Physically-Based Rendering of a Damselfly in Distress

Oroni H.

August 2025

1 Introduction

Some of the key methods involved in rendering this damselfly in distress (due to its lack of wings) in this project included path tracing, a widely used technique for global illumination by accounting for multiple bounces of light. The path tracer used techniques such as Monte Carlo integration, importance sampling, the Cook-Torrance BRDF, and an attempt at volumetric effects.

2 Path Tracing Overview

Path tracing estimates the rendering equation:

$$L_o(x, \omega_o) = L_e(x, \omega_o) + \int_{\Omega} f_r(x, \omega_i, \omega_o) L_i(x, \omega_i)(\omega_i \cdot n) d\omega_i \tag{1}$$

Each pixel value is computed by tracing many light paths from the camera into the scene. Rays reflect or refract at surfaces, and their contributions are accumulated using importance sampling to reduce variance.

3 Monte Carlo Integration

Due to the high dimensionality of the rendering equation, Monte Carlo integration is used to approximate the integral:

$$\int_{\Omega} f(x) dx \approx \frac{1}{N} \sum_{i=1}^{N} \frac{f(x_i)}{p(x_i)} \tag{2}$$

where x_i are samples drawn from the probability distribution $p(x)$. In this path tracer, Monte Carlo sampling is applied to directions on the hemisphere, guided by the BRDF.

4 Cosine-Weighted Importance Sampling

To reduce variance in the Monte Carlo estimator when sampling diffuse surfaces, cosine-weighted importance sampling is employed. Instead of sampling directions uniformly over the hemisphere, samples are distributed proportionally to the cosine of the angle between the sample direction and the surface normal:

$$p(\omega_i) = \frac{\omega_i \cdot n}{\pi} \tag{3}$$

This aligns the sampling distribution with the Lambertian cosine term $(\omega_i \cdot n)$ in the rendering equation, increasing the efficiency of the estimator. The resulting paths more accurately capture light transport in diffuse regions, which is especially beneficial for large, matte surface areas like parts of the damselfly's wings and body.

Sampling is typically performed using a change of variables in the local tangent space, with stratified or random sampling over the hemisphere. Cosine-weighted sampling is particularly effective in scenes dominated by indirect lighting or soft shadows.

5 Cook-Torrance BRDF

The Cook-Torrance model provides a physically-plausible microfacet-based reflection model:

$$f_r(\omega_i, \omega_o) = \frac{D(h)F(\omega_i, h)G(\omega_i, \omega_o, h)}{4(n \cdot \omega_i)(n \cdot \omega_o)} \tag{4}$$

Where:

- $D(h)$ is the normal distribution function (in this case, GGX was used)
- $F(\omega_i, h)$ is the Fresnel term (Schlick's approximation)
- $G(\omega_i, \omega_o, h)$ is the geometry term (Smith's geometry term was used which also includes SchlickGGX's geometry terms in the calculation)

This BRDF captures specular highlights and roughness accurately, essential for materials like the iridescent surface of a damselfly.

6 Volumetric Effects

In addition to surface interactions, light scattering within participating media was also considered. This is relevant for simulating effects such as translucency in the damselfly's body and subtle glows resulting from subsurface interaction.

The volume rendering integral is used to account for in-scattering and absorption:

$$L(x, \omega) = \int_0^d T(t)\, \sigma_s(x(t))\, L_s(x(t), \omega)\, dt + T(d)\, L_s(x(d), \omega) \tag{5}$$

where:

- $T(t) = \exp\left(-\int_0^t \sigma_t(x(s))\, ds\right)$ is the transmittance,
- σ_s is the scattering coefficient,
- $\sigma_t = \sigma_s + \sigma_a$ is the extinction coefficient (sum of scattering and absorption),
- L_s is the in-scattered radiance at point $x(t)$.

To model directional scattering behavior in the participating medium, we employed the Henyey-Greenstein phase function:

$$p(\theta) = \frac{1}{4\pi} \frac{1 - g^2}{(1 + g^2 - 2g\cos\theta)^{3/2}} \tag{6}$$

where θ is the angle between the incoming and outgoing directions, and $g \in [-1, 1]$ is the asymmetry parameter:

- $g = 0$: isotropic scattering
- $g > 0$: forward scattering (common in biological tissue)
- $g < 0$: backward scattering

However, the effects of this method are not so noticeable due to the lack of other objects in the scene.

7 Damselfly Model and Material

The damselfly mesh was modeled using Blender and the materials were set using Metasequoia to ensure the body had a material that was akin to a diffuse metal texture, with the eyes meant to exhibit greater shininess.

8 Results

Rendered images were produced at 512×384, with 20 samples per pixel. Below is a sample rendering:

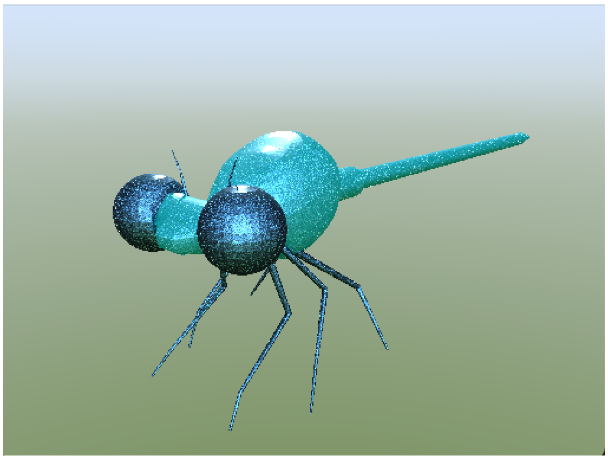

Figure 1: Damselfly in Distress