Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi
Dokuz Eylul University Faculty of Engineering Journal of Science and Engineering

Basılı/Printed ISSN: 1302-9304. Elektronik/Online ISSN: 2547-958X

An Analysis of Goniochromatic and Sparkle Effects on Multi-Layered Materials

Çok Katmanlı Malzemelerde Açısal Renk Değişimleri ve Işıltı Etkilerinin Analizi

Sermet Mir [1*], Barış Yıldırım [2], Murat Kurt [3]

[1] Faculty of Fashion and Design, Ege University, Izmir, TURKEY
[2,3] International Computer Institute, Ege University, Izmir, TURKEY

Sorumlu Yazar / Corresponding Author *: sermet.mir@ege.edu.tr

Geliş Tarihi / Received: 24.09.2021
Kabul Tarihi / Accepted: 04.02.2022
Araştırma Makalesi/Research Article
DOI:10.21205/deufmd.2022247205
Atıf şekli/ How to cite: Mir, S., Yıldırım, B., Kurt, M.(2022). An Analysis of Goniochromatic and Sparkle Effects on Multi-Layered Materials. DEÜ FMD 24(72), 737-746.

Abstract

Multi-layered materials are layered structures of composing anisotropic media where each layer may have a separate scattering behavior. Multi-layered materials are widely used in cosmetics, jewelry or automobile paint industries. In addition, many real world materials may consist of microscopic particles that can lead to goniochromatic and/or sparkling appearance. Therefore, the accurate representation of these effects is crucial for the photorealistic appearance of the material and many models have been proposed to overcome this problem. In this paper, we analyze various models proposed for representing goniochromatic and sparkle effects and run experiments on their capability of accurately simulating the final appearance of a multi-layered automobile paint structure. We also compare the performance of each model providing their computation times in the experiments. Finally, we provide a table for the readers which summarizes the complex special effects included in each model.
Keywords: *Goniochromism, BSDF, Sparkle, SVD, Automobile Paints, Microflake*

Öz

Çok katmanlı malzemeler, her bir katmanı farklı bir saçılım davranışına sahip olabilen ve katmanları içerisinde anizotropik davranışa sahip bileşenler barındıran malzeme yapılarıdır. Çok katmanlı malzemeler kozmetik, mücevher ve araba boyası endüstrilerinde yoğun olarak kullanılmaktadır. Ayrıca, bir çok gerçek dünya malzemesi kompozisyon içeriğinde açısal renk değişimi (goniochromatic) ve ışıltı (sparkle) etkilerine neden olan mikroskobik parçacıklar içerir. Bu sebeple, malzemenin gerçekçi görselleştirmesini sağlamak için malzemenin doğru temsil edilmesi büyük önem arz etmektedir ve bu doğrultuda bir çok model önerilmiştir. Bu makalede, çok katmanlı modern araba boyası malzemesi baz alınarak, malzemenin üzerinde görülen açısal renk değişimleri ve ışıltı etkilerini modelleyebilen çalışmaların analizi yapılmış ve deneysel karşılaştırmalar ile modellerin örnek malzemeleri doğru temsil etme kapasiteleri karşılaştırılmıştır. Ek olarak, çalışmamız içerisinde modellerin performans değerleri de karşılaştırılarak deneysel çalışmalarımız içerisinde bu bilgiler paylaşılmıştır. En son kısımda ise bir tablo halinde analizi yapılan çalışmaları içerdikleri karmaşık özel etkileri özetleyerek, okuyucuların bilgisine sunmaktayız.
Anahtar Kelimeler: *Açısal Renk Değişimi, BSDF, Işıltı, SVD, Otomobil Boyaları, Mikro Sedef*

1. Introduction

The usage of multi-layered materials is common in cosmetics, jewelry or automobile paints. In the latest products, the complex structure of such materials are enriched with the inclusion of microscopic particles (special effect flakes or pigments) that lead to complex scattering behavior of goniochromism and/or sparkling. Goniochromatic effects are due to the iridescent structure in which the perceived color changes when the material is viewed from different directions. Sparkle effects occur when the material is covered with special effect pigments or coated flakes which result in high-frequency angular and spatial variations. Although a number of appearance models have been proposed to perform such complex effects [1-5], efficient and accurate representation of such complex materials remains as a challenge in computer graphics.

In the case of automobile paints, we can generally define the material as a four optically-thin layered structure with each having a distinct scattering behavior [6]. The clearcoat is the upmost layer in the material in which the specular reflection is the dominant behavior. Then, we have the basecoat which consists of the flakes and pigments. The basecoat is the layer that leads the final appearance of the material to have the complex effects of goniochromism and sparkling. The primer is placed under the basecoat for protecting the substrate from the effects of corrosion. It mainly absorbs the scattering light coming from the microscopic particles. At the bottom, we have the substrate which is the main body of the automobile. In the computer simulations, the substrate is generally ignored by the models since it does not have a reflective behavior [6].

