Capturing Relightable Images using Computer Monitors

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Abstract

Image based relighting techniques are a popular choice for generating photo-realistic images of objects under any lighting condition. A typical process for creating such a model involves photographing the object lit from different directions using a hemispherical lighting array. While generating high-quality results, this requires a customized hardware construction that puts the technology beyond average consumer reach. We investigate the use of monitor illumination as a light source for capturing relightable models, and show that comparable accuracy can be achieved using commodity hardware. In addition, monitors allow increased flexibility in terms of adaptive sampling of light positions. We also present a method of correcting extrapolation artifacts by augmenting hemispherical harmonics with a low order model when reconstructing novel lighting conditions outside the originally sampled region.

1. Introduction

Image based relighting techniques allow the creation of photo-realistic images of objects under any lighting condition, and their applications range from inserting a character into a new environment in a movie to digitizing an interesting archaeological artifact in a museum. A typical process for creating such a relightable model involves photographing the object lit from different directions using a hemispherical lighting array. A custom built dome with lights for this purpose can cost upwards of thousands of dollars. While this is of little issue for a commercial purpose, a small museum or a hobbyist would think twice before making an initial investment for hardware based on a relatively new technology. This remains an entry barrier which prohibits widespread adoption of image based relighting in general.

We investigate the use of monitor illumination as the light source for capturing relightable models, and show that comparable results can be achieved using a normal computer monitor. We present two capture configurations for image acquisition, using a digital camera next to a single monitor or between a pair of monitors. We also discuss the trade-offs involved in using the monitor for illumination and how they can be alleviated.

It is useful to begin by reviewing the steps involved in constructing a relightable model. The first step, as already mentioned, is taking a number of photographs of an object, with each lit by light coming from a different angle. This gives us a stack of observed intensities under different lighting for each pixel. The goal is to reconstruct an image of the object under any novel lighting condition, which means we have to estimate the intensity of each pixel under that lighting. If the sampling is dense enough, we can directly interpolate between adjacent samples to see what the object would look like under light coming from a new direction. The more common approach, requiring far fewer samples, is to fit a reflectance model to the full set of measurements at a pixel. Past research has looked at a number of suitable reflectance models, including but not limited to Polynomial Texture Maps [12], Wavelets[21], Spherical harmonics [17] and Hemispherical harmonics [9]. Once a model is fit, any novel lighting condition can be smoothly interpolated.

How to extrapolate accurately from a given set of samples to a lighting angle outside the measured samples is less well understood. This must be addressed when using a small monitor as a lighting device with only a limited span of incident lighting directions. We propose an extrapolation method where the measured samples are augmented with synthetic images rendered under a simple lambertian reflectance model. This allows a smooth extrapolation into the region outside the originally sampled lighting directions. We also show that by using the flexibility provided by monitor based illumination, we can incrementally acquire additional samples as needed based on the residual error of reconstruction. This leads to an adaptive acquisition approach based on the object complexity which reduces total capture time.

The main contributions of this research are:

1. A comparison of relightable image capture using a conventional lighting dome and a monitor as the source illuminant.

2. An extrapolation technique that mitigates the limited

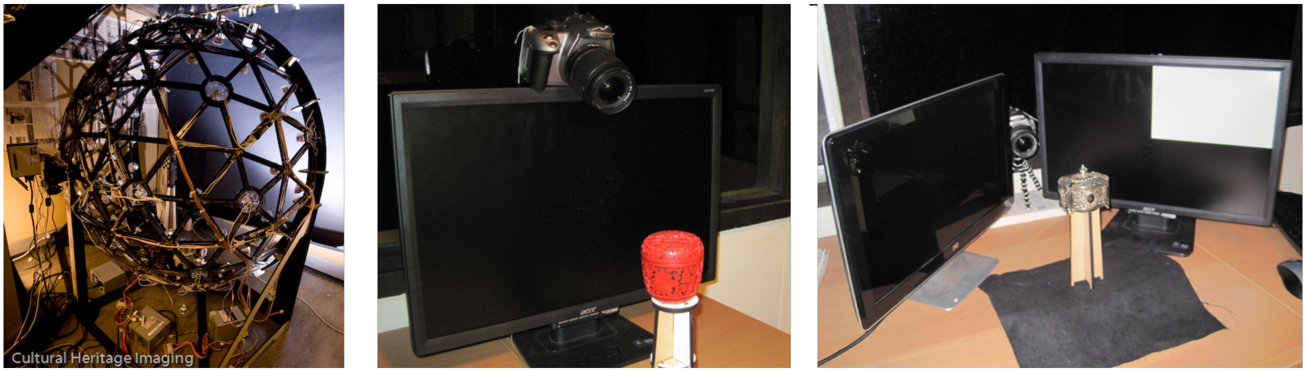


Figure 1. Left to Right : (a) A custom built lighting dome (b) Single monitor capture setup (c) Dual monitor capture setup. *Dome image courtesy of Cultural Heritage Imaging*

angular span of measured lighting directions.

