the difference in illumination. Note that in this image the spheres have different surface reflectance properties.
Rendering with Natural Lighting

Figure 9. Spheres rendered under each of the real-world illuminations used in the matching experiments. All spheres shown here have the same surface reflectance properties. It should be noted that these spheres do not have the maximum specular reflectance or minimum roughness used in the experiments. Therefore additional detail was visible in some experimental conditions.

Different appearance of the same surface under different lighting conditions
Rendering with Natural Lighting

Best reflectance matching performance under the natural lighting conditions.
Sensitivity to Environment Map Deformations

Illumination transformations used in the experiments

User interface used in the experiment
Sensitivity to Environment Map Deformations

Figure 6: Summary of results for the experiments. The top and bottom rows show results for the blur and warp studies, respectively. Green circles mark cases where objects rendered with transformed illumination maps had the same appearance as objects rendered with reference maps. Red squares show cases where object appearance was different from the reference. Among the green circles (same appearance), there is a further distinction between the cases where images were indistinguishable (solid circles) and cases where the images were different but conveyed the same appearance (circles with a dot). Visual equivalence is represented by this latter set.
Natural Lighting Acquisition

- SpheroCam from Spheron VR
- Light probes and multi-exposure techniques

Light probe  VR: rendering
Problem Statement

• Radiance leaving a point \( x \) in direction \( w_o \)

\[ L(x, w_o) = \int L_{hdr}(w)V(x, w)f_r(w, x, w_o)\cos \theta dw \]

• Monte Carlo integration

\[ L(x, w_o) = \frac{1}{N} \sum_{i=0}^{N-1} \frac{L_{hdr}(w_i)V(x, w_i)f_r(w_i, x, w_o)\cos \theta_i}{p(w_i)} \]

• Importance sampling
  - For diffuse surfaces: \( p(w) \sim L_{hdr}(w) \cdot V(x,w) \)
    • Since \( V(x,w) \) difficult to estimate in practice only \( p(w) \sim L_{hdr}(w) \) is considered
  - For glossy surfaces: \( p(w) \sim L_{hdr}(w) \cdot V(x,w) \cdot f_r(w,x,w_o) \)
    • Difficult to take the triple function product into account
    • In practice \( p(w) \sim L_{hdr}(w) \) or \( p(w) \sim f_r(w,x,w_o) \)
Basic Idea

- Importance sampling with $p(w) \sim L_{hdr}(w)$ for each pixel separately leads to noisy images.
- Select a representative set of directional light sources for a given environment map and use this set for all pixels.

$$L(x, w_o) = \sum_{i=0}^{N-1} B_i V(x, w_i) f_r(w_i, x, w_o) \cos \theta_i$$
Generic Processing Pipeline

Illumination Acquisition → Light Sources Computation → Rendering:
- GPU Techniques
- Ray Tracing
- Monte Carlo Techniques
GPU Rendering with Shadows
Structured Importance Sampling

- A combination of importance and stratified sampling
  - Environment map thresholding according to pixel intensity values and connecting similar regions
    - For the illumination standard deviation $\sigma$ in the map, the thresholds $t_i = i \cdot \sigma$ are selected for $i = 1, ..., d-1$
  - Importance sampling: Assign the number of light samples for each thresholded region based on summed energy of its pixels
    - Small regions with high energy concentration penalized to avoid excessive lights concentration (e.g., in the sun)
  - Stratification: Maximize distance between samples in each coherent region
    - NP-hard k-center problem: Hochbaum-Shmoys approximate algorithm

[Agarval et al., Siggraph 2003]
Importance Metric $\Gamma$

- **Two competing sampling strategies:**
  - Area based stratified sampling
    - Subtended solid angle $\Delta w$ used as the area measure
  - Intensity based importance sampling
    - Integrated pixel energy $L$ used as the intensity measure

\[
\Gamma(L, \Delta w) = L^a \Delta w^b
\]

- **Choice of $a$ and $b$ parameters**
  - $a = 1$ and $b = 0$: intensity importance sampling
    - Oversampling of small bright light sources
  - $a = 0$ and $b = 1$: stratified sampling
    - Undersampling of the small bright light sources
**Importance Metric $\Gamma$**

- **Empirically derived best choice**
  \[ \Delta w_0 = 0.01, \ a = 1 \text{ and } b = \frac{1}{4}: \]
  \[ \Gamma(L, \Delta w) = L \cdot (\min(\Delta w, \Delta w_0))^{1/4} \]
  \[ \Gamma_j = \Gamma(\sum_{i \in C_j} L_i, \sum_{i \in C_j} \Delta \omega_i) \]

- **The number of samples per region $C_j$**
  \[ N_j = N \frac{\Gamma_j}{\Gamma_{4\pi}} \]

- **(a) Map**
- **(b) $a = 0, b = 1$**
- **(c) $a = 1, b = 0$**
- **(d) $a = 1, b = 0.25, t_2$**
- **(e) $a = 1, b = 0.25, t_1$**
- **(f) $a = 1, b = 0.25, t_0$**
Hochbaum-Shmoys Algorithm

