Image-Based Lighting Design

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In this paper, we present a lighting design framework for near-diffuse real objects, starting from a set of prerecorded photographs of an object under various lighting conditions. Light sources are placed at fixed positions around an object, for which the intensities are to be determined. Using existing digital imaging software, the lighting designer paints the desired illumination distribution on a photograph of an object. This painted-on illumination is used to determine the light intensities which produce a shading of the real object matching the desired illumination distribution. Certain areas in the painted image can be favored among others by weighting their importance in the optimization algorithm.

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Categories and Subject Descriptors (according to ACM CCS): I.3.4 [Computer Graphics.]: Graphics Utilities. Paint Systems. I.3.6 [Computer Graphics.]: Methodology and Techniques. Interaction techniques. F.2.1 [Analysis Of Algorithms and Problem Complexity.]: Numerical Algorithms and Problems. Computations on matrices

1. Introduction

Given a full scene specification such as the geometry, material properties and camera parameters, the look and feel of an environment highly depends on the lighting setup. Good lighting can significantly improve the character of an environment, reducing under- or over-illuminated regions, enhancing contrast, etc. In certain spaces (workshops, storage, utility rooms) one is usually interested in bright, shadowless light. But in other areas (lobbies, boardrooms, restaurants, museums) one might be looking for a little style, drama, or have the lighting be part of an artistic expression.

Inverse lighting design starts from desired illumination objectives and constraints, such as the position of shadows, the intensity of highlights, or the overall brightness level of the environment. Using a cost function for each of the desired targets, an optimization process determines the most optimal positioning and color of light sources to satisfy the objectives and constraints of the lighting design. This inverse approach requires an *a priori* knowledge of the desired appearance.

With the availability of advanced rendering techniques and global illumination algorithms, an approach widely used in lighting design, is to make a 3D model of the real environment and find a suitable lighting design for the virtual environment. While this is a very flexible approach in exploring the space of possible lighting designs, applying a design back in reality still remains a problem. Building an exact 3D model with appropriate material parameters for a real environment or object can be a demanding task. One has to address all these problems when performing virtual simulations.

In this paper, we present a novel inverse lighting design technique for real objects, starting from a set of prerecorded photographs of an object under various lighting conditions. The designer is able to specify the desired illumination by painting on a photograph of the object using existing digital image software, such as Adobe Photoshop. A least squares optimization algorithm is then used to work backwards and establish a linear combination of the photographs, suiting the designers goals. Additional input can be provided to the optimization algorithm by giving painted areas different importance. Afterwards, we show our lighting design can be reproduced in reality.

Since we only use photographs, real world lighting design for which virtual descriptions of an object are difficult

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to construct, can benefit from our approach. For instance, designing a lighting configuration for fragile or highly valuable objects for which it is difficult to acquire the geometry from can be done with any type of light source. There are no constraints on the type of light sources as well. Our approach might also be applicable in stage design as long as photographs can be made of the possible lighting setup. However, our approach is limited to near-diffuse objects since we use only one point of view to design an illumination and our set of possible light positions is rather sparse.

2. Previous and Related Work

Lighting design techniques address the problem of finding lighting parameters, such as position, orientation or intensity, that yield a desirable lighting configuration. Inverse lighting design techniques in computer graphics so far, have mostly addressed this problem for virtual environments.

Poulin [PRJ97], [PF92] allowed the designer to specify design goals by sketching shadows and highlights, from which the light source position and surface roughness are inferred. Related to this approach, [PTG02] presented a technique in which shadows are considered as modeling primitives. Costa [CSF99] presents a methodology in which fictitious luminaries can be defined and placed in a virtual scene to describe a desired radiance distribution. Kawai [KPC93] controls light emissions and directions, as well as surface reflectance to create a room for which the user will have a feeling of comfort, or to minimize the overall energy. Dorsey [DSG91] designed and simulated opera lighting and projection effects using global illumination techniques. An entirely different approach for exploring the space of possible design solutions is presented by *Design Galleries* [MAB*97]. Their interface presents the user with the broadest selection, automatically generated and organized, of perceptually different lighting configurations. Shacked et al. [SL01] determine various lighting parameters by optimizing quality objective functions such as contrast or histogram equalization.

