Transient Photon Beams

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ABSTRACT

Recent advances on transient imaging and their applications have opened the necessity of forward models that allow precise generation and analysis of time-resolved light transport data. However, traditional steady-state rendering techniques are not suitable for computing transient light transport due to the aggravation of inherent Monte Carlo variance over time, specially problematic in participating media. We address this problem by presenting the first photon-based method for transient rendering of participating media that performs density estimations on time-resolved precomputed photon maps. We first introduce the transient integral form of the radiative transfer equation into the computer graphics community, including transient delays on the scattering events. Based on this formulation we leverage the high density and parameterized continuity provided by photon beams algorithms to present a new transient method that allows to significantly mitigate variance and efficiently render participating media effects in transient state.

CCS CONCEPTS

•Computing methodologies → Ray tracing;

KEYWORDS

transient rendering, participating media, radiative transfer

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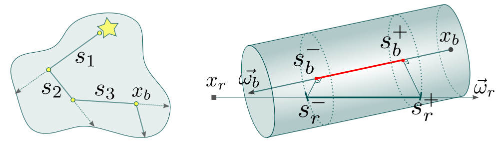

Figure 1: Left: A photon emitted from the light source takes $t = \frac{\eta_m}{c}(s_1 + s_2 + s_3)$ to reach $\mathbf{x}_b$. Right: Ray-beam density estimation with a 2D kernel. Time delays will depend on the the blur region, the speed of light, and the index of refraction.

1 INTRODUCTION

Accurate time-resolved light transport data is key to provide insights and analysis for transient imaging techniques [Jarabo et al. 2017]. Forward rendering models are a powerful tool to generate this kind of data under controlled synthetic setups. The recent work by Jarabo and colleagues [Jarabo et al. 2014] addressed variance issues of steady-state techniques in transient rendering by proposing new time-based importance sampling methods and progressive approaches in a time-resolved bidirectional path tracer for both surfaces and media. Still, their method remains very sensitive to variance due to the nature of path tracing methods. Other existing methods [Jarabo 2012; Smith et al. 2008] have addressed transient rendering, including 2D implementations [Bitterli 2016], but they either are too narrowly scoped or generate suboptimal solutions.

Steady-state methods based in photon tracing trade variance for bias in participating media rendering by performing density estimations on stored light paths across the scene. In particular, techniques based on *photon beams* [Jarosz et al. 2011a,b; Křivánek et al. 2014] densely populate media with full photon trajectories, which significantly increasing rendering efficiency. We make the key observation that full photon trajectories allow to render media at arbitrary temporal resolutions thanks to closed-form radiance estimations between camera rays and photon beams. Along with increased media sampling density, these features make this kind of algorithm very suitable for transient rendering, which requires higher sampling rates to fill up the extended temporal domain.

2 OUR APPROACH

We introduce a new method for efficiently computing transient light transport in participating media. While original radiative transfer theory [Chandrasekhar 1960] accounts for light time of flight, classic use in computer graphics is time-agnostic due to the assumption of infinite speed of light. We introduce the time-dependent integral form of the radiative transfer equation into the computer graphics community, and build upon it to present a new time-resolved method based on photon beams for efficiently rendering participating media in transient state, accounting for indirect illumination, multiple scattering and complex caustics.

Transient Radiative Transfer. A beam of light reaching a participating medium may undergo scattering and absorption effects. The radiative transfer equation models this behavior in a time-resolved manner, but its integral form used in traditional rendering ignores the temporal dependence by assuming infinite speed of light. To solve the RTE at time scales comparable to the speed of light we need to include light travel time into the equations. Radiance takes a certain amount of time to propagate through space, and therefore light transport from a point $\mathbf{x}_0$ towards a point $\mathbf{x}_1$ does not occur immediately, having $L(\mathbf{x}_1, \vec{\omega}, t) = L(\mathbf{x}_0, \vec{\omega}, t - \Delta t)$ where $\vec{\omega}$ is a direction outgoing from $\mathbf{x}_0$ towards $\mathbf{x}_1$, and Δt is the time it takes the

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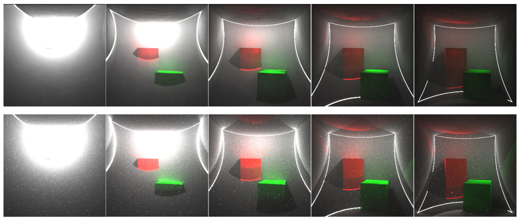

Figure 2: Equal-time renders of the *Cornell blocks* sequence with transient path tracing (bottom) and our method (top).

