Department of Computer Science
Faculty of Mathematics, Physics and Informatics
Comenius University, Bratislava

Overview of Reflectance Models Focused on Car Paint Simulation

Bachelor's Thesis

Róbert Smetana

Field of study: 9.2.1 Informatics

Advisor: doc. RNDr. Roman Ďurikovič, PhD. Bratislava, 2008

I hereby declare I wrote this thesis by myself, with the help of referenced literature, under supervision of my thesis advisor.

. . . .

Abstract

Author :	Róbert Smetana
Thesis title :	Overview of Reflectance Models Focused on Car Paint Simulation
University :	Comenius University, Bratislava
Faculty :	Faculty of Mathematics, Physics and Informatics
Department :	Department of Computer Science
Advisor :	doc. RNDr. Roman Ďurikovič, PhD.
Field of study :	9.2.1 Informatics
Thesis length :	31 pages

Bratislava, June 2008

The main objective of this work is to describe models of bidirectional reflectance distribution functions well established in paint industry. We give the basic BRDF equations in the most practically used forms, summarize input parameters that should help us to easily spot the parameters that can be measured by conventional measurement devices. These five selected models are candidates for BRDF paint standards. Also a concept for an object oriented black box color representation standard is proposed.

Keywords: BRDF, Reflectance models, Car paint, Appearance parameters, Black box model

Preface

My motivation for this work was to gain experience in computer graphics. I chose the area of car paint rendering because it is interesting from both visual and analytical perspective. In international context it is an open field of research, applications of which extend to many branches. This thesis is intended as a summarization to map the current situation which is necessary for future development. Main sources for this work were publications from conferences on computer graphics, available results from independent projects and professional experience of my advisor. As a result we propose a solution which could improve the capabilities of light reflection models.

I have already presented a part of this thesis as a student poster titled "Overview of Contemporary BRDF Models Focused on Car Paint Simulation" at the Spring Conference on Computer Graphics in April 2008.

For the continuous guidance and patient answering of my questions I thank my advisor Roman Ďurikovič, who has introduced me to modelling and rendering techniques. I would like to express special thanks to Oľga Smetanová, Marián Haburčák, Michal Švirec and Matej Juračka for valuable advice and support during the writing of this thesis and also to many of my friends and colleagues who helped me keep working.

Robert Smetana

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Today's computer graphics give a new standard to realistic rendering. Consumers of the global market are used to previewing the product they are about to buy in a computer simulation. Whether it is a picture, animation or a virtual model, it has become the standard way of presentation. Quality and realistic appearance are key attributes of a successful presentation, because they give the customer an authentic feeling about the product. In automotive industry it is a basic option for a customer to select several visual properties of a car before it is custom built for him. It's impossible for the car manufacturer to have all the options on display in every sales office all around the world. This is where computer graphics play an important role. Interactive 3D applications are being created where these parameters can be adjusted freely. While selecting the car paint is the most visible aspect it is also the most difficult to visualize correctly under various lighting conditions.

Bidirectional Reflectance Distribution Function (BRDF) is a mathematical function expressing the quotient of energy being reflected from a point of a surface (this energy is named radiance) and the energy of light incident to that point (named irradiance), for all points of the surface. It is a part of the rendering equation responsible for correct reflection of light and as we explain in Chapter 2 it describes physical properties of the paint. This function is the key to make images render fast, smooth and realistic. Several reflection models have been created in the past, however not all of them can produce satisfying results. Models are required to compute with large numbers of parameters and operate in real time intervals to deliver a more genuine experience. Such requirements can hardly be met by traditional simulation techniques [LFTG97, Pho75, War92] often focusing solely on one appearance aspect. Fortunately 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.

A short introduction to measuring of parameters is given in Chapter 3. Reflectance models mentioned in this thesis incorporate both micro- and macro-scale reflections and often consist of multiple functions simulating different parts of the overall effect. Many of them are based on an older physical model, although they introduce new concepts that aim to improve particular properties for rendering metallic surfaces. We discuss our five chosen models and their recent applications in Chapter 4. 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. Finally we discuss available results in form of rendered images based on fitted data in Chapter 5.

Chapter 2

Theoretical basis

Before we can make satisfactory measurements of a BRDF, we need to understand the behaviour of light it will be modelling. In general there are three types of interaction between a light ray and a material: absorption, transmittance and reflection. In this thesis we are not considering the special case of a material emitting light.

2.1 Simplification of general light transport function

These three basic interactions can be expressed in one general equation, where each ray is described by six parameters (the position on the surface (u, v), the incident/outgoing direction (ω_i, ω_o), the time of interaction t and specific wavelength λ). Since we have incoming and outgoing rays that are not the same this creates a 12 dimensional function. It is possible to take into account all of the parameters of a general function and work with the rendering equation on some of the high-end computer systems. However, to achieve real-time renderings with good realistic quality on common computer setups we must simplify the function to a more practical level. It is also much more time efficient to fit measured parameters to the simplified function.

First step is 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 surface 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 as suggested in [CHM+05]. Another step is to represent wavelength by only three bands commonly used in computer graphics – 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 we dismiss the effect of subsurface scattering, which means the light is entering and leaving the surface at exactly the same position. This results in a spatially varying BRDF (SVBRDF). Last step is assume that the material is homogenous in which case the result is a homogenous 4D BRDF.

