Recovering Real-world Reflectance Properties and Shading from HDR Imagery

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Agenda

1. Introduction
2. Background - Rendering Equation
3. Approach
   a. Microfacet BRDF Model
   b. Lit Diffuse HDR Texture
   c. Shading and Albedo Reconstruction
   d. Specular Appearance Estimation
4. Experiments
   a. Albedo and Shading Validation
   b. Specular Appearance Validation
   c. Relighting
5. Conclusion
Introduction

- Given an HDR video capture, its poses and a 3D reconstruction of the scene:
  - Use HDR textures to estimate albedo and shading per surface element
  - Calculate ideal target frames (TF) for each object in the scene given an object segmentation
  - Use each object's TF to estimate its non-diffuse material

- Enables faithful reconstructions
- Plausible scene relighting
- Visually accurate rendering of virtual objects
Background - Rendering equation

Rendering Equation [Kajiya 1986]

\[ I(p) = L_o(x, \omega_o) = \int_{\mathcal{H}^2} f_r(x, \omega, \omega_o) L(x, \omega) \langle \omega, n \rangle \, d\omega \]

- \( I(p) \): Image at pixel \( p \in \mathbb{R}^2 \)
- \( L_o(x, \omega_o) \): Observed radiance \( L_o \) at \( x \in \mathbb{R}^3 \) in viewing direction \( \omega_o \in \mathcal{H}^2 \)
- \( \mathcal{H}^2 \): Upper hemisphere
- \( f_r \): Bidirectional Reflectance Distribution Function (BRDF)
- \( L \): Incoming radiance at \( x \in \mathbb{R}^3 \) from direction \( \omega \in \mathcal{H}^2 \)
- \( \langle \omega, n \rangle \): Dot-product between incident direction \( \omega \) and surface normal \( n \)
Approach - BRDF

We use a dichromatic BRDF [Shafer 1985], i.e.

\[ f_r(x, \omega, \omega_o) = f_d(x) + f_{nd}(x, \omega, \omega_o) \]

\( f_d(x) \): Albedo \( \rho(x) \) at surface point \( x \in \mathbb{R}^3 \): \( f_d(x; \rho) = \rho(x) \)

\( f_{nd}(x, \omega, \omega_o) \): Non-diffuse microfacet BRDF [Torrance and Sparrow 1967] with parameters roughness \( \varphi \) and specular \( \psi \), \( f_{nd}(x, \omega, \omega_o; \varphi, \psi) \):

\[ f_{nd}(\varphi, \psi) = G(\varphi)D(\varphi)F(\psi) \]

\[ G(\varphi) = G_1(\langle n, \omega \rangle, \varphi)G_1(\langle n, \omega_o \rangle, \varphi); \quad G_1(x, y) = \frac{1}{x + \sqrt{x^2 + y^2 - x^2y^2}} \]

\[ D(\varphi) = \frac{\varphi^2}{\pi(1 + (\varphi^2 - 1)\langle n, h \rangle^2)^2}; \quad h = \frac{\omega + \omega_o}{\|\omega + \omega_o\|} \]

\[ F(\psi) = \psi + (1 - \psi)(1 - \langle \omega, h \rangle)^5 \]
Approach - Reformulation Rendering Equation

Plugging the BRDF model into the rendering equation gives:

\[
L_0(x, \omega_o) = L_d(x) + L_{nd}(x, \omega_o)
\]

\[
L_d(x) = \rho(x) \int_{H^2} L(x, \omega) \langle \omega, n \rangle \, d\omega
\]

\[
L_{nd}(x, \omega_o) = \int_{H^2} f_{nd}(x, \omega, \omega_o; \varphi, \psi) L(x, \omega) \langle \omega, n \rangle \, d\omega
\]

We solve for \( L_d, \rho, \varphi, \) and \( \psi \) for each surface element of a complete indoor scan.
Approach - Proposed Overall Algorithm
Approach - Lit Diffuse HDR Texture $L_d$
Approach - Lit Diffuse HDR Texture $L_d$

Running mean on HDR 16-bit data results in artifacts

Use median instead of mean [Riviere et al. 2016]

- All values have to be stored for median calculation
- => Very expensive, memory demanding, time consuming

