Spring Conference on Computer Graphics
SCCG 2008

in cooperation with
Eurographics and ACM SIGGRAPH

Conference Materials and Posters

Budmerice
April 21 - 23, 2008

Publisher: Comenius University, Bratislava
Editor: Martin Samuelčík
Cover page & logo design: Matej Novotný, Jozef Martinka
Production: Martin Samuelčík

Webpage: http://www.sccg.sk

ISSN: 1335 - 5694

International Programme Committee

IPC chairman
Prof. Karol Myszkowski
Max-Planck Institute for Informatics,
Germany

Jeroen van Baar
Sebastiano Battiato
Alexander Belyaev
Bedřich Beneš
Peter Birkholz
David Breen
Jiří Bittner
Alan Chalmers
Pavel Chalmovianský
Ján Cíger
Silvester Czanner
Miguel Chover
Roman Ďurikovič
Miquel Feixas
Petr Felkel
Andrej Ferko
Franca Giannini
Markus Grabner
Helwig Hauser
Vlastimil Havran
Bert Jüttler
Maxim Kazakov
Ivana Kolingerova
Rafal Mantiuk
Simone Marini
Karol Myszkowski
László Neumann
Alexander Pasko
Giuseppe Patanè
Bernard Péroche
Tomas Plachetka
Werner Purgathofer
Przemyslaw Rokita
Mateu Sbert
Benjamin Schmitt
Peter Shirley
Pavel Slavík
Martin Šperka
Daniel Thalmann
Petr Vaneček
Ivan Viola
Michael Wimmer
Pavel Zemčík
Borut Žalik
Jiří Žára

List of Reviewers

Jeroen van Baar
Sebastiano Battiato
Alexander Belyaev
Bedřich Beneš
Peter Birkholz
David Breen
Jiří Bittner
Pavel Chalmovianský
Ján Cíger
Silvester Czanner
Miguel Chover
Piotr Didyk
Roman Ďurikovič
Miquel Feixas
Petr Felkel
Andrej Ferko
Franca Giannini
Markus Grabner
Thorsten Grosch
Helwig Hauser
Vlastimil Havran
Matthias Hullin
Matthias Ihrke
Bert Jüttler
Maxim Kazakov
Ivana Kolingerova
Rafal Mantiuk
Simone Marini
Karol Myszkowski
Alexander Pasko
Giuseppe Patanè
Tomas Plachetka
Werner Purgathofer
Tobias Ritschel
Przemyslaw Rokita
Mateu Sbert
Benjamin Schmitt
Peter Shirley
Elena Šikudová
Pavel Slavík
Martin Šperka
Kateřina Tátraiová
Daniel Thalmann
Zsolt Tóth
Petr Vaneček
Ivan Viola
Michael Wimmer
Pavel Zemčík
Borut Žalik
Jiří Žára

Overview of Contemporary BRDF Models Focused on Car Paint Simulation

Robert Smetana*
Comenius University

Roman Ďurikovič †
Comenius University

Abstract

Our aim in this paper is to review some of the newest BRDF models used in car paint simulation. We give the basic equations and summarize the input parameters that should help us to easily spot the parameters that can be measured by conventional measurement devices.