2.2 Reflection hemisphere

Light ray incident to a point on the surface can be reflected only to the hemisphere above the surface as illustrated on Figure 2.1. For consistent notation in this thesis, we define following basic terms: $\omega_\mathbf{i}$ is the direction towards light source, $\omega_\mathbf{o}$ is the direction towards viewer, Ω_+ denotes the hemisphere above surface, u, v are surface coordinates and $\vec{x}$ is the macroscopic surface normal vector at point x. Directions are defined in the spherical coordinates by polar θ ($\vec{x}$ to ω) and azimuthal φ (u to v) angles. For alternative concepts please refer to paper [EBJ+06].

2.3 Radiometric terms

The energy transport that is simulated in computer graphics is often modelled using ray optics where light with a specific power spectrum travels along independent rays. Since there is no explicit interaction between the different light rays, effects like diffraction, interference, and polarization are hard to simulate. To some extent they are incorporated into the reflection model,

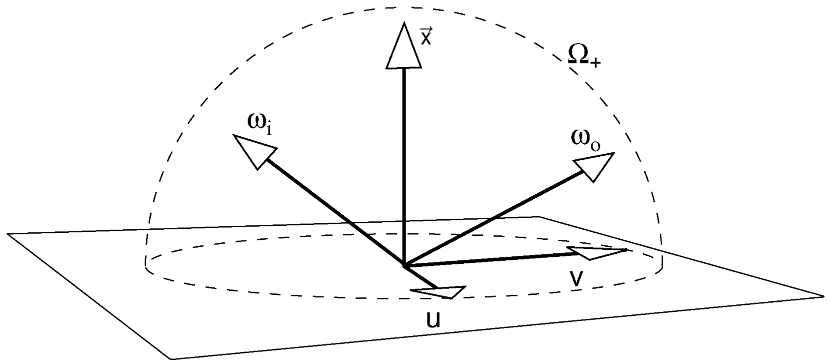

Figure 2.1: Scheme of reflection from point $x = (u, v)$ on a surface. Vector $\vec{x}$ represents the normal at point x, ω_i and ω_o are directions.

otherwise interaction of light with matter is modelled purely geometrically, determining only the direction of the outgoing rays and the transported energy.

2.3.1 Definition of radiometric terms

In this section we define the physical quantities that can be used to describe radiant energy transport:
Radiant energy Q is the basic unit of radiometry measured in Joules (J).
Radiant flux or power is the amount of energy per time radiated through a boundary. It is denoted Φ and its unit is Watt (W):

$$\Phi = \frac{dQ}{dt} \tag{2.1}$$

Radiance is denoted L and is measured in W/m^2sr. It is formally defined as the power per unit projected area perpendicular to the ray per unit solid angle in the direction of the ray:

$$L(\vec{x}, \omega) = \frac{d^2\Phi(\vec{x}, dA, \omega, d\omega)}{dA.d\omega.\cos\theta}, \tag{2.2}$$

where θ denotes the angle between the surface normal $\vec{x}$ at point x and direction ω (polar angle). Term $d^2\Phi(\vec{x}, dA, \omega, d\omega)$ in numerator represents the

differential radiance flux being reflected from infinitesimal area dA around point x in a differential solid angle θ around direction ω. In order to have a well-defined limit for the BRDF, we must also define the term
Irradiance E as the radiant power per unit area incident on a surface. The differential irradiance because of a small solid angle $d\omega_i$ is then

$$dE(\vec{x}, \omega_i) = L_i(\vec{x}, \omega_i) cos(\theta_i) d\omega_i, \tag{2.3}$$

where ω_i is a solid angle and $\vec{\omega}_i$ is its corresponding vector. Further information about radiometric terms can be found in “Principles of optics” [BW65].

2.3.2 Energy conservation

An ideal physically based BRDF is both reciprocal and energy-conserving. Reciprocity is expressed formally by equation 2.4:

$$\rho(\omega_i, \omega_o) = \rho(\omega_o, \omega_i) \tag{2.4}$$

Which means that the ratio expressed by the BRDF function remains unchanged when we change the direction of radiation (i.e. interchange positions of light source and observer). Energy conservation principle guarantees that the material is not self-emitting and only allows absorption. It can be formally expressed by equation 2.5:

$$\forall \omega_o \int_{\Omega_+} \rho(\omega_i, \omega_o)(\omega_i \cdot \vec{x}) d\omega_i \leq 1 \tag{2.5}$$

2.4 Rendering equation

With sufficient background we can now define the bidirectional reflectance distribution function formally by Equation 2.6:

$$\rho(\vec{x}, \omega_i, \omega_o) = \frac{dL(\vec{x}, \omega_o)}{dE(\vec{x}, \omega_i)} = \frac{dL_o(\vec{x}, \omega_o)}{L_i(\vec{x}, \omega_i) cos(\theta_i) d\omega_i} \tag{2.6}$$

The BRDF function is then included in the rendering equation that calculates brightness levels for every pixel of the image. Since there are three bands

(RGB), for every band the renderer will evaluate the Equation 2.7:

$$L_o(\vec{x}, \omega_o) = \int_{\Omega_+} \rho(\vec{x}, \omega_i, \omega_o) L_i(\vec{x}, \omega_i) cos(\theta_i) d\omega_i \tag{2.7}$$

2.5 Surface types

For a scene to appear realistic it is necessary to capture material properties as they would appear in real life. Optical properties of a material depend on the microstructure of the surface. This means correctly rendering perceivable effects such as colour, transparency, shadows and mirror like reflection. Usually, microstructure is not defined in the object's geometrical representation, as it would be both memory and time consuming. Therefore, optical properties are embedded in reflectance functions expressing the probability of the light being reflected in a particular angle. Two basic types of surfaces are diffuse and specular surfaces. Surfaces that are rough tend to refract and reflect light in all directions equally, this effect when the brightness is distributed uniformly is called diffuse scattering. Specular reflection occurs most commonly on mirrors when the incident light is reflected in one direction. As we discuss in Section 2.6 car paint does not behave strictly in one or the other way, therefore for a model to be realistic it has to interpret both aspects correctly.

