Modeling Anisotropic Surface Reflectance with Example-Based Microfacet Synthesis

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Paper Info

• Modeling Anisotropic Surface Reflectance with Example-Based Microfacet Synthesis

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Goal

• Modeling spatially varying anisotropic reflectance
Anisotropic Reflectance

isotropic

anisotropic
Contributions

• Generality
  – Modeling and acquiring BRDF of a surface (cf. wood, hair, cloth, fur)

• Simplicity
  – *Single-view* acquisition

• Accuracy
  – Results consistent with appearance of real-world samples
BRDF

• Bidirectional reflectance distribution function
• Describes how light is reflected from a surface given:
  – Incoming light direction
  – Outgoing view direction

$$\rho(\mathbf{i}, \mathbf{o}) = \frac{dL_o(\mathbf{o})}{dE_i(\mathbf{i})}$$
SVBRDF

• *Spatially varying BRDF*

• Captures BRDF variation based on spatial location

\[
\rho(x, i, o) = \frac{dL_o(x, o)}{dE_i(x, i)}
\]
Rendering Using BRDF

- Rendering equation

\[ L(x, o) = \int_{\Omega_+(n)} \rho(x, i, o)L(x, i)(i \cdot n)di \]
BRDF Characteristics

• Laws of physics impose two constraints on any BRDF

• Helmholtz reciprocity
  – ‘If I can see you, then you can see me.’
  \[ \rho(i, o) = \rho(o, i) \]

• Conservation of energy
  – Outgoing energy cannot be greater than incoming one
  \[ R(i) = \int_{\Omega_+}(o)(o \cdot n)d\omega \leq 1 \]
Fresnel Reflectance

- Specular reflectance at interface of two materials

\[
F_r = \frac{1}{2} (\rho_{||}^2 + \rho_{\perp}^2)
\]

\[
\rho_{||} = \frac{\eta_2 \cos \theta_1 - \eta_1 \cos \theta_2}{\eta_2 \cos \theta_1 + \eta_1 \cos \theta_2}
\]

\[
\rho_{\perp} = \frac{\eta_1 \cos \theta_1 - \eta_2 \cos \theta_2}{\eta_1 \cos \theta_1 + \eta_2 \cos \theta_2}
\]
BRDF Models

• Purely empirical models
  – Gouraud (1971) and Phong (1975)
  – Controllable with a few intuitive parameters

• More complex models
  – Schlick (1994) for efficiency
  – Ward (1992) to include anisotropy
    • Empirical Gaussian-based model
    • Ignores underlying microstructure
    • Misses details in many real-world materials
  – Lafortune (1997) to enforce reciprocity
Direct Measurement of BRDF

• Alternative approach to acquiring BRDF
  – Gonioreflectometer, light dome, etc.

• Tabulated BRDF
  – Realistic
  – Large data set
  – Difficult to capture
    • Lengthy process
    • Expensive hardware
    • Image registration
Microgeometry

- Surface detail in microscale
  - Too small to be seen directly
  - *Statistical* description of light-scattering effects

- Microscale surface normals (vs. macroscopic surface normal)
  - Produce most important visual effect
Distribution of Surface Normals

• Isotropic
  – Rotational symmetry
  – Lacking any inherent directionality

• Anisotropic

brushed metal  velvet
Shadowing & Masking

- Geometrical effects
  - Another effects of microgeometry on surface reflectance
  - Less important than the distribution of normals itself
Microfacet Theory

• A mathematical analysis of effects of microgeometry on reflectance
  – Torrance and Sparrow (1967)
  – Blinn (1977)
  – Cook and Torrance (1981)

• Models microgeometry as a collection of *microfacets*
  – Tiny, flat Fresnel mirror on surface, with its own normal

\[ l \equiv i \]

\[ v \equiv o \]
Limitation

• Focuses on modeling first-bounce specular reflection
  – No multiple bounces
  – No subsurface scattering

• Suffices for accurately modeling most materials
  – Additional *diffuse* term used for complete BRDF
Half Vector

- Vector pointing exactly halfway between $i$ and $o$
  \[ h = \frac{i + o}{\|i + o\|} \]

- Participating or *active* microfacets given $i$ and $o$
  - Those whose normal is $h$
  - Reflectance depends on the fraction of active microfacets
NDF

• **Normal distribution function**
  – Probability density function: $D(h)$
  – High values in directions where normals are more likely to be pointing
  – Dominates surface appearance
Microfacet-Based BRDF Model

- Cook and Torrance (1981)

\[ \rho(x, i, o) = \rho_d(x, i, o) + k_s(x) \rho_s(x, i, o) \]

- Diffuse term: \( \rho_d(x, i, o) = k_d(x) / \pi \)
- Specular term

\[ \rho_s(x, i, o) = \frac{D(x, h) G(x, i, o) F(x, i, o)}{4(i \cdot n)(o \cdot n)} \]
Geometry Factor

