Conveying Shape and Features with Image-Based Relighting

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Abstract

Hand-crafted illustrations are often more effective than photographs for conveying the shape and important features of an object, but they require expertise and time to produce. We describe an image compositing system and user interface that allow an artist to quickly and easily create technical illustrations from a set of photographs of an object taken from the same point of view under variable lighting conditions. Our system uses a novel compositing process in which images are combined using spatially-varying light mattes, enabling the final lighting in each area of the composite to be manipulated independently. We describe an interface that provides for the painting of local lighting effects (e.g. shadows, highlights, and tangential lighting to reveal texture) directly onto the composite. We survey some of the techniques used in illustration and lighting design to convey the shape and features of objects and describe how our system can be used to apply these techniques.

CR Categories: I.3.4 [Computer Graphics]: Graphics Utilities— Paint Systems; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques; I.3.8 [Computer Graphics]: Applications; J.2 [Physical Sciences and Engineering]: Archaeology

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1 Introduction

Algorithms for lighting simulation have continued to improve in recent years. Lighting design, however, remains a big problem. An application where good lighting design is important is technical illustration. The example of a human skull shown at the top of Figure 1 is from the Guild Handbook on Scientific Illustration [Hodges 1989]. The illustration on the right does a better job of depicting the form and important features of the skull than the photograph on the left. One reason for its effectiveness is its careful use of lighting.



Figure 1: Above: A photograph of a human skull, followed by an artist's handmade drawing of the same skull [Hodges 1989]. Arrows in the drawing indicate variance in the local lighting direction that the artist used to emphasize the shape and texture of the skull. Below: A photograph of a baboon skull, followed by a composite image we generated from a set of many photographs taken under different lighting directions. (Top row images are used by permission of John Wiley & Sons, Inc.)

Lighting can be used to convey:

- Orientation: On smooth portions of a curved surface, directional light is used to create diffuse shading, which helps viewers estimate the local orientation of the surface and differentiate between convex and concave parts of the shape.
- Curvature: Regions with high curvature or edge discontinuities are often emphasized with highlights. Photographers depict metallic objects using linear lights, aligning highlights with directions of zero curvature.
- Bumps and texture: Small-scale surface features are much easier to detect under side or raking lighting. Shadows cast by these features create regions of high contrast and reveal texture. The best landscape photographs are often taken at dawn or dusk; the best views of the moon's craters occur along its terminator [Koenderink and Pont 2002].
- Silhouettes: The silhouette of an object is one of its most distinctive features. Rim lighting is often used along the edge of an object to distinguish it from a dark background. Rim shadowing serves the same purpose against a light background.

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Since conveying shape and form is a primary goal of illustration, illustrators are generally not concerned with physically accurate lighting. In fact, to a photographer or illustrator, real-world lighting often has unintended side effects:

- **Over- and under-exposure**: A well-lit photograph has uniform exposure and good contrast. Achieving both of these goals is difficult in practice, particularly in natural environments that exhibit a high dynamic range.
- **Shadows**: While they provide useful cues of relative position, shadows often hide important details. Moreover, their umbral and penumbral boundaries can be distracting. The illustration of the human skull in Figure 1 has fewer shadows than the photograph.
- Distracting highlights: Shiny objects often have distracting highlights in confusing positions. For example, anthropologists have reported great difficulty in photographing obsidian tools because of their high specularity [Rick and White 1975].

Any photographer or illustrator knows that lighting design is a hard problem. The lights are carefully controlled in a photographer's studio or on a motion picture set. Photographers often think of lights in terms of their effects or purposes (e.g. key light, rim light, etc.). In Figure 1, the arrows in the human skull diagram on the right indicate how the illustrator used lighting to emphasize the important aspects of the skull. Diagrams like this are often used to teach illustrators and photographers how to use lighting effectively.

In this paper, we describe a simple interactive tool to produce technical illustrations from a collection of photographs of an object, each taken under a different lighting environment. These photographs are combined using spatially-varying light mattes to determine the final lighting for different regions of the composite. The interface provides a convenient set of tools that allow an artist to combine photographs to create high quality illustrations like that of the human skull shown in Figure 1. It should be noted that our goal is not physical accuracy, even though our composite images often appear realistic. As with many scientific illustration techniques, we sacrifice physical accuracy in order to effectively convey the shape and features of an object.

We have been working with anthropologists who often need to produce well-lit depictions of artifacts for publication. Currently, this involves one of two labor-intensive processes: either solving the difficult traditional lighting-design problem for photography, or producing handmade illustrations. Our system allows users to quickly produce photographic illustrations with far less effort or artistic skill.