2.6 Paint composition

Typical metallic car paint is composed of different layers. 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 2.2. Finally on the top is the clear coat which is approximately 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 Fresnel's formulae for dielectrics. Our focus is on the basecoat layer since it is where all the light is reflected. It consists of binder with colour 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. Especially in sunlight these flakes remain prominently visible even for distances in the range of meters [RMS+08]. The diameter of the flake particles is usually larger than the thickness of the basecoat layer. 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 colour shifts dependent on the view and light directions.

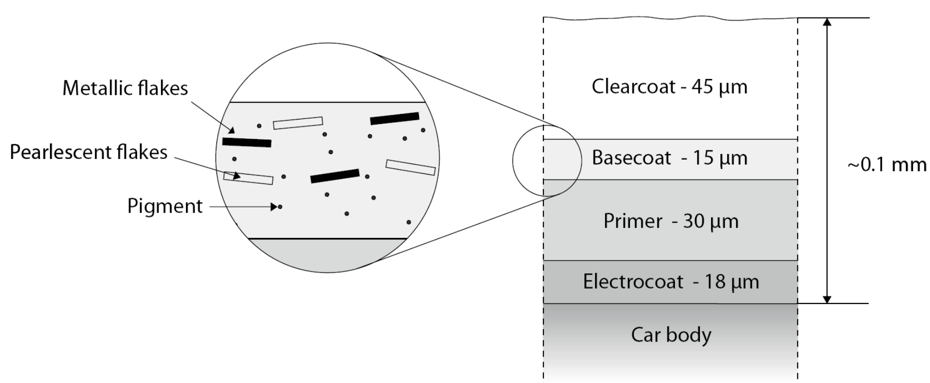

Figure 2.2: Scheme illustrating the layers inside a metallic paint with multiple types of flakes

The appearance attributes of metallic and pearlescent paints can be 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 [McC96] in his comprehensive review introduces the following main macro-appearance attributes: shade, glitter and gloss. The shade attribute is the colour of the paint under ambient illumination. Glitter is a micro-appearance attribute describing the appearance of bright or coloured 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.

2.7 Lobes

Rather than explicitly creating a separate equation for every appearance attribute that is needed for correct visualization, it is more practical to combine the terms for shade, glitter and gloss into the BRDF function. Under various angles of incidence and specular reflection, different terms of the function are dominant. When this effect is visualised as a probability distribution function in two dimensional or three dimensional space the resulting graph is composed of several distinct domes or lobes. In most cases these lobes are geometrically continuous, however, for certain extremely rough surfaces the assumptions of mean surface slope of some models are violated, which reduces the realism in final visualisation. As stated in paper by Westin, Li and Torrance [WLT04]:

> As the surface roughness increases, the ideal specular reflectance angle is smaller, and a new directional diffuse lobe emerges. At first, this lobe is centered on the specular direction, but can move to off-specular directions at large incidence angles. Surfaces in this range of roughness can only be handled by a full physical-optics model like that of He-Torrance. None of the simpler lobe-like models can accurately produce an ideal specular component, so the range of roughness they model is limited.

These simpler models then produce errors under obscure angles and thus creating implausible visual results. Therefore to gain advantage from multiple lobe approach a model must be based on some physical principles.

Chapter 3

Measurement

3.1 Categories of models

The BRDF models can be broadly classified into physically based models, empirical models and semi-empirical models. Physically based models are the most computationally demanding and therefore were designed only for specific surface types. They include geometric optical models, turbid medium models, hybrid models and computer simulation models. These models are dependent upon the structural and state attributes of the surface. Empirical models consist of a function that fits the measured data which then predicts reflection behaviour. These models often introduce coefficients that may not have a physical meaning. Semi-empirical models try to provide balance by providing empirical coefficients that have a physical meaning.

Well-founded BRDF models are rather difficult to create, because satisfying both reciprocity and energy conservation constraints requires an advanced mathematical background. Empirical BRDF models often enforce reciprocity at the cost of energy conservation (e.g., [LFTG97, AS00]). This can cause the specular lobes of a BRDF to extend below the surface, which is of course an incorrect behaviour. According to research by Edwards [EBJ+06]:

> Renderers based on such models will attempt to gather light coming from below the surface, which cannot contribute to outgoing

> light. Visually, this phenomenon appears as "light leakage": the loss of energy at near-grazing viewing directions causes surfaces to appear darker near silhouette edges.

This defect can be somewhat improved by adjusting the parameters to fit expected results:

> In theory, it is possible to rescale the BRDF to account for the portion of the lobe that is below the surface. But for most models it is difficult to calculate the correct factor for rescaling, and hence rescaling is not performed, leading to energy loss.

An extensive framework is developed in the already mentioned work [EBJ+06], using which these situations can be avoided.

3.2 Measurement methods

There are several strategies for creating a BRDF model. They can be roughly divided into four categories:

Direct measurement: The BRDFs can be measured directly using gonioreflectometers which are mechanical tools that automatically vary the position of a small light source and a spectral sensor that collects a large number of point samples [GLF+99]. Simpler and less accurate devices can also be constructed using CCD imaging devices [War92]. More complex CCD devices can be used to gather data quickly with accuracy close to that of full gonioreflectometry [MWL+99]. If enough is known about the microstructure of a material, which is not usually the case of more complex pigments, a BRDF can be simulated by using a virtual gonioreflectometer, where statistical ray tracing followed by density estimation is used to create BRDF data [CMS87, GLF+99]. These devices measure most of the parameters needed including shade, glitter, gloss and LAB composition.

