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François Desrichard, David Vanderhaeghe. Analysis of Path Space for Layered Light Editing. Journées Françaises d'Informatique Graphique, Nov 2018, Poitiers, France. hal-01941014v2

HAL Id: hal-01941014
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HAL Id: hal-01941014
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Submitted on 30 Nov 2018 (v1), last revised 30 Nov 2021 (v2)

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Journées Françaises d'Informatique Graphique,
Poitiers, 13 - 16 Novembre 2018

Analyse de l'espace des chemins pour une édition de la lumière par calques

Analysis of Path Space for Layered Light Editing

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Résumé

Dans le domaine de la synthèse d'images 3D, et en particulier dans le cadre du cinéma d'animation, l'éclairage est une composante artistique de premier ordre qui permet de créer une atmosphère, de guider l'action ou de transmettre des émotions. L'apparence de la lumière est le résultat d'une propagation globale qui dépend de l'intégralité de la scène. Son édition nécessite traditionnellement de nombreux rendus successifs dont la lenteur rend le travail des graphistes fastidieux. Nous proposons une décomposition du rendu sous la forme d'une superposition de calques éditables en espace image.

Abstract

In computer generated images, and particularly those produced by the movie industry, lighting is a primary source of artistic expression which is used to set up atmospheres, guide action or convey emotions. The appearance of light is the result of a global propagation throughout the scene. Its editing typically relies on successive renders, making it tedious for artists. We propose an image space decomposition of the render as a superposition of custom editable layers.

Keywords: Rendering; Path Space Analysis; Frequency Analysis; Artistic Editing of Lighting.

1. Introduction

Monte-Carlo rendering methods simulate plausible lighting by generating paths that carry radiance throughout the scene, before integrating their contribution on the camera plane [Vea98]. These algorithms are now widely used in the movie industry, where lighting plays an important part in the overall artistic process. Because light transport is a complex phenomenon that depends on the properties of the scene, anticipating the result of a light setup is difficult and artists traditionally have to work by trial and error, until satisfaction. But populating the path space being a lengthy process, they have to wait during rendering to preview their modifications, which makes light editing a particularly tedious task.

Elementary techniques were devised by artists to circumvent this problem, such as the use of basic rendering passes, which are renders of a partial information from the scene that are composited in image space after the simulation. For example, participating media present inside the scene is placed inside a separate layer to be transformed after the main render. This observation motivates the use of a more advanced image space decomposition incorporating some of the information generated during light propagation.

Hence, the artistic workflow is divided into two main parts: first, the setup of the camera, materials and lighting before the render; second, the compositing stage after the render, where different layers and effects are adjusted in image space to finalize the result.

Our long-term objective is a real time editing tool based on a superposition of custom editable layers. These edits should remain consistent and predictable in an animated scene. To this end, our approach is to compute a set of *meaningful* layers that users can manipulate in post-process. In this paper we present our first experiments towards this goal: an image space decomposition of the rendered image based on a controllable clustering of path space. This clustering builds on Covariance Tracing [Bel12] and Light Path Expressions [Son09], which both convey information on the history of light propagation.

One key point is to define what makes a layer *meaningful*; this definition would be identified in future work in collaboration with lighting designers, but our first guess is that a layer has to incorporate consistent information regarding light travel from light sources to the camera. We thus let the user define what *kind* of paths to store in a given layer according to the values we can extract from Covariance Tracing and Light Path Expressions.

2. Previous Work

Manipulation of light transport lets users transform lighting by directly altering light paths. Schmidt *et. al.* [SNM*13] offer linear deformations of such paths, which allow to bend

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and retarget the lighting while shadows are edited via proxies. Subileau *et. al.* [SMVP17] propose to teleport light rays through portals placed in the scene. Textures may be mapped onto the interface to change the traversing light's color. These two contributions leverage Heckbert notation [Hec90] to influence only certain paths. iCheat [OKP*08] offers an affine control over light transport coefficients throughout the scene, allowing for spatially precise manipulation of the overall lighting. In BendyLights [KPD10], the authors enhance regular spot lights using customizable and animatable spline control points. The linearity of light propagation is conserved by applying the inverse transformation to the whole scene, but this inversion prevents the addition of multiple sources whereas we intend to present the user with several lighting primitives.

Manipulation of light transport approaches are set up before the rendering process, and need costly computations for each update. Our approach takes place at the compositing stage, in image space, fitting in today's production workflow.

Intrinsic decomposition of a 2D image has it expressed as the product of albedo and lighting [BKPB17]. Generally an ill-posed problem, intrinsic decomposition is easily achievable in a synthetic scene; it can then be used to retouch lighting in image space. Innamorati *et. al.* [IRWJM17] automatically separate incident light in a generic input image into multiple layers, using a convolutional neural network. Conversely, our focus is on synthetic images, although we are interested in decoupling albedo and lighting into layers as well. In particular, we aim to define multiple lighting layers to separate between different aspects of the lighting.

