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Progressive photon mapping for daylight redirecting components

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Abstract

Daylight redirecting components (DRCs) are characterised by complex transmissive and reflective behaviour that is difficult to predict accurately largely due to their highly directional scattering, and the caustics this produces. This paper examines the application of progressive photon mapping as a state of the art forward raytracing technique to efficiently simulate the behaviour of such DRCs, and how this approach can support architects in assessing their performance.

Progressive photon mapping is an iterative variant of static photon mapping that effects noise reduction through accumulation of results, as well as a reduction in bias inherent to all density estimation methods by reducing the associated bandwidth at a predetermined rate. This not only results in simplified parametrisation for the user, but also provides a preview of the progressively refined simulation, thus making the tool accessible to non-experts as well.

We demonstrate the effectiveness of this technique with an implementation based on the RADIANCE photon mapping extension and a case study involving retroreflecting prismatic blinds as a representative DRC.

Keywords: Daylight simulation; Light redirection; Caustics; Raytracing; Physically based rendering; Monte Carlo

1. Introduction

The accurate simulation of daylight redirecting components (DRCs) is essential in assessing their performance and predicting their energy saving potential through daylight autonomy. Raytracing techniques have proven to be particularly expedient in this application as they accurately model the light transport within the components (assuming an accurate representation of material properties) and how it propagates in a typical office environment.

Although light transport along a ray is inherently bidirectional (reversing the direction of light propagation does not invalidate the model), there is a distinction between backward and forward raytracers; the former emit rays at the view or measurement point(s), whereas the latter emit rays from the light sources. Forward raytracing is particularly effective at modelling highly specular DRCs with strong redirection to produce concentrated highlights (-caustics), which can compromise an office occupant's visual comfort.

Photon mapping (Jensen, 2001) is a forward raytracing technique which supplements a standard backward raytracer, resulting in bidirectional light transport. The technique mimics light particle transport by recording indirect hitpoints along with their associated energy, and uses density estimation to reconstruct the resulting irradiance on the surfaces.

The forward raytracing solution presented in this paper is based on a photon mapping extension to the RADIANCE

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rendering system originally developed by the author (Schregle, 2004). It extends the Radiance backward raytracing core (Ward, 1994) with a forward raytracer for bidirectional light transport as described above.

The standard photon mapping approach has since been superseded by recent developments in the computer graphics community; progressive photon mapping is now the state of the art forward raytracing approach, which overcomes a number of issues with the original implementation that improve its usability for non-experts, notably in the context of daylight simulation.

2. Previous work

A number of publications have documented raytracing simulations applied to a broad spectrum of DRCs, notably those with strong redirection for which raytracing is best suited.

de Boer (2006) presented a new method for modelling DRCs by representing the light transmitted though the system as a luminous intensity distribution obtained with raytracing, effectively presaging the `genBSDF` solution now bundled with Radiance. The results were validated with Radiance using measured BRDFs with wavelet based data compression. In his introduction, de Boer points out the necessity of supplementing existing backward raytracers with a forward raytracing pass for accurate simulation of DRCs.

Wittkopf et al. (2010) simulated light pipes and ducts fitted with different collector types using a commercial forward raytracer (Photopia) to obtain luminous intensity distributions. The results were then used to characterise the systems based on transmitted flux as performance criterion. Such DRCs could not be simulated with comparable accuracy and computation time using a backward raytracer due to excessive noise.

Klammt et al. (2012) simulated microstructured light redirecting devices using 2D raytracing; a comparison of the results with measurements indicated good agreement aside from deviations introduced by manufacturing tolerances, which are amplified by specular redirection.

A hybrid simulation using raytracing and radiosity was used by Chan and Tzempelikos (2012) to assess glare from specular venetian blinds in various configurations. Specular light transport is raytraced, while diffuse transport (from the underside of the blinds and room surfaces) is obtained from a radiosity solution. As the latter disregards all specular components, simulations using only radiosity revealed significant errors of up to 40% compared to the hybrid approach. Chan and Tzempelikos also validated their results against simulations with Radiance.

More recently, Appelfeld and Svendsen (2013) characterised glare and energy savings for light redirecting glass shading systems using Radiance's 3-phase method for annual daylight utilisation.

McNeil et al. (2013) described the recently developed `genBSDF` tool from the Radiance suite to obtain bidirectional scattering distribution functions (BSDFs) from fenestration systems and DRCs using raytracing. The resulting data was validated against analytically derived solutions for trivial cases, and against a commercial raytracer and goniometric measurements for more complex cases such as specular blinds and microperforated film.

There are few documented cases of photon mapping being used as forward raytracer in daylight simulation. Photon mapping is particularly efficient at simulating caustics, albeit subject to a bias/noise tradeoff (Schregle, 2003). Validated results of the photon mapping extension to Radiance were documented by Schregle and Wienold (2004). The simulation tool outlined in this paper is based on this software.

A more recent application of the Radiance photon map was documented by Su et al. (2012), who used the tool to evaluate the optical performance of lens-walled compound parabolic concentrators. In their work, they compared the results with those obtained from the Photopia forward raytracer and theoretical estimates; in both cases the deviations were within 5%. Su astutely noted that some deviations were probably attributed to the local bias inherent in the photon map's density estimates.

Progressive photon mapping was first proposed by Hachisuka et al. (2008) as an iterative extension of the standard static photon mapping approach as implemented in the Radiance extension. It combines multiple smaller photon maps to approximate a much larger one which may not fit into memory using the traditional approach. Through iteration, the process mitigates the noise inherent in Monte Carlo raytracing by combining successive results and averaging them. At the same time, the density estimate bandwidth[1] (radius or number of nearest photons) is gradually reduced to mitigate bias. As Hachisuka points out, the accumulated density estimates converge to an unbiased solution in the limit.

An alternative interpretation of progressive photon mapping was presented by Knaus and Zwicker (2011), who developed a statistical model for the variance and bias from photon density estimates to study their asymptotic behaviour as more photons are generated and the bandwidth is reduced. The approach is considerably simpler than Hachisuka's as there is no need to maintain local statistics from previously generated photon maps, and the iterations are independent and can thus be performed in parallel; this is leveraged in our implementation, which draws heavily on Knaus and Zwicker's work.

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[1] Bandwidth describes the support, or area of influence, of a filter used to weight the photons retrieved from the photon map during a nearest neighbour lookup on a surface (Jensen, 2001). The resulting irradiance is proportional to the photon density, and the bandwidth is defined by the distance (radius) to the furthest photon found. In this paper, we generalise the term to describe either the radius or the number of nearest neighbours for a density estimate, depending on the implementation.