- Accounts for shadowing and masking
  - $0 \leq G(x, i, o) \leq 1$
  - Probability the ray from $i$ is reflected to $o$ without being shadowed or masked at $x$

- Ashikhmin (2000)

$$G(x, i, o) = S(x, i)S(x, o)$$

$$S(x, k) = \frac{(k \cdot n)}{\int_{\Omega_{+}(k) \cap \Omega_{+}(n)} (h \cdot k)D(x, h)dh} \quad (k = i, o)$$

$\leftarrow$ completed determined by NDF
Final SVBRDF Model

- Microfacet-based SVBRDF model

\[ \rho(x, i, o) = \frac{k_d(x)}{\pi} + k_s(x) \frac{D(x, h)S(x, i)S(x, o)F(x, i, o)}{4(i \cdot n)(o \cdot n)} \]

- Shadowing function

\[ S(x, k) = \frac{(k \cdot n)}{\int_{\Omega_+(k) \cap \Omega_+(n)} (h \cdot k)D(x, h)dh} \quad (k = i, o) \]
Overall Procedure

Setting Up BRDF Model

Measuring BRDF

Fitting and Completing NDF

\[
\rho(x, i, o) = \frac{k_d(x)}{\pi} + k_s(x) \frac{D(x, h)S(x, i)S(x, o)F(x, i, o)}{4(i \cdot n)(o \cdot n)}
\]
BRDF Acquisition
Capturing Process
Reflectance Data Acquisition

- Product of capturing process
  - BRDF sample $\rho(x, i, o)$
    - At every $x$
    - Densely sampled $i$
    - Approximately constant $o$
NDF Fitting

• Obtaining NDF from specular BRDF data
  – By iterative updates
  – Specular term
    \[ \tilde{\rho}_s(x, i, o) = \frac{D(x, h)S(x, i)S(x, o)F(x, i, o)}{4(i \cdot n)(o \cdot n)} \]
  – Shadowing function
    \[ S(x, k) = \frac{(k \cdot n)}{\int_{\Omega_+(k) \cap \Omega_+(n)} (h \cdot k)D(x, h)dh} \quad (k = i, o) \]

• Partial domain and bias problem
Partial NDF

- Obtained NDF covers only a subregion of $\Omega_+(n)$

example-based microfacet synthesis
Biased Estimation

\[ \tilde{\rho}_s(x, i, o) = \frac{D(x, h)S(x, i)S(x, o)F(x, i, o)}{4(i \cdot n)(o \cdot n)} \]

\[ S(x, k) = \frac{(k \cdot n)}{\int_{\Omega_+(k) \cap \Omega_+(n)} (h \cdot k)d\mathbf{h}} \]
Remedy for Bias

- Minimizing the bias
  - Isotropically constrain shadowing function in each iteration

[Diagram showing the effect of constraint on shadowing function]
Recovered Partial NDF

ground truth

Ngan (2005)

Wang (2008)
Completing NDF

• Key observation
  – Many surface points share similar NDF (but in different, i.e. rotated, local frame)
Example-Based Microfacet Synthesis
NDF Synthesis

- partial NDF to complete
- merged partial NDFs
- completed NDF
Synthesis Procedure

For each surface point $\mathbf{x}$

$$D_0(\mathbf{x}) = D(\mathbf{x})$$

$$\Omega_0(\mathbf{x}) = \Omega(\mathbf{x})$$

While $\Omega_i(x) \not\subset \Omega_+$

$$(\mathbf{x}', \varphi') = \text{argmin}_{\tilde{x}, \tilde{\varphi}} \{ \| D \tilde{\varphi}(\tilde{x}) - D_i(\mathbf{x}) \| \}$$

$$D_{i+1}(\mathbf{x}) = \text{merge}[D_i(\mathbf{x}), D\varphi'(\mathbf{x}')]$$
Synthesis Acceleration

• Search Pruning
  – To accelerate the search by pruning the set of candidates
  – Idea
    • NDF domain is extended azimuthally => the overlap region is mostly determined by the candidate merged last and the current candidate (overlap region : \( \Omega(\phi) = \Omega \cap R(\phi) \Omega \)
Synthesis Acceleration (con’t)

• Search Pruning
  – Idea
    • Since the candidates have a 50~85% overlap with \( D_i(x) \), \( \varphi \) need to be chosen in a limited range. 
      \[
      \text{result : } \{ \Omega(\varphi_i) \mid i = 1, 2, \ldots, n_\Phi \}
      \]
    • Within each \( \Omega(\varphi_i) \), compute the histogram of \( D(x,h) \) at each surface point \( x \) using \( m=32 \) buckets. (\( D \)'s range \([0,1]\))
    • Use 32D vector as a search key to find merge candidates
    • To find quickly, precompute an ANN tree before synthesis
Synthesis Acceleration (con’t)