The complex special effects observed on automobile paints are mainly caused by the scattering of the flakes and pigments in the basecoat layer. As these microscopic particles are distributed over the layer, the incoming light may hit many of these particles along its path which is known as multiple scattering in computer graphics. Therefore, representing a paint material generally depends on the accurate modeling of the multiple scattering behavior.

The Radiative Transfer Equation (RTE) is mainly used in the description of the multiple scattering behavior. However, the general form of RTE is limited to isotropic media. Jakob et al. [7] proposed an alternative form of RTE to represent the anisotropic translucent materials. There are also methods to represent isotropic and anisotropic layered materials [8-11]. However, goniochromatic and sparkle effects are not included in these models.

Ergun et al.'s [6] automobile paint representation is a volumetric model that can produce its synthetic data with an input of composition parameters. Their model also performs goniochromatic appearance by introducing translucent flakes. In addition, they employed a Singular Value Decomposition (SVD) technique to evaluate the Fourier coefficients which resulted in an improvement in the rendering performance. Belcour and Barla [3] proposed an extension to microfacet theory and replaced Fresnel term with an Airy term to perform the goniochromatic appearance of thin-films with varying thickness. Their approach is more simplified and flexible compared to Ergun et al.'s [6] model. However, their experiments have shown that there is a small difference of color saturation due to the complex structure of Ergun et al.'s model [6]. There are also data-driven models for goniochromism [2,12,13]. However, they are computationally more expensive due to the measurement costs. Guillen et al. [14] proposed a spectral BSDF model with an extension in parameters (substrate thickness). This extension resulted in an improvement in terms of accuracy. However, the model is computationally more expensive compared to Ergun et al.'s [6] model.

For the simulation of sparkle effects, a number of methods have been proposed [5,15-18]. Although these models can perform visually plausible sparkling appearance, they do not perform goniochromism. Some models take diffraction based BSDFs into account [12,13]. Thus, the iridescence on scratch like surfaces can be performed with such an extension. However, these models require the storage of explicit microstructures. Guo et al.'s model [4] is a simplified model extending Belcour and Barla's [3] with the model of Jakob et al.'s [17]. This model can perform gonichromatic appearance of special effect pigments and also create a sparkling appearance at the same time.

However, the model omits the global goniochromism due to the multiple scattering.

2. Material and Method

In this work, we compare three appearance models by reproducing the visual appearance of a sample automobile paint material: Ergun et al.'s microflake model [6], Belcour and Barla's [3] model extending the microfacet theory and Guo et al.'s model for special effect pigments [4].

Ergun et al.'s [6] micro-flake model employs the adding-doubling method to solve the RTE for layered automobile paint materials. They introduced translucent flakes to perform goniochromatic appearance. In their approach, they adopted the micro-flake model of Jakob et al. [7] which is defined for opaque flakes with a modification on the transmittance term:

$$\sigma_s\left(\vec{\omega}_i\right) = a\rho \int_{S^2} R\left(\left|\vec{\omega}_i \cdot \vec{m}\right|\right)\left|\vec{\omega}_i \cdot \vec{m}\right| D\left(\vec{m}\right) d\vec{m}, \quad (1)$$

$$\sigma_t\left(\vec{\omega}_i\right) = a\rho \int_{S^2} \left(1 - T\left(\left|\vec{\omega}_i \cdot \vec{m}\right|\right)\right)\left|\vec{\omega}_i \cdot \vec{m}\right| D\left(\vec{m}\right) d\vec{m}, \quad (2)$$

where σ_s and σ_t stand for the scattering and attenuation coefficients, $\vec{\omega}_i$ denotes to the incoming light direction. a and ρ representing the surface area of the flake and density of flakes per unit volume. R and T define the flake's reflectance and transmittance functions and D stands for the probability density function of flake normals on a sphere where $\vec{m}$ is the orientation of the flakes. As the sum of R and T cannot be bigger than 1, the modification of $(1 - T)$ in Eq. (2) takes the transmittance term into consideration and allowing the simulation of translucent flakes by substituting these coefficients inside the RTE proposed by Jakob et al. [7].

The simulation of effects requires a solution for the RTE. Therefore, the adding-doubling method is applied. This method basically slices each layer separately into imaginary thin layers and defines the scattering operators for them. These operators are doubled until the desired thickness values are achieved for the actual layers. Then, the scattering operators for the whole coating are computed through the adding operations considering the Fresnel boundaries. The proposed model also requires to define the distribution of flake normals which was done through Beckmann distribution:

$$D(h(\mu_i, \mu_o, \phi)) = \frac{2^{1/2} f_{rem}(\phi)\exp(A + B\cos\phi)}{\alpha^2\pi|\mu_i - \mu_o|^3}, \quad (3)$$

$$f_{rem}(\phi) = (1 - \mu_i\mu_o - \sqrt{(1 - \mu_i^2)(1 - \mu_o^2)}\cos\phi)^{3/2}, \quad (4)$$

$$A = (\mu_i^2 + \mu_o^2 - 2)/(\alpha^2(\mu_i - \mu_o)^2), \quad (5)$$

$$B = 2[(1 - \mu_i^2)(1 - \mu_o^2)]^{1/2} / [\alpha^2(\mu_i - \mu_o)^2], \quad (6)$$

where, μ_i and μ_o stand for the cosine of the elevation angles for incoming and outgoing light directions, respectively. ϕ defines the azimuth angle and $h()$ function computes the halfway vector and α stands for Beckmann roughness of a layer. The reflection term is substituted with an exponential term and a function of remaining coefficients (f_{rem}) for the numerical integration. For the details of their formulation, please refer to the original study [6].

