Real time rendering of realistic surface diffraction with low rank factorisation

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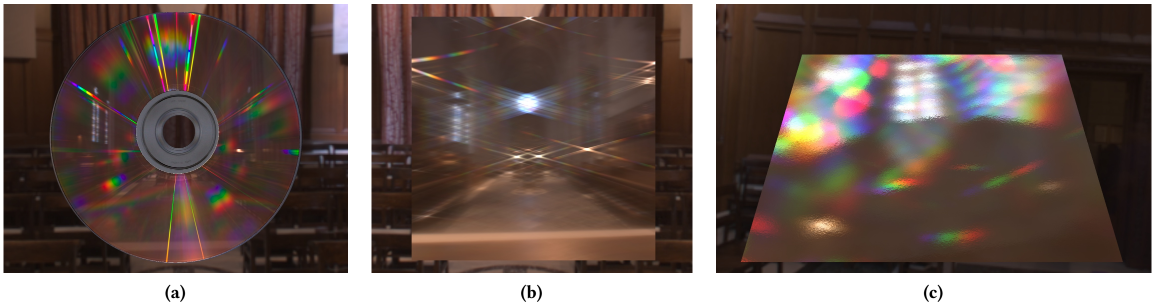

Figure 1: Real time renderings of diffraction effects in the Grace Cathedral. (a) Compact Disc. (b) Diffraction pattern of a LG 42” Smart TV. (c) Wide diffraction lobes on a rough specular holographic paper.

ABSTRACT

We present a novel approach for real-time rendering of realistic diffraction effects in surface reflectance under environmental illumination. Renderings in arbitrary environments require the computation of a convolution. In the case of diffraction, the convolution kernel is large due to the high frequency details contained in diffraction patterns, making computations at real time framerate impractical. We propose a low rank factorisation of the diffraction kernel that allows the computation of the convolution in two passes with smaller kernels instead of a large 2D kernel. We present renderings of the diffraction produced by several surfaces and reach a performance of 50 to 100 FPS.

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1 INTRODUCTION

Diffraction effects can produce astonishing rainbow colours in surface reflectance. They happen when the microgeometry of a surface reaches a size close to the wavelength of light (around the micrometer). When light is reflected by such a surface, light waves interfere and the angle of reflection becomes wavelength dependent. As a result white light is decomposed into its main colours.

Stam (Stam 1999) was the first to propose a physically based diffraction BRDF derived from Kirchoff theory of diffraction. Although very accurate such a model cannot be used for real time renderings of arbitrary diffraction patterns as it relies on heavy computations at every frame of an animation. Dhillon et al. (Dhillon et al. 2014) proposed a reformulation of Stam's BRDF for real-time renderings under point light sources using a Taylor expansion and a precomputation of the Taylor terms. However no real time renderings under arbitrary illumination is presented in their work. Recently, Toisoul&Ghosh (Toisoul and Ghosh 2017) have proposed a reformulation of Stam's BRDF using a first order approximation as well as a measurement setup to directly measure diffraction patterns on homogeneous planar surfaces. Their measurements are carried out at a single wavelength (using a spectral filter), and their method is able to recover the diffraction pattern under an arbitrary light spectrum. The result is stored in a diffraction lookup table that can be used for real time renderings under point light sources as well as arbitrary illumination using a prefiltering method based on a convolution. However such prefiltering only works for an axis-aligned orientation of the diffractive sample. In this work, we propose an approach to compute such a convolution in real time using a low rank factorisation of the diffraction lookup tables of (Toisoul and Ghosh 2017). As a result correct renderings of diffraction can be produced under arbitrary rotations about the view vector, with potential realistic rendering applications in games and VR.

2 DATA-DRIVEN REFLECTANCE MODEL

This work builds on the recent work of Toisoul&Ghosh (Toisoul and Ghosh 2017) and employs their first order diffraction BRDF model given in equation 1 where F and G are the common Fresnel and Geometric terms, ω_i and ω_o are the light and camera directions respectively.

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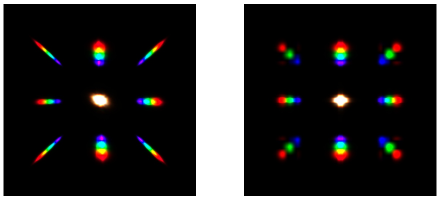

Figure 2: Diffraction table of a holographic paper. (a) Original table. (b) Rank 1 reconstruction using SVD.

$$f_{r,diffraction}(\vec{\omega}_i,\vec{\omega}_o) = 4\pi^2 F^2(\vec{\omega}_i,\vec{\omega}_o) G(\vec{\omega}_i,\vec{\omega}_o) S_d(\vec{h}) \quad (1)$$

The main component of the BRDF is the diffraction lookup table S_d that is computed from a measurement of the diffraction pattern at a single wavelength. An example of the diffraction table of a holographic paper is shown in figure 2a. In the next section, we explain how this 2D lookup table can be factorised into an outter product of two lower rank matrices for real time computations.