Empirical methods are usually applied when a certain set of parameters is available. The model is then constructed based on the hand chosen ones, which are usually intuitive. There are a variety of purely empirical reflection models, the most familiar being the models introduced by Gouraud and Phong [Pho75]. A variety of more complex methods have been introduced to improve characteristics of the Phong model for efficiency [AS00], to include anisotropy [War92], and enforce physical constraints such as reciprocity. Other models have been developed to fit measurement data as opposed to being intuitive [LFTG97].

Microfacet theory: These models assume that the surface consists of a large number of small flat mirrors ("micro-facets") which reflect light only in the specular direction. The BRDF is found by computing the number of visible microfacets at the appropriate orientation to specularly reflect light from the source to the viewer. This method is used for example by models 4.2 and 4.3.

Height correlation: BRDF models are defined by a rough surface created by Gaussian random process based on some physical assumptions. The process can be described by its correlation function which is directly related to surface height correlations. This is the most complete surface representation used in computer graphics. Some of the most detailed descriptions of light scattering by a surface, including wave optics effects, were obtained using He-Torrance model (4.5). Such models require parameters that are physically based and often difficult to measure.

In cases where some properties of a surface are unknown, starting with measurement is a good idea that can give the basis for advancement. Empirical models can be used when target viewers are not expected to be interested in high quality detail as long as the overall image seems satisfactory. Models based on microfacet theory are often a good alternative for more complex pigments, but they also need more parameters. Where optical details are of importance, height correlation methods should be used, as they produce the most realistic visualizations. Therefore all of these methods can prove useful in practice.

Chapter 4

Reflectance models

In this chapter we give an overview of the five selected models, describe their parameters and explain BRDF functions used. Since the mathematical derivations for BRDF models are usually broad and space consuming, we decide to present only the BRDF equations in final or most practically used forms. It is important to note that while four of these models work with one layer of metallic paint, the basecoat, the Ershov et al. model 4.4 is designed for two layers each with one type of particles. We select these models because they are being proposed as standards for BRDF representation on which future models will be based.

4.1 Cook and Torrance model

For the first example we chose the well-known Cook-Torrance BRDF model in its multi-lobe 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 modelling 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 [RMS+08] 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 modelling the responsible effect particles. Data for both parts are measured simultaneously using a BTF measurement device. Their method divides the rendering problem in two parts. First part focuses only on macro-scale reflection behaviour of the base and the top layer of the paint. This is the part modelled where lobe-based BRDF is used to represent the reflection behaviour of the base paint and the highly specular finish. The second part is the spatially varying BTF describing effects caused by aluminium flakes.
Cook-Torrance formula used in this paper:

$$\rho(\omega_i, \omega_o) = \frac{k_d}{\pi} + \sum_{l=1}^{K} k_{s_l} \frac{F_{t_l} D_{r_l} G}{\pi \sin\theta_i \cos\theta_o} \tag{4.1}$$

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 [CT81]. While the model is well suited for modelling the glossy and specular lobes of uniformly coloured car paint it has difficulties with the flip-flop effect present in pearlescent paint.

4.2 Ashikhmin et al. model

In this section The older Ashikhmin model [APS00] follows the approach of Torrance and Sparrow original microfacet theory [TS67], 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.

$$\rho(\omega_{\mathbf{i}}, \omega_{\mathbf{o}}) = \frac{p(\mathbf{h}) P(\omega_i, \omega_o, \mathbf{h}) F((\mathbf{kh}))}{4(\omega_i \cdot \vec{x})(\omega_o \cdot \vec{x})\langle(\vec{x} \cdot \mathbf{h}) P(\vec{x}, \mathbf{h})\rangle} \tag{4.2}$$

$\rho(\omega_i, \omega_o)$	BRDF
$\mathbf{h}$	normalized half-vector between ω_i and ω_o
$p(\mathbf{h})$	probability density function of microfacet normals
$F(\cos\theta)$	Fresnel reflectance for incident angle θ
$P(\omega_\mathbf{i}, \omega_\mathbf{o}, \mathbf{h})$	Probability that light from $\omega_\mathbf{i}$ reflecting in direction $\omega_\mathbf{o}$ is not shadowed
$\langle f \rangle$	average of function f over distribution $p(\mathbf{h})$

Table 4.1: Parameters used by Ashikhmin et al. model

4.3 Ďurikovič et al. model

Our third described 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" [ĎÁ07] 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 Cook–Torrance model [CT81] is physically based and has shown to perform well with many materials [NDM05]. In its multi-lobe 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 [KM31], 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 is expressed by Equation 4.3:

$$\rho(x, \omega_i, \omega_o) = \kappa + \tau\Bigg((1 - A_m - A_p)R_l + \frac{(A_m R_m) D_m G}{\pi(\vec{x}\cdot\omega_i)(\vec{x}\cdot\omega_o)} + \frac{(A_p R_p) D_p G}{\pi(\vec{x}\cdot\omega_i)(\vec{x}\cdot\omega_o)}\Bigg) \tag{4.3}$$

where κ 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; 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; 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 [CT81].

- 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

Table 4.2: Parameters used by Ďurikovič et al. model

Figure 5.1 in Chapter 5 shows the rendered coatings using this model.

