Physically-based Rendering of Highly Scattering Fluorescent Solutions using Path Tracing

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Abstract

We introduce a physically-plausible Monte Carlo rendering technique that is capable of treating highly scattering participating media in the presence of fluorescent mixtures. Our model accounts for the actual intrinsic spectroscopic characteristics of fluorescent dyes. The model leads to an estimator for simulating the light interaction with highly scattering fluorescent-tagged participating media. Our system is applied to render images of two fluorescent solutions under different conditions. The model is qualitatively analyzed and validated against experimental emission spectra of fluorescent dyes.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Rendering

1. Introduction

Rendering fluorescent materials is an important topic in computer graphics, computational photography and microscopy to accurately predict object appearance under different lighting conditions and material compositions. Several methods have been developed to render fluorescence. Glassner [Gla95] extended the radiative transfer equation (RTE) and presented the first mathematical formalism to simulate the light interaction with fluorescent media. This model did not consider the distinct properties of fluorescent materials. Cerezo and Gutierrez [CS04, GSMA04] have presented further extensions to integrate the missing parameters in Glassner's model to render the fluorescent pigments in the ocean using discrete ordinates and curved photon mapping. Their models ignored the actual spectral characteristics of the fluorescent dyes and used simplified approximations for the excitation and emission spectra. Moreover, their rendering methods were *biased*. Abdellah *et al.* [ABE*, ABE*15] have discussed another physically plausible method that can render fluorescent participating media relying on the realistic spectral properties of fluorescent materials. However, this model was limited to low scattering participating media. This work presents a new model that accounts for the spectral properties of the medium and is capable of rendering highly scattering fluorescent mixtures. The developed method is applied to render highly scattering fluorescent solutions.

2. Main Contributions

1. Development of Monte Carlo estimator that handles highly scattering fluorescent participating media while taking into account the fundamental characteristics of the fluorescent dyes including their emission and excitation spectra, quantum efficiency, molar absorptivity and concentration for a given mixture. The model introduces a new term into the RTE called the *path fluorescence visibility* that acknowledges the presence of a fluorescence emission along the path or not.
2. Qualitative validation of the resulting images by comparing their spectral responses with experimental emission spectra of different fluorescent dyes.

3. Fluorescence Model Description

Our fluorescence model evaluates the radiance $L_\mathrm{i}(\mathbf{x}_0, \omega, \lambda_\mathrm{m})$ arriving to the film at certain emission wavelength due to multiple scattering using the following Monte Carlo estimator

$$L_\mathrm{i}(\mathbf{x}_0, \omega, \lambda_\mathrm{m}) \approx \frac{1}{N_\lambda}\frac{1}{N}\sum_{\lambda=1}^{N_\lambda}\sum_{i=1}^{N}\frac{L_\mathrm{e}(\mathbf{x}_l, \lambda_\mathrm{x})\hat{V}_i}{p(\mathbf{x}_l)p(\lambda_\mathrm{x})}V_{\mathrm{f}_i}\prod_{j=1}^{M}\frac{\hat{V}_j\hat{C}_jG_j}{p(\omega_j)p(t_j)}$$

$$\hat{V}_i = \tau(\mathbf{x}_l, \mathbf{x}_i, \lambda_\mathrm{x})V(\mathbf{x}_l, \mathbf{x}_i)$$

$$\hat{V}_j = \tau(\mathbf{x}_j, \mathbf{x}_{j-1}, \lambda_\mathrm{m})V(\mathbf{x}_j, \mathbf{x}_{j-1})$$

$$\hat{C}_j = f_p(\mathbf{x}_j, \omega_j, \omega_{j+1}, \lambda_\mathrm{m})\sigma_s(\mathbf{x}_j, \lambda_\mathrm{m})$$

where $p(.)$ is the probability density function for sampling a point $\mathbf{x}_l$ on the light source, an excitation wavelength λ_x from the emission spectrum of the light source, a scattering event with a direction ω_j and a distance t_j. L_e is the radiance emitted from the light at λ_x, $\tau(\mathbf{x}, \mathbf{y}, \lambda) = exp(-\int_0^{|\mathbf{x}-\mathbf{y}|}\sigma_t(t, \lambda)dt)$ is the transmittance between $\mathbf{x}$ and $\mathbf{y}$ at specific wavelength, G is the geometry term, V is the binary visibility between two points, f_p and σ_s are the phase function and the the scattering coefficient at the scattering event and λ_m. The term V_{f_i} is called the *path binary fluorescence visibility* that

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indicates whether the path i has encountered a fluorescent emission or not. This term is expressed as a function of the optical properties of the participating medium, the intrinsic characteristics of the fluorophore and the concentration of the fluorescent solvent in a given composition. The probability of a fluorescent emission is expressed in terms of three independent probabilities: (1) sampling a fluorescent event along the path, (2) absorption of the incident photon λ_x, and (3) re-emission of the photon at different wavelength λ_m.