Inverse lighting design using prerecorded photographs, the approach we follow in this paper, relates strongly to the field of image-based relighting [NSD94][DKNY95][GH00] [DHT*00][DWT*02]. By photographing an object under different illumination conditions, the reflectance field of the object for a fixed viewpoint can be captured. Using this reflection field, the object illuminated by any environment map can be rendered as a linear combination of the basis images. The core technique in our paper is to inversely apply the image-based relighting approach: If an image of an object is given, what is the linear combination of basis images that resembles the target image as close as possible?

Our user interface is somewhat related with work presented by Schoeneman [SDS*93]. By painting light on the geometry present in the scene, they optimize the light source intensities necessary to obtain the desired shading. The number and positions of the light sources are known in advance. We constrain our problem the same way, but instead of working on virtual environments using radiosity based calculations, we apply our technique to real objects using an image based optimization procedure.

3. System Overview

An overview of the system is graphically presented in figure 1.

Acquisition. Once an object for which a lighting configuration is to be designed has been chosen, the designer selects the positions of all possible light sources in the light stage (section 4), as well as the camera position. We do not address the automatic placement of the light sources. Subsequently, for each light source, a photograph or basis image is recorded. The resulting set of basis images determines the search space in which the optimal lighting configuration for the specified design will be found. Thus, it is important that the designer selects the light source positions such that the lighting design can later be applied in reality. E.g. only light source positions on the ceiling might be considered, or floor or wall lighting might be added. Generally, the light source positions have to match the allowable light source positions in the final setup.

Design specification. Our system allows the designer to paint the desired illumination on a photograph of the object. The photograph shows the object under 'neutral' lighting (i.e. an equal weighted combination of all basis images, thus eliminating as much direction-specific shading artifacts as possible). The designer can indicate areas or pixels with a specific desired color, can increase contrast, or can perform any other manipulation that changes the color or intensity. It is important to note that this manipulation happens on a photometric image such that existing digital image software can be used. The painted object should match as close as possible to what will be seen in reality. There is no need to specify radiometric radiance values.

Optimization. The optimization procedure will only take into account the painted areas. Thus, pixels which did not receive any target illumination values will not be considered. Additionally, areas can be favored among others by weighting their importance in the optimization procedure. The result of the optimization is a weighted combination of basis images. These weights specify the intensity of each of the light sources at the corresponding positions in the light stage.

Lighting configuration. Once the intensity for each of the light sources has been computed, the lighting configuration can be realized. Each light source emits an intensity and color of light, as described above. The object is now illuminated in such a way, that if a photograph would be recorded from the same camera position as used for the basis images, a close match is obtained with the specified target illumination.

