

Un modèle de BRDF bi-échelle combinant : Diffraction et Micro-facettes

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Un modèle de BRDF bi-échelle combinant Diffraction et Micro-facettes

Nicolas Holzschuch & Romain Pacanowski

Journée "Tout sur les BRDF" Poitiers 15 Juin 2017

Realistic Image Synthesis



Realistic Image Synthesis



Realistic Image Synthesis



3

Lots of BRDF Models



Few BRDF Measurements Database

- MERL Data Base:
 - 100 materials
 - 2 versions: 2003 and 2006



Cornell





BRDF Model comparisons

Study of fitting capabilities of BRDF Models [Ngan2005]



Winners: Cook-Torrance [1982] and A simplified version of He et al. [1991]

Microfacet Theory

- Good prediction of Specular peak
- Less Good for low values



Microfacet Theory

- Good prediction of Specular peak
- Less Good for low values

- Common solution:
 - To add a constant or diffuse term
 - For subsurface scattering behavior of the material
 - To add new lobes ==> No Physical Reality



$\lambda = 3,39$ microns

$\lambda = 10,6$ microns



Grit-Blasted Nickel

[Butler et al. 2015] (SPIE Imaging Spectrometry)

Observations on Measurements

Specular lobe

Wavelengths light Dependency

⇒ Contradicts Microfacet Theory

Microfacet Hypothesis



- Microfacet: Perfect Mirror with a Fresnel Coefficient
- Microfacet $\gg \lambda =$ light wavelength
 - Geometrical Optics
- Fresnel is the only wavelength dependent term
- How can we model this phenomenon?

Two-Scale Reflectance Model



Two-Scale Reflectance Model



Two-Scale Reflectance Model





Wave Optics, Diffraction:

- Necessary to model Scattering of small scale surface
- Reflectance depends on wavelength

Surface Characteristics



 σ_s : RMS of the surface roughness

l: autocovariance length

Angular Wideness





Angular Wideness

Rayleigh-Rice [Löw 2012]





Angular Wideness

Rayleigh-Rice [Löw 2012]

Beckman-Kirchoff. [He 91, Stam 99]

Smooth

Rough

Angular Wideness

Rayleigh-Rice [Löw 2012]

Harvey-Shack [HK 1975]

Beckman-Kirchoff. [He 91, Stam 99]

Smooth

Rough







All Theories: **SINGLE** Scattering ONLY

Generalized Harvey-Shack

- Gaussian Surface Profile
- Arbitrary Autocovariance
 Function

 \Rightarrow Our Model utilizes it

Modified Beckman-Kirchoff

Gaussian Surface Profile

Gaussian Autocovariance
 Function

Main Idea: Surface = Transfer Function on the incident wave



i

BRDF: Specular Peak (Dirac) + Diffraction Lobe

2

BRDF: Specular Peak (Dirac) + Diffraction Lobe

$\rho(i,o) = Fresnel(i,o) \left[A\delta(refl(i),o) + (1-A) \underbrace{\mathcal{F}_{|x,y}\{C(x,y,i,o)\}}_{} \right]$

2D Fourier Transform

BRDF: Specular Peak (Dirac) + Diffraction Lobe

$\rho(i, o) = Fresnel(i, o) \left[A\delta(refl(i), o) + (1 - A) \mathcal{F}_{|x,y} \{ C(x, y, i, o) \} \right]$ 2D Fourier Transform

$$\mathcal{F}_{|x,y}\{C(x,y,i,o)\}: \text{Fourier Transform per light and view}$$
$$C(x,y,i,o) \propto AutoCovariance(x,y) C'(i,o)$$
$$A = exp\{-(2\pi(\cos\theta_i + \cos\theta_o)\frac{\sigma_s}{\lambda})^2\}$$

Summary on Generalized Harvey-Shack



$$\rho(i,o) = \dots(1-A) \mathcal{F}\{G(x,y,i,o)\}$$
$$-\left(2\pi(\cos\theta_i + \cos\theta_o)\frac{\sigma_s}{\lambda}\right)^2$$
$$A = e^{-\left(2\pi(\cos\theta_i + \cos\theta_o)\frac{\sigma_s}{\lambda}\right)^2}$$

- Valid for all roughness and all angles
- Reflectance Depends on Wavelength
- BUT ...
- Fourier Transform per directions



Diffraction into our Two-Scale Model

• Hypotheses

- Micro-geometry: ROUGH
- Nano-geometry: SMOOTH
- \Rightarrow GHS simplifies a bit



Each Microfacet is a diffractive element

• Final BRDF :

Convolution of Diffractive Elements with Micro-geometry

 $\rho(i,o) = Fresnel \left[A \,\delta(refl(i),o) + (1-A) \,\mathcal{F}\{C(x,y,i,o)\} \right]$

 $\rho(i,o) = Fresnel \left[A \,\delta(refl(i),o) + (1-A) \,\mathcal{F}\{C(x,y,i,o)\} \right]$

• Fourier Transform depends only on the surface

 $\rho(i,o) = Fresnel \left[A \,\delta(refl(i),o) + (1-A) \,\mathcal{F}\{C(x,y,i,o)\} \right]$

