Predicting Environment Illumination Effects on Material Appearance

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Abstract

Environment illumination is a key to achieving a realistic visualization of material appearance. One way to achieve such an illumination is an approximation by rendering of the material surface lit by a finite set of point light sources. In this paper we employed visual psychophysics to identify a minimal number of point light sources approximating realistic illumination. Furthermore, we analyzed stimuli images and correlation of their statistics with obtained psychophysical data. Finally, image statistics were identified which can predict such a minimal environment representation for three tested materials, depending on the visual properties of the illumination environment.

1 Introduction

Achieving a realistic appearance of real-world materials in virtual scenes is impossible without environment illumination. Such an environment can be approximated by its model to any required precision. In an idealized model we could assume that parameters of the environment are known. Unfortunately, the exact environment parameters are seldom known, therefore an application of the model mostly introduces unknown approximation errors. One way to achieve the desired illumination is to use a global illumination approach, generating an image by tracing the path of light through pixels in an image plane and simulating the effects of its encounters with virtual objects. This approach theoretically provides excellent quality at the cost of high computational requirements, so achieving real-time rendering in this way requires specialized graphics hardware. Several image-based approaches emerged to remedy these drawbacks. These approaches typically represent captured illumination environment by a finite set of directional lights. Although methods exist nowadays allowing real-time rendering from such environment representations, they rarely take into account the visual properties of environment illumination (further denoted as EI) and/or the material being illuminated.

Prior work: The idea of illumination by means of environment maps was first introduced in [2] and further applied in [3]. As global illumination algorithms based on ray-tracing were computationally demanding, importance sampling methods were developed [1], [4] representing the environment map by means of a finite set of directional lights. The importance of context environment information and specular reflection for perception of surface reflectance was studied by [7] with the conclusion that observers can match correct environment based only on the surface reflectance. [10, 11, 8] studied effect of shape, EI and reflectance on human perception. Subjects’ perception of realistically textured scenes was analyzed [9, 6] and used for [5] material appearance data compression. We are not aware of any work that has applied psychophysical methods to assess both bidirectional textured material appearance and EI-dependent perceptual effects.

Paper contribution: In this paper, we use a psychophysical study (Section 3) to determine the simplest representation of EI which preserves visual fidelity of the original environment. Furthermore, we use this information to derive a statistical feature (Section 4) predicting such representations automatically for novel EIs (Section 5).

2 Data Preparation

Environment Acquisition and Representation

For purposes of our work we acquired ten different illumination environments (see Fig. 1). Each environment was obtained by merging eight overlapping photos taken with a fish-eye lens. Each such environment (2048 × 1024 pixels) was represented by a finite set of directional lights using the median-cut algorithm [4] as follows. Every environment image is first gamma-
correction compensated ($\gamma = 2.2$) to obtain the original linear response of the camera sensor. The algorithm then iteratively splits the input environment map image into even sets of regions by cutting the regions at the point where the medians of the cut regions’ luminance are mutually equal. For rendering, the environment map is wrapped over a sphere surrounding the illuminated object. To compensate over-representation of regions near the poles, the luminance pixels of the environment map are weighted by cosine of the inclination angle. Fig. 2-top shows the compensated environment 02 represented by 128 light by means of the median-cut algorithm. An example of the sphere illuminated by a different number of lights approximating the environment by median-cut algorithm is shown in Fig. 2-bottom. The quality of shading and presence of disturbing seams on the object’s surface are clearly dependent on a number of lights. Our goal is to identify the lowest number of lights that preserve the naturalness of EI and suppress these visible artifacts.

**Materials Representation**

Contrary to using reflectance only (BRDF) [10, 11, 8] we represented material appearance using view- and illumination-dependent textures (BTF) [5] samples alu (Fig. 2), corduroy, and leather (Fig. 3) from the BTF Database Bonn1.

Rendering of BTF using a finite set of $n_i$ directional lights can be described as their convolution with each pixel

$$L_r(x, y, v) = \sum_{i=1}^{n} B T F(x, y, \omega_i, \omega_v) L_i(x, y, \omega_i), \quad (1)$$

where $\omega_i, \omega_v$ are illumination and viewing directions, $L_i(x, y, \omega_i)$ is radiance of individual lights and $L_r(x, y, v)$ is final radiance reflected by the sample.

**3 Psychophysical Experiment**

The goal of the experiment was to analyze the material-dependent sensitivity of human subjects to a simplified representation of different real-world illumination environments.

Pairs of static images of size $640 \times 640$ pixels were used as experimental stimuli, representing a material BTF rendered on a sphere. Each pair consisted of a reference rendering using the 256 lights and another rendering using a set of 16, 32, 64, 128, or 256 lights. Pairs of images were displayed simultaneously, side-by-side as shown in Fig. 3. We used the shape of a sphere because its geometry provides a wide range of illumination and viewing combinations without introducing unwanted higher curvatures, which could mask sought artifacts. All three test materials were rendered in ten test environments. As some environments were used in multiple views, the total number of different tested illuminations was fifteen. Azimuthal positions of views are shown in Fig 1 as red (the first view), green (the second view), and blue (the third view) dots at the bottom of environment maps. Given three materials, fifteen environments, and five quality levels of illumination representation, the total number of stimuli was 225.

