Theory and Analysis of Transient Rendering

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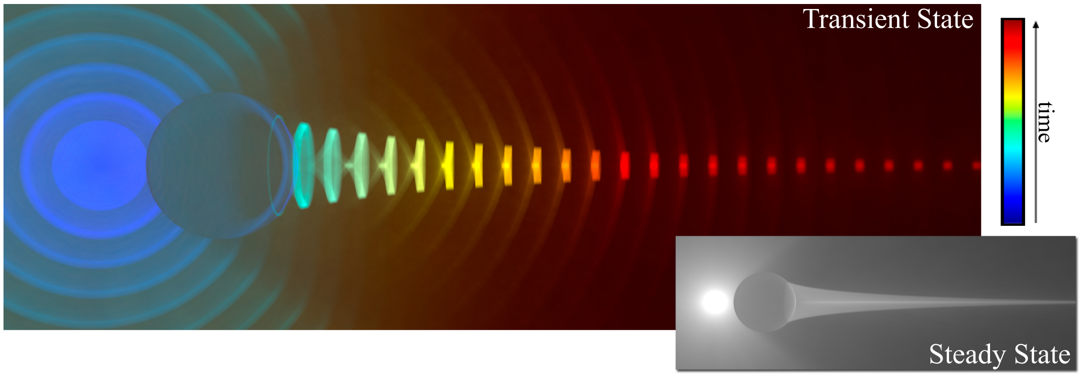

Figure 1: *Visualization of our time-resolved render of a volumetric caustic produced by an spherical lens in a scattering medium. It can be seen how the caustic wavefront is delayed due to the longer optical path traversed within the sphere, and how its shape is distorted by the lens.*

1 Introduction

One of the most general assumptions in computer graphics is to consider the speed of light to be infinite, which leads to the simulation of light transport in steady state. This is a reasonable assumption, since most of the existing imaging hardware is very slow compared to the speed of light.

The recent development of ultra-fast image capture devices has enabled the visualization of light in motion [Velten et al. 2013], which not only allows the understanding of light transport at a different scale, but also has a number of applications including geometry and material estimation.

2 Transient Rendering

Despite these breakthroughs in technology, there is currently a lack of tools to simulate and analyze transient light transport, which would be very beneficial for the graphics and vision communities. In addition, these tools can become instrumental in teaching the complexities of light transport, as well as visualizing in detail some of its most cumbersome aspects, such as the formation of caustics, birefringence, or the temporal evolution of chromatic dispersion.

Although some recent rendering techniques already leverage some transient light transport properties, it is not clear how current algorithms can be extended to this higher-dimensional domain, or whether their specific advantages and characteristics carry over to transient-state. It is thus important to have solid theoretical tools to analyze existing simulation methods and develop new ones.

Transient rendering is however, challenging: first, introducing the temporal domain makes needed to account all possible sources of delay due to light propagation and interaction, which are in general simplified, when not directly ignored for steady-state light transport. Additionally, the frequency of the signal is overall augmented, reducing part of the softness which is commonly used in traditional rendering to reduce computational costs when removing variance, making transient rendering algorithms slower to converge. Finally, time-of-flight images depict non-trivial phenomena, which might be very hard to understand, specially in complex scenes.

3 Our Contributions

In this work, we establish a theoretical framework for light transport in transient state, based on the path integral formulation [Veach 1997] and including time delays due to propagation in free space as well as scattering in both surfaces and participating media.

This allows us to examine two families of steady-state rendering methods (path tracing and density estimation), understand how to elevate them to transient algorithms and identify their strengths and weaknesses when solving this more difficult light transport problem. We demonstrate that the direct extension of this methods can lead to significant inefficiencies and a decay of the signal-to-noise ratio (SNR) in the temporal domain.

Based on that, we devise new sampling techniques adapted to the temporal behavior of light. These strategies distribute samples uniformly in time, instead of sampling focusing on radiance as steady-state sampling methods generally do. This allows us to generate time-of-flight movies keeping uniform SNR over time.

Finally, we render time-resolved phenomena which are impossible to see in steady state, such as caustics propagation, fluorescence or temporal chromatic dispersion, leading to animations that enable not only an interesting visualization of each phenomenon, but a better understanding of the nature of light transport itself.

References

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