The approach requires the definition of the reflectance function R differently for each type of particles which is repeated during the rendering operation. Therefore, a discrete Fourier transform is applied on f_{rem} for each pair of (μ_i, μ_o) over the azimuth angle. Thus, the size of the coefficients is stored following an SVD technique which reduces the original size of the matrix as a product of two smaller sized matrices [6]. These coefficients are stored in a file and used in the computation whenever it is necessary.

Belcour and Barla's [3] approach follows a different path. Their approach considers that the goniochromatic effect is caused by the inter-reflection of light inside the thin film layer which is placed on top of a base material

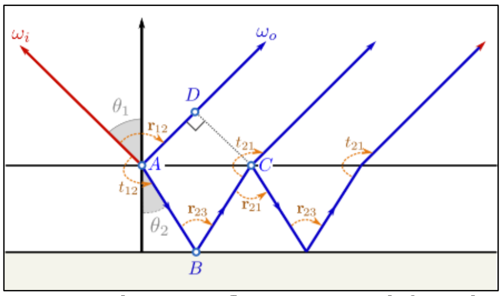


Figure 1. The Airy reflectance term defines the goniochromism by summing all the inter-reflected rays coefficients that considers the interference caused by phase shifts (image from [3]).

defined as a microfacet surface. Considering the microfacet BRDF which can be computed by:

$$\rho(\vec{\omega_o}, \vec{\omega_i}, \lambda) = \frac{D(\vec{\omega_h})G(\vec{\omega_o}, \vec{\omega_i})F(\vec{\omega_h} \cdot \vec{\omega_i}, \lambda)}{4(\vec{\omega_o} \cdot \vec{n})(\vec{\omega_i} \cdot \vec{n})}, \quad (7)$$

where $\vec{\omega_o}$, $\vec{\omega_i}$ and $\vec{n}$ stand for outgoing, incoming and surface normal vectors, λ is the wavelength, $D()$ is the microfacet distribution function, $\vec{\omega_h}$ is the halfway vector, $G()$ is the shadowing-masking term and $F()$ is the Fresnel reflectance term. In addition, the classical Fresnel term depends only on wavelength and goniochromatic effects may also occur due to multiple scattering inside the thin-film. Therefore, they needed a more complex definition than the classical Fresnel term inside the microfacet theory, and they replaced the Fresnel term with an Airy reflectance term. As shown in Figure 1, Airy reflectance can be found by adding the contributions of all occurring inter-reflection.

Thus, the complex coefficient r becomes:

$$r = r_{12} + \frac{t_{12} r_{23} t_{21} e^{i\Delta\phi}}{1 - r_{21} r_{23} e^{i\Delta\phi}}, \quad (8)$$

where r and t terms denote the inter-reflected and transmitted rays and $\Delta\phi$ denotes for the phase shift caused by optical path difference. This modification allows the definition of phase shifts on transmission which is the main source of goniochromism in their approach. The phase shift is defined as:

$$\Delta\phi = (2\pi v P_d), \quad (9)$$

where, P_d denotes to optical path difference. v denotes to $1/\lambda$, where λ is the wavelength. In the model, thin film layer is manipulated by the thickness parameter d and index parameter η_2. As d is only used in the P_d, P_{inc} is defined as $P_{inc} = 2\eta_2 d$ which denotes to the P_d at normal incidence. Then, P_d can be calculated by $P_{inc}\cos\theta_2$. Belcour and Barla [3] also developed a technique to incorporate the spectral rendering integration into the summation term for fixing the saturation problems. Finally, $F()$ term which is the Fresnel reflectance term in the microfacet BRDF (see Eq. (7)) is substituted with spectral(ly) antialised reflectance term $R_i()$ that expands the Airy summation and becomes:

$$\rho(\vec{\omega_o}, \vec{\omega_i}, \lambda) = \frac{D(\vec{\omega_h})G(\vec{\omega_o}, \vec{\omega_i})R_i(\vec{\omega_h} \cdot \vec{\omega_i}, \lambda)}{4(\vec{\omega_o} \cdot \vec{n})(\vec{\omega_i} \cdot \vec{n})}. \quad (10)$$

Guo et al. [4] follows a similar approach to Belcour and Barla's [3] technique. However, they replaced the smooth normal distribution function (NDF) with the discrete one proposed by Jakob et al. [17] in order to perform sparkling appearance which takes both spatial and directional domain into account. The microfacet BRDF (see Eq. (7)), which takes thickness d and spatial position x becomes:

$$\rho(\mathrm{x}, \vec{\omega_o}, \vec{\omega_i}, d) = \frac{D(\mathrm{x}, \vec{\omega_h}, d)G(\vec{\omega_o}, \vec{\omega_i})R_i(\vec{\omega_h} \cdot \vec{\omega_i}, d)}{4(\vec{\omega_o} \cdot \vec{n})(\vec{\omega_i} \cdot \vec{n})}. \quad (11)$$