Assuming monochromatic excitation and ignoring secondary fluorescence effects, a valid fluorescent path (where $V_{f_i} = 1$) can only have one fluorescence emission that involves changing the wavelength of the incident photon from λ_x to λ_m. Figure 1 lists all the possible events that could occur within a fluorescent mixture during the path sampling. In theory, the events 1, 4 are invalid because changing wavelength cannot be realized in elastic interaction. Event 8 is also invalid because λ_m cannot emit a photon at λ_x. The events 2, 3, 6 and 7 reflect elastic scattering interactions. Such events are valid, but they do not exhibit fluorescence emission and in turn the light source is not sampled at their interactions.

The light is only sampled when fluorescence emission exists at a fluorescent event, such as event 5, and thus the incident wavelength λ_x is scattered at λ_m. Consequently, a valid fluorescent path expresses a series of elastic scattering events and a single fluorescent emission event. If a fluorescent interaction occurs along the path, the light source is importance sampled with respect to its spectral emission profile, and the path contribution is added to the pixel value and the path is terminated, otherwise the V_{f_i} term is set to zero and the path is terminated.

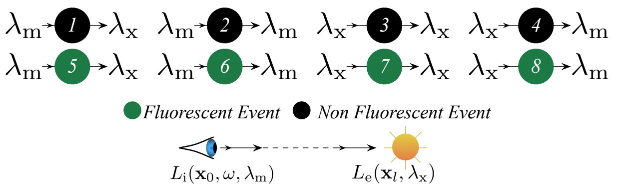

Figure 1: *Eight possible events within the participating medium during the path sampling. Notice the directions of the arrows with respect to eye and light.*

Implementation Our model is implemented in a spectral path tracing integrator within the context of the physically-based rendering toolkit (PBRT) [PH10]. The integrator evaluates the radiance $L_i(\mathbf{x}_0, \omega, \lambda_m)$ at 1 nm spectral sampling to maximally reduce the color noise.

4. Results, Conclusion and Future Work

Figure 2 shows a rendering of two glass cuvettes filled with 0.06 moles per liter of green fluorescent protein (GFP) and red fluorescent protein (RFP) dissolved in highly scattering solutions. The two cuvettes are excited with monochromatic light sources emitting at 460 and 520 nm for GFP and RFP respectively. The excitation wavelengths are selected to guarantee that all the emitted light from the two cuvettes is only due to fluorescence.

Preliminary Validation Two basic tests have been performed to provide a primary assessment of the presented model. The first one ensures that the radiance emitted from the exciting light source is relatively greater than the total radiance detected by the film. The other test compares the spectral profiles of the normalized spectral power densities (SPDs) of the rendered image with the experimental emission spectra of the corresponding fluorescent dye. The SPDs are measured at the image plane before their conversion into RGB. Since the detected radiance is recorded from fluorescence emission only, the two curves should have similar profiles. The normalized SPDs of the two images are shown in comparison with the emission spectra of GFP and RFP respectively in Figure 3. This work is still in progress. Multiple importance sampling is being investigated to increase the efficiency of our estimator. Validating the spectral responses of the images against physical fluorescent experiments is also considered.

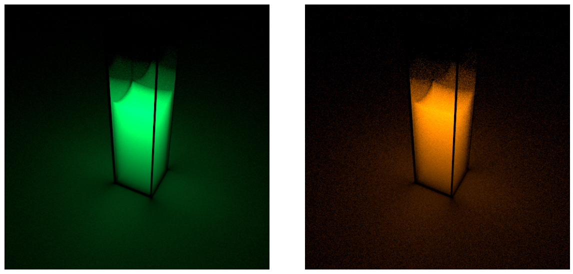

Figure 2: *Rendering of fluorescent cuvettes filled with GFP and RFP solutions.*

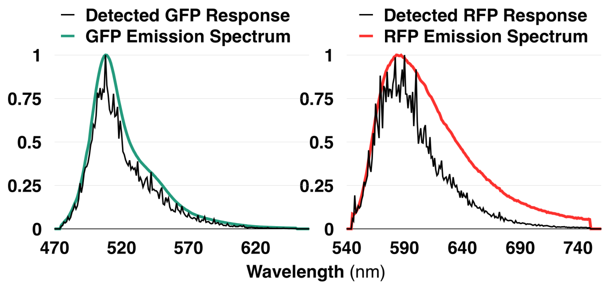

Figure 3: *Normalized SPDs detected at the image plane in comparison with the emission spectra of two dyes.*

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