2 Related Work

The goals and techniques of cinematic lighting design are discussed in detail in books on photography [Adams 1999; London and Upton 1997], film [Alton 1995] and stage lighting [Millerson 1991]. Calahan [2000] has summarized this classic work and practice in the context of computer-generated imagery. In contrast, functional lighting design has different goals, such as the minimization of glare or the even lighting of a work surface [Kaufman and Christensen 1984]. In this paper, we concentrate on using lighting design for technical illustration and draw upon illustration manuals such as the Guild Handbook discussed in the introduction [Hodges 1989].

In computer graphics, lighting design tools are often based on inverse lighting algorithms. For example, it is possible to compute the intensities of light sources based on photographs of an object [Yu et al. 1999; Ramamoorthi and Hanrahan 2001]. Alternatively, a user can paint the desired lighting qualities, and algorithms exist to solve for the properties of a uniform area light source in a diffuse environment [Schoeneman et al. 1993; Kawai et al. 1993]. Techniques are also available for controlling the position of lights by direct manipulation of shadows [Poulin and Fournier 1992; Pellacini et al. 2002] and highlights [Poulin and Fournier 1992].

One of the most important insights in relighting algorithms is that light transport is linear. The image of a scene illuminated with multiple sources may be computed by summing the images of the scene illuminated by each single source. Lighting design by digitally compositing multiple light images is a simple technique for adjusting light intensities and controlling the relative amount of diffuse and specular lighting. A variation that works for environment maps is to project the lighting onto a different basis, such as spherical harmonics [Nimeroff et al. 1994; Dobashi et al. 1995; Teo et al. 1997; Sloan et al. 2002], or to compute the Principal Component Analysis of the collection of images to form eigenlight images. Epstein et al. [1995] and Ramamoorthi [2002] have shown empirically that usually only a few images are needed to approximate any desired lighting. In all these linear techniques, the light images are combined using a single weight per image; in this paper, we use spatially-varying weights.

An important motivation for our approach is new technology for rapidly collecting a large number of images under different illumination conditions. This has been done using a robotically controlled light source [Debevec et al. 2000], a set of electronically controlled flashes at selected points on a sphere [Georghiades et al. 2001; Debevec et al. 2002; Malzbender et al. 2001], or a set of handheld light sources [Masselus et al. 2002]. The goal of these previous capture systems has been to collect a set of images so that objects can be relit in real time [Malzbender et al. 2001] or using illumination from a natural environment [Debevec et al. 2000; Hawkins et al. 2001; Debevec et al. 2002].

Finally, there are several recent papers that develop nonphotorealistic (NPR) lighting models for illustration. Gooch et al. [1998] describe a cool-to-warm shading model to produce pictures in the style of technical illustration. Sloan et al. [2001] introduced the idea of the LIT sphere, an idealized environment map that produces simple, effective lighting effects. Hamel [2000] introduced a component-based lighting model that is based on ideas in the Guild Handbook. (See Strothotte and Schlechtweg [2002] for a nice discussion of this model.) Anderson and Levoy [2002] have also used NPR lighting effects to illustrate unwrapped 3D scans of cuneiform tablets. Our approach is the first to produce NPR lighting effects with linear basis images combined using spatially-varying weights.

3 Relighting for Illustration

This section describes our image composition technique and a novel user interface that can be used to easily create illustrations that effectively convey the shape and features of an object.

3.1 Spatially Varying Lighting

Our system takes a set of photographs as input and produces a single composite image as output. The input images consist of photographs taken from the same point of view but with differing incident lighting directions. We associate each source photograph s_i with a matte image w_i that modulates its contribution to the final composite image at each pixel p(x, y). The *n* weighted source images are then added together to produce the final composite. To ensure that the composite photograph has the same average brightness as the input images, we require that the weights at each pixel sum to one. For each pixel p(x, y) in the composite image:

$$p(x,y) = \sum_{i=1}^{n} w_i(x,y) s_i(x,y), \quad and \quad \sum_{i=1}^{n} w_i(x,y) = 1$$
(1)



Figure 2: Three sample photographs of a baboon skull cast taken under different lighting conditions, shown above their corresponding mattes. The composite image is shown on the right. Arrows indicate local variation in the lighting direction across the resulting composite.

After changing one of the weights $w_k(x,y)$ to $w_k'(x,y)$, we can renormalize the sum by multiplying each of the n-1 remaining weights for that pixel by a single coefficient. Since the weights sum to one before the adjustment, we can perform this calculation incrementally by deriving this coefficient in terms of the old and new weights of the k'^h image:

$$w_i'(x,y) = \left(\frac{1 - w_k'(x,y)}{1 - w_k(x,y)}\right) w_i(x,y) \quad \forall i \neq k$$
(2)

We clamp w_k' to a value slightly less than one to preserve the relative proportions of the other weights for that pixel. This also precludes the possibility of division by zero in Equation 2.