Then, the simulation of special effect pigments is applied using a multi-scale BRDF which is computed as:

$$\rho'(\mathcal{P}, \vec{\omega_i}, \Omega_o) = \frac{\int_P \int_{\Omega_o} \int_{\boldsymbol{R}^+} \rho(\mathrm{x}, \vec{\omega_i}, \vec{\omega_o}, d) \mathrm{d}\vec{\omega_o} \, \mathrm{dx} \, \mathrm{d}d}{Area(\mathcal{P}) Area(\Omega_o)}, \quad (12)$$

where, $\mathcal{P}$ denotes to a projected pixel on the surface, having the area of $Area(\mathcal{P})$ as the projected query area, Ω_o stands for a finite solid angle centered around $\vec{\omega_o}$ that has an area of

$Area(\Omega_o)$. In addition, the sparkling appearance is observed on a specific directional domain that considers $\vec{\omega}_i$ and $\vec{\omega}_o$ which is defined as a conic section having the radius of γ and the integration is computed over all possible thickness $d \in \mathbf{R}^+$. In this multi-scale BRDF, the discrete NDF is defined as:

$$D(\mathrm{x}, \vec{\omega}_h, d) = \frac{1}{K} \sum_{k=1}^{K} \delta(\mathrm{x}, \mathrm{x}^k) \delta_\Omega(\vec{\omega}_h, \vec{\omega}_h^k) \delta(d, d^k). \quad (13)$$

x^k, $\vec{\omega}_h^k$ and d^k define the position, the normal and the thickness values of facet k. $\delta()$ and $\delta_\Omega()$ stand for Dirac delta functions in cartesian and spherical coordinates, respectively. Then, substituting Eq. (13) together with Eq. (11) into Eq. (12), we get the reflectance term $R(\mathcal{P}, \vec{\omega}_i, \Omega_o)$ as:

$$R\left(\mathcal{P}, \vec{\omega}_i, \Omega_o\right) = \frac{1}{K} \sum_{k=1}^{K} \mathcal{I}\,(\Omega_h)(\vec{\omega}_h^k) \mathcal{I}(\mathcal{P})(\mathrm{x}^k) R_i(\vec{\omega}_i \cdot \vec{\omega}_h^k, d^k). \quad (14)$$

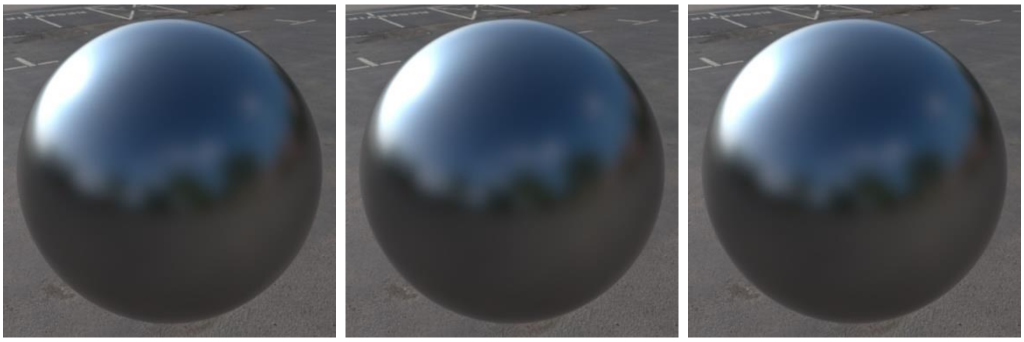
In Eq. (14), $\vec{\omega}_h$ defines the halfway vector, Ω_h is the finite solid angle centered around $\vec{\omega}_h$ and $\mathcal{I}()$ is the indicator function which is used for the evaluation of $R()$. Similarly with the work of [3], $R_i()$ is the Airy reflectance term that includes spectral quantities. By integrating it over each color channels, the goniochromatic effects can be simulated in addition to the sparkling appearance caused by the discrete NDF. The details of the formulations can be achieved from their studies [3,4].