Painting metaphors are a familiar and efficient approach explored by Pellacini *et. al.* [PBMF07] to automatically add and adjust light sources from user input strokes in image space. However, the method is impeded by the optimization procedure, as real time editing is out of reach even in simple setups. Poulin and Fournier [PF95] explore a similar interaction scheme where the brushes operate directly on the surface of objects. The lighting setup is then derived from the least-square minimization of an objective function. The procedure only considers direct illumination, whereas we operate in a global illumination context. Nowrouzezahrai *et. al.* [NJS*11] focus on volumetric lighting and allow an artist to turn participating media into full-fledged light sources. Light beams are painted in the scene, their emissive properties being customizable beyond physical plausibility. Once again, although efficiently handled by Photon Beams [JNT*11], these primitives cannot be previewed in real time.

As manipulation of light transport, the aforementioned painting approaches impact the rendering process and need costly re-computations. However, an extension of our approach could use painting as a tool to select layers.

3. Technical Background

Our work builds on the theory of frequency analysis of light transport [DHS*05, BSS*12] and more specifically on Covariance Tracing (CT) [Bel12, BSS*13, BBS14]. CT studies light transport in vicinity of a central ray, as depicted in figure 1. Along this central ray, secondary rays are parameterized by two spatial and two angular parameters: $\delta u, \delta v, \delta\theta, \delta\phi$. The analysis is kept local inside a neighborhood, allowing for first-order approximations that linearize the action of most operators. The local radiance l is then studied in the Fourier domain:

$$\hat{l}(\xi) = \int_{t\in\mathbb{R}^4} l(t) e^{-2i\pi\langle t,\xi\rangle}\,\mathrm{d}t$$

Keeping track of the whole transform soars memory consumption, as it would imply storing n^4 samples for each ray, where the number n has to be significant to faithfully account for high frequencies. Instead, the authors use a lightweight representation, the 4×4 covariance matrix Σ. Its entries are estimates of the support size of the spectrum along the standard basis direction (e_i, e_j):

$$\Sigma_{ij}(\hat{l}) = \int_{t\in\mathbb{R}^4} \langle t, e_i\rangle \langle t, e_j\rangle \hat{l}(t)\,\mathrm{d}t \qquad (1)$$

Expressing the first entry of Σ using equation (1) yields:

$$\Sigma_{11}(\hat{l}) = \int_{t=(\delta u,\ldots)\in\mathbb{R}^4} \delta u^2 \hat{l}(t)\,\mathrm{d}t \qquad (2)$$

Equation (2) shows that the first entry of Σ is a comparison between the spectrum of l and the quadratic term δu^2 over $\mathbb{R}^4$, effectively estimating its extent in the spatial frequency δu. The covariance matrix is used to describe the action of numerous operators on the local light field, such as:

Transport Free-space propagation of rays corresponds to a linear reparameterization of the light field, transforming angular offset into spatial offset with distance.

Curvature (C) The curvature of a surface also reparameterizes the incoming light field, but transforms spatial offset into angular offset instead.

Texture (T) A 2D signal multiplicative with the light field operates additively in the covariance representation. Its matrix is exclusively spatial.

Reflectance (R) Expressing the action of the reflectance function involves reparameterizing the light field with respect to the surface. In essence, separable reflectance is represented by an angular covariance matrix.

Occlusion Because a whole neighborhood of rays is studied, occlusion has to be accounted for. It adds spatial frequencies and correlation between space and angle.

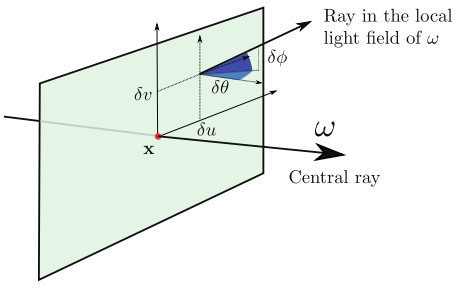


Figure 1: Paraxial parameterization. Illustration taken from Belcour *et. al.* [BBS14]

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4. Path Space Clustering

Light Path Expressions (LPEs) leverage Heckbert notation to describe the history of a light path. They use some of the scene's semantic such as light, object and material names; for example, $L_{Wall} \rightarrow D_{Towel} \rightarrow S \rightarrow E$ targets paths emitted from a lamp on a *Wall*, reflected diffusely on a *Towel* then specularly before reaching the camera.