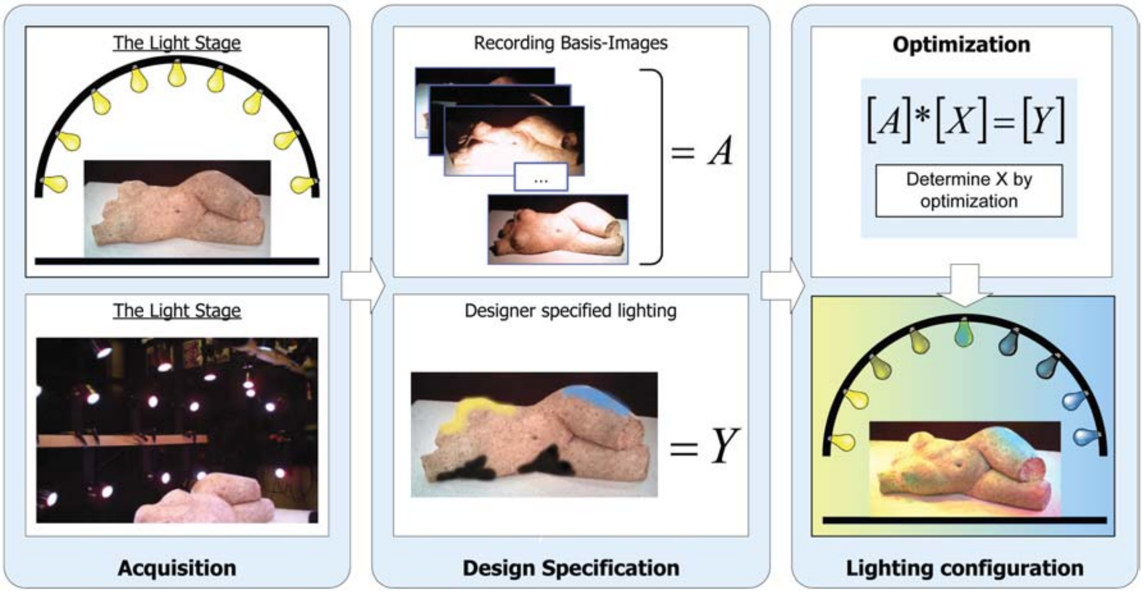


Figure 1: *System Overview*

4. Hardware

To record all the basis images, a light stage was built, inspired by the approach followed by Debevec [DWT*02]. Light sources can be freely placed around the object, mounted on a wooden frame. The light sources can be positioned approximately at 1m distance from the object.

We have 40 IColor MR lamps available from Color Kinetics . Each IColor light consists of a combination of 18 LEDs (red, green and blue) which can be remotely controlled by 8-bit values ranging from 0 to 255. Adding more lamps to the construction, and thus allowing an easier recording session, is in principle not a problem.

All our photographs are recorded using a Canon EOS D30 digital camera. For each light source, a high dynamic range image is constructed using photographs with different shutter times. Since the final result of our algorithm consists of an intensity level for each color channel for each light source position, the calibration of both light sources and camera response curves has to be done very accurately. We calibrated the camera using a white reflection standard, illuminated by a clear sky without direct sunlight. This data is used for calculating the camera response curve [DM97]. For calibrating our IColor MR light sources, we followed the approach outlined in [DWT*02], and obtained similar results. This calibration process provides us with a function that maps the desired linear intensity levels of the light sources to their 8-bit input values.

5. Illumination Design

Processing all the images used in our technique requires linearizing all the images into a vector v_i. These vectors are then stored column wise in a matrix A for further processing: $A = [v_1, ..., v_n]$. Notice that we will have three matrices A: one for each color channel. For the simplicity of this text however, we will only illustrate the mathematical calculations for one channel A since the calculations for the other channels are similar.

Multiplying matrix A by a vector $x = [x_1, ..., x_n]$ results in a radiometric image. Each x_i determines the intensity of light source i, which can be applied in the light stage. Hence, we will determine an optimal vector x, such that $\|f(Ax) - y\|_2^2$ is minimal. f is the tone-mapping operator, y is the painted target image and $\|. - .\|_2^2$ defines the Euclidean distance between $f(Ax)$ and y.

5.1. Tone reproduction

We should compare the target image y with a possible lighting configuration result Ax. First of all, a target image is defined by simply painting color information on the image using standard digital imaging software. This provides us with an image y in photometric space which has to be compared with Ax residing in radiometric space. Advanced perceptual difference metrics based on the human visual system exist for comparing two images [LMK98]. We adopt a $L2$ norm instead for comparing photometric images as a trade-off between speed and accuracy. A tone-mapping operator f converts the relative scene luminance Ax to perceived brightness values. A gamma function, fitted to the camera response curve, is used as operator f:

$$f(Ax) = (\Delta t(Ax))^{\frac{1}{\gamma}}. \tag{1}$$

Δt is the exposure time, used to map the relative luminance values into absolute ones. Ax are the luminance values of a linear combination and γ is the gamma value, found by fitting the curve to our camera response curve. f should mimic the camera curve as good as possible. We found a gamma function works well enough for our purposes.

5.2. Optimization algorithm

Using a nonlinear optimization algorithm to minimize the least square distance between $f(Ax)$ and y, our objective function O can be formulated as follows:

$$O(x) = \sum_i w_i \left[(\Delta t < a_i, x >)^{\frac{1}{\gamma}} - y_i) \right]^2, \tag{2}$$

where i iterates over those pixels which have received some color information and $< a_i, x >$ is the dot product between the ith row of A and x. Additionally, for each pixel, a weight w_i can be provided to modulate the importance of some pixels or areas. Also, since our basis images are taken at maximum intensity of the light sources and emitting negative light is impossible, our weights x are limited to $[0..1]$.