3. Results

In this section, we present various experimental results to evaluate the effectiveness of different models. The scenes in Figure 2, Figure 3 and Figure 4 were rendered on a computer with Intel-Xeon X5650 CPU, 48 GB RAM, NVIDIA GeForce GTX 690 and NVIDIA Quadro 4000. The default image resolution is 512×512 while the default sampling rate is 1024 samples per pixel. All the images were generated by using Mitsuba renderer [19]. The multi-layered coating samples based on Ergun et al.'s [6] work were created by Layerlab [20]. In Figure 2, we compare Ergun et al.'s [6] approach using raw and compressed data with the reference image which was rendered using Monte Carlo path tracing. The sphere object in the reference images is defined as a heterogeneous medium and the sampling is processed using the Simpson integration over the ray segments. In the rendering of the metallic gray particle, RGB is defined as {0.6,0.6,0.6} and the cadmium red requires an RGB value of {0.89,0.0,0.13}. The raw data requires a storage space of 96 MB which stores $n^2 \times m$ Fourier coefficients of the reflectance function where n represents the number of elevational samples and m represents the number of azimuthal samples. However, the storage is reduced by factorizing the original matrix of $n^2 \times m$ into two matrices with dimensions of $n^2 \times k$ and $k \times m$, such that $k << n, k << m$. The factored matrices are stored in the compressed data file where $k = (r^2 + r)/2$ and r representing the number of coefficients. Then, the compressed file only requires of 4.5 MB for metallic gray particle and 5 MB for cadmium red particle to compute the rendering operation successfully. The compression mechanism is built on SVD technique which is explained in detail in Ergun et al. [6]. Moreover, the peak signal-to-noise ratio (PSNR) [21] comparisons show that the loss is minimal with the compressed data which only differs by $0.02 - 0.03$ dB. As shown in Table 1, the required time for the rendering operation significantly decreases by using Ergun et al.'s model [6], and the compression procedure decreases the storage needs of the approach.

Table 1. A comparison of the computation times (in seconds) of Ergun et al.'s [6] model for raw and compressed data with the computation time of the reference Monte Carlo model (in minutes).

Particles	*Monte Carlo*	*Raw Data*	*Compressed Data*
Metallic Gray	43 min.	6.8 sec.	4.5 sec.
Cadmium Red	72 min.	4.65 sec.	4.21 sec.



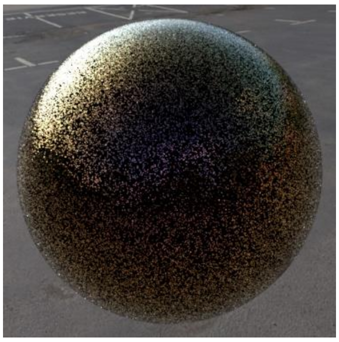
Monte Carlo Output - Mirror Flake	Raw Data - Ergun et al. [6]	Compressed Data - Ergun et al. [6]
Reference Image - Metallic Gray	PSNR Value = 50.32 dB	PSNR Value = 50.29 dB

Monte Carlo Output - Mirror Flake	Raw Data - Ergun et al. [6]	Compressed Data - Ergun et al. [6]
Reference Image - Cadmium Red	PSNR Value = 50.04 dB	PSNR Value = 50.02 dB

Figure 2. The comparison of the sphere scene using Monte Carlo simulations, and the automobile paint model proposed by Ergun et al. [6] using raw and compressed data. Each of the images were rendered using 1024 samples per pixel. The images in the middle column were rendered using Ergun et al.'s [6] model with the raw data representation, and the images in the right column were rendered using Ergun et al.'s [6] model with the compressed data representation. The raw data requires 96 MB in the memory where compressed data reduces this amount to 4.5 MB for Metallic Gray particle and 5 MB for Cadmium Red particle.

Figure 3 shows the effect of different number of facets in Guo et al.'s [4] model. As it's seen in Figure 3, the sparkle effect in the spheres increases as the total number of facets decreases. In Table 2, the required times for the rendering process of the sphere scenes in Figure 3 were compared. Table 2 illustrates that as the total number of facets increases, the rendering time also increases. γ is the radius of the queried cone and α is the roughness of the smooth NDF. We set them as $\gamma = 3°$ and $\alpha = 0.07$. In addition, our results show that an increase in the number of facets still compute the glittery appearance. However, the output images result in a smoother appearance in comparison with the output images rendered using the less number of facets.

According to our results, the details of the models are summarized in Table 3. Ergun et al.'s model [6] is a volumetric model that physically builds the layers of the paint based on the parameters provided in the scene. Their model is capable of simulating goniochromatic effects which is computed through the scattering of the flakes and their composition. In addition, their model is specifically designed for the automobile paints and the number of layers may be modified based on the detail of the modelled paint sample. Thus, the authors provide a compression procedure that increases



P_{inc} = 570 nm

Total Number of Facets = 10^7

P_{inc} = 570 nm

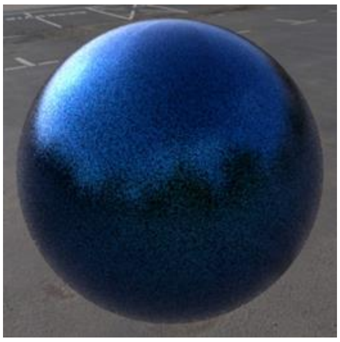
Total Number of Facets = 10^8

P_{inc} = 570 nm

Total Number of Facets = 10^{11}

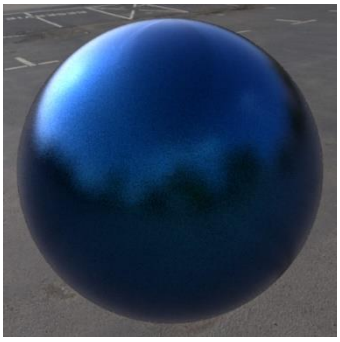
P_{inc} = 665 nm

Total Number of Facets = 10^7



P_{inc} = 665 nm

Total Number of Facets = 10^8



P_{inc} = 665 nm

Total Number of Facets = 10^{11}

Figure 3. The sphere scene was rendered with different parameters. The parameters and the rendering times for each scene are shown in Table 2.