light to go from $\mathbf{x}_0$ to $\mathbf{x}_1$,

$$\Delta t(\mathbf{x}_0 \leftrightarrow \mathbf{x}_1) = \int_{\mathbf{x}_0}^{\mathbf{x}_1} \frac{\eta(\mathbf{x})}{c} \mathrm{d}\mathbf{x}, \tag{1}$$

where $\eta(\mathbf{x})$ is the index of refraction at a medium point $\mathbf{x}$ and c is the speed of light in vacuum. The integral form of the RTE accounting for this travel time therefore yields,

$$L(\mathbf{x}, \vec{\omega}, t) = T_r(\mathbf{x}, \mathbf{x}_s, t) L_s(\mathbf{x}_s, \vec{\omega}, t - \Delta t_s) + \int_0^s T_r(\mathbf{x}, \mathbf{x}_r, t) L_i(\mathbf{x}_r, \vec{\omega}, t - \Delta t_r) \mathrm{d}r \tag{2}$$

$$L_i(\mathbf{x}, \vec{\omega}, t) = \int_\Omega \int_0^t \mu_s(\mathbf{x}_r, t - t') \rho(\mathbf{x}, \vec{\omega}_i, \vec{\omega}, t - t') L(\mathbf{x}, \vec{\omega}_i, t) \mathrm{d}t' \mathrm{d}\vec{\omega}_i \tag{3}$$

While we include time dependence of scattering, transmittance, and phase function for completeness, in the following we ignore any delays at particle level and focus in propagation delays to illustrate how to perform time-aware density estimations in photon beams.

Transient Photon Beams. Photon beams algorithm [Jarosz et al. 2011a] provides a numerical solution for steady-state rendering of participating media by (1) tracing photons from the light sources by sampling the steady-state RTE, and storing their full trajectories as *beams* with a direction $\vec{\omega}_b$, position $\mathbf{x}_b$ and power Φ_b; (2) computing radiance seen by the camera by accumulating density estimations at every ray-beam intersection (Figure 1, right). In the following we present our extension to transient state based on the 2D kernel within homogeneous media. Similar procedure applies for extending 3D and 1D kernels of Jarosz et al. to transient state. To compute time-resolved radiance, we have to account for photon timings along its way from the light sources to the camera. A photon starting at the light source (see Figure 1) has taken a certain time to get to the origin of a photon beam $\mathbf{x}_b$. This time $t_{\mathbf{x}_b}$ can be computed while stochastically sampling Equations 2 and 3, as a function of the distances s_j traveled by that photon up to $\mathbf{x}_b$

$$t_{\mathbf{x}_b} = \sum_{s_j \in \Pi} \Delta\, t(s_j) = \sum_{s_j \in \Pi} \frac{\eta_{m_j}}{c} s_j, \tag{4}$$

where $s_j \in \Pi$ is the optical path from the light source to $\mathbf{x}_b$, and η_{m_j} are the indices of refraction of the media crossed by the photon b. For a point within the ray-beam blur region at distance s_b from the beam start $\mathbf{x}_b$ (see Figure 1), the photon takes $t_b = \frac{\eta_m}{c} s_b$ time to get from $\mathbf{x}_b$ to s_b (Equation 1 for constant $\eta(\mathbf{x}) = \eta_m$). Finally, that photon will take $t_r = \frac{\eta_m}{c} s_r$ to reach the camera $\mathbf{x}_r$ from the corresponding point at s_r. Therefore, the total time a photon takes to get from the light source to a point within the blur region and

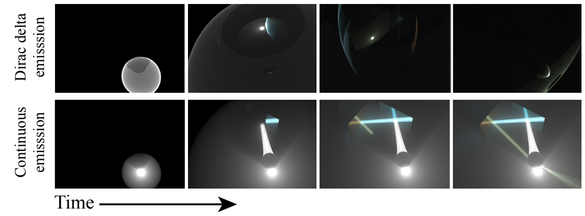

Figure 3: Comparison between Dirac delta (top) and continuous emission (bottom) for the *Mirrors* scene.

then to the camera $\mathbf{x}_r$ yields

$$t = t_{\mathbf{x}_b} + \frac{\eta_m}{c} s_b + \frac{\eta_m}{c} s_r. \tag{5}$$

Original closed-form of the density estimation [Jarosz et al. 2008] integrates the radiance L_b in the 2D blur region defined by $[s_b^-, s_b^+]$ and $[s_r^-, s_r^+]$ into a single pixel. In transient state, however, radiance L_b does not arrive instantly, and is bounded within the time interval $\Delta t(L_b) = [t^-, t^+]$ defined by the region where $t^- = t_r^- + t_b^-$ and $t^+ = t_r^+ + t_b^+$. We can therefore evenly distribute integrated radiance over the time interval $t_{\mathbf{x}_b} + [t^-, t^+]$. Note that due to transmittance, the photon energy actually varies as it travels across the blur region, and evenly distributing radiance across the interval introduces certain bias. However in our comparisons against path traced results (see Figure 2) we observed this even distribution provides a good tradeoff between bias, variance. We also illustrate two different visualizations of transient light transport with continuous and delta emission (Figure 3), where we can observe caustic effects due to wavefronts reflected in the mirrors and refracted by the glass ball. Full details of this work can be found in [Marco et al. 2017].

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