Figure 2 illustrates the application of spatially-varying mattes to produce a composite photograph of a baboon skull cast.

3.2 An Interactive Application

Since our input data typically consist of hundreds of photographs, creating composite photographs with them can be difficult using existing image manipulation tools. The challenges include navigating this large set of input images as well as updating and rendering the composite at interactive rates. To address these concerns, we have developed an interactive application designed to make it easier to produce effective technical illustrations using our technique. Figure 3 shows a labeled screen shot of our interface. Please see the included video footage for some examples of its use.

3.2.1 Painting Interface

Our interface is built on a familiar painting paradigm, in which the artist uses a virtual airbrush to paint directly into the matte images associated with each photograph. The airbrush has several attributes: light direction, brush size, and brush weight. A trackball interface gives the artist the ability to choose any lighting direction on the sphere. Each direction selects a single original photograph, which is displayed to the side of the composite image. The brush affects the matte for the currently selected photograph, implicitly modifying all other non-zero mattes when the weights are renormalized. A gaussian falloff function is used to smoothly decrease the weight contributions across the width of the brush. A large brush size gives the artist the ability to make sweeping changes to the composite photograph, while a small brush size allows for small, sharp changes (e.g. applying rim lighting around the silhouette of the object or removing small shadows or highlights that obscure important details.) Finally, the weight of the brush controls the rate at which virtual paint is deposited on the canvas.

3.2.2 Interpolating the Light Direction

Since the lighting direction is an attribute of the brush, painting can become tedious when the artist wants to change the light direction smoothly across the composite. To address this, we provide a mode in which it is possible to place 3D arrows directly onto the composite image, forming a vector field of lighting directions. When the user applies a brush to the canvas in this mode, the lighting directions are interpolated across the extent of the brush according to the vector field. The interpolated light direction at a pixel is computed by taking an average of all the vectors weighted by the inverse square of their distance to that pixel. Figure 5 illustrates the use of this tool to create an illustration of the moon's surface.

3.2.3 Environment Maps

As the mouse cursor is moved across the composite, the system displays the environment map for the pixel currently under the cursor. This map is displayed as a point rendering of a sphere, in which each point is color coded according to the amount of light coming from that direction. This is helpful in two ways: (1) it indicates which input photographs contribute to the composite at any given pixel so that their corresponding mattes can be found quickly for editing, and (2) it gives a physical depiction of the lighting environment (as a set of point lights) for each region of the composite to help the user create desired local lighting effects.

3.3 Implementation

The main challenge in the implementation of our system is processing the large number of input images that we use (typically hundreds). To enable the manipulation of the composites at an interactive rate, we make heavy use of graphics hardware acceleration. Each source image and matte is stored as a texture on the graphics card and is loaded only when the matte contains non-zero entries. Image composition is accomplished by modulating each source image with its associated matte using multi-texturing and then combining the weighted slices using additive blending. This implementation allows rendering to proceed in real time on consumer graphics hardware.

Storing the matte textures separately from the source images (rather than as an alpha channel) allows us to represent the mattes at lower resolutions. Experimentation indicates that the mattes can be represented at about $\frac{1}{4}$ the resolution of the photographs without introducing artifacts in the composites. This greatly reduces the time required to update the mattes as the artist paints.



Figure 3: Our interactive painting system consists of two separate components: a composite window (left) and a controls window (right). The artist manipulates the light direction in the controls window to select a source photograph from the input dataset. The matte image corresponding to this source photograph is shown in the upper right. Using the brush, the artist then paints features from the currently selected source photograph into the composite. The matte image is updated during painting to reflect changes. As the mouse cursor is moved across the composite, the environment map changes to show the lighting distribution for the pixel under the cursor.

4 Results

We used the following three datasets to test our illustration system:

- 1. **Baboon Skull Cast**: Photographs of a cast of a male baboon skull with detailed texture and an intricate shape.
- 2. **Robotic Assembly**: Photographs of a small metallic object with anisotropic reflection.
- 3. **The Moon**: Twelve photographs of the moon taken at different phases of the lunar cycle.

To collect the skull and robotic assembly data, we used an automated light stage to acquire a set of images from a single viewpoint and under varying lighting directions. We sampled the sphere of lighting directions at 36 equal intervals in ϕ and 19 unequal intervals in θ . Sampling in latitude was done in equal intervals of $cos(\theta)$ to sample the radiance uniformly.

The baboon skull (Figure 1) presents a significant lighting challenge to a photographer with its complex, self-shadowing shape and intricate surface texture. Good photographs of such objects are so hard to produce that anthropologists often resort to time-consuming handmade drawings in lieu of photographs. The baboon skull composite generated by our system has many features in common with the handmade human skull illustration, as enumerated in Figure 4.