Table 2. A comparison of the rendering times (in hours) of Guo et al. [4]'s model at different parameters. K is the total number of facets. In Belcour and Barla's [3] model the base material has an index of η_3 + iκ_3. On top of it a thin film layer is placed which has an index of η_2. The parameters are determined experimentally.

P_{inc}	K	η_2	η_3	κ_3	*Time*
570 nm	10^7	1.8	1.08	0.51	2.22
570 nm	10^8	1.8	1.08	0.51	2.38
570 nm	10^9	1.8	1.08	0.51	3.49
665 nm	10^7	1.97	1.12	0.0	2.23
665 nm	10^8	1.97	1.12	0.0	2.42
665 nm	10^9	1.97	1.12	0.0	3.52

Table 3. The special effects that are included in the compared models of [6], [3] and [4]. (1) Goniochromism, (2) Sparkling.

Model Name	***(1)***	***(2)***
Ergun et al. [6]	Yes	No
Belcour and Barla [3]	Yes	No
Guo et al. [4]	Yes	Yes

the efficiency with a minimized loss. However, the sparkling appearance is not added in their model that can be seen in the metallic paints coated with aluminum flakes. Belcour and Barla [3] proposes an approximate model that simulates goniochromatic effects considering the thin-film layer coated on a material. Their model is a general model that can be used on many types of materials and it simplifies the operation by reducing the number of paremeters needed in the rendering operation. However, the model does not represent sparkle effects and the goniochromatic appearance on the automobile paints have small differences compared to Ergun et al.'s [6] mostly resulting in color saturation. This is mainly related with the multi-layered structure of [6] which is not modelled in the work of [3]. Finally, Guo et al. [4] proposed a model that replaces the smooth NDF in Belcour and Barla's approach [3] with a discrete NDF for adding the sparkling appearance on the final image. Thus, the model can represent both of the goniochromatic and sparkle effects. However, the efficiency is decreased since the proposed approach uses a 4D search in the spatial and directional domain to simulate sparkling appearance. Therefore, the rendering of the sample images in Figure 3 requires more time compared to Belcour and Barla's model [3].

As all models can simulate goniochromatic effects, we rendered similar materials using all proposed models, which can be seen in Figure 4. In the first column, the images of Ergun et al. [6]'s model are shown. In the upper image, the paint layer was composed of translucent flakes coated with 80 nm titanium dioxide (TiO_2) platelets. In the bottom image, the thickness value of TiO_2 platelets was set to 110 nm which affects the final appearance of the automobile paint. The images in the second column were rendered by using Belcour and Barla's [3]

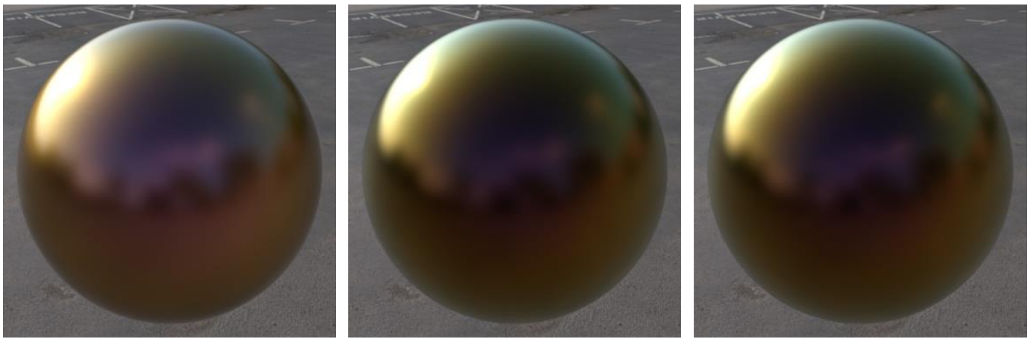
Table 4. A comparison of the rendering times (in seconds) of Ergun et al.'s model [6], Belcour and Barla's model [3] and Guo et al.'s model with the exclusion of sparkle effect [4].

Particles	$TiO_2(80nm)$	$TiO_2(110nm)$
Ergun et al. [6]	7.29 sec.	7.36 sec.
Belcour and Barla [3]	78 sec.	80 sec.
Guo et al. [4]	335 sec.	347 sec.