A *Sequential Quadratic Programming* (SQP) [Fle80] method is used to minimize O. At each major iteration, an approximation is made of the Hessian of the Lagrangian function using a quasi-Newton updating method. This is then used to generate a QP subproblem to calculate the search direction for a line search procedure. SQP is a fast and robust approach to a nonlinear problem. The gradient of O is a vector containing the first derivatives of O with respect to x_j:

$$\frac{\partial O}{\partial x_j} = \frac{2\Delta t}{\gamma} \sum_i w_i a_{ij} \left[\frac{1}{(\Delta t < a_i, x >)^{\frac{\gamma-2}{\gamma}}} - \frac{y_i}{(\Delta t < a_i, x >)^{\frac{\gamma-1}{\gamma}}}) \right]. \tag{3}$$

Providing the analytical gradient to the SQP method results in a speed-up factor of 10 for the optimization procedure, instead of estimating the gradient numerically using a finite differencing approach.

6. Implementation & Results

A combination of the Java programming language and MATLAB numerical analysis software was used to create a user friendly interface to our technique. The optimization procedure takes only into account the painted pixels. Other pixels can be added if necessary. The optimization process takes about 15 seconds to complete on a standard computer (1.2 Mhz). If the result is not satisfying, user defined areas or pixels can be given more weight. All the examples presented use the same lighting setup: 40 light sources are positioned around several objects. The same light source positions and directions are used for all the examples.

In figure 2a, an abstract artwork is painted blue on the outside, yellow on the inside. The design, our algorithm output and a photograph of the object applying our design back into the light stage is shown. Important to notice is that our design result exactly matches the lighting configuration applied in reality. In (b) and (c), red and blue gradient patterns are painted illustrating somewhat contradictory design. While a red gradient loops from red to white in the left example, it loops from white to red in the other one. The same applies to the blue gradient. Both images are matched within the same lighting setup.

Figure 3 illustrates lighting configurations we achieved by painting bright and dark regions. In figure 3a we painted an illumination distribution using white and black paint to mimic the light coming from the left. In figure 3b some areas are selected in the image for which the brightness and contrast is adjusted. We designed the light to illuminate the head with a small rim of light.

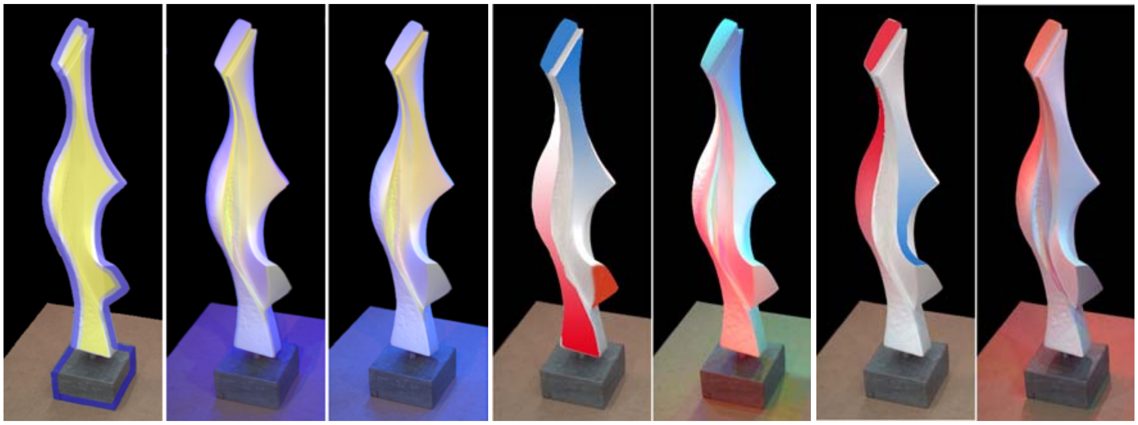
Finally, blue, yellow and dark regions are painted on a photograph of a real-life sculpture (figure 4). The optimal lighting configuration, matching the painted design as good as possible, is computed and applied in reality.

7. Discussion & Future Work

Due to the image based approach, all basis images must be photographed in advance. For each possible position and direction a light source might be placed, a photograph must be made. This manual placement might be a difficult job for architectural complex environments or rooms where mounting real lights is not possible. On the other hand, to have a broad selection of possible lighting solutions, various lights should cover different areas of an object. This requires some user decisions before photographing the object. Further research can be done in mounting light sources more efficiently.