 Fourier Transform depends only on the surface



 $\mathcal{F}\{C(x,y)\}: PSD(Surface) \approx \text{K-Correlation}(\sigma_s, f)$ $||\mathbf{f}|| = \frac{2}{\lambda}\sin\theta_h\cos\theta_d$

 $\rho(i,o) = Fresnel \left[A \,\delta(refl(i),o) + (1-A) \,\mathcal{F}\{C(x,y,i,o)\} \right]$

 Fourier Transform depends only on the surface

refl(i)

$$\lambda f$$

 $\mathcal{F}\{C(x,y)\}: PSD(Surface) \approx \text{K-Correlation}(\sigma_s, f)$ $||\mathbf{f}|| = \frac{2}{\lambda}\sin\theta_h\cos\theta_d$

• f ⇔ Alternative Parametrization [Barla et al. Mam 2015]
Renormalization of the Diffraction Lobe

 $\mathcal{F}{C(x,y)} \approx \text{K-Correlation}(\sigma_s, \mathbf{f})$

$$\sigma_s^2 = \iint \text{K-Correlation}(\sigma_s, \mathbf{f}) \, df$$



Renormalization of the Diffraction Lobe

 $\mathcal{F}\{C(x,y)\} \approx \text{K-Correlation}(\sigma_s, \mathbf{f})$ • Renormalization $\sigma_s^2 = \iint \text{K-Correlation}(\sigma_s, \mathbf{f}) \, df$



- Enforce Energy repartition between dirac and diffraction [Harvey2012]
- Comes from the Autocovariance Function Property
- Precomputed for a large range of values: 8.9MB

Diffraction into our Two-Scale Model

- Microfacet Framework [Walter2007]
- Convolution of a Microfacet BRDF



Diffraction into our Two-Scale Model



Diffraction into our Two-Scale Model



• In Our Case, Smooth Diffractive Microfacet: $\rho_m(i, o, m) = Fresnel \left[A \,\delta(refl(i), o) + (1 - A) \, K_{\sigma_s}(f) \right]$

$\rho(i,o) = \int_{\Omega_m} Fresnel(i,o) \Big[A \,\delta(refl(i),o) + (1-A) \,K_{\sigma_s}(f) \Big] G(i,o) D(m) \,d\omega_m$

$$\rho(i,o) = \int_{\Omega_m} Fresnel(i,o) \Big[A \,\delta(refl(i),o) + (1-A) \,K_{\sigma_s}(f) \Big] G(i,o) D(m) \,d\omega_m$$

$$\rho(i, o) = \int_{\Omega_m} Fresnel(i, o) A \,\delta(refl(i), o) G(i, o) D(m) \,d\omega_m$$

Microfacet-based BRDF
$$+ \int_{\Omega_m} Fresnel(i, o) (1 - A) K_{\sigma_s}(f) G(i, o) D(m) \,d\omega_m$$

Diffraction Part

$$\rho(i,o) = \int_{\Omega_m} Fresnel(i,o) \Big[A \,\delta(refl(i),o) + (1-A) \,K_{\sigma_s}(f) \Big] G(i,o) D(m) \,d\omega_m$$

$$\rho(i, o) = \frac{Fresnel(i, o)D(\theta_h)G(i, o)}{4\pi \cos \theta_i \cos \theta_o}$$

$$+ \int_{\Omega_m} Fresnel(i,o) (1-A) K_{\sigma_s}(f) G(i,o) D(m) d\omega_m$$

Diffraction Part

 $\rho_{ghs}(i,o) = \int_{\Omega_m} Fr(i,o) \left(1 - A_{\sigma_s}(i,o)\right) K_{\sigma_s}(f) G(i,o) D(m) \, d\omega_m$



$$\rho_{ghs}(i,o) \approx Fr\left(1-A\right)G(i,o) \int K_{\sigma_s}(f) \ D(m) \ (h \cdot m)^2 \ d\omega_m$$

$$f = 2 \cos\theta_d \sqrt{(1-(h \cdot m)^2)} \qquad Convolution \approx K' \ (f)$$

Convolution Computation

- Product of Zonal Harmonics. 100 Coefficients
- Result is a new K-Correlation Function
- 4D Table Precomputed

- Parameters : $\frac{\cos \theta_d}{\lambda}$, D(m) and K-Correlation Model

Our Model for Conductor

Combination of a Specular Lobe and Diffractive Lobe

$$\rho(i,o) = A_{\sigma_s}(\theta_d) \underbrace{\rho_{epd}(i,o)}_{} + \underbrace{\rho_{ghs}(i,o)}_{}$$

specular diffraction

Specular Lobe: Exponential Power Disbribution (EPD)

$$epd(x) = \frac{p}{\pi\beta^2\Gamma(1/p)} e^{-(x/\beta^2)^p}$$

Exponential Power Distribution NDF

- Generalization of Gaussian Distribution
 - Kurtosis control
 - Similar to [Brady2014]
- Analytical Importance Sampling
 - Distribution only
- Shadowing Term
 - Precomputed for large range of possible values for the parameters
 - 390 KB 2D Array



