Accurate Image Based Re-lighting through Optimization

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Report CW 336, April 2002

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In this report we present a new re-lighting technique that, for a single viewpoint, accurately captures the reflectance field of real and virtual objects, without restrictions on their geometrical complexity or material properties. As a result the objects can be re-lit under arbitrary lighting conditions. To capture the reflectance field, we take photographs of an object lit by several lighting patterns on a surrounding discretized hemicube. The illumination of each pixel due to emitted radiance from each discrete patch on the hemicube is approximated by a reflection coefficient and a rectangular support which are found through an optimization procedure. The discretization of the hemicube ensures sufficient angular sampling to capture diffuse material properties. The use of a per patch support accommodates the small solid angle of a incoming light important for specular materials. To re-light the object, the target illumination, a high-dynamic range environment map, is averaged over the support and multiplied by the reflection coefficient, per pixel and per discrete patch on the hemicube. The results obtained show accurate re-lighting of diffuse as well as specular objects.

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Abstract

In this report we present a new re-lighting technique that, for a single viewpoint, accurately captures the reflectance field of real and virtual objects, without restrictions on their geometrical complexity or material properties. As a result the objects can be re-lit under arbitrary lighting conditions. To capture the reflectance field, we take photographs of an object lit by several lighting patterns on a surrounding discretized hemicube. The illumination of each pixel due to emitted radiance from each discrete patch on the hemicube is approximated by a reflection coefficient and a rectangular support which are found through an optimization procedure. The discretization of the hemicube ensures sufficient angular sampling to capture diffuse material properties. The use of a per patch support accommodates the small solid angle of a incoming light important for specular materials. To re-light the object, the target illumination, a high-dynamic range environment map, is averaged over the support and multiplied by the reflection coefficient, per pixel and per discrete patch on the hemicube. The results obtained show accurate re-lighting of diffuse as well as specular objects.

1 Introduction

Image-based re-lighting represents a class of techniques that apply new lighting conditions to a scene, given a set of base images. Possible applications range from lighting design to augmented reality. Lighting design can be a tedious task, since moving objects and light sources is not always feasible. Objects can be very fragile (e.g. archaeological artifacts), the illumination is not controllable (e.g. the sun through a sky-window) or an object is too massive to move around (e.g. a statue). Augmented reality applications are constantly evolving and pushing the limits of widely accepted techniques. Placing real objects in virtual environments influences the appearance of the objects. It is not always possible to approximate the desired illumination at the moment an object is captured (e.g. special effects in a movie or computer games which combine real and virtual environments).

In this report we develop a re-lighting technique that combines strengths from techniques as the Light Stage[2, 5] and environment matting[1, 14] into a single framework. This allows us to capture complex geometrical objects without placing restrictions on material properties or losing practical usability. To capture the reflectance field a hemicube around the object is decretized in several light patches. Each patch emits a series of illumination patterns and for each pattern a high-dynamic range photograph[3] is recorded. Currently we use a calibrated CRT monitor per hemicube side to emit the illumination patterns. For each pixel and for each light patch the emitted radiance is then approximated by a reflection coefficient and a support area on the light patch. A least square minimization procedure on the pixel radiance over different lighting patterns is used to determine the best approximation for the support. To re-light the scene with an arbitrary high-dynamic range light-map, the illumination on the support is calculated and multiplied by the reflectance factor. This is repeated for each pixel and each light patch.

Our report is structured as follows: In the next section we discuss previous work. In section 3 a mathematical framework is developed. The developed technique is presented as a three step algorithm in sections 5, 6 and 7. The relation with the Light Stage and environment matting is further explored in section 8. We conclude this report with results in section 9 and future work in section 10.

2 Previous Work

In this section we give an overview of work related to image based re-lighting. A number of techniques requires or reconstruct a geometrical model of the scene. Loscos et. al.[8, 9] reconstructs a simplified geometrical model, approximates the illumination and calculates un-occluded illumination textures with an adapted radiosity algorithm. Re-lighting is done by modifying real and virtual light intensities. Yu et. al.[12, 13] focus mainly on recovering the reflectance properties of materials by using an iterative optimization procedure to find parameters to represent the reflectance properties of surfaces. The obtained results are re-rendered using a global illumination rendering system. Reconstruction of geometry is advantageous when visualization from multiple viewpoints is desired, but is a disadvantage when a scene consist out of geometrical complex objects.