4.4 Ershov et al. model

In this section we describe a model created by Ershov et al. [EKM01] that can also be used for finding pigment composition of a paint from its BRDF. It is a complete model for the paint layers and their components (binder, pigment particles, flakes, flake coatings). Computation time efficiency is increased using a technique that divides each paint layer into artificial sub-layers inside which multiple scattering between flakes can be neglected, calculating the BRDF and then recursively merging the sub-layers. It gives the possibility to compute reflection and transmission operators for the sub-layers based on the physical properties of the contained elements which can be assembled to a reflection operator of the whole paint. As the model uses a different angular representation, in Figure 4.1 we include the image where the alternative spherical coordinates are explained. The resulting BRDF is expressed by Equation 4.4 and the parameters used are listed in table 4.3:

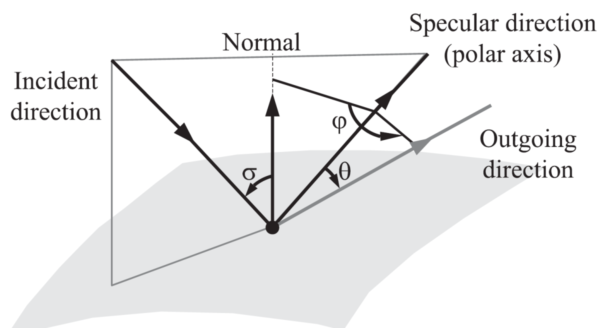

Figure 4.1: Alternative (θ, φ) coordinate system for BRDF presentation with the polar axis along the specular direction as seen in paper [EĎKM04]

$$
\begin{aligned}
\rho(\sigma, \theta, \varphi) &= r_\eta(\sigma) \frac{1}{2\pi w^2} e^{\frac{\cos\Theta - 1}{w^2}} \\
&+ (1 - r_\eta(\sigma))(1 - r_\eta(\theta)) \frac{R_{\text{eff}}}{4\eta^2 \cos\bar{\sigma} \cos\bar{\theta}} \\
&+ (1 - r_\eta(\sigma))(1 - r_\eta(\theta)) a_{\text{eff}} \qquad (4.4)
\end{aligned}
$$

An interesting application of this model is to solve an inverse problem of

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
α	Angle between ray and flake normal
β	Angle between flake and paint normals
$P(\beta)$	Distribution of orientations of flakes
R_{eff}	Effective bulk reflectance of flakes
τ	Optical thickness along ray path

Table 4.3: Parameters used by Ershov et al. model

determining paint composition based on appearance parameters [EĎKM04]. Such reverse engineering can serve as a starting point for subsequent design of new paints in terms of appearance attributes that are directly connected to the physical parameters of the model. This allows the user to have a paint composition in parallel with the appearance being designed. Figure 4.2 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.

4.4.1 Sparkling effect

Important addition to this model, in the original paper [EKM01], is the ability to simulate "sparkles". This effect can be seen under direct illumination when certain metallic flakes reflect light directly to the observer with as slight

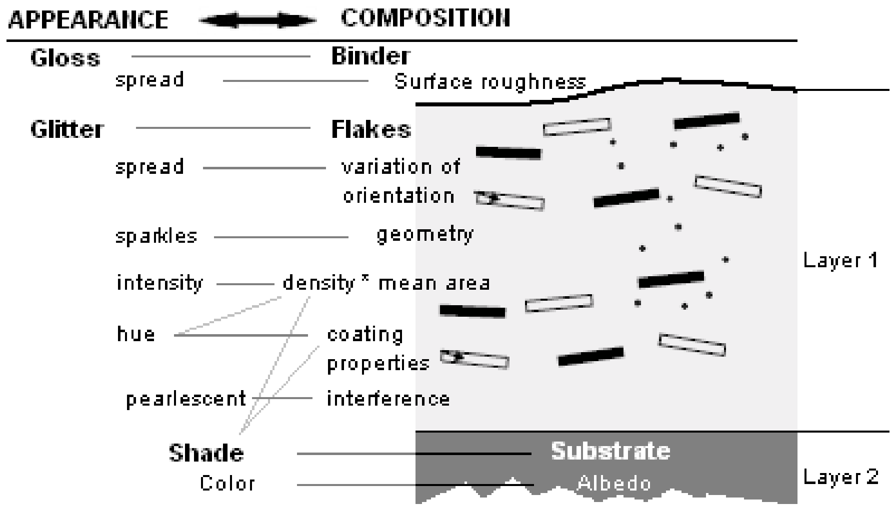

Figure 4.2: Scheme of appearance based paint design demonstrating approximate relations between the appearance attributes and the composition parameters of a two layer paint

change in colour. The BRDF (4.5) of this luminance fluctuation is added after the total luminance of a pixel is computed, for several light sources this is a mean value of the sum of all parallel lights:

$$BRDF_{sparkle} = D\langle S\rangle h \cdot \frac{[1-r_\eta(\theta_i)][1-r_\eta(\theta_o)]}{4\eta^2\cos\theta_i\cos\theta_o} \cdot \frac{1-e^{[\tau(\overline{\theta_i})+\tau(\overline{\theta_o})]h}}{[\tau(\overline{\theta_i})+\tau(\overline{\theta_o})]h} \cdot P(\beta) r_p(\cos\alpha) \tag{4.5}$$

4.5 He et al. model

He-Torrance-Sillion-Greenberg reflection model most commonly known as the He-Torrance BRDF has been based on several techniques to avoid limitations of its predecessors, which would allow its application to a wide range of materials including both metals and non-metals and rough surfaces. Building on previous knowledge of Cook-Torrance and Beckmann Electromagnetic wave theory applications this model has probably the best potential for being the most general physically based model to date. One of the great improvements

