Can You See the Heat? A Null-Scattering Approach for Refractive Volume Rendering

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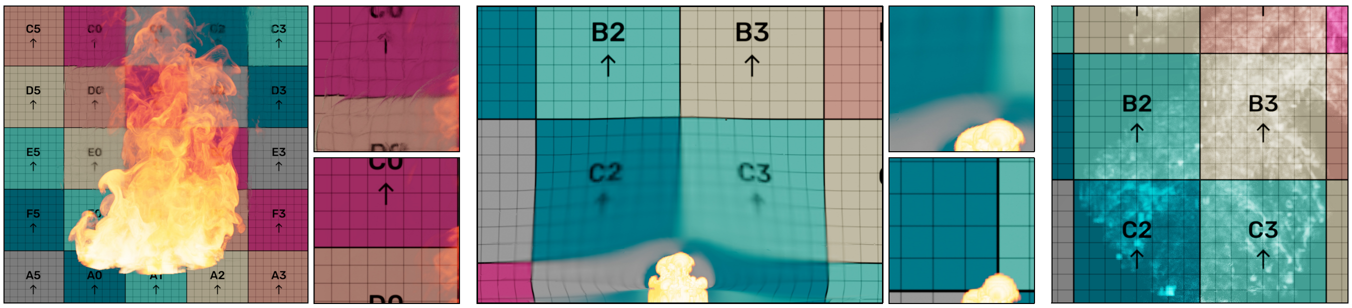

Figure 1: From left to right, we render with our method (top insets) the heat haze of a fire*, the blast wave of an explosion, and the caustics of a fire lit by an area light. Taking into account the temperature or pressure changes in refractive volumes allows for a richer range of appearance in comparison to classic volume rendering (bottom insets).

ABSTRACT

Although production volume rendering has been well studied over the past decade, there are still some volumetric features that cannot be rendered with the latest methods. In particular, when rendering fire or explosion volumes, current state-of-the-art techniques lack refraction effects due to temperature or pressure changes and are especially problematic when using next event estimation. In this talk, we present two unbiased volume rendering algorithms that can achieve a wide range of refractive effects, such as heat haze, blast waves and caustics. We demonstrate on a set of test scenes that these new features significantly improve the visual appearance of these volumes.

CCS CONCEPTS

• **Computing methodologies → Ray tracing**.

KEYWORDS

refractive light transport, null scattering, Monte Carlo integration

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1 INTRODUCTION

Most production rendering pipelines treat the volume refractive effects as a post-processing step. For example, artists can fake the heat haze of a fire using hand-placed animated textures during the composition stage. On the other hand, we use accurate volume generation methods, that can simulate the thermal flow and pressure dynamics inside volumes (e.g. Houdini Pyro). In an attempt to automate physics-based refractive effects during the rendering stage, we propose a novel approach that combines accurate calculation of *refractive indices* (IOR), stochastic volume sampling methods and caustic resolution methods.

The recent introduction of fictitious (null) particles in the *Radiative Transfer Equation* (RTE) [Miller et al. 2019] enables unbiased stochastic random walks to render participating media with spatially constant IOR. To account for spatially varying IOR, Ament et al. derive the *Refractive Radiative Transfer Equation* (RRTE). They propose a solution based on nonlinear ray tracing via Hamiltonian transport and biased photon mapping to solve it. More recently, Pediredla et al. present new path tracing estimators to solve the RRTE. They rely on the same nonlinear transport method, but their technique is limited to mediums with interfaces. Additionally these techniques cannot achieve *Next event estimation* (NEE) through refractive media such as fire. Contrary to these approaches, our key idea is to combine linear ray tracing and refractive null interactions to take into account the change of IOR within the volumes. Our solution readily extends state-of-the-art volume rendering methods, can be built on top of any linear ray tracing engine, and successfully achieve refractive effects.

2 METHOD OVERVIEW

We first derive the IOR at each point in space and its gradient to be used as the normal of the refractive isosurface (subsection 2.1). When tracing rays forward through a volume, we modify the delta tracking algorithm to account for refractive interfaces (subsection 2.2). When connecting two path interactions for NEE (subsection 2.3), we modify the ratio tracking algorithm to build a valid caustic path in the spirit of the *Specular Manifold Sampling* [Zeltner et al. 2020].

2.1 Index of refraction

The spatial IOR $\eta(x)$ of a volume can be either specified by the user, simulated on a 3D grid, or computed from physical quantities. Assuming that we are simulating rare gas, the IOR can be derived from the Hauf - Grigull relation [Hauf and Grigull 1970] that relates a gas state and its index of refraction, $\eta(x)-1 = \frac{3}{2}\frac{rMP(x)}{RT(x)}$, where r is the gas refractivity, M the molar mass, R the ideal gas constant, P the pressure (in Kelvin) and T the temperature (in Pascal). The change of index of refraction between two states in the same gas is then given by the following formula, $\eta_2(x) = 1 + (\eta_1(x) - 1)\frac{P_2(x)T_1(x)}{P_1(x)T_2(x)}$, which further reduces when we consider ambient air ($\eta_1 = 1.000292$, $P_1 = 101325$ Pa, $T_1 = 300$ K). The normal of the refractive isosurface is defined as the gradient of the index of refraction, $n(x) = \frac{\mathrm{d}\eta(x)}{\mathrm{d}x}$, that can be computed by deriving the above equation or from the user defined IOR using finite differentiation.