Another class of techniques circumvents the problem of complex geometrical models by directly manipulating images. Nimeroff et. al.[10] introduced the concept of linearly weighting and combining base images of a scene. These base images are rendered with a number of lighting conditions from which the desired final lighting can be constructed. Wong et. al.[11] based their re-lighting method on light field rendering[4, 6]. By sampling the scene under different viewpoints and illumination an apparent BRDF for each surface pixel is found. Lin. et. al.[7] define a reflected irradiance field, the dual of a light field, and derive upper sampling bounds per BRDF to reproduce them truthfully. The Light Stage[2, 5] uses base images of a scene lit by lights regularly spaced on a sphere surrounding the scene. A light-map is applied by linearly combining and weighting these base images into a single resulting image. Environment matting, originally introduced by Zongker et. al.[14] and extended by Chuang et. al.[1], capture the reflectance properties of specular and refractive materials by illuminating them with different lighting patterns. The direction and solid angle can be derived from this information in the form of a reflection coefficient and a support on the back or side-drops.

3 Mathematical Framework

In this section we develop an unifying mathematical framework for re-lighting. We derive the re-lighting equation in subsection 3.1. In subsections 3.2, 3.3 and 3.4 we express our and other re-lighting techniques with this re-lighting equation.

We derive a formula, based on reflection fields, which we call the re-lighting equation throughout this report. With this mathematical framework, we have a correct mathematical basis in which we can solidly develop our technique and can compare our method on a mathematical basis with other techniques.

3.1 Re-lighting equation

We use a notation simular to Debevec et. al.[2]. The reflectance field at a closed surface A is defined as a 8 dimensional function:

$$R = R(R_i, R_r) = R(u_i, v_i, \theta_i, \phi_i; u_r, v_r, \theta_r, \phi_r) \tag{1}$$

where R_i represents the incident light field at A and R_r represents the radiant (exitant) light-field at A. (u, v) is a parameterization of A and (θ, ϕ) is used to denote directions.

We make the following assumption: The incident light field $L_i(\theta, \phi)$ originates from a point at infinity. This allows us to express the incident light field independent of (u_i, v_i) on A.

$$R_i(u_i, v_i, \theta_i, \phi_i) = R_i(\theta_i, \phi_i)$$

This assumption reduces (1) to a 6 dimensional function:

$$R = R'(\theta_i, \phi_i; u_r, v_r, \theta_r, \phi_r) \quad (2)$$

The reflectance field for a fixed camera position can be expressed as the reflectance function R_p through a pixel p of a photograph. The total radiance L seen through a pixel p:

$$L(p) = \int_{\Omega_{4\pi}} R_p(\theta_i, \phi_i) L_i(\theta_i, \phi_i) d\omega \quad (3)$$

where $\Omega_{4\pi}$ represents the entire sphere. We approximate $R_p(\theta_i, \phi_i)$ by a discrete sum of reflection coefficients $R_{p,j}$ and a set of normalized basis functions $S_j(\theta_i, \phi_i)$, each defined over a set of discretized solid angles.

$$R_p(\theta, \phi) \approx \sum_j R_{p,j} S_j(\theta, \phi) \quad (4)$$

and $\forall j : \int_{\Omega_j} S_j(\theta, \phi) d\omega = 1$. Combining (3) and (4) we arrive at the re-lighting equation:

$$L(p) \approx \sum_j R_{p,j} \int_{\Omega_j} S_j(\theta_i, \phi_i) L_i(\theta_i, \phi_i) d\omega = I_p \quad (5)$$

where $\bigcup_j \Omega_j = \Omega_{4\pi}$.

The purpose of this report is to compute for each pixel the reflectance coefficients $R_{p,j}$.

3.2 Choice of the reflection coefficient $R_{p,j}$ and support $S_j(\theta, \phi)$

The choice of the reflection coefficient $R_{p,j}$ and support $S_j(\theta, \phi)$ depends on the implementation of a particular technique. The choice of $S_j(\theta, \phi)$ is of great influence on which kind of re-lighting is possible. When a narrow support function is chosen, emphasis is put on spacial sampling. Choosing a variable but detailed support, local sampling can be done in great detail.