Keywords: BRDF, Reflection, Car Paint, Model, Review

1 Introduction

Today's computer graphics give a new standard to realistic rendering. Models are required to compute with large numbers of parameters and operate in real time intervals to deliver a more genuine look. Such requirements can hardly be met by traditional simulation techniques often focusing solely on one appearance aspect. Luckily there are many new methods being developed, that can simulate highly complex materials like car paints and industrial coatings, which are able to operate with substantial quantities of data. These new models incorporate both macro- and micro- scale reflections and often consist of multiple functions simulating different parts of the overall effect. By combining several approaches a model can prosper from the strengths of both, but perhaps also inherit some weaknesses. We find it important to give a broader view of similar models used in industry today.
A Bidirectional Reflectance Distribution Function (BRDF) is essentially a simplified general reflectance function which describes the most general case of photon interaction with a given material. In this general function each photon is described by six parameters (the position on the surface (x,y), the incident/outgoing direction (ω_i, ω_o) the time of interaction t and a specific wavelength λ). Since in the general case the incoming and outgoing photons are not the same this creates a 12D function. Some of these parameters are not necessary for realistic simulation of car paint because the material interacts with light in a limited number of ways. This observation enables us to make some assumptions about the environment and also exclude those properties of light which will not affect visualization. We may drop the dependency on time assuming our car paint does not change over the time period we are working with. Furthermore, we can neglect fluorescence and phosphorescence effects as they don't occur in standard paints. Another step is to represent wavelength by only three bands – red, green and blue instead of the whole spectrum. This now produces an 8 dimensional Bidirectional Scattering Surface Reflectance Distribution Function (BSSRDF). To obtain a 6D function it is possible to either ignore the effect of subsurface scattering, then the light is entering and leaving the surface at exactly the same position resulting in a spatially varying BRDF (SVBRDF), or to assume that the material is homogenous. If both simplifications are made the result is a homogenous 4D BRDF.
Car paint simulation is a quite challenging problem because the materials used today show not only interesting and subtle angular dependency but also significant spatial variation. Especially in sunlight these variations remain visible up to a few meters and give the coating a strong impression of depth which cannot be reproduced by a single BRDF model or the kind of procedural noise textures typically used.

2 The Models

It is important to note that the first three of these models work mostly with one layer of metallic paint – the basecoat, while the last one is designed for two layers each with one type of particles.
Typical metallic car paint is composed of different layers. On the top is the clear coat which is a 20 μm thick layer of resin that has the same index of refraction as the layer with pigment and flakes. The only important factor here is the interface between the air and clear coat that is simulated by Fresnels formulae for dielectrics. The lowermost layer is the so called substrate. At modern cars this is an electroplated layer of tin (as corrosion prevention) covered by a primer made of polished white or light gray powder. The main layer of the paint, we call it basecoat, is applied between them as shown on figure 1. It consists of binder with color pigments that cause scattering and absorption of incoming light. In the case of metallic paints there are also a large number of disc like metallic particles – flakes mixed into this layer. In particular in sunlight these flakes remain prominently visible even for distances in the range of meters. The diameter of the flake particles is usually larger than the thickness of the basecoat layer. [Rump et al. 2008] An extension to metallic paints are the pearlescent paints (or so called "flip-flop" paints) where the flakes are covered with half transparent layers of mostly metal oxides. These coatings lead to cancellation of certain wavelengths depending on the viewing angle which results in color shifts dependent on the view and light directions.

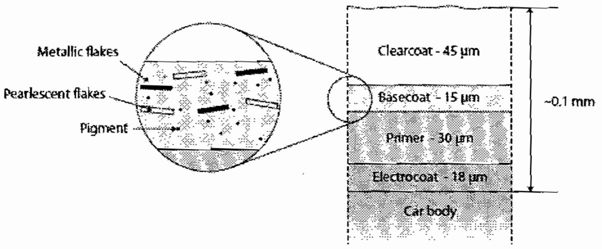

Figure 1: Scheme illustrating the layers inside a metallic paint with multiple types of flakes

The appearance attributes of metallic and pearlescent paints can be

---

*e-mail: robert.smetana@gmail.com

†e-mail: durikovic@fmph.uniba.sk

categorized into two kinds, those observed at a distance of several meters and those observed at less than a meter, so called macro- and micro- appearance, respectively. McCamy [McCamy 1996] in his comprehensive review introduces the following main macro-appearance attributes: shade, glitter and gloss. The shade attribute is the color of the paint under ambient illumination. Glitter is a micro-appearance attribute describing the appearance of bright or colored reflection near the specular angle allowing metallic coating to enhance curvature of surfaces and gloss is the appearance of bright reflection at the specular angle.