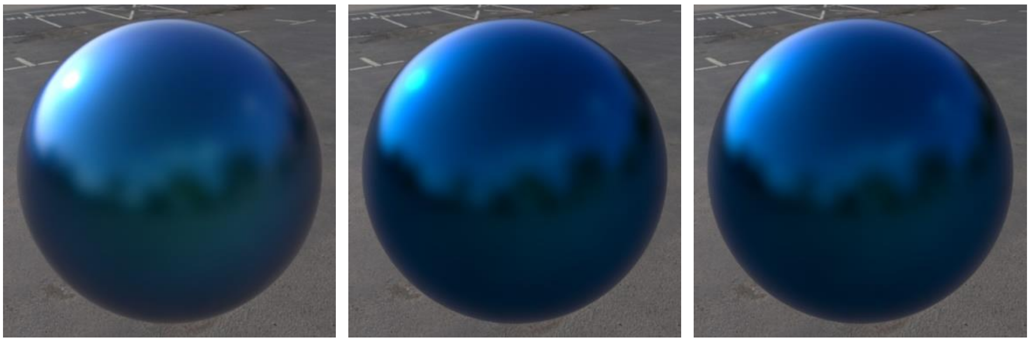
model. As an analytical model, the parameters of these scenes were adjusted to create a similar appearance with Ergun et al. [6]'s work. The parameters used in these images are reported in Table 2 where η_2, η_3 and κ_3 parameters are used in this model. To render the images in the last column, we eliminated the sparkle effect proposed by Guo et al. [4]'s model by using a smooth NDF similar to Belcour and Barla's [3] model. Therefore, the resulting images only include goniochromatic appearance like other models. Once again, the parameters in Table 2 were used to generate these images. As it can be seen in Figure 4, the compared models create similar goniochromatic effects. However, the resulting images of Ergun et al. [6]'s model are more saturated in terms of color appearance which is caused by the multi-layered structure of their model that is not modelled in other works. The rendering times of each model for the specified scenes are given in Table 4. As it can be seen, Ergun et al.'s [6] model requires less time than other models once the precomputed data file is available since the provided data is used in the repeated computations due to multiple scattering. If not, the precomputation step requires 1.9-2 minutes to compute and store the data file to be used in rendering operation for all the scenes shown in Figure 2 and Figure 4.

4. Discussion and Conclusion

In this paper, we present and compare several models proposed for representing complex special effects on automobile paints. In our comparisons, we focus on goniochromism and sparkles which are becoming popular and common effects in modern automobile paints. As these effects are observed due to the multi-layered structure of the coating and the microscopic particles distributed inside the basecoat layer, the realistic appearance of



Ergun et al. [6] Belcour and Barla [3] Guo et al.'s model [4]



Ergun et al. [6] Belcour and Barla [3] Guo et al.'s model [4]

Figure 4. The comparisons of goniochromatic effects in the presented models. The first column consists of images rendered using Ergun et al.'s [6] model. The material was composed of TiO_2 particles with 80 nm thickness in the upper image and 110 nm in the bottom image. The middle column was rendered using Belcour and Barla's [3] model and the images in the right column were rendered by using Guo et al.'s [4] model. The parameters used in Guo et al.'s [4] model were reported in Table *2* and the same parameters were used in Belcour and Barla's [3] model excluding the K parameter. The rendering times for each image were provided in Table *4*.

a paint coating is based on the accurate representation of the scattering caused by these particles. Thus, we made experiments on these models by analyzing their outputs for different kinds of materials in terms of accuracy and performance.

Our experiments demonstrate that all three models are capable of simulating the goniochromatic effects. The models of Belcour and Barla [3] and Guo et al. [4] approximately predict the final color of the material using the index of refraction and the thickness parameters. With a change in those parameters, we observed that the color of final material changes in parallel. The model of Ergun et al. [6] takes an input parameter set of composition. Moreover, their model can create it's own synthetic data and also introduces an SVD-based compression procedure. We have shown that the raw and compressed data generate visually plausible results statistically by comparing it with a reference Monte Carlo path tracing model. In addition, the compression procedure improves the performance with a minimal loss in accuracy. However, the models of Belcour and Barla [3] and Ergun et al. [6] are limited with goniochromatic effects and cannot model sparkling appearance. On the other hand, Guo et al.'s [4] model can also simulate sparkles with a dramatic increase in computation time.

In our future work, we are planning to build a model that can simulate both goniochromatic and sparkle effects on automobile paints accurately and efficiently. Additionally, we are planning to create a database of several materials' outputs which can be used as reference images for future studies.

Acknowledgment

This work was supported by the Scientific and Technical Research Council of Turkey (Project No: 119E092).

References

[1] Ershov, S., Kolchin, K., Myszkowski, K. 2001. Rendering Pearlescent Appearance Based on Paint-Composition Modelling, Computer Graphics Forum, Vol. 20, No. 3, pp. 227-238. DOI: 10.1111/1467-8659.00515

[2] Rump, M., Müller, G., Sarlette, R., Koch, D., Klein, R. 2008. Photo-realistic Rendering of Metallic Car Paint from Image-Based Measurements, Computer Graphics Forum, Vol. 27, No. 2, pp. 527-536. DOI: 10.1111/j.1467-8659.2008.01150.x

[3] Belcour, L., Barla, P. 2017. A Practical Extension to Microfacet Theory for the Modeling of Varying Iridescence, ACM Transactions on Graphics (TOG), Vol. 36, No. 4, pp. 65:1-65:14. DOI: 10.1145/3072959.3073620

