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A comprehensive geometrical optics application for wave rendering ☆

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ABSTRACT

This paper presents a novel method to model wave effects in a ray tracer which attempts to account for the attenuation, scattering and absorption of light affected by participating media along rays. Inspired by diffraction shaders (DS), we propose an extension of this model to construct a new Bidirectional Reflectance Distribution Function (BRDF) to simultaneously take into consideration the phase and amplitude variation of light. The new method can simulate diffraction effects of a variety of materials, where we introduce the Fresnel factor and a microfacet scattering metric which affect the absorption and geometrical attenuation of photons. Incorporating Wigner Distribution Function (WDF), our method is further extended to model interference effects after multiple bounces by deferring the phase calculation. An acceleration algorithm is also implemented to real-time model diffraction effects of different apertures. We demonstrate the validity of our method by generating wave patterns for diverse scenes.

1. Introduction

When light passes through obstacles with the size of several wavelengths, it will deviate from its original direction of propagation to bend into the geometrical shadow region of obstacles, and generate the uneven distribution of the radiant energy. This type of phenomenon is called diffraction which can be accurately explained with scalar diffraction theory [1], where the rainbow hologram is a representative example.

In computer graphics, it is desirable to construct appropriate reflection models to model the interaction of light and surfaces of objects for the sake of realistically simulating scenes such as butterfly wings and feathers. These reflection models are mainly based on the two theories, namely geometrical optics and wave optics. In geometrical optics, light is abstracted as a collection of rays and some common geometrical phenomena, such as diffuse, specular highlight and refraction, can be realistically rendered in ray-based frameworks. In wave optics, light is a kind of electromagnetic field with amplitude and phase. A series of wave reflection models [2–4] have been proposed to simulate diffraction effects from microstructures such as compact discs and diffraction gratings, where the height field model or the correlation function is widely used to encapsulate the phase variations into reflected rays. These methods are able to approximately describe wave phenomena, but few of them consider the amplitude factor which determines the absorption or attenuation of light, and are only applied to the far field (i.e., the Fraunhofer region) or special surfaces.

In this paper, we propose a new Bidirectional Reflectance Distribution Function (BRDF) diffraction model for a variety of materials based on the Torrance-Sparrow reflection model [5] and diffraction shaders (DS). This model takes into account the variable Fresnel coefficient dependent on the wavelength and introduces a microfacet scattering metric. The amplitude and phase variations of light are thus encapsulated into our wave model in the

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form of the radiant intensity of reflected rays to explain the absorption, shadowing or interreflection of photons, where the Monte Carlo method [6] is used to solve our wave equation. In addition, we incorporate the Wigner Distribution Function (WDF) into the proposed BRDF wave optics model to simulate interference effects after multiple bounces by deferring the phase calculation to a later stage. We render the realistic wave effects from many objects such as disks or spheres in a ray-based framework using the proposed BRDF wave model, where our wave equation can strictly describe the amplitude and phase variations by referring to the physical optics. We also implement an acceleration algorithm to real-time render the wave effects of apertures using the CUDA [7].

The rest of this paper is organized as follows. Some related techniques are briefly reviewed in Section 2. Section 3 outlines a set of physical models for rendering wave phenomena. Our methods are described in detail in Section 4. The experimental results and analysis are provided in Section 5. We finally conclude this paper with discussions on future work in Section 6.

2. Related work

2.1. Geometrical optics

Torrance and Sparrow [5] proposed the Torrance-Sparrow microfacet model to describe the reflection properties of the metal surfaces, which was introduced to graphics by Blinn [8], and Cook [9] constructed a similar reflection model. Phong [10] summed up several shading techniques and hidden surface deletion methods, and also presented a geometrical reflection model. Oren and Nayar [11] constructed the Oren-Nayar BRDF model to model the aggregate reflection effects of the collection of grooves, where microfacets were regarded as symmetrical V-shaped grooves and it assumed that each individual microfacet exhibited the perfect Lambertian distribution. Granier et al. [12] proposed a RGB BRDF model for the specular and diffuse reflection of layered materials. Pharr et al. [6] conducted a complete theoretical illustration and comparison for physical-based reflection models.

The advantage of modeling using geometrical optics is to make the interaction of light and surfaces easier to control and not consider the complex phase variation. This approach not only directly improves the computational efficiency, but also makes the renderer based on geometrical optics simulate specular reflection and refraction effects realistically by selecting several control parameters to generate the different spatial distributions of ray intensity. However, it is difficult to model the wave phenomena such as diffraction and interference in ray-based renderers out of the lack of the effective description of the phase variation of the wave.

2.2. Wave optics

Beckmann and Spizzichino [13] proposed an early physical model to describe the reflection effects from microfacets, laying the foundation for the application of wave optics in graphics. Moravec [14] proposed the wave optics model based on the phase tracking technology which was applied to graphics in 1981. Kajiya [15] developed a BRDF anisotropic reflection model using a numerical solution to solve the Kirchhoff integral formula. In addition, He et al. [16] also described a sophisticated physical model to simulate the reflection phenomena from a variety of surfaces.

Nayar et al. [17] proved that if the surface is very rough, the wave reflection models are similar to the ones based on geometrical optics, where the reflected radiances generated by wave models can be approximated by results using geometrical optics. More recently, the numerical calculation methods such as Monte Carlo and fast Fourier transform (FFT) are widely applied to solve the wave rendering equation. The representative example is the BRDF model of diffraction shaders [2], where the Fourier optics theory and the correlation function related to the height field are used to encapsulate the spatial density of light energy into outgoing rays which contain phase variations. In addition, Wigner distribution function is also commonly used to construct wave models [18–20]. Cuypers et al. [21], for instance, presented the wave Bidirectional Scattering Distribution Function (WBSDF) for rendering wave effects after several bounces by deferring the phase calculation. There also exist multiple diffraction models applied to the rendering of sound in acoustics [22,23].

Although wave models are able to explain the phase and amplitude variations of light, they are not usually worth their computational cost for many applications. We thus implement a simple acceleration algorithm on the current graphics hardware to improve the rendering efficiency, which can be further used for glare generation in 3D scenes [24].

3. Principles of wave rendering

The interaction of light and microfacets is often described by geometrical reflection models (see Fig. 1). However, there have been multiple physical optics models proposed to render the wave effects from microfacets such as apertures and diffraction gratings. Since these wave models can explain lots of physical phenomena, they have attracted more and more attentions. According to the Maxwell's theory, when light interacts with the surfaces of objects, reflection equations should be solved as the boundary value problem of the electromagnetic field. In practice, because of the computational complexity of the generic solution, most of wave models use some approximate numerical algorithms. Stam, for instance, uses the

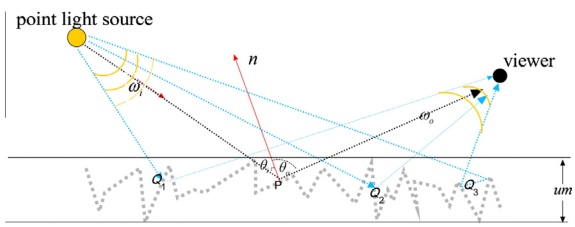

Fig. 1. A schematic illustration of the interaction of light and microfacets.