2.1 Rump et al. model

For the first example we chose the well-known Cook-Torrance BRDF model in its multilobe version. It has been very recently used in an interesting hybrid concept to represent the homogeneous BRDF part of the car paint. With only the analytical approach to car paint modeling it is very difficult to fit the numerous measured parameters needed to achieve a proper result. Similarly, only by interpolating the photographed textures of paint using BTF the result will show many defects, most noticeably a blurred specular reflection. The authors of paper [Rump et al. 2008] propose to use image-based reflectance measurements of real paint samples and represent their spatial varying part by Bidirectional Texture Functions (BTF) instead of explicitly modeling the responsible effect particles. Data for both parts are measured simultaneously using a BTF measurment device. Their method divides the rendering problem in two parts. First part focuses only on macro-scale reflection behavior of the base and the top layer of the paint. This is the part modeled where lobe-based BRDF is used to represent the reflection behavior of the base paint and the highly specular finish. The second part is the spatially varying BTF describing effects caused by alluminium flakes.
Cook-Torrance formula used in this paper:

$$\rho_X(\omega_i,\omega_o) = \frac{k_d}{\pi} + \sum_{l=1}^{K} k_{s_l} \frac{F_{t_l} D_{r_l} G}{\pi \sin\theta_i \cos\theta_o} \tag{1}$$

Here k_d is the diffuse intensity. k_{s_l} , r_l and t_l are the per-lobe specular coefficient, the distribution exponent and the Fresnel parameter respectively. K is the number of lobes (we use 2-3 lobes), for the microfacet distribution D we use standard Blinn-Phong and the geometric attenuation term G is from the original paper [Cook and Torrance 1981]. X denotes the whole set of parameters. While the model is well suited for modeling the glossy and specular lobes of uniformly colored car paint it has difficulties with the flip-flop effect present in pearlescent paint.

2.2 Ashikhmin et al. model

The older Ashikhmin model [Ashikhmin et al. 2000] follows the approach of Torrance and Sparrow original microfacet theory [Torrance and Sparrow 1922], but introducing the probability of a microfacet not to be shadowed, which achieves very good results in simulating surfaces whose primary characteristic is the shape of the specular highlight. Using this model does not require much hand tuning of parameters because the diffuse term and energy conservation are handled in a natural manner. However, for surfaces whose appearance is not dominated by the specular highlight, this model is not well-suited.

$$\rho(\mathbf{k_1},\mathbf{k_2}) = \frac{p(\mathbf{h})P(\mathbf{k_1},\mathbf{k_2},\mathbf{h})F((\mathbf{kh}))}{4(\mathbf{k_1}\cdot n)(\mathbf{k_2}\cdot n)\langle(\mathbf{n}\cdot\mathbf{h})P(\mathbf{n},\mathbf{h})\rangle} \tag{2}$$

Where

$(\mathbf{ab})$	scalar (dot) product of vectors **a** and **b**
$\mathbf{k_1}$	normalized vector to light
$\mathbf{k_2}$	normalized vector to viewer
$\mathbf{n}$	surface normal to macroscopic surface
$\rho(\mathbf{k_1},\mathbf{k_2})$	BRDF
$\mathbf{h}$	normalized half-vector between $\mathbf{k_1}$ and $\mathbf{k_2}$
$p(\mathbf{h})$	probability density function of microfacet normals
$F(\cos\theta)$	Fresnel reflectance for incident angle θ
$P(\mathbf{k_1},\mathbf{k_2},\mathbf{h})$	Probability that light from $\mathbf{k_1}$ reflecting in direction $\mathbf{k_2}$ is not shadowed
$\langle f \rangle$	average of function f over distribution $p(\mathbf{h})$

2.3 Ďurikovič et al. model

Third BRDF model is based on microfacet theory similar to that of Ashikhmin, but which also takes into account the subsurface scattering of the pigmented layer. In article "Prediction of optical properties of paints" [Ďurikovič and Ágošton 2007] authors design a theoretical model with unique combination of real parameters based on which they are able to predict the appearance of measured paints in artificial environments. The CookTorrance model [Cook and Torrance 1981] is physically based and has shown to perform well with many materials [Ngan et al. 2005]. In its multilobe form, the Cook-Torrance BRDF can be used as a reflectance model, including all components such as clear coat reflectance, pigment layer reflectance, and reflectance of metallic and pearl flakes. Some of the parameters are derived from Kubelka and Munk's theory [Kubelka and Munk 1931], which is well suited for calculating the reflectance within one layer of paint with multiple types of particles present. The composite BRDF f_r of the car coating for given incoming direction ω_i and outgoing direction ω_o can be expressed:

$$f_r(x,\omega_i,\omega_o) = \rho + \tau \quad (1 - A_m - A_p)R_l + \frac{(A_m \cdot R_m)D_m G}{\pi(\mathbf{n}\cdot\omega_i)(\mathbf{n}\cdot\omega_o)} + \frac{(A_p R_p)D_p G}{\pi(\mathbf{n}\cdot\omega_i)(\mathbf{n}\cdot\omega_o)} \tag{3}$$

where ρ and τ are the reflectance and transmittance of the clear coat, respectively; A_m and A_p are the area ratio of visible metallic and pearlescent flakes, respectively; R_l is the reflectance of the pigmented layer; R_m and R_p are the reflectance of metallic and pearlescent flakes embedded in the pigmented layer, respectively; D_m and D_p are the angular distributions of the metallic and pearlescent flakes, respectively; and G is the geometric attenuation factor as defined by the Cook and Torrance model. The normal vector to the painted surface is denoted as **n**.

Summary of the parameters used:

- Pigmented Layer
    1. the spectral reflectance of the primer
    2. the thickness of the layer
    3. the respective concentration of pigments
    4. parameters K and S for each pigment
- Metallic Flakes
    1. the kind of flakes (complex index of refraction of metal)
    2. the angular distribution of flakes (close to 0°)
    3. the area ratio where flakes are visible
    4. the average depth of visible flakes
- Pearlescent Flakes
    1. the thin film thickness
    2. the angular distribution of flakes (close to 0°)
    3. the area ratio where flakes are visible

4. the average depth of the visible flakes

Figure 2 shows the rendered coatings using Eq. 3

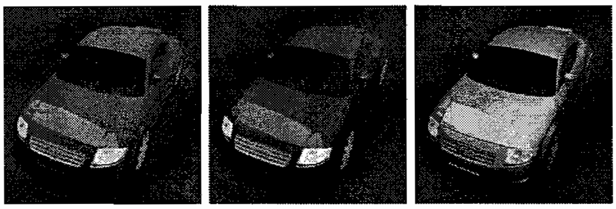

Figure 2: Cars with different coatings. Blue pigment only, added metallic flakes, added pearlescent flakes, respectively.

2.4 Ershov et al.

The final model discussed in this paper [Ershov et al. 2001] is also used by Erschov et al. in the "Reverse engineering approach to appearance-based design of metallic and pearlescent paints" [Ershov et al. 2004] to build an interactive system for paint appearance rendering based on its composition.
Figure 3 shows some of the relations describing what appearance attribute relates to which composition parameter for two-layer paints. Some appearance attributes depend on multiple-composition parameters but their corresponding sets of parameters do not overlap, therefore changing one of those appearance attributes does not affect the other attributes. The BRDF used is a complete model for the paint layers and their components (binder, pigment particles, flakes, flake coatings). It uses a technique that divides each paint layer into artificial sublayers which are chosen thin enough, that multiple scattering inside these layers can be neglected. This makes it possible to compute reflection and transmission operators for these layers based on the physical properties of the contained elements. These operators can than be assembled to a reflection operator of the whole paint, which in fact is the BRDF:

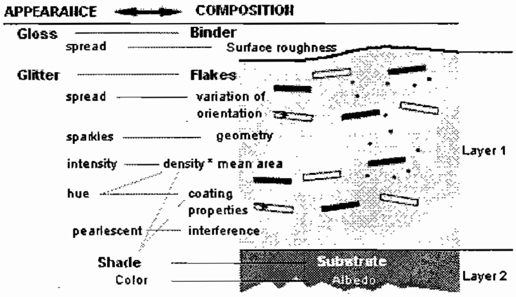

Figure 3: Scheme of appearance based paint design demonstrating approximate relations between the appearance attributes and the composition parameters of a two layer paint

$$
\begin{aligned}
BRDF(\sigma,\vartheta,\varphi) = {} & r_\eta(\sigma)\frac{1}{2\pi w^2}e^{\frac{\cos\Theta-1}{w^2}} \\
& + (1-r_\eta(\sigma))(1-r_\eta(\vartheta))\frac{R_{\mathrm{eff}}}{4\eta^2\cos\bar{\sigma}\cos\vartheta} \\
& + (1-r_\eta(\sigma))(1-r_\eta(\vartheta))a_{\mathrm{eff}} \qquad (4)
\end{aligned}
$$