$a(\lambda)$	Ambient wavelength
$\|F\|^2$	Fresnel reflectivity
$\mathcal{F}$	Function derived from Fresnel coefficients
g	Function for effective surface roughness
	$g = [\frac{2\pi\sigma}{\lambda}(\cos\theta_i + \cos\theta_o)]^2$
$\mathbf{p}$	Incident polarization state vector
S	Shadowing function
$\vec{v}$	Wave vector change
	$v_{xy}^2 = v_x^2 + v_y^2$
$\vec{x_b}$	Bisecting unit vector
τ	autocorrelation length

Table 4.4: Parameters used by He et al. model

of this model gained from incorporating Kirhoff diffraction theory is that completely treat polarization and directional Fresnel effects. This approach lowers the number of errors produced during visualization. It was also the first model to introduce the concept of an effective roughness depending on the angles of illumination and reflection. In contrast to the Cook-Torrance model 4.1 it has greater angular freedom for incident and reflected directions under which it performs well. The following BRDF equation (4.6) is not explicitly stated in this form in the original work [HTSG91], however, this form is only a substitution of the three components (specular, uniform diffuse and directional diffuse, respectively) into the original equation:

$$\begin{aligned} \rho(x, \omega_i, \omega_o) &= \frac{|F|^2 \exp(-g) S}{\cos\theta_i d\omega_i} \cdot \Delta + a(\lambda) \\ &+ \frac{\mathcal{F}(\vec{x_b}, \vec{x_b}, \mathbf{p}) S}{\cos\theta_i \cos\theta_o} \cdot \frac{\tau^2}{16\pi} \cdot \sum_{m=1}^{\infty} \frac{g^m \exp(-g)}{m! \cdot m} \exp(-\frac{v_{xy}^2 \tau^2}{4m}), \end{aligned} \tag{4.6}$$

where Δ stands for specular function defined as 1 when ω_o is in specular direction and 0 otherwise. Furthermore this model uses parameters listed in table 4.4. Detailed mathematical construction is included in [HTSG91], experimental analysis can be found in [NDM05].

Chapter 5

Evaluation

5.1 Result summary

From available experimental analysis [WLT04, EĎKM04, NDM05, GCG+05, RMS+08] we learned that the newer models perform a little better, but all of the models selected on this thesis are able to produce high quality results. Each model was designed for a slightly different purpose and thus can perform better than others in that area. In the analysis by Ngan [NDM05] the additional lobe for the Cook-Torrance model can reduce the error by more than a quarter. Results with the added second lobe were also better for the Ashikhmin 4.2 model.

Inexpensive measurement devices (gloss meters, colorimeters) can be used for measuring the basic properties of BRDF that produce parameters κ, τ and R_l for a global BRDF model. Gloss and haze in reflection models can be also determined using these instruments. Metallic surfaces can be rendered using parameters gained from as few as four measurements. One specular gloss measurement and three colorimetric measurements in directions opposite to the specular one [ĎÁ07].

Excellent images were rendered by Günther [GCG+05] from Max Planck Institute for informatics. They based their reflection model on a Cook-Torrance model in two-lobe form, but also used ideas such as microfacet

Figure 5.1: Cars with different coatings. Blue pigment only, added metallic flakes, added pearlescent flakes, respectively. Rendered using model 4.3 in paper [ĎÁ07]

paint composition from Ďurikovič, which enhanced specular reflection when viewed from close proximity and added sparkling effect 4.4.1.

Ershov et al. model 4.4 with a correct calibration has a very low mean error of $\approx 5\%$. It is a very well defined physical model that can be used also for finding pigment composition, which can prove very useful in industrial applications. On the other hand, it requires a large set of parameters to be set. If these are not set correctly, it is possible to "mix" a colour that is physically impossible. An interesting benchmark would be to compare renderings of production coatings on virtual car models for each of the BRDFs to actual photographs of cars with these coatings.

Figure 5.2: Car with “Opel Titan” silver metallic paint and its detail on right. Rendered by Günther et al., [GCG+05] as part of “The CarPaint Project”

Figure 5.3: Cars with all types of flakes with different industrial colours. Rendered by Günther et al., [GCG+05] as part of "The CarPaint Project"

5.2 Black box concept

Contemporary research in the area of car paint modelling is heading for improved global-purpose models that would not only be able to simulate metallic surfaces correctly, but that could also be extended for other types of surfaces. As the designers and manufacturers from automotive industry are often reluctant to publish certain properties and parameters of pigments used as a part of the know-how, we propose a solution that could satisfy the requirements of both car manufacturers and general public.

The concept of a black box model is based on simple principles. It should be an object oriented BRDF model incorporating all of the standard BRDF representations and a complete set of paint parameters. As we present in the concept class diagram 5.4, all of the five models described in this thesis are included. By analysing the input data, that can be an image, a set of parameters or the name code of a car paint, the model will automatically decide which internal representation will be used. It should contain routines for calculating missing parameters based on reverse engineering methods proposed by Ershov and Ďurikovič [EĎKM04, ĎÁ07]. Ideally, it will also have access to a database of car paints from which it can retrieve parameters needed for rendering, but which would remain unknown for the user.

We see the assets of the black box model in solving the problem of supplying parameters that are not measurable in practice to advanced models (4.4, 4.5) and also giving the general public the possibility to use authentic paints without compromising guarded parameters. Detailed design and practical requirements should be a subject for future research and development.