Because a frequency representation is useful to describe or generate patterns and textures [GGM11], our idea consists in augmenting LPEs with the information retrieved by CT. We thus aim to refine them into a more predictable and customizable path selection tool. Particularly interesting for an artistic edit are curvature, texture and reflectance of surface interactions; they may be used in our implementation with the corresponding symbols along with comparison operators. Formally, the interaction symbols D and S of LPEs are now followed by the operators C, T and R along with conditions on the norm of the covariance matrix:

$$D \underbrace{C(\|\Sigma_C\| = 0)}_{\text{curvature}} \underbrace{T(\|\Sigma_T\| > 6)}_{\text{texture}} \underbrace{R(\|\Sigma_R\| > 2)}_{\text{reflectance}}$$

This enhanced expression captures diffuse interactions on a locally plane surface ($\|\Sigma_C\| = 0$) where both texture and reflectance contain high frequencies ($\|\Sigma_T\| > 6,\ \|\Sigma_R\| > 2$).

5. Early Implementation and Results

Evaluation of the covariance matrix of operators is done during rendering. The last N bounces of every light path are stored inside an index file, which also holds the norm of the encountered operators' matrix. In our implementation, we chose $N = 5$; the rendering still uses more bounces, and terminates paths in an unbiased way, as usual.

Once the path space has been populated from the scene and stored in the index, the layer extraction may begin. Aside from the main render, the user expresses queries to fetch a subset of paths using our enhanced LPEs. The program then extracts the light contribution of the selected paths inside a new layer, using regular expressions. Layers are extracted in full-range precision to ensure linear relationships between them, and may be composed together to transform the base render inside a classic image editing program.

We present the first results generated using our implementation based on the PBRT renderer [PH10]. Figure 2 shows layers extracted considering the texture rays last bounced on before reaching the camera. Figure 2b retains only paths with non-null covariance, keeping the contribution of most surfaces but discarding the sky and glasses (lights, painting). Setting the minimum norm to 6 isolates high-frequency textures such as roughcast walls and ceiling or veined leaves. Figure 3 also discriminates on the last bounce, considering the reflectance operator this time. In figure 3b, purely diffuse walls and towels have disappeared as only non-null reflectances are targeted. In figure 3c, selecting reflectances exhibiting a covariance matrix of norm greater than 2 isolates the lacquered wood on the furniture, which is glossier than the ceramic composing the sinks. This effectively allows us to disambiguate the otherwise generic symbols S and D of Heckbert notation.



(a) Original render. *San Miguel* scene as featured in PBRT

(b) Last bounce on a texture with non-null covariance

(c) Last bounce on a texture with covariance norm > 6

Figure 2: Selection of paths using the texture operator

6. Perspectives

The storage space required by the index file (several gigabits) is the main liability of the method, even though we chose not to store the covariance matrices but only their norm. Keeping track of whole matrices would give finer control over the selection of paths, allowing to differentiate between directions in both space and angle, but would require a more efficient storage solution. We also identified the evaluation of the regular expressions underlying enhanced LPEs as the major performance bottleneck when extracting layers, but we believe a refined representation could introduce hierarchy among paths, effectively pruning entire subsets of the path space during selection.

To be effectively usable by artists, the queries for new layers should be expressed by natural means instead of plain-text LPEs. We wish to design an efficient user interface to allow fast and predictable selection of paths. Three leads emerge: first, a graphical interface allowing user to formulate their query using traditional widgets, each successive bounce being described by a set of controls featuring every operator. Second, a point-and-click solution that would display information on the nature of the paths contributing to the pointed pixel or region, and help formulate a corresponding query. Finally, we wish to explore a more natural expression of LPEs and the involved quantities. For example, *"diffuse surface with a striped texture"* would translate into $D\,T(\Sigma_{11} \gg \Sigma_{22}$ or $\Sigma_{11} \ll \Sigma_{22})$.

Observing artists at work with a prototype during usability testing sessions would give us further clues towards the best solution to adopt. Inputs from lighting designers are particularly valuable to our long-term ambition: designing an autonomous clustering of the path space. Ideally, layers would be extracted automatically to each hold a *light touch* - the smallest light primitive that one would want to manipulate while remaining consistent in the presence of animations.

Acknowledgements

Special thanks go to Mathias Paulin for his helpful comments and advices. This work was partially funded by the ANR project CALiTrOp (ANR-16-CE33-0026).

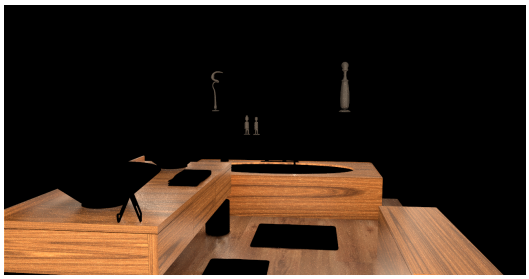
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(a) Original render. *Bathroom* scene as featured in PBRT



(b) Last bounce on a reflectance with non-null covariance



(c) Last bounce on a reflectance with covariance norm > 2

Figure 3: Selection of paths using the reflectance operator

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