A Surface-based Appearance Model for Pennaceous Feathers

Juan Raúl Padrón-Griffe
juanraul.padron@unizar.es
I3A, Universidad de Zaragoza
Zaragoza, Spain

Dario Lanza
dlanza@unizar.es
I3A, Universidad de Zaragoza
Zaragoza, Spain

Adrián Jarabo
ajarabo@unizar.es
I3A, Universidad de Zaragoza
Zaragoza, Spain

Adolfo Muñoz
adolfo@unizar.es
I3A, Universidad de Zaragoza
Zaragoza, Spain

Figure 1: A rendering of an Amazon parrot wing. Left: A reference photograph. Center: A surface-based rendering of the wing feathers using a hair scattering model [Marschner et al. 2003] for the barbs and a shading model for the multi-scale structure similar to previous work [Baron et al. 2022]. Right: The same scene rendered using our model accounting for accurate masking and complex medulla using our BCSDF. Our far-field reflectance model represents more accurately the feather substructures and coloration mechanisms matching reference appearance closer including features such as the diffuse look of feathers, and the subtle goniochromatism due to visibility changes between barbs and barbules.

ABSTRACT

The appearance of a real-world feather is the result of a complex light interaction with its multi-scale biological structure including the central shaft, branching barbs and interlocking barbules on those barbs. In this work, we propose a practical appearance model for feathers encoded as 2D textures where the overall appearance is a weighted BSDF of the implicit representations of the key biological structures. This BSDF can be applied to any surface and does not require the explicit geometrical modeling of the internal microstructures (barbs and barbules) as in previous works. Our model accounts for the particular characteristics of feather fibers such as the non-cylindrical cross-sections of barbules and the hierarchical cylindrical cross-sections of barbs. To model the relative visibility between barbs and barbules, we derive a masking term for the differential projected areas of the different components of the feather's microgeometry, which allows us to analytically compute the masking between barbs and barbules without costly Monte Carlo integration.

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1 INTRODUCTION

The appearance of feathers is diverse and rich, different among species, and is partially explained by the geometrical complexity of their structure at several levels. Each feather is composed of a central shaft, called the rachis, with its base (the calamus) inserted into the skin. Serial fiber-like branches (barbs) emerge from both sides of the rachis. A second level of branching emerges from the barbs (the barbules), which in pennaceous feathers become attached to adjacent barbs, forming a flattened surface (the vane). Compared to other biological appearances such as skin, hair [Marschner et al. 2003] or fur [Yan et al. 2015], rendering of feathers, and in particular of pennaceous feathers, is a relatively unexplored area in computer graphics, with some notable exceptions baked bidirectional texture function [Chen et al. 2002], iridescent rock dove neck feathers [Huang et al. 2022], or expensive curve-based representations for the barbs with simplified scattering functions [Baron et al.

2022]. While modeling the barbs as curves [Baron et al. 2022; Huang et al. 2022] is flexible, allows for a very fine-detailed representation of the feathers, and explicitly accounts for geometric effects such as visibility, it might become prohibitively expensive in applications with many feathers.

In this work, we propose a far-field surface-based appearance model for pennaceous feathers, that encodes the geometric complexity of a feather with lightweight textures. We introduce a bidirectional scattering distribution function (BSDF) that combines the scattering of barbs and barbules stochastically, based on their density and orientation, as well as their relative visibility. For each barb and barbule, we introduce a bidirectional curve scattering distribution function (BCSDF) that accounts for the ellipticity of the fibers, and the effect of the internal non-centered scattering medulla. In some species, the internal structure of the barbs has a quasi-ordered nanoscopic structure producing diffuse structural coloration that can be approximated with a diffuse medulla, a phenomenon ignored by all previous works.

2 APPEARANCE MODEL

Our model represents the aggregated scattering from barbs and barbules inside a small surface patch of differential area, where we assume that both barbs, distal barbules, and proximal barbules are locally parallel with each other, and have similar local optical properties. It takes as input a set of lightweight texture maps encoding the geometry of the feather, and the per-point optical properties. In particular, we store the tangent direction of the barb in the feather's reference frame and a segmentation map to identify the feather structure (rachis, the vane, or empty space). The optical properties of the feather are defined globally, though can be easily implemented as additional texture maps.

In render time, the geometry map defines the local frame for the barb, from which we derive the local frame for proximal and distal barbules. These hierarchical local frames are key for computing the scattering of each of the components using our BCSDF. For the BCSDF, we implement a solution inspired by previous work [Yan et al. 2015] where the barbs and barbules can be represented as elliptical dielectric fibers and we introduce a non-concentric diffuse medulla for the barbs. The scattered radiance for each component is then weighted based on their respective projected visible area. We validate our analytical masking against Monte Carlo simulations on explicit 2D geometry, resulting in a perfect match.

3 RESULTS AND CONCLUSIONS

In Figure 1 we compare our appearance model to previous work on a practical application of appearance matching of a parrot wing. In this experiment, we show the importance of our contributions: an analytical masking term to combine barb and barbules and a diffuse medulla for the barbs. In Figure 2 we show view-dependent color and transmittance effects and compare them with photographs. As the feather rotates, it becomes more opaque, as there is less visibility through barbs and barbules, and changes in hue also occur due to occlusions among them. This goniochromatic effect comes from our masking expression and the weights.

To reduce the complexity of the problem and build our BSDF, we ignore three effects: (1) wave-optical effects between barb and barbules, (2) multiple scattering between barb and barbules, and (3) the shadowing term. Still, further research is needed to fully understand the accuracy of these assumptions. Nevertheless, we believe that the most exciting direction for future research would be to delve deeper into the internal structures of barb and barbules and their impact on structural coloration mechanisms. In particular, formal wave-optics solutions, as some of the most fascinating feather appearances can only be explained by wave optics.

Without masking With masking Photograph

Figure 2: Appearance matching on an *Amazon parrot* feather, for a frontal (top) and lateral (bottom) view. As the feather rotates, view-dependent changes in the feather's color become apparent: these variations are produced by visibility changes between barbs (yellow) and barbules (green). Our masking term can roughly predict these changes. Please see the supplemental video for a dynamic example.

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