**Figure 2.** Example of environment illumination. The spheres are illuminated by different numbers of lights.

**Figure 3.** Experimental stimuli showing a sphere in illumination environment (256 vs. 32 lights).

Twenty volunteers (8 females, 12 males) participated in the experiment. All participants had normal or corrected to normal vision and were naive with respect to the purpose and design of the experiment. The participants were shown the stimuli in a random order and asked a yes-no question: ‘Can you spot any differences in the material covering the two objects?’ Participants were asked to answer in 3 seconds to avoid decision based on a minor local difference. It turned out that 94% of the responses were made in 2 seconds. All stimuli were presented on a calibrated monitor during night under dim room ceiling light.

By averaging the responses of all participants, we obtained psychometric data relating the average response to different numbers of lights, environments, and materials. The numbers of lights required for each EI and material were obtained from a psychometric function using 25% threshold [5] and are shown in Fig. 4.

**4 Relation to Illumination Maps Statistics**

We analyzed the relation between obtained human visual attention and feasibly computable statistics of stimuli and environment maps. We were inspired by the image salience methods, therefore we took a cir-
Figure 4. Estimated minimal number of lights for EI
and materials.

Figure 5. Example of the tested statistics (σ = 5)

Stimuli Images Analysis

First we used the six proposed features for description
of stimuli images used in the experiments. As these im-
gages comprise two distinct parts – an environmen-
tally illuminated textured sphere and background – we
analyzed these parts separately. Tab. 1 shows corre-
lation of the features with results of the main psychophysi-
cal experiment. The correlation was computed as a Pear-
son correlation coefficient $R_{X,Y} = \frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X \sigma_Y}$, where $X, Y$ are compared average subject responses with a feature’s values, $\mu$ and $\sigma$ are their means and standard deviations. The table shows coefficients for three tested materials and background for a width of Gaussian window $\sigma = 10$. Correlation of the features for textured sphere was relatively low (the highest values $R \approx 0.5$) for $\mu(\sigma_L)$ and $\mu(e_L)$. What is surprising is a higher correlation ($R = 0.63$) of $\sigma(\mu_L)$ computed in a stimuli background. This suggests the hypothesis that variance in stimuli background or contrast between
the background and textured sphere significantly influences perception of visual artifacts caused by insufficient representation of environment illumination.

Environment Maps Analysis

The results obtained from analysis of the stimuli im-
age opens a question of whether it might be general-
ized to environment map images. For this reason we
identified the region in the maps roughly correspond-
ing to the background visible in the stimuli images (see
Fig. 5-left) and computed the proposed features directly
on such parts of environment maps. Results of the fea-
tures’ correlation with subjects’ responses from the ex-
periment are shown in the last row of Tab. 1. Again
there is a high ($R = 0.61$) correlation of $\sigma(\mu_L)$ (vari-
ance of the locally averaged part of the environment
map) regardless of the size of $\sigma$. Such correlation val-
ues were also achieved by a local energy feature $\sigma(e_L)$, however only for $\sigma > 9$.

5 Illumination Complexity Prediction

In the applied context of this research we aimed at
development of a simple computational method for au-
tomatic prediction of a minimal acceptable representa-
tion of illumination environment. Such a method would
describe dependency of an optimal number of lights on
material statistics and environment map statistics. For
this purpose, we plotted dependency of the estimated
number of lights from the experiment on values of the
best feature $\sigma(\mu_L)$ in Fig. 6. While (a) shows such a
dependency of $\sigma(\mu_L)$ computed on the tested materials
and background from stimuli images, (b) shows depen-
dency of $\sigma(\mu_L)$ on the tested materials and their aver-
age, computed directly from environment maps. The
plot for each material contains 15 points correspond-
ing to the tested illuminations. In all plots we can see the
tendency toward requirement of an increasing num-
ber of lights with the increase of a feature’s value. To
express this dependence analytically we fitted the data
points by polynomials of different ranks. Due to a low
number of data points and their low consistence, how-
ever, this resulted in data overfitting. Therefore, the
data points were finally approximated by a linear regres-
sion ($y = kd + q$) in a least square sense, resulting in the red
outlines shown in the plots. From the slants of the out-
lines it is apparent that this tendency is clearly material-
dependent. Vertical offset of the fitted outlines confirms
our previous finding that visual artifacts, introduced by
representation of minimal number of lights, were the
least apparent for structured corduroy and the most ap-
parent for diffuse leather.
To show a practical application of our conclusions we acquired an additional five environment maps as is shown in the first row of Fig. 7, and computed the $\sigma(\mu_L)$ feature on backgrounds of selected views (red dots at the bottom of the images). A number of lights was predicted from the regression parameters $k, q$ (Fig. 6) and the feature values. When observing renderings of materials in all test environments there are not any visible artifacts, and the minimal numbers of lights required for rendering vary across both tested environments and materials.

6 Conclusions

In this paper we analyzed human observers’ ability to detect visual artifacts caused by under-representation of environmental illumination by a limited set of directional lights. We have found that this ability significantly depends on the type of illuminated material as well as on the type of illumination environment. Generally, an increase of the standard deviation of local mean value in an environment map increases the ability of human observers to detect visual artifacts introduced by means of an insufficient number of lights representing the environment. Therefore, the more visually complex/rich the environment is the more lights are required for its proper representation. We have shown how this number of lights depends on the type of illuminated material, and how it can be predicted from an environment map’s statistics.

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