Simulation of Light Scattering in Automotive Paints

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Modern automotive paints are of great interest in research works. They contain colorant particles and thin flat metallic or pearlescent flakes distributed in a clear varnish. There are two main approaches to simulation of light scattering in a dispersed media. The first one is based on the continuous medium model. This model is faster but less accurate. The second approach is the simulation of light propagation through an ensemble of paint flakes and particles represented as an explicit geometry. This model correctly calculates light scattering but is rather time-consuming.

Keywords: light scattering ; dispersed medium ; lighting simulation ; paint realistic rendering

1. Introduction

Nowadays, the use of computer simulation to develop new materials has become a widespread practice. From the point of view of the visual perception of the material, it is important to model the interaction of light with it. Many modern materials are dispersed media, i.e., they consist of optically contrasting particles distributed in the volume of a transparent substance. Such media are used in modern light sources (diffusers in flat sources, luminous linear sources and devices in car interior), and they are also the basis of modern paints, auto glass, plastics, and inks for 3D printers.

Visual appearance is the main characteristic of paint and it manifests itself through the human perception of objective optical properties, such as color, brightness (reflection coefficient), glossiness, texture (spatial heterogeneity), etc. Hence, simulation and visualization of optically complex materials, such as multilayer paints with a complex microstructure (like pearlescent and metallic paints) in the automotive industry, have been developed in recent years. Advanced software allows one to simulate light propagation through a paint composed of clear varnish with pigment particles and flakes (metallic or interference ones) dispersed in it. The color of these paints depends on the observation and illumination directions. Therefore, its visual appearance should be described by a bidirectional reflectance distribution function (BRDF). The primary task is to calculate how the paint with given composition looks under given illumination and observation directions [1].

2. Simulation of Light Scattering in Automotive Paints

Many studies are devoted to the simulation of paints or 3D printer inks as disperse media. Simulated BRDF of paint layer is then used for visualization of a virtual car. Some works propose the paint models and try to realistically visualize the paint appearance based on the paint composition. An approximate model for predicting the car paint appearance by the paint composition is presented in the paper [2]. Therein, authors proposed to use a modified version of the micro-flake model based on double-sided specularly reflecting flakes. Their model provides visually satisfactory results in the appearance of multilayer automotive paint, if one is to ignore sparkling. Accurate representation of the reflectivity of metallic paint using a two-layer model with sample distribution functions of microfacets was proposed in [3]. This model provides better accuracy due to the use of the nonparametric terms and allows the analysis of the characteristics of metal particles using the analytical form built into the model.

Texture is proposed to model sparkling effect. The sparkling texture is usually calculated by modulating the BRDF with random field whose statistical characteristics are taken from light interaction with an ensemble of individual particles [1][4]. This is inevitable because continuous medium (i.e., LTE) cannot have a texture. Several approaches for obtaining the spatial variation of the luminance are considered in [5]. The basic approach based on a bidirectional texture function is compared with four variants of half-difference parametrization. With the help of a psychophysical study, the authors concluded that bivariate representations better preserve the visual accuracy of effect coatings.

Several works are devoted to paint rendering. Some of them operated with measured data either combined with analytical solution [6] or postprocessed to archive effective and realistic rendering of real car paint [7]. An interactive interpolation between measured metal paints for cars was presented in [8]. It can be used to create new realistic-looking metallic paint.

The authors consider optimal transfer between types of metallic paints by clustering the color information presented in the measured bidirectional texture function responsible for the sparkling effect. The work in [9] describes the methodology of metallic paint visualization based on the measured data. The authors matched the measured spectral reflectivity of several paint samples to the BRDF analytical model to obtain its parameters. To achieve the sparkling effects, several images of the surface were taken at different light incidence.