For $\Omega_{4\pi}$ we use a hemicube and divided each side in a number of patches Ω_j. We use for $S_j(\theta, \phi)$ a box-filter on a axis-aligned support within a patch. A more complex filter is possible, but the results obtained with a box-filter were good. If Ω'_j is a rectangular support in Ω_j then:

$$\begin{aligned} S_j(\theta, \phi) &= \frac{1}{\Omega'_j} \quad if\ (\theta, \phi) \in \Omega'_j \\ &= 0 \quad otherwise \end{aligned}$$

and $R_{p,j}$ can be calculated by defining $L_w(i)$ a constant illumination function for patch Ω_i:

$$\begin{aligned} I_{p_i} &= \sum_j R_{p,j} \int_{\Omega_j} S_j(\theta,\phi) L_w(i) d\omega \\ &= \sum_j R_{p,j} L_w(i) \\ &= R_{p,i} L_w(i) \end{aligned}$$

thus:

$$R_{p,i} = \frac{I_{p_i}}{L_w(i)} \tag{6}$$

3.3 The Light Stage

We show that the Light Stage can be expressed with the re-lighting equation(5). Debevec et. al. used the following definition:

$$L(x,y) = \sum_{\theta,\phi} R_{x,y}(\theta,\phi) L_i(\theta,\phi) \delta A(\theta,\phi)$$

where $L(x,y)$ is a recorded image, $R_{x,y}$ is the reflectance function through a pixel (x,y) with incoming direction (θ,ϕ). $L_i(\theta,\phi)$ the incoming radiance and $\delta A(\theta,\phi) = \sin(\phi)$.

Set j and $S_j(\theta,\phi)$ as follows:

$$\begin{aligned} j &= \{(\theta_j,\phi_j) \mid fixed\ positions\ on\ the\ sphere\} \\ S_j(\theta,\phi) &= \delta(\theta = \theta_j \wedge \phi = \phi_j) \end{aligned}$$

Define Ω_j accordingly to j and then the re-lighting equation(5) results in:

$$\begin{aligned} I_p &= \sum_j R_{p,j} \int\int_{\Omega_j} S_j(\theta_i,\phi_i) L_i(\theta_i,\phi_i) \sin(\phi_i) d\theta_i d\phi_i \\ &= \sum_{\theta_j,\phi_j} R_{p,\theta_j,\phi_j} L_i(\theta_j,\phi_j) \sin(\phi_j) \end{aligned}$$

By using a Dirac function as a support, emphasis is put on discrete spatial sampling. Reflection details of materials are limited by the discretization of $\Omega_{4\pi}$ in (θ,ϕ).

3.4 Environment matting

We show that environment matting can be expressed with the re-lighting equation(5). Zongker et. al. used the following definition:

$$C = F + (1-\alpha)B + \sum_{i=1}^{m} R_i \mathcal{M}(T_i, A_i)$$

where C is the recorded pixel color, F the foreground color that the object reflects without applying controlled illumination. α the matte and determines the coverage of a pixel by the object. B the backdrop color seen through the pixel. The number (m) of illumination textures T_i which are used to display controlled illumination on the object is 3 in the original paper (back and side-drops). R_i the reflection coefficient and $\mathcal{M}(T_i, A_i)$ is a box filtered support of an area A_i in T_i which determine the main direction and solid angle of visually important light for a pixel.

We ignore the foreground color F, since we assume that the illumination only originates from infinity and is completely controlled. Set $\Omega_i = T_i$ and $\Omega_{m+1} = B$. Using the re-lighting equation(5) we obtain:

$$\begin{aligned} I_p &= \sum_{j}^{m+1} R_{p,j} \int_{\Omega_j} S(\theta_i, \phi_i) L_i(\theta_i, \phi_i) d\omega \\ &= R_{p,m+1} \int_{B} S(\theta_i, \phi_i) L_i(\theta_i, \phi_i) d\omega \\ &+ \sum_{j}^{m} R_{p,j} \int_{T_i} S(\theta_i, \phi_i) L_i(\theta_i, \phi_i) d\omega \end{aligned}$$

By choosing $S(\theta, \phi)$ as follows:

$$\int_{T_i} S(\theta, \phi) L_i(\theta, \phi) d\omega = \mathcal{M}(T_i, A_i)$$

and setting A_{m+1} equal to B and $\alpha = 1 - R_{p,m+1}$, we obtain:

$$I_p = (1-\alpha)B + \sum_{j}^{m} R_{p,j} \mathcal{M}(T_i, A_i)$$

which was the equation we were looking for. Since m is low (e.g. 3), emphasis is put on detailed local illumination supports, which are proficient for capturing specular and transparent materials.