[4] Guo, J., Chen, Y., Guo, Y., Pan, J. 2018. A Physically-based Appearance Model for Special Effect Pigments, Computer Graphics Forum, Vol. 37, No. 4, pp. 67-76. DOI: 10.1111/cgf.13476

[5] Wang, B., Hašan, M., Holzschuch, N., Yan, L. Q. 2020. Example-based Microstructure Rendering with Constant Storage, ACM Transactions on Graphics (TOG), Vol. 39, No. 5, pp. 162:1-162:12. DOI: 10.1145/3406836

[6] Ergun, S., Önel, S., Ozturk, A. 2016. A General Micro-flake Model for Predicting the Appearance of Car Paint, Proceedings of the Eurographics Symposium on Rendering: Experimental Ideas & Implementations, June 22-25, Dublin, 65-71.

[7] Jakob, W., Arbree, A., Moon, J. T., Bala, K., Marschner, S. 2010. A Radiative Transfer Framework for Rendering Materials with Anisotropic Structure, ACM Transactions on Graphics (TOG), Vol. 29, No. 4, pp. 53:1-53:13. DOI: 10.1145/1778765.1778790

[8] Jakob, W., d'Eon, E., Jakob, O., Marschner, S. 2014. A Comprehensive Framework for Rendering Layered Materials, ACM Transactions on Graphics (TOG), Vol. 33, No. 4, pp. 118:1-118:14. DOI: 10.1145/2601097.2601139

[9] Belcour, L. 2018. Efficient Rendering of Layered Materials using an Atomic Decomposition With Statistical Operators, ACM Transactions on Graphics (TOG), Vol. 37, No. 4, pp. 73:1-73:15. DOI: 10.1145/3197517.3201289

[10] Zeltner, T., Jakob, W. 2018. The Layer Laboratory: A Calculus for Additive and Subtractive Composition of Anisotropic Surface Reflectance, ACM Transactions on Graphics (TOG), Vol. 37, No. 4, pp. 74:1-74:14. DOI: 10.1145/3197517.3201321

[11] Yamaguchi, T., Yatagawa, T., Tokuyoshi, Y., Morishima, S. 2020. Real-Time Rendering of Layered Materials with Anisotropic Normal Distributions, Computational Visual Media, Vol. 6, No. 1, pp. 29-36. DOI: 10.1007/s41095-019-0154-z

[12] Werner, S., Velinov, Z., Jakob, W., Hullin, M. B. 2017. Scratch Iridescence: Wave-Optical Rendering of Diffractive Surface Structure, ACM Transactions on Graphics (TOG), Vol. 36, No. 6, pp. 207:1-207:14, DOI: 10.1145/3130800.3130840

[13] Yan, L. Q., Hašan, M., Walter, B., Marschner, S., Ramamoorthi, R. 2018. Rendering Specular Microgeometry with Wave Optics, ACM Transactions on Graphics (TOG), Vol. 37, No. 4, pp. 75:1-75:10, DOI: 10.1145/3197517.3201351

[14] Guillén, I., Marco, J., Gutierrez, D., Jakob, W., Jarabo, A. 2020. A General Framework for Pearlescent Materials, ACM Transactions on Graphics (TOG), Vol. 39, No. 6, pp. 253:1-253:15, DOI: 10.1145/3414685.3417782

[15] Yan, L. Q., Hašan, M., Jakob, W., Lawrence, J., Marschner, S., Ramamoorthi, R. 2014. Rendering Glints on High-Resolution Normal-Mapped Specular Surfaces, ACM Transactions on Graphics (TOG), Vol. 33, No. 4, pp. 116:1-116:9, DOI: 10.1145/2601097.2601155

[16] Yan, L. Q., Hašan, M., Marschner, S., Ramamoorthi, R. 2016. Position-Normal Distributions for Efficient Rendering of Specular Microstructure, ACM Transactions on Graphics (TOG), Vol. 35, No. 4, pp. 56:1-56:9, DOI: 10.1145/2897824.2925915

[17] Jakob, W., Hašan, M., Yan, L. Q., Lawrence, J., Ramamoorthi, R., Marschner, S. 2014. Discrete Stochastic Microfacet Models, ACM Transactions on Graphics (TOG), Vol. 33, No. 4, pp. 115:1-115:10, DOI: 10.1145/2601097.2601186

[18] Guo, Y., Hašan, M., Zhao, S. 2018. Position-Free Monte Carlo Simulation for Arbitrary Layered BSDFs, ACM Transactions on Graphics (TOG), Vol. 37, No. 6, pp. 279:1-279:14. DOI: 10.1145/3272127.3275053

[19] Jakob, W. 2010. Mitsuba Renderer. http://www.mitsuba-renderer.org (Access Date: 18.09.2021).

[20] Jakob, W. 2015. Layerlab: A Computational Toolbox for Layered Materials. SIGGRAPH 2015 Courses, ACM, New York.

[21] Richardson, I. E. 2002. Video Codec Design: Developing Image and Video Compression Systems. John Wiley & Sons, Inc., New York, 328s.