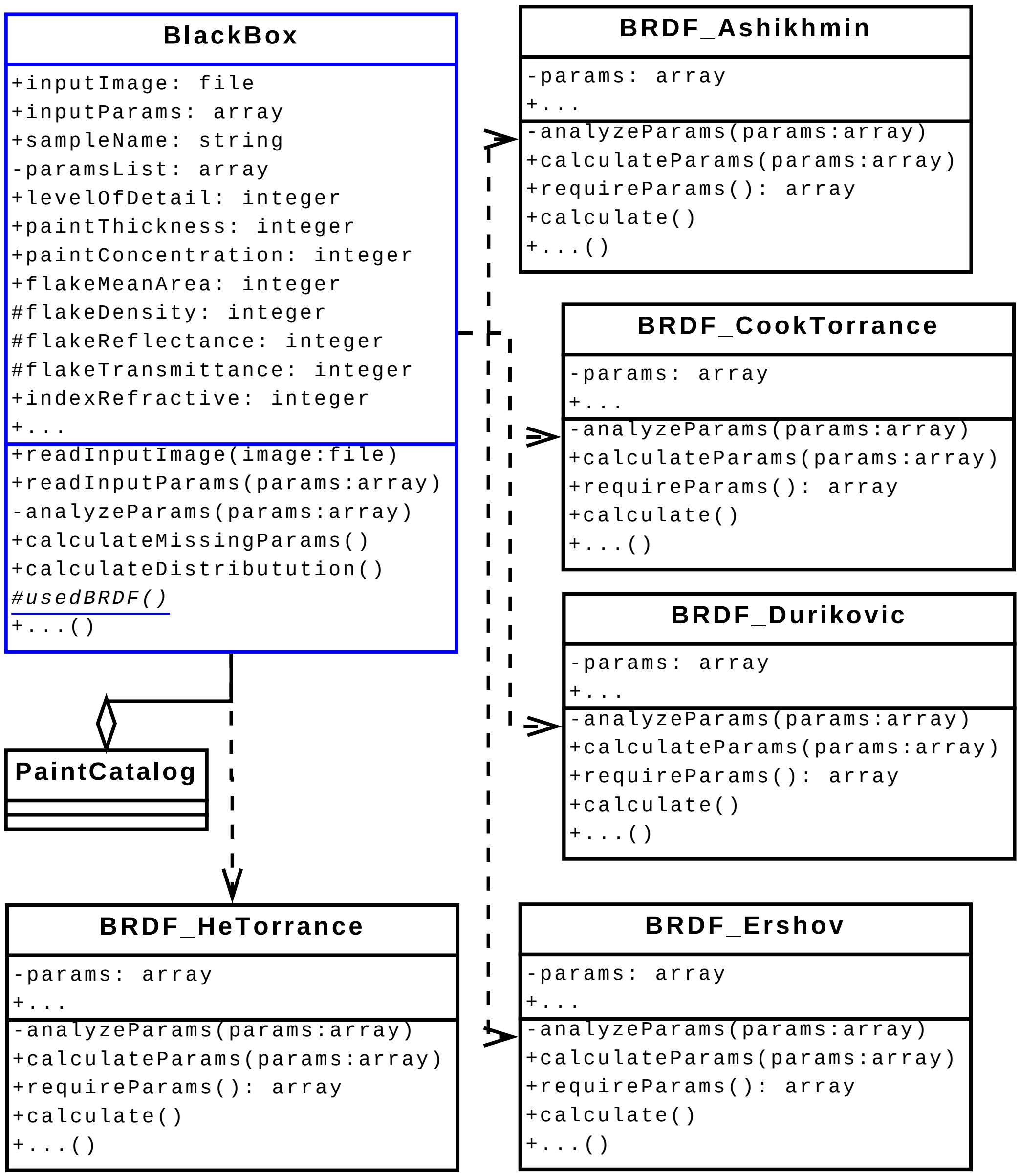

Figure 5.4: Concept of a class diagram for the Black box model

Chapter 6

Conclusion

Even though the models are designed specially for the metallic and pearlescent paints (4.2, 4.3, 4.4) or should perform well for these surfaces (4.1, 4.5) because of their general-purpose character, none of them achieve outstanding results for more complex coatings. From the published results for each model the improvement in realistic visualization is evident, however, since not all of the parameters can be measured precisely, to some degree the "plastic-like" appearance still remains from the past. As can be seen in Chapter 5, experimental results from available publications are visually plausible, but still there are elements which could be improved.

We have learned that models like Ershov's (4.4) have many parameters that have a mathematical meaning but we cannot 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 [ĎÁ07] uses parameters that are hard to estimate such as "the average depth of the visible flakes". Comparing parameters of these two models for metallic an pigmented layer are measurable for model 4.3 with standard industry devices spectrophotometers, calorimeters and gloss meters, while it was not possible for sophisticated Ershov's model. However, both models use parameters for pearlescent pigments that are not measurable by available tools.

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.

Rather than designing a brand new reflectance model, the current situation in the industry requires a versatile solution that would utilize well understood methods. Based on these facts we proposed the concept for a black box model, which can avoid present difficulties by combining potentials of several established industrial models. We intent that this rough concept will be a subject to future development. Since the market demand is increasing, we can expect the work needed for implementation starting in near future.

Bibliography

[APS00] Michael Ashikhmin, Simon Premože, and Peter S. Shirley. A microfacet-based BRDF generator. In *Proceedings of ACM SIGGRAPH 2000*, Computer Graphics Proceedings, Annual Conference Series, pages 65–74, July 2000.

[AS00] Michael Ashikhmin and Peter S. Shirley. An anisotropic phong BRDF model. *Journal of Graphics Tools*, 5(2):25–32, 2000.

[BW65] Max Born and Emil Wolf. *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*. 1965.

[CHM+05] Chuang, Hawkins, Marschner, Matusik, and Mueller. Realistic materials in computer graphics. SIGGRAPH 2005 Course #10 Notes, July 2005.