4 Three step algorithm

The goal of our re-lighting technique is to capture objects without placing restriction on material properties and to faithfully reproduce these objects under arbitrary lighting conditions. In the following three sections we discuss the three stages of our method build on the mathematical framework developed in the previous section.

Firstly, enough input data has to be acquired to extract the reflectance properties for each pixel for a fixed viewpoint (section 5). Once the input data is gathered, the reflectance properties are calculated and stored for fast re-lighting afterwards (section 6). This processing step is only done once for each scene. When all data is processed, an arbitrary light-map can be applied to the illumination of a scene (section 7). This re-lighting can be done an arbitrary number of times with different light-maps and requires little processing time.

5 Data Acquisition

To capture the reflectance field, the object is lit by several light patches located on a surrounding hemicube. Each light patch emits a series of illumination patterns, and for each pattern a high dynamic range photograph[3] is recorded.

It is important that the recorded high-dynamic range photographs are not under or over-saturated, because this might result in loss of accuracy. High intensity as well as low intensity radiance from the illumination patterns are important for finding a correct support for specular materials. Every emitted radiance value results in extra information regarding the reflectance properties of a pixel. Since a low number of patterns is used, this information must be maximized. Low intensity radiance in the resulting high-dynamic range photograph is needed to accurately calculate the reflectance coefficient for diffuse materials. Low intensity radiance in the input data, does not necessarily map to low intensity radiance in the re-lit result and large relative errors (associated with these low intensity radiance data) can cause visual artifacts.

5.1 Illumination Patterns

The illumination patterns are a key element in our method. From the different radiance values in the high-dynamic range photographs, due to the illumination patterns, a reflection coefficient is calculated and a support is searched through a optimization procedure (section 6). The idea of using illumination patterns to find a support on the light patch was introduced by Zongker et. al.[14] and extended by Chuang et. al.[1].

Zongker et. al. used horizontal and vertical stripes as illumination patterns, while Chuang et. al. used Gaussian stimuli. These patterns are not directly usable for our method because they require a large amount of photographs to be recorded (this number grows even more when taken in account that we use high-dynamic range photographs). Chuang et. al. also introduce an approach for materials with neutral color. A slice through a RGB-cube (a gradient) is used and is sufficient for finding the support on the backdrop.

We want to limit the number of photographs that have to be recorded, thus a maximum of information must be contained in a single illumination pattern. Chuang et. al have shown that a single gradient is sufficient to capture white material with just one photograph, we extent this idea to use a number of differently oriented gradients. The question now remaining is: which gradients and which orientations?

From formula (6) follows that the reflection coefficient $R_{p,j}$ can be easily derived when a solid illumination pattern $L_w(j)$ is used. Another way to extract the reflection coefficient is to use inverse illumination patterns for one or for all gradient illumination patterns. We define a inverse illumination pattern by stating that the sum of a pattern and its inverse equals a solid constant pattern. This sum can then be used to estimate $R_{p,j}$. The use of inverse patterns has advantages over a solid pattern, because it is not meaningful to optimize for a support over a solid pattern, while this still is possible for inverse illumination patterns. In practice we used both, but for another reason. If for some reason something goes wrong during the recording of the high-dynamic range photographs, it is possible to reconstruct the lost photograph from the solid pattern or its inverse pattern.

To make the optimization procedure more robust, a few other constraints are put on the choice of gradients. First of all, smooth gradients are easier to optimize for. Secondly, the difference between the average illumination of areas with the same position and size in different illumination patterns must be as large as possible. The idea is that if the difference in applied illumination is maximized, the difference in resulting radiance is also maximized. Furthermore the average illumination between different areas on the same illumination pattern must also be as large as possible, making it easier to uniquely identify the supports from each other.