The moon example illustrates an application of our system to a dataset acquired outside of a controlled lighting lab. The moon was photographed on twelve consecutive nights during the waxing portion of its cycle. The inclination and elliptical shape of the moon's orbit give it a slight apparent wobble that causes its surface features to drift out of alignment over the course of the lunar cycle. We corrected this misalignment by projecting the photographs of the moon onto a sphere, which we then rotated to compensate for the wobble. In each photograph, detail of the lunar terrain is most visible along its terminator, the area where the sun's light strikes the surface detail over the entire area of the moon's disk was well-suited to the light direction interpolation feature of our system (Figure 5).

The robotic assembly (Figure 6) poses a different set of challenges to our system, largely due to its highly specular metallic



Figure 4: Results from applying our method to photographs of a baboon skull cast. Note the use of tangential lighting to emphasize foramina (nerve channels) along the nose (1), removal of shadows from the eye socket (2), shadow placement to emphasize the zygomatic arch (3), plateau lighting in large flat areas (4), darker shading to emphasize areas of high curvature (5), use of rim shadowing along the lower jaw (6), and the placement of a small shadow behind the left canine tooth to emphasize its size (7).



Figure 5: Above: Twelve photographs of the moon taken on consecutive nights during the waxing portion of the lunar cycle. Below, from left to right: a) An unmodified photograph of a full moon. b) A set of control arrows used to define a field of incident lighting directions that lie tangent to the moon's surface across its breadth. c) The resulting composite photograph, which combines surface detail from the terminator zones of each of the input photographs. The disk's flat appearance results from the loss of large scale shading variation during composition. Source moon photographs (©2002-2003 Tom Talbott (http://www.blarg.net/~thomast/).



Figure 6: Above: Three example images of a robotic assembly taken under three different lighting directions (indicated by arrows). Below: An image composite produced with our system. The colored arrows indicate the predominant lighting direction used in selected regions of the composite. The first two were used to add highlights to the cylindrical base, while the third was used to reveal the brushed texture of a flat surface. Not all photographs contributing to the composite are shown.

appearance. The assembly's specular surface presents a problem with dynamic range; no single exposure setting can capture all of its important features. To solve this problem, we supplemented our data set by taking photographs at two different exposures. Longer exposures revealed darker regions of the object, while shorter exposures avoided oversaturation in regions with bright specular highlights. We painted with photographs from both exposure sets when creating the composite, using the interface to alternate between exposures as needed. We also used highlights from both exposure sets to create alternating bands of light and dark oriented along lines of zero curvature. Such bands have traditionally been used by illustrators to identify objects as metallic and to indicate their shape, since they mimic real-world anisotropic reflection effects [Gooch et al. 1998].

5 Discussion

Our goal has been to develop techniques that make it easy to create illustrations of complex objects that effectively communicate their shape and texture using common lighting design techniques. We have presented an interactive tool that allows a user to relight objects by compositing a large number of photographs taken under different lighting conditions. Our illustration system is the first of its kind to suggest the idea of spatially varying the lighting across an image.

While it is theoretically possible to produce images like ours with traditional image compositing tools, it is infeasible in practice. Several of our features address this infeasibility and distinguish our application from compositing tools available in systems like Adobe[®] Photoshop[®]:

- **Image navigation**: There are hundreds of source images in our skull and robotic assembly data sets; we provide the ability to use lighting direction to navigate them quickly.
- Painting many mattes simultaneously: The interpolating brush (Sec. 3.2.2) allows one to adjust several of the mattes at once and maintain smooth transitions in the composite between areas drawn from different input images. We used this feature heavily in the moon example.
- **Renormalization**: To avoid oversaturation when using so many additive blending operations, we enforce a normalization constraint across all the mattes for each pixel.
- Efficiency: In order to provide real-time feedback to the user during painting, we take advantage of graphics hardware acceleration to perform the compositing operations quickly.

Our interface makes it possible to produce image composites with little time or effort. The skull and robotic assembly composites each took about 10 minutes to produce, and the moon about 45 minutes. In all three cases, the "artist" was a CS graduate student without any experience in art or illustration. Indeed, much of our enthusiasm for this technique stems from the ease with which we obtained our results without possessing particular artistic skill.

We think this approach to photographic illustration is promising and suggests many directions for future work. While we suspect that artists will always play some role in the illustration process, we believe that parts of this process can be automated. Burt and Kolczynski [1993] have developed image fusion operators that combine different images (for example, different exposures) to form a composite. Their methods could be applied to the problem of combining images under different illuminations. We could also provide higher-level interaction tools (e.g. a contrast brush) to make the artist's job easier.

Finally, it is becoming easy to collect a set of images using a "smart" camera. Can cameras be programmed to always collect a useful set of images? What is that useful set? And, can general interactive tools be built for processing those image sets?

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