Summary of the parameters used:

Binder:	
w	Highlight peak width
η	Refractive index of the binder
r_η	Fresnel reflectance of binder surface with the refractive index η
h	Thickness of paint layer
Flakes:	
D	Volumetric density of flakes
δ	Variation of flake orientation
S	Mean flake area
r,t	Reflectance and transmittance of flake surface
β	Angle between flake and paint normals
$P(\beta)$	Distribution of orientations of flakes
R_{eff}	Effective bulk reflectance of flakes

3 Conclusion

Ershov's model [Ershov et al. 2001] has many parameter that have mathematical meaning but we can not estimate or measure them from real paint samples. Such parameters are "Effective bulk reflectance of flakes" or "Variation of flake orientation" or "Highlight peak width". Similarly model proposed in [Ďurikovič and Ágošton 2007] uses parameter that is hard to estimate such as "the average depth of the visible flakes". Comparing those two models parameters for metallic an pigmented layer are measurable for model [Ďurikovič and Ágošton 2007] with standard industry devices spectrophotometres, calorimeters, gloss meters that was not possible for sophisticated Ershov's model. However, both models use not measurable parameters for pearlescent pigments.

Pigment producers give the information of the particle size, recommended concentration interval and the dominant wavelength. Adding more effect pigments than the maximum recommended concentration will not increase the pearl effect any more. The problem that we need to solve is to rewrite the part of the model that simulated the pearlescent effect to take into account any available information from pigment producers.

4 Acknowledgements

This research was sponsored by grant from EU-FP6-MC-040681-APCOCOS.

References

ASHIKHMIN, M., PREMOŽE, S., AND SHIRLEY, P. S. 2000. A microfacet-based brdf generator. In *Proceedings of ACM SIGGRAPH 2000*, Computer Graphics Proceedings, Annual Conference Series, 65–74.

COOK, R. L., AND TORRANCE, K. E. 1981. A reflectance model for computer graphics. In *Computer Graphics (Proceedings of SIGGRAPH 81)*, 307–316.

ERSHOV, S., KOLCHIN, K., AND MYSZKOWSKI, K. 2001. Rendering pearlescent appearance based on paint-composition modelling. *Computer Graphics Forum 20*, 3, 227–238.

ERSHOV, S., ĎURIKOVIČ, R., KOLCHIN, K., AND MYSZKOWSKI, K. 2004. Reverse engineering approach to appearance-based design of metallic and pearlescent paints. *The Visual Computer 20*, 8–9, 586–600.

KUBELKA, P., AND MUNK, F. 1931. Ein beitrag zur optik der farbenstriche. *Zurich Tech. Physik 12*, 493–561.

MCCAMY, C. S. 1996. Observation and measurement of the appearance of metallic materials. part i. macro-appearance. *Color Res. and App. 21*, 4, 292–304.

NGAN, A., DURAND, F., AND MATUSIK, W. 2005. Experimental analysis of brdf models. In *Rendering Techniques 2005: 16th Eurographics Workshop on Rendering*, 117–126.

RUMP, M., MÜLLER, G., SARLETTE, R., KOCH, D., AND KLEIN, R. 2008. Photo-realistic rendering of metallic car paint from image-based measurements. *Computer Graphics Forum 27*, 3, in press.

TORRANCE, K. E., AND SPARROW, E. M. 1922. Theory for off-specular reflection from roughened surfaces. *Radiometry*, 32–41.

ĎURIKOVIČ, R., AND ÁGOŠTON, T. 2007. Prediction of optical properties of paints. *Central European Journal of Physics 5*, 3, 416–427.