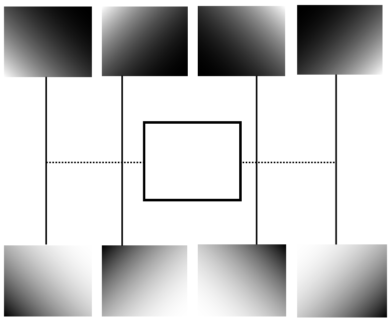

Figure 1: The 9 illumination pattern used. The solid pattern is displayed in the center. Inverse patterns are displayed on opposite sides.

A wide range of gradient patterns are possible. A choice has to be made between accuracy and the number of illumination patterns (and thus the number of photographs that have to be recorded). We have chosen for 4 quadratic (gray-scale) gradients each differing 90 degrees in orientation and starting at 45 degrees. We also use 4 inverse illumination patterns and 1 solid white pattern (figure 1). Empirical test show good results with these patterns, but a slight blurring occurs for specular materials.

5.2 Practical Setup

For the practical setup, we have chosen to use a calibrated CRT monitor for each side of the hemicube. This choice is motivated by the general availability and the large view angle of CRT monitors. We use a 4×4 grid of light patches per hemicube side, which gives good results in reproducing various material properties and requires only a moderate number of high-dynamic range photographs (figure 2).

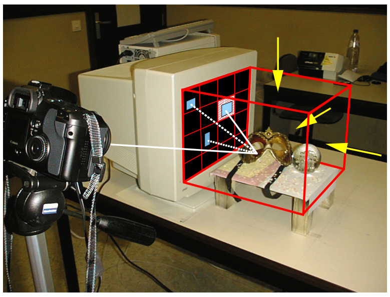

Figure 2: For each pixel and each light patch a reflection factor and support area is calculated. Our current setup limits monitor placement to 4 sides, excluding the side where the camera is located. Each hemicube side consist of a 4×4 grid of patches and we use 9 different gradient patterns per patch.

A calibrated CRT monitor is used, because we want to optimize on radiance values. An approach simular to Chuang et. al.[1] is used for the monitor calibration. A calibration pattern (figure 3) containing all possible gray-scale pixel-values is displayed and a high-dynamic range photograph is recorded. The radiance values per pixel-value are extracted and the inverse mapping from radiance value to pixel-value is applied on the illumination patterns. The resulting emitted radiance is now according to our quadratic gradient pattern.

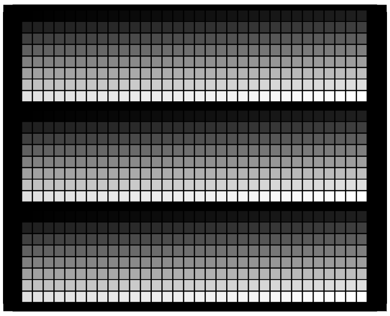

Figure 3: Monitor calibration pattern. A high-dynamic range photograph is recorded and samples per gray-scale pixel-value are taken at three different location on the screen to limit the effects of noise. The radiance value per gray-scale value is extracted from the recorded photograph.

The use of a CRT monitor limits monitor placement to 4 sides of a hemicube, excluding the side where the camera is located. We use a single CRT monitor, which is moved around for each hemicube side. The placement of the CRT monitor has to be carefully measured. Gaps between light patches at the borders result in visible artifacts in the results.

6 Processing of the input data

Once the high-dynamic range photographs are recorded, the reflectance coefficient is calculated and support is searched through an optimization procedure per pixel and per light-patch.

The reflectance coefficient $R_{p,j}$ can be directly calculated from the recorded radiance values of the illumination from a solid pattern or the combination of illumination patterns and their inverse patterns.

A least-squared minimization per pixel and per light patch Ω_j is used to optimize the support. The least-squared error is defined by (using the notation from section 3):

$$Error_{\Omega_j}(p) = \sum_k (R_{p,j} \int_{\Omega_j} S_j(\theta_i, \phi_i) L_{i_k}(\theta_i, \phi_i) d\omega - L_k(p))^2$$

where k is the number of patterns we optimize on and $L_k(p)$ is the recorded radiance at pixel p illuminated with $L_{i_k}(\theta, \phi)$, the incoming radiance from pattern k. We use a steepest descent optimization algorithm per pixel and per patch:

```
Algorithm 1:

1) Select an initial support
2) Calculate the least-squared error
3) while not minimized
   a) Test all (80) expansion possibilities of the support
   b) Calculate least-squared errors and select minimum error
   c) if minimum error < error then update support
      else minimized = true
```

The 80 possible expansion are obtained by moving a side of the axis aligned support 1 step to both directions. Combining this for 2, 3 and 4 sides results in 80 possibilities.

