Interactive Diffraction from Biological Nanostructures

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Abstract

We describe a technique for interactive rendering of diffraction effects produced by biological nanostructures such as snake skin surface gratings. Our approach uses imagery from atomic force microscopy that accurately captures the nanostructures responsible for structural coloration, that is, coloration due to wave interference, in a variety of animals. We develop a rendering technique that constructs bidirectional reflection distribution functions (BRDFs) directly from the measured data and leverages precomputation to achieve interactive performance. We demonstrate results of our approach using various shapes of the surface grating nanostructures. Finally, we evaluate the accuracy of our precomputation-based technique and compare to a reference BRDF construction technique.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture

1. Introduction

In biology, structural coloration is the production of color through the interaction of light with nanoscale surface structures or intra-cellular submicron photonic crystals. Color production is due to wave interference with quasiperiodic structures whose periodicity leads to interaction with visible light. Spectacular examples of structural colors include the vivid and sometimes iridescent colors of some insects' wings, bird feathers, and reptile scales. Stam [Sta99] pioneered diffraction shaders for rendering structural colors for *analytically known* nanostructures. This was followed by a number of efforts to model wave effects in computer graphics. Cuypers et al. [CHB*12] proposed "wave-based BSDFs" (WBSDFs) using Wigner Distribution Functions (WDFs). Other approaches include Optical Path Differences (OPD) [ZCG08] and Augmented Light Fields [OKG*10], which also employ WDFs. All these methods involve complex computations and are unsuitable for interactive rendering. Lindsay and Agu [LA06] focus on interactive rendering using low order spherical harmonics. This approach is too simplistic to model complex nanostructures. Thus, most existing techniques are either too slow, or rely on simplifying assumptions to achieve real-time performance.

In this paper, we instead derive reflectance models suitable for interactive rendering directly from physical measurements of biological structures. In particular, our approach applies to surfaces with quasiperiodic nanostructures that can be represented as heightfields. We develop a technique to precompute look-up tables that allow us to efficiently evaluate the BRDF and achieve real-time performance. We demonstrate our approach using nanostructures acquired from the sheds of two snake species, *Elaphe guttata* and *Xenopheltis unicolor*, which exhibit moderate and intense iridescence of the skin, respectively. We also verify our technique by comparing with their measured reflectances.

2. Overview

Our method is based on the pioneering work of Stam [Sta99] which shows how to directly formulate BRDFs in terms of nanoscale heightfields. The BRDF of a nanostructure $h(x,y)$ can be expressed in terms of the Fourier transform P of the function $p(x,y) = e^{iwkh(x,y)}$ as,

$$BRDF_\lambda(\omega_i,\omega_r) = \frac{F^2 G}{\lambda^2 A w^2}\left\langle \left| P\left(\frac{u}{\lambda},\frac{v}{\lambda}\right)\right|^2 \right\rangle. \quad (1)$$

Here, λ represents a specific wave-length, and ω_i and ω_r are the incident and reflected unit direction vectors pointing away from the surface. F represents the Fresnel term and u,v,w are computed from the incident and reflected directions as $(u,v,w)^T = -\omega_i - \omega_r$. Please refer to Stam's work [Sta99] for details about the other terms in Equation 1.

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