Parameters of the Model

Diffraction Lobe

RMS of Surface Roughness : 1 Index of Refraction : 2 per wavelength K-correlation Model : 2 parameters

Specular Lobe

 β : Width p: Kurtosis

Diffraction Parameters Behaviour



 $\sigma_s imes 3, b/3$

 $\sigma_s \times 1, b \times 1$

 $\sigma_s \times 4, b \times 4$

Specular Lobe Behavior



 $\beta \times 4$

 $\beta \times 1$

 $\beta/4$

Diffraction parameters remain unchanged

Comparison for Nickel



Comparison for Alum-Bronze



Difference

Reference

Fitting Results outside the Incident Plane



blue-metallic-paint2





Löw et al. (diffraction only)

SGD (microfacet only)

Lobe width variation



Extension for Plastic Material





• Diffuse Part: Model from [Weidlich et Wilkie 2007]

Conductor Part: Real Index of Refraction

Results for Plastic Model

• Varnish on a diffuse surface:



Gray-Plastic Material



Reference

Fitting Results in Incident Plane





Gray-plastic

Fitting Results outside Incident Plane







Löw et al. (diffraction only)

Two-Layer Model for Subsurface



 $\rho_{subsurface}(i,o) = \rho_{conductor}(i,o) + \rho_{single}(i,o) + \rho_{multi}(i,o)$

Subsurface Model from Jensen et al. Sigg. 2001

Result for Subsurface Model





Microfacet



Diffuse



Alumina-oxide Material





Result for Subsurface Model

ALUMINA-OXYDE



1.5

-1

0.5

Result for Subsurface Model

ALUMINA-OXYDE



RMS Error of BRDF * cosine

Fitting Strategy

• Similar to Bagher et al. 2016

- Compressive Weights ⇔ less weight on high values
- Measurement Apparatus Compensation
- One Pass of all parameters
- Approx. 10 minutes on 2.6 GHz Intel i7
 - C++. Levenberg-Marquardt impl. Lourakis

General Fitting Comparisons



Rendering Comparions : SMAPE Metric



Rendering Comparions : SMAPE Metric



Bad Fits:

Pink Plastic

Pink Felt

Gold-Metallic Paint 2



Merl Data Reference



Our Model

Gold-Metallic Paint 2



Merl Data Reference

Our Model Difference sMAPE:0.048

Gold Metallic Paint2



Merl Data Reference



Löw Model
Gold Metallic Paint2





Merl Data Reference

Löw Model Diff. sMAPE: 0.148

Gold Metallic Paint2





Our Model Difference sMAPE:0.048

Löw Model Diff. sMAPE: 0.148

Regarding He et al. Model

- Based on Beckman-Kirchoff Diffraction
 - Our implementation and fitting
- Overall POOR Results
 - Better:
 - Fitting: 3 materials
 - Rendering: 4 materials
- Different from Ngan et al. results

Yellow Mate Plastic



Number of parameters

MODEL	NUMBER OF PARAMETERS	DIFFRACTION THEORY
Our Model	11	Hybrid Harvey-Shack
Exponential Distribution and Lambert	11	None
Shifted Gamma Distribution	18	None
He et al. Model	11	Beckman - Kirchoff
Löw et al. Smooth	9	Inspired from Rayleigh-Rice

Conclusion

Our two-scale model:

- Better explanation of Measured Data
 - Lobe Size/Width depends on Wavelength
- Micro-facet Theory: Specular Peak
- Limitations:
 - No multi-bounces
 - One Layer of Diffraction

Future Work

Multiple Scattering and Diffraction



Multi-Layers and Diffraction



+ polarisation ?

Future Work

- Using Diffraction as shading "enhancer"
 - Virtual transformation of a non-metallic surface
- Anisotropic Version of the Model
- A unified Representation
 - PSD for Nano-facet, Normal Distribution for Micro-facet
- Further Validation with precise Measurements:
 - Surface height-field
 - Wavelength BRDF

Future Work

• Further Validation with precise Measurements:

- Surface height-field
- Wavelength BRDF

Thank you for your attention

More on Microfacet convolution

 $\rho_{ghs}(i,o) = \int_{\Omega_m} Fr(i,o) \left(1 - A_{\sigma_s}(i,o)\right) K_{\sigma_s}(f) G(i,o) D(m) \, d\omega_m$

• Second: Geometrical Term $(1 - A_{\sigma_s}(i, o)) = 1 - e^{-\left(2\pi \frac{\sigma_s}{\lambda}(\cos \theta_i + \cos \theta_o)\right)}$ $(1 - A_{\sigma_s}(i, o)) \approx (1 - A_{\sigma_s}(\theta_d))(h \cdot m)^2$



 $h \cdot m$

More on Microfacet convolution

$$(1 - A_{\sigma_s}(i, o)) \approx (1 - A_{\sigma_s}(\theta_d))(h \cdot m)^2$$



h·m

Fresnel and Polarization Factor Q

- Q is NOT the Fresnel Term
- Q comes from Rayleigh-Rice Theory
- For Perfect Specular direction Q = 2 Fresnel_Coefficient
- Q is re-introduced into GHS empirically for comparisons