The algorithm can be optimized by using a Levenburg-Marquardt optimization or alternatively, instead of on expanding the support 1 pixel in the illumination pattern, also expand *x* pixels (e.g. 5% of the total size of the pattern), this helps speeding up the optimization process and avoiding small local minima.

The choice of the initial support Ω'_j is done as follows: if the difference in pixel-value with the previous pixel is less then a certain threshold, the support of the previous pixel is used, otherwise the entire light patch is set as initial support. The idea is that simular neighboring pixels probably have the same material properties and thus have a simular support.

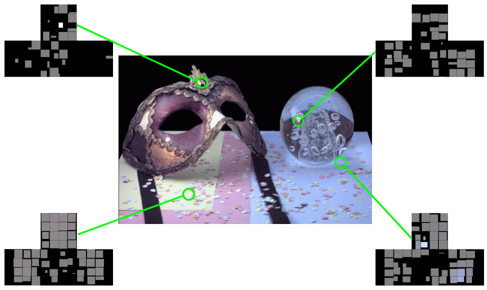

Figure 4: We plotted the 4 sides of the hemicube for 4 different pixels. At each hemicube side the different optimized supports are shown. (the plot per hemicube is organized as follows: up; left, back, right)

The reflectance coefficient $R_{p,j}$ and the support Ω'_j (figure 4) are stored on disk for re-lighting afterwards. A per pixel or per scanline compression is possible to reduce storage requirements.

7 Re-lighting

To re-light the scene using an arbitrary high-dynamic range environment map, the illumination is averaged over the support and multiplied by the reflection coefficient, for each pixel and for each patch.

8 Discussion

Due to the subdivision of the hemicube in light patches, diffuse materials are captured correctly. However, this subdivision is too coarse for correctly capturing specular highlights. The use of of illumination patterns makes it possible to find sub-patch areas which are needed to simulate the small solid angle required for specular materials. This approach combines the strengths of the Light Stage and environment matting.

In section 3.3 and 3.4 we showed that both the Light Stage and environment matting can be derived from the re-lighting equation (formula (5)).

The subdivision of the hemicube matches the fixed position of light source on the sphere in the Light Stage (the sum in formula(5)). This limited angular resolution is sufficient to capture diffuse materials and reproduce them faithfully. The use of a support (the integral in formula(5)) directly maps to environment matting and enables us to find small areas on the environment that matches the small solid angle needed for specular materials. While each technique, the Light Stage and environment matting, fail to reproduce respectively specular and diffuse materials, our method cleverly combines the strengths of each technique and is able to re-light specular as well as diffuse materials.

9 Results

The results show two scenes. One containing a Venetian mask and a decorative glass sphere and a diffuse colored surface. The other scene displays a glossy wooden car on a diffuse surface. Each scene is re-lit with 4 different environment maps. The scene with the Venetian mask shows the accurate capturing and reproduction of diffuse materials (surface), specular and transparent materials (glass sphere and pearl on top of the mask) and caustics (in the base of the glass sphere). The scene with the wooden car shows glossy highlights (the round curves) and soft shadows (on the surface below the wooden car).

We recorded these scenes using a 19” Iiyama CRT monitor for each side of the hemicube. The photographs were recorded using a Canon EOS D30 camera. We automated the process of capturing and only the CRT monitor had to be moved. The recording time was about 10 hours (of which at least 6 hours were overhead due to the slow speed of the camera). Recording could be done in a matter of minutes when using a synchronized digital video camera and different F-stop filters to acquire high-dynamic range images.

The processing lasted for 20 hours on a Athlon 1.2Ghrz system with 512meg ram. This processing time can be divided among different computer systems because each patch and each pixel can be processed independently of each other.