- The brightest region is processed first
- The position of once selected samples does not change
Hochbaum-Shmoys Algorithm

- The second brightest region is processed then
- The boundary samples from the brighter region participate in the distance maximization for the darker region
Hochbaum-Shmoys Algorithm

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- The boundary samples from the brighter region participate in the distance maximization for the darker region
Hochbaum-Shmoys Algorithm

- The final sample layout
Results

The Galileo map

Structured importance sampling w/ 300 samples
The two rows of close-ups show the results of (top) stratified importance MC sampling and (bottom) structured imp. sampling.
Lloyd’s Relaxation Algorithm

- Transform $L_{\text{hdr}}$ into a set $(\omega_i, B_i)_{i=0}^{N-1}$ of directional light sources, such that
  \[ L(x, \omega_o) \approx \sum_{i=0}^{N-1} B_i V(x, \omega_i) f_r(\omega_i, x, \omega_o) \langle n(x), \omega_i \rangle \]

- Define the quadrature rule $(\omega_i, B_i)_{i=0}^{N-1}$ by a partition $(\Omega_i)_{i=0}^{N-1}$ of $\Omega$, where
  - radiosities $B_i := \int_{\Omega_i} L_{\text{hdr}}(\omega) d\omega$
  - mass centroidal directions $\omega_i$, i.e.
    \[ \int_{\Omega_i} (\arccos(\langle \omega_i, \omega \rangle))^2 \| L_{\text{hdr}}(\omega) \| d\omega \text{ is minimal} \]

- Choice of Partition $(\Omega_i)_{i=0}^{N-1}$
  - $\max_{0 \leq i < N} \| B_i \|$ as small as possible
    \[ \Rightarrow \text{ limiting error made on each } \Omega_i \]
  - each $\Omega_i$ is the Voronoi region of $\omega_i$ with respect to the set $(\omega_i)_{i=0}^{N-1}$
    \[ \Rightarrow \text{ limiting error when neglecting visibility } V \]
Lloyd’s Relaxation Algorithm

1. Randomly select an initial set \((\omega_i)_{i=0}^{N-1}\) of directions
2. Replace \(\omega_i\) by one of the mass centroidal directions of its Voronoi region \(\Omega_i\)
3. If maximum movement is above threshold \(\theta_T\) go to step 2
4. Compute the weights \((B_i)_{i=0}^{N-1}\)

Lloyd’s relaxation is very sensitive to the initial choice of \(\omega_i\) - the algorithm is often trapped by local minima

**Improved Algorithm**

- Incrementally determine the set \((\omega_i)_{i=0}^{N-1}\) of directions
  - split direction with maximum radiosity (weight)

Adding directional light sources one by one incrementally leads to the much better layout of directional lights on the sphere
Visual Comparison of Lights Layout

Lloyd’s relaxation

Improved algorithm
Visual Comparison of Rendered Images

- Lloyd’s relaxation

  \[ N = 32 \quad N = 64 \quad N = 128 \quad N = 256 \]

- Improved algorithm

  \[ N = 32 \quad N = 64 \quad N = 128 \quad N = 256 \]
Video Environment Maps: Real Time System

HDR camera

12 bit

CPU
22fps

inverse camera response

projection to polar coordinates

light source generation

luminance in [cd/m²]
fisheye projection

GPU
7fps

rendering of VEM

rendering shadow map
BRDF

tone mapping

arbitrary geometry
e.g. animated meshes

display
Natural Lighting Acquisition

- HDR camera (IMS CHIPS)
  - 12bits logarithmic response
  - 8 orders of magnitude dynamic range
- Fish-eye lens
- Resolution 640 x 480
- Photometric calibration possible

http://www.mpi-inf.mpg.de/resources/hdr/calibration
Video Environment Map

- HDR image on hemisphere defined by meridians and parallels
- Extension to time domain
- Luminance corresponds to the probability density function on the hemisphere (grid points)
2D Importance Sampling

Figure 5: Plot of the piecewise-constant sampling distribution for the St. Peter’s environment map (top) and the marginal density function $p_u(u)$ (bottom). First the 1D distribution at the bottom is used to select a $u$ value, giving a column of the image to sample. Columns with bright pixels are more likely to be sampled. Then, given a column, a value $v$ is sampled from that column’s 1D distribution.

For more details refer to: http://pbrt.org/plugins/infinitesample.pdf
Importance Sampling Properties

- Arbitrary number of directional light sources
- The same energy for each light source
- Progressive light source sequence
- Local blue noise properties
- Small memory requirements
- Real-time performance
- Dependence on the surface normal
- Energy and position of light sources processed with FIR filters
- GPU used - NVidia GeForce 6800GT
- Shadow maps tiled in large textures
Mixed Reality Application

- Digitized object rendering
- Real world object
- HDR camera

Realistic Image Synthesis SS15 – Environment Map Sampling