2.2 Refractive null-scattering

The null scattering formulation of volume light transport takes into account three types of events: *absorption* (A), *scattering* (S), and *null* (N). The *Delta Tracking* algorithm performs a random walk on a ray and alternate between 1) distance sampling and 2) event sampling. During step 1) a distance is sampled with a PDF proportional to the combined transmittance $\bar{T}$ multiplied by the majorant coefficient $\bar{\mu}$ that bounds the medium extinction. Then step 2) consists in sampling an event with probability $P_e = \frac{\mu_e}{\bar{\mu}}, e \in \{A, S, N\}$. In case of an A event, we gather emissions and stop the walk. In case of a S event, we perform NEE, sample the phase function to get a new continuation direction, and start a new walk. In case of a N event, we continue walking forward because the directional component H is a Dirac function that constrain null events to happen on a straight line [Miller et al. 2019, eq. 19].

To account for spatially varying IOR, we replace the original H to satisfy the refractive constraint as follows: $H(\omega_o, x, \omega_i) = \{1 \text{ if } \omega_i = \text{refract}(\omega_o, \eta, n(x)) \text{ else } 0\}$, where n is the normal of the isosurface, and η is the ratio of incident (carried by the ray) over outgoing (at position x) IOR. Our modified Refractive Delta Tracking algorithm is summarized algorithm 1, where changes has been highlighted in blue. This algorithm correctly bends rays w.r.t the change of IOR and successfully achieve the heat haze and shockwave refraction effects depicted in Figure 1.

2.3 Solving volume caustics

Direct lighting connections (NEE) between light points and shading points are crucial to reduce variance in path traced images. In presence of participating media, we also evaluate the transmittance between the two points using the *Ratio Tracking*, which allows for unbiased estimates of the transmittance using null-particle sampling. However, it is limited to spatially constant IOR.

Our Refractive Ratio Tracking solution proceeds similarly as Specular Manifold Sampling [Zeltner et al. 2020]. First, we generate a candidate seed path connecting the two endpoints using Ratio Tracking. The resulting path $\bar{x} = \{x_0, \ldots, x_n\}$ is a chain of specular events with two fixed endpoints, that do not satisfy the refractive constraint of the media. Fortunately, the refractive isosurface of the volume is a path-space manifold that can be walked to solve this constraint. We thus build an angular constraint matrix C that encodes the refraction constraints c_i for each triplet of vertices:

$$C(\bar{x}) = \begin{bmatrix} c_1 \\ \vdots \\ c_{n-1} \end{bmatrix} \qquad c_i(\omega, x_i, \omega') = \begin{cases} |\theta(R(\omega,\eta,n)) - \theta(\omega')| \\ |\phi(R(\omega,\eta,n)) - \phi(\omega')| \\ 1 \end{cases} \tag{1}$$

where R returns the refracted direction, η is the ratio of incident and outgoing IOR, n is the isosurface normal at x_i, $\theta(\omega) = \cos^{-1}(\omega_z)$ and $\phi(\omega) = \text{atan2}(\omega_y, \omega_x)$. We also remap the angular differences in range $[-\pi, \pi]$. We use a numerical optimization method (Levenberg-Marquardt) to find a path, $\hat{x} = \text{argmin}_{\bar{x}}\, C(\bar{x})$, that satisfies the constraint. We then perform several trials to estimate the inverse probability density of finding this root. This approach successfully reproduce the heat caustics of a fire as illustrated in Figure 1.

Algorithm 1:

RefractiveDeltaTracking(Point x, Vector ω, Random r)
while true
  $t \leftarrow$ SampleDistance $(\bar{\mu}, r)$
  $x \leftarrow x + t \cdot \omega$
  $e \leftarrow$ SampleEvent $(P_A(x), P_S(x), P_N(x), r)$
  if $e = A$
    return $\mathrm{L_e}\,(x, -\omega)$
  elif $e = S$
    $\omega \leftarrow$ SamplePhase $(x, -\omega, r)$
  elif $e = N$
    $\omega \leftarrow$ Refract $(-\omega, \eta(x), n(x))$

3 CONCLUSION

We propose a new approach for rendering refractive volumes. Our early prototype is on average three times slower than our proprietary renderer on the fire sequence, due to the extra data grids and queries, but we think the visual improvement is remarkable. We leave as future work deriving a complete refractive null scattering formulation, and exploring controls we could offer artists to experiment with refractive effects.

REFERENCES

Marco Ament, Christoph Bergmann, and Daniel Weiskopf. 2014. Refractive Radiative Transfer Equation. *ACM Trans. Graph.* 33, 2 (apr 2014).

W Hauf and U Grigull. 1970. Optical methods in heat transfer. In *Advances in heat transfer*. Vol. 6. Elsevier, 133–366.

Bailey Miller, Iliyan Georgiev, and Wojciech Jarosz. 2019. A Null-Scattering Path Integral Formulation of Light Transport. *ACM Trans. Graph.* 38, 4 (jul 2019).

Adithya Pediredla, Yasin Karimi Chalmiani, Matteo Giuseppe Scopelliti, Maysamreza Chamanzar, Srinivasa Narasimhan, and Ioannis Gkioulekas. 2020. Path Tracing Estimators for Refractive Radiative Transfer. *ACM Trans. Graph.* 39, 6 (nov 2020).

Tizian Zeltner, Iliyan Georgiev, and Wenzel Jakob. 2020. Specular Manifold Sampling for Rendering High-Frequency Caustics and Glints. *ACM Trans. Graph.* 39, 4 (aug 2020).