We verified the results on a virtual scene by rendering the scene illuminated with the target illumination and comparing it with the re-lit result. The results showed the same visual features. A slight blurring occurs when highly specular materials are used, but this is mainly because of the choice of illumination patterns. A choice has to be made between recording time and reproduction quality.

When high-dynamic range environment maps are used as light map that are of much larger dynamic range then the recorded input data, visual artifacts appear. This is caused by noise in the recorded high-dynamic range photographs and optimization errors augmented to visual levels.

10 Conclusions

We developed a mathematical framework in which we derived the re-lighting equation. Using this mathematical framework we developed a new re-lighting technique. This technique is suited for capturing a reflectance field of objects, from a single view point, consisting of any material property and with complex geometry. This methods is practically usable and is able to capture diffuse and specular material, caustics and transparent materials.

A whole new range of applications is possible: the digital capture and display of objects with a mix of diffuse and specular appearance (e.g. jewelry or sensitive archaeological objects), augmented reality applications, (interactive) re-lighting of fully virtual scenes, ...

Future research will focus on faster and easier capturing of the reflectance field, the use of other projection devices such as VR-caves that can accommodate larger objects and reducing the number necessary photographs by using better patterns and better optimization procedures.

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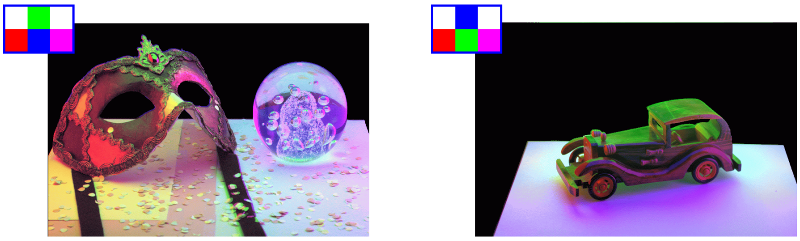

Figure 5: A Venetian mask with glass sphere and wooden car lit by a virtual environment map.

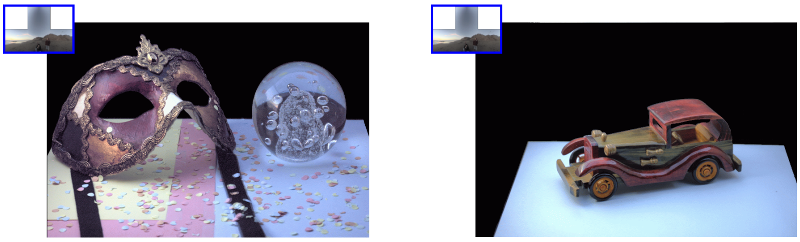

Figure 6: A Venetian mask with glass sphere and wooden car lit by a environment map of a beach.

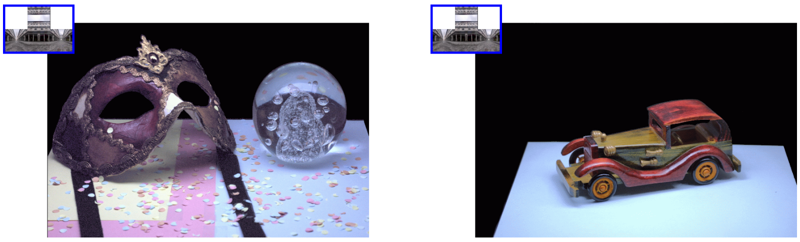

Figure 7: A Venetian mask with glass sphere and wooden car lit by a environment map of the uffizi galleria.

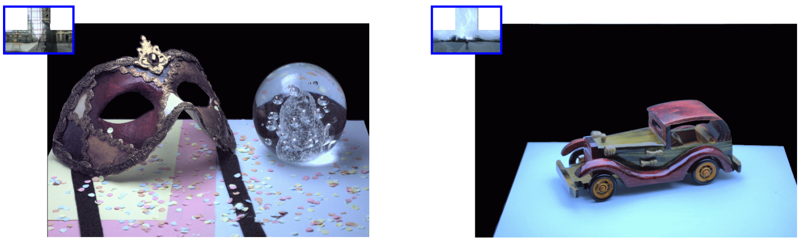

Figure 8: A Venetian mask with glass sphere lit by an environment map of a building with a glass ceiling and a wooden car lit by an environment map recorded at the parking space outside our office.