3 RANK FACTORISATION

The diffraction lookup table S_d can be factorised into an outter product of two matrices of a lower rank r. This factorisation corresponds to solving the following optimisation process :

$$\begin{aligned} &\arg\min_{\tilde{S}_d} && \|S_d - \tilde{S}_d\|_F \\ &\text{subject to} && rank(S_d) = r \end{aligned} \quad (2)$$

$\tilde{S}_d$ is the final rank r matrix that best approximate S_d. It can be found analytically using a singular value decomposition (SVD) $S_d = U\Sigma V^T$ where the matrices U and V are orthogonal matrices and Σ is a diagonal matrix containing the singular values of S_d. Then only the r largest singular values are kept as shown in equation 3. The matrices U_r and V_r are the r first column of U and V and Σ_r is the diagonal matrix containing the r largest singular values of S_d (Markovsky 2008). Note that the optimisation is applied independently to each color channel.

$$\tilde{S}_d = U_r \Sigma_r V_r^T \quad (3)$$

The horizontal and vertical convolution filters of rank r that are stored to compute the two pass convolution are given by $U_r \Sigma_r^{\frac{1}{2}}$ and $\Sigma_r^{\frac{1}{2}} V_r^T$. Note that such a method works for axis aligned diffraction patterns. In the case of a non axis aligned pattern we first apply an affine transformation to make it axis aligned before computing the low rank factorisation. The inverse affine transformation is applied during the rendering.

4 RENDERING

4.1 Convolution

For rendering, we employ the diffraction lookup tables of (Toisoul and Ghosh 2017). Each table can be parametrised by the non normalized half vector $\vec{h} = \vec{\omega}_i + \vec{\omega}_o$ where the horizontal and vertical axis of the table correspond to the projection of $\vec{h}$ onto the tangential coordinate frame $(\vec{t}, \vec{n} \times \vec{t})$. The convolution is then computed using the method of (Karis and Games 2013) under the assumption $\vec{\omega}_o = \vec{n} = \vec{r}$ where $\vec{n}$ and $\vec{r}$ are the normal and reflection vector. We convolve the environment map in two passes using the two low rank filters obtained in section 3. In each pass, we first calculate projection of $\vec{h}$ in the (x, y) plane and rotate it depending on the local orientation of the tangent $\vec{t}$ (to take into account the rotations of the sample). Then the z coordinate of $\vec{h}$ is given by $1.0 + \sqrt{1.0 - h_x^2 - h_y^2}$ ($\vec{h}$ is not normalized) due to the above assumption.

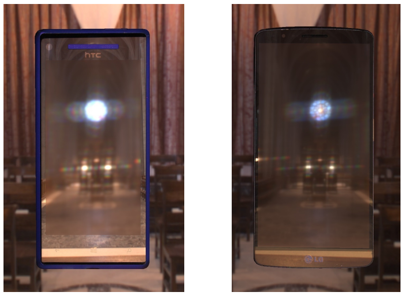

Figure 3: Rendering of the diffraction pattern of two phones in the Grace Cathedral. (a) HTC 8X. (b) LG G3.

4.2 Results

We present renderings in the Grace Cathedral environment in the accompanying video and figures 1 and 3 using a rank 1 factorisation. The CD rendering is computed using single pass 1D convolutions in the direction of the local grooves. The TV rendering is modelled as the sum of two 1D convolutions (single pass) in the main directions of the diffraction pattern. We reach around 100 FPS at a resolution of 1920x1080 with a NVIDIA GTX 1080 GPU for these renderings. The renderings in fig. 1c and 3 are computed in two passes by first convolving the environment map with one factored filter and then convolving in the orthogonal direction with the second filter. For these renderings, we reach an average of 50 FPS.

5 CONCLUSION

We present a method to compute realistic diffraction effects in real time under arbitrary illumination. Such a technique currently works in real time using a rank 1 factorisation of the diffraction table. Better results are very likely to be achieved with a higher rank but will require more powerful GPUs to handle such computations.

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