There are many works that investigate propagation of light in a medium where positions of particles are correlated [10][11][12][13]. The authors have proven that the extinction of light beam is no longer exponential, as it would be for the classic case. Although there are sophisticated mathematical models to handle this effect, its base idea is rather intuitive and is illustrated in Figure 1 of [11], which explained it so perfectly that it was re-used in [12]. The basic LTE is then replaced by a sort of generalized equation of similar type, termed “Generalized Boltzmann Equation” [12]. Indeed, there is some similarity with the classic Boltzmann equation, at least in the integral (scattering) term. It still has the same structure as the classic LTE: a sort of convolution of the local angular intensity with the phase function. The latter is still treated as usual in the classic continuous medium approximation, i.e., it is the phase function of an isolated particle scaled to the local density. Investigation into ensembles of correlated particles is advanced in [13]. Its authors finalize their work using the numerical method of calculation of light propagation (and scattering) based on MCRT. A slightly different method of calculation of light propagation in correlated medium and resulting “anomalous extinction” can be found in [14].

While the studies [10][11][12][13][14] operate ray optics, there are investigations proceeding from the wave theory of light. The first thing which this is aimed at is the interference between particles. Indeed, the LTE (and even its above generalizations) requires phase function of medium, i.e., scattering by the elementary volume dV. It can contain many particles at close distance and inevitably diffraction of light by this group is different from the sum over isolated, not interacting with particles. While the phase function of medium is usually assumed proportional to the scattering of an isolated particle, it would be more accurate to compute it as a diffraction of light by the group of particles within dV. Here, it is silently assumed that the result converges as researchers increase dV. Such an approach is pursued in [15], wherein only the multiple body diffraction problem (scattering by many close particles) is calculated.

In [16][17][18], the radiative transfer problem is considered for particle agglomeration and dependent scattering. Calculations are performed for very close, particles with refraction close to the bounding medium one. The Percus–Yevick approximation is used in these works to obtain the local concentration and the rule of its change from the cluster center. Then, in [16][17], the authors calculate scattering of the wave field by this group of particles, which is effectively a piece of inhomogeneous medium with correlated variation of refraction index. This scattering gives the local phase function of the elementary volume of the medium. However, this approach still remains a hybrid of wave optics (used to compute phase function of small volume) and ray optics to handle the change of illumination by large and meso scale.

An ultimate wave optics approach would use wave optics consistently at all space scales. Additionally, an attempt of such a treatment is made in [19]. Roughly, the method of calculation of [19] is the development and extension of the single-scattering method from statistical electrodynamics [20] where researchers use the Born approximation of the wave equation, i.e., a homogeneous medium with volumetric source being incident wave field times the deviation of the squared local refraction from its mean value $n2(x)-\langle n2\rangle 2-\langle 2\rangle$. Scattered wave field is then naturally linear in that deviation. Intensity of light is squared field averaged over the random distribution of refraction. It results in the local intensity of scattered light proportional to the spatial correlation function of refraction. Whilst the above is the first approximation, one can try to go further and improve the volumetric source by including the scattered field in it. Continuing successive approximation, researchers obtain the scattered field as the sum of an infinite series whose terms are local Green resolvents of homogeneous medium. This procedure is somewhat similar to the operator series of solution of the global illumination equation in ray optics [21].

The authors of [19] take the base wave equation in a stochastically inhomogeneous medium and then write its solution through the propagators of wave field. The authors investigate in detail the extreme cases of long and short wave limits. For long waves, the role of short-scale spatial variations decreases (cf. Rayleigh law) and eventually light propagates like in a homogeneous medium with effective refraction index derived from formulae [19]. The effective medium is similar to the Bruggemann formula for a molecular-level mixture of several substances. For short wave limit, they naturally approach the ray optics. Their transport equation converges to a sort of generalized LTE.

A similar approach can be found in [22]. Higher orders of scattering (scattering of scattered field) are calculated as iteration of the integral operator. The scattering operator includes the spatial correlation of the squared refraction index (= dielectric permittivity), so it also enters the higher order scattering terms.

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