[CMS87] Brian Cabral, Nelson Max, and Rebecca Springmeyer. Bidirectional reflection functions from surface bump maps. *SIGGRAPH Comput. Graph.*, 21(4):273–281, 1987.

[CT81] Robert L. Cook and Kenneth E. Torrance. A reflectance model for computer graphics. In *Computer Graphics (Proceedings of SIGGRAPH 81)*, pages 307–316, August 1981.

[ĎÁ07] Roman Ďurikovič and Tomáš Ágošton. Prediction of optical properties of paints. *Central European Journal of Physics*, 5(3):416–427, 2007.

[EBJ+06] Dave Edwards, Solomon Boulos, Jared Johnson, Peter Shirley, Michael Ashikhmin, Michael Stark, and Chris Wyman. The halfway vector disk for BRDF modeling. *ACM Trans. Graph.*, 25(1):1–18, 2006.

[EĎKM04] Sergey Ershov, Roman Ďurikovič, Konstantin Kolchin, and Karol Myszkowski. Reverse engineering approach to appearance-based design of metallic and pearlescent paints. *The Visual Computer*, 20(8–9):586–600, 2004.

[EKM01] Sergey Ershov, Konstantin Kolchin, and Karol Myszkowski. Rendering pearlescent appearance based on paint-composition modelling. *Computer Graphics Forum*, 20(3):227–238, 2001.

[GCG+05] Johannes Günther, Tongbo Chen, Michael Goesele, Ingo Wald, and Hans-Peter Seidel. Efficient acquisition and realistic rendering of car paint. In *Proceedings of 10th International Fall Workshop - Vision, Modeling, and Visualization (VMV) 2005*, pages 487–494. Akademische Verlagsgesellschaft Aka GmbH, November 2005.

[GLF+99] Donald P. Greenberg, Eric P. F. Lafortune, Sing-Choong Foo, Kenneth E. Torrance, James A. Ferwerda, Sumanta N. Pattanaik, and J. Arvo. A framework for realistic image synthesis. *Commun. ACM*, 42(8):44–53, 1999.

[HTSG91] Xiao D. He, Kenneth E. Torrance, François X. Sillion, and Donald P. Greenberg. A comprehensive physical model for light reflection. In *Computer Graphics (Proceedings of SIGGRAPH 91)*, pages 175–186, July 1991.

[KM31] P. Kubelka and F. Munk. Ein beitrag zur optik der farbenstriche. *Zurich Tech. Physik*, 12:493–561, 1931.

[LFTG97] Eric P. F. Lafortune, Sing-Choong Foo, Kenneth E. Torrance, and Donald P. Greenberg. Non-linear approximation of reflectance functions. *Computer Graphics*, 31(Annual Conference Series):117–126, 1997.

[McC96] C. S. McCamy. Observation and measurement of the appearance of metallic materials. part i. macro-appearance. *Color Res. and App.*, 21(4):292–304, 1996.

[MWL+99] Stephen R. Marschner, Stephen H. Westin, Eric P. F. Lafortune, Kenneth E. Torrance, and Donald P. Greenberg. Image-based BRDF measurement including human skin. In *Eurographics Rendering Workshop 1999*, June 1999.

[NDM05] Addy Ngan, Frédo Durand, and Wojciech Matusik. Experimental analysis of BRDF models. In *Rendering Techniques 2005: 16th Eurographics Workshop on Rendering*, pages 117–126, June 2005.

[Pho75] Bui-Tuong Phong. Illumination for Computer Generated Pictures. 18(6):311–317, 1975.

[RMS+08] Martin Rump, Gero Müller, Ralf Sarlette, Dirk Koch, and Reinhard Klein. Photo-realistic rendering of metallic car paint from image-based measurements. *Computer Graphics Forum*, 27(3):in press, 2008.

[TS67] K. E. Torrance and E. M. Sparrow. Theory for off-specular reflection from roughened surfaces. *Journal of the Optical Society of America (1917-1983)*, 57(9):1105–1114, September 1967.

[War92] Gregory J. Ward. Measuring and modeling anisotropic reflection. *SIGGRAPH Comput. Graph.*, 26(2):265–272, 1992.

[WLT04] Stephen H. Westin, Hongsong Li, and Kenneth E. Torrance. A comparison of four BRDF models. Technical report PCG-04-02, Program of Computer Graphics, Cornell University, April 2004.

Abstrakt

Autor :	Róbert Smetana
Názov bakalárskej práce :	Prehľad odrazových modelov a ich vyhodnotenie pre potreby simulácie lakov
Univerzita :	Univerzita Komenského, Bratislava
Fakulta :	Fakulta matematiky, fyziky a informatiky
Katedra :	Katedra informatiky
Vedúci bakalárskej práce :	doc. RNDr. Roman Ďurikovič, PhD.
Študijný odbor :	9.2.1 Informatika
Rozsah :	31 strán

Bratislava, jún 2008

Hlavným cieľom tejto práce je opísať modely dvojsmernej odrazovej distribučnej funkcie (BRDF) bežne pouzívané v priemysle. Pri modeloch uvádzame rovnice vo forme zaužívanej v praxi, sumarizujeme vstupné parametre, ktoré by mali pomôcť odhaliť parametre merateľné bežnými meracími prístrojmi. Všetky modely uvedené v tejto práci sú kandidátmi pre priemyselný štandard reprezentácie automobilových lakov pomocou BRDF. Navrhujeme tiež prvý koncept pre objektovo orientovaný “black box” štandard reprezentácie lakov.

Kl’účové slová: BRDF, odrazové funkcie, automobilové laky, priemyselné parametre , black box model