• NDF Clustering
  – To reduce both the number of NDFs that must be synthesized and searched.
  – Idea
    • To find the representatives applying k-means clustering to the partial NDFs of all surface points.
    • Representative in each cluster is closest to the cluster center.
    • The number of representatives set to be 1% of the number of surface points
    • Ensure each cluster contains only similar samples
Synthesis Acceleration (con’t)

• NDF Clustering
  – Idea
    • Find interpolation weights on the partial data.

\[ D(x_i, h) = \sum_{j \in N_i} w_{ij} D(x_{i^*}, h), \]

  – \( D(x_i, h) \): (non-representative) partial NDF
  – \( D(x_{i^*}, h) \): neighbor representatives
  – \( j \in N_i \): indexes of the neighbor representatives of \( x_i \)
    » k=16 nearest representatives, excluding those whose distance < 5\( \lambda \)
    (\( \lambda \): smallest distance between 2 representative NDFs)
  – \( w_{ij} \): interpolation coefficients
    » \( \sum_{j \in N_i} w_{ij} = 1 \)
Experimental Results

- Full 6D SVBRDF data as well as 4D
- Fixed-view data slices captured with simple device

<table>
<thead>
<tr>
<th>Sample</th>
<th>Image Res.</th>
<th>Light Res.</th>
<th>NDF Res.</th>
<th>View (θ, φ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>red satin</td>
<td>850×850</td>
<td>20×24</td>
<td>32×32</td>
<td>(57.6°, 0.6°)</td>
</tr>
<tr>
<td>yellow satin</td>
<td>750×750</td>
<td>20×24</td>
<td>32×32</td>
<td>(58.3°, -0.2°)</td>
</tr>
<tr>
<td>wallpaper</td>
<td>800×800</td>
<td>20×20</td>
<td>32×32</td>
<td>(63.6°, -0.8°)</td>
</tr>
<tr>
<td>velvet</td>
<td>600×500</td>
<td>20×20</td>
<td>32×32</td>
<td>(61.2°, 2.1°)</td>
</tr>
<tr>
<td>rose wood</td>
<td>600×600</td>
<td>40×65</td>
<td>32×32</td>
<td>(53.3°, 4.6°)</td>
</tr>
<tr>
<td>oak wood</td>
<td>800×800</td>
<td>40×65</td>
<td>32×32</td>
<td>(48.6°, -0.3°)</td>
</tr>
<tr>
<td>aluminium</td>
<td>250×400</td>
<td>40×65</td>
<td>128×128</td>
<td>(40.8°, 4.9°)</td>
</tr>
<tr>
<td>copper</td>
<td>800×800</td>
<td>40×50</td>
<td>32×32</td>
<td>(51.0°, 1.9°)</td>
</tr>
</tbody>
</table>
Experimental Results (con’t)

• PC specification
  – Intel Core™2 Quad 2.13GHz
  – 4GB memory

• Capturing time
  – About 1 hour using single-exposure acquisition (for less specular materials like velvet)
  – About 5-10 hours using multiple-exposure acquisition (for highly specular materials like aluminum)
Experimental Results (con’t)

• Image Data Processing
  – 2~4 hours
  – It is dominated by disk I/O

• Microfacet synthesis algorithm
  – Partial NDF reconstruction takes about 1 hour
  – Synthesis takes 2~3 hours
  – Estimation of the remaining BRDF parameter takes 3~4 hours
  – Results using only ray tracing, and direct lighting effect
Experimental Results (con’t)

• Validation with Dense-View Data

(a) (b) (c)

(d) (e) (f)

(g) (h)
Experimental Results (con’t)

- Results with Single-View data
  - (1), (3) : original sample
  - (2), (4) : rendered by synthesized model
  - (a) : yellow satin
  - (b) : brushed aluminum
  - (c) : oak
Experimental Results (con’t)

- Results with Single-View data
  - Synthesized microfacet model VS fitted Ward model
    - (a) : real measured appearance, (b) Synthesized model
      (c) : isotropic Ward, (d) : anisotropic Ward
Experimental Results (con’t)

- Results with Single View-data
  - (a) weathered copper, (b) brushed aluminum
  - (c) oak wood, (d) rose wood
Experimental Results (con’t)
Conclusions

• Pros
  – High resolution (spatial & angular), realistic result
  – To avoid image registration
  – Easier data acquisition and processing
    • Single-view capture
    • Cheap device
    • Shorter capturing time

• Cons
  – Does not capture unusual phenomena dominated by multiple light bounces, such as retro-reflection
Future Works

• Further optimizing in performance
  – Data capture, synthesis, and parameter estimation algorithms
• To handle samples that are not flat
• Generalizing to capture translucent objects and multiple bounce effects
Thank You