=> Estimate an approximation of the median using the P-Square algorithm [Jain and Chlamtac 1985]
Approach - Running Average on HDR data
Approach - Lit Diffuse HDR Texture $L_d$

=>$\text{median texture equals diffuse radiance } L_d, \text{ and we call it } \text{Lit diffuse HDR texture}$

\[\text{Median texture} = L_d = \text{Lit diffuse HDR texture}\]
Approach - Shading and Albedo Reconstruction
Approach - Shading and Albedo Reconstruction

\[
L_0(x, \omega_o) = L_d(x) + L_{nd}(x, \omega_o)
\]

\[
L_d(x) = f_d(x; \rho) \int_{\mathcal{H}^2} L(x, \omega) \langle \omega, n \rangle \, d\omega
\]

\[
L_{nd}(x, \omega_o) = \int_{\mathcal{H}^2} f_{nd}(x, \omega, \omega_o; \varphi, \psi) L(x, \omega) \langle \omega, n \rangle \, d\omega
\]
Approach - Shading and Albedo Reconstruction

\[
\begin{align*}
\overbrace{L_d(x)}^{\text{Median Texture}} &= \overbrace{\rho(x)}^{\text{Albedo}} \cdot \overbrace{S(x)}^{\text{Shading}} \\
S(x) &= \int_{\mathcal{H}^2} L(x, \omega) \langle \omega, n \rangle \, d\omega
\end{align*}
\]

Solve for albedo with

\[
\rho(x) = \frac{L_d(x)}{S(x)}
\]
Approach - Estimate Shading

\[ S(x) = \int_{\mathcal{H}^2} L(x, \omega) \langle \omega, n \rangle \, d\omega \approx \sum_{i=1}^{N} L(x, \omega_i) \langle \omega_i, n \rangle \]

- Cast \( N \) rays \((x, \omega_i), i = 1, \ldots, N\), at each surface point \( x \in \mathbb{R}^3 \) in direction \( \omega_i \in \mathcal{H}^2 \)
- At each rays hitpoint \( \tilde{x}_i \in \mathbb{R}^3 \): \( L(x, \omega_i) = L_d(\tilde{x}_i) \)
Approach - Target Frame Calculation

- HDR video capture + poses
- Object segmentation
- Select Target Frame
- Target Frames
- Calculate Specular Appearance
- Roughness, Specular
- Calculate Albedo
- Lit Diffuse HDR Texture
- Running Median
- Estimate Shading
- Shading
- Albedo

Given Input
Estimated Output
Algorithm
Approach - Target Frame Calculation

Use *only one* target frame for each object

- Less computational complexity
- Fast

Target frame should fulfill:

- $A_1$: High chance of specular highlight caused by direct illumination
- $A_2$: HDR capture consists of valid pixels, i.e. not over-/under-saturated
### Approach - Target Frame Calculation

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>✔</th>
<th>✘ (no specularities)</th>
<th>✔</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_2$</td>
<td>✘ (under-saturated)</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>TF</td>
<td>✘</td>
<td>✘</td>
<td>✔</td>
</tr>
</tbody>
</table>
Approach - Roughness and Specular Estimation
Goal: Estimate i-th object non-diffuse material parameters $\varphi^i, \psi^i$

$$I^i(p) = I^i_d(p) + I^i_{nd}(p; \varphi^i, \psi^i)$$

$$\min_{\varphi^i, \psi^i \in [0,1]} \sum_{p \in \Omega^i} \left\| I^i(p) - (I^i_d(p) + I^i_{nd}(p; \varphi^i, \psi^i)) \right\|^2, \quad \forall i$$

=> Grid search in $\varphi^i$, with nested least squares optimization in $\psi^i$
Experiments

Real-world data set “Replica” [Straub et al. 2019] used for quantitative and qualitative evaluation

Provides:

- Geometry of complete 3D scenes
- HDR video
- Per frame camera poses
- Object instance segmentation
Experiments - Shading and Albedo Validation

Office 3
Input
Albedo
Shading

Room 2
Input
Albedo
Shading
Experiments - Specular Appearance Validation

Lit Diffuse HDR Texture  Proposed  Ground Truth Video Capture
Experiments - Relighting
Conclusion

- Calculate lit diffuse HDR texture
- Calculate albedo and shading per surface element
- Automatically calculate target frame for every object
- Calculate specular appearance parameters for every object