Another subject of future investigations might be designing a target illumination for multiple camera viewpoints. Once a viewer will walk away from the chosen camera position, the illumination will be perceived differently. Highlights might shift position on glossy surfaces, or obscured parts of the objects might come into view. Also, more complex environments, such as rooms, could be taken into account.

Our system only allows working on one photograph of the object, from a single point of view. Currently, this prohibits specifying any illumination constraints on parts of the object not visible in the photograph. Also, fine details such as sharp highlights are not within our reach because our illumination basis is rather sparse. So we are limited to objects with near-diffuse materials. On the other hand, one should



(a) (b) (c)

Figure 2: *(a) An abstract artwork is painted blue on the outside, yellow on the inside. The design, our algorithm output and a photograph of the object applying our design back into the light stage, is shown. In (b) and (c), red and blue gradient patterns are painted illustrating somewhat contradictory design results using the same lighting setup.*

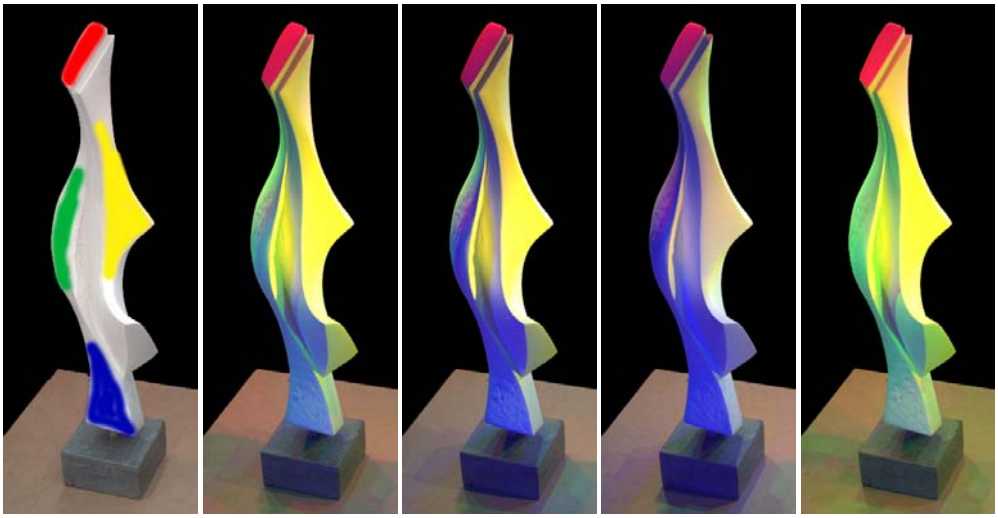
(a) (b)

Figure 3: *A lighting configuration was designed by painting bright and dark regions. The statue is about* 50 *cm tall and is made of brown stone. Two different configurations are shown in (a) and (b).*

Figure 4: *Blue, yellow and dark regions are painted on a photograph of a real-life sculpture to design a surrounding lighting configuration (left). An optimal lighting configuration, matching the painted design as good as possible, is computed and applied in reality (right).*

(a) (b)

Figure 5: *Optimization results for various types of objects. Figure (a) represents a lying venus (*1 *m wide) for which the light is designed to produce dark and bright regions. In figure (b), green light is coming from the right, while a red side and rim light is visible on the left.*



(a) (b) (c) (d) (e)

Figure 6: *Optimization results for an abstract artwork. By applying a weighting factor in the optimization strategy, pixels can receive importance in the final result. (a) shows the target image, painted in an image editor. In (b), all pixels are equally important. In (c) and (d), the blue pixels are given more and more weight in the optimization algorithm. Figure (e) shows a result in which the blue pixels receive less weight.*

include multiple viewpoints to make designing highlights useful.

Since we are using existing imaging software, we cannot give feedback about whether the painted illumination can be achieved in reality. Some feedback could be given based on the consequences of the designers actions: the designer can be restricted to paint certain colors, he can be provided with a set of possible illumination solutions for pixels he did not touched yet, etc.

Computing the design with photographs provides us with a solution which is perfectly reproducible in reality without further knowledge of geometry or material attributes. This is certainly not the case with virtual objects, since rebuilding a virtual design in reality will have problems with light attachment, simulating the virtual lights with real ones, etc. In virtual environments there is a lot of freedom with does not exist in reality.

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