2. Related Work

Lighting Hardware : Acquiring and generating relightable models of real world objects has been a topic of interest in computer graphics and vision for some time. The early work, including Acquiring Reflectance of a Human Face and Polynomial Texture Maps, relied on custom-constructed hemispheric domes with many lights that could be controlled individually [4] [12]. This kind of apparatus has proved very effective and remained the most popular way to capture relighting datasets over the years, being custom made for that purpose. Unfortunately, even the simplest such rigs cost several thousand dollars or more, placing them out of the market for a casual user. Research into Bidirectional Reflectance Distribution Functions (BRDFs) often makes use of even more sophisticated acquisition hardware, including a mechanical arm that repositions the light [14].

Monitors have been used as illumination sources for matting ([24], [2], [13]) and relighting ([15], [23], [18]). Our work focuses on comparing the results obtained using monitor illumination to a conventional lighting dome. In the work by Schechner et al. [19] a planar pattern of lit-pixel segments is projected on to a white wall to generate a multitude of incident lighting angles. Their focus was on using multiplexed light patterns during capture. A projected image covers a much larger angular span than a typical computer monitor which is restricted to a limited set of incident lighting angles. We propose an extrapolation correction technique which allows monitors to be used as illuminants.

Computer monitors have been used as light sources for carrying out photometric stereo [20] [8]. Clarke presents a formula to approximate a distant point light source with a nearby planar patch, which we use in our work [3].

Extrapolation with limited samples : Since most capture scenarios involve fully sampling the hemisphere of lighting directions, most research has focused on interpolation and not extrapolation. Ghosh considers BRDF extrapolation when transforming samples from a zonal basis to a spherical harmonic basis for the purpose of extrapolation [10]. Since the BRDF is sampled from multiple directions and multiple viewpoints in their examples, the spherical harmonics provides a suitable low order basis for extrapolation. However, given the range of our samples, even a low order spherical harmonics fit will not provide accurate extrapolation results (as shown in Figure 8) , and the physically constrained Lambertian reflectance model performs better. Similarly a general spherical harmonics extrapolation method is unsuited to our application since it works well only when the region of missing samples is small [16].

Dealing with limited samples has been studied in a variety of other ways. Prior work has analyzed the number of samples needed for relighting [7] [5] [1]. Hertzman does not fully sample each pixel, and instead represents scene pixels using a linear combination of basis BRDFs [11]. Adaptive capture techniques and compressive sensing have been used to capture highly detailed reflectance models [6] [15] [22]. The simple adaptive sampling method in this paper is only meant to demonstrate the feasibility of using these more sophisticated methods with a monitor.

3. Background

The typical relighting capture setup consists of a hemisphere (or in certain cases a full sphere) of lights placed around the object of interest with the camera pointing at the object which is at the center of the hemisphere (figure 1a). Each light is lit in turn and an image is taken under that illumination. Once the stack of images under different lighting conditions has been captured, a variety of means can be used to reconstruct the scene under a novel virtual lighting condition. One way to interpolate lighting is to fit a parametric function, such as a Polynomial Texture Map, Spherical Harmonic, or Wavelet representation, to the pixel-wise reflection data.

We fit a Hemispherical Harmonics (HSH) model independently to each pixel in the image. Hemispherical Harmonics are a set of orthonormal basis functions defined over a hemisphere, and are derived from Spherical Harmonics. The intensity of a pixel lit under incident light from direction (θ, ϕ) can be calculated as follows,

$$f(\theta, \phi) = \sum_{l=0}^{n} \sum_{m=-l}^{l} c_l^m H_l^m(\theta, \phi) \quad (1)$$

where $H_l^m(\theta, \phi)$ is the Hemispherical harmonics basis function as presented in [9] , n is the *order* of the hemispherical harmonic and c_l^m is a per pixel scene dependent weighting coefficient. To render a scene under novel lighting we must compute these hemispherical harmonic coefficients.

We can expand equation (1) and express it in matrix form as follows,

$$f(\theta, \phi) = \vec{H} \cdot \vec{c}$$

where $\vec{H} = [H_1^1(\theta, \phi), H_1^2(\theta, \phi), \ldots, H_n^n(\theta, \phi)]$ and $\vec{c} = [c_1^1, c_1^2, \ldots, c_n^n]^T$. If a single lighting direction (θ, ϕ) is indexed by i, this can be rewritten as,

$$f_i = \vec{H}_i \cdot \vec{c}$$

By stacking up measured samples of m different lighting directions, we can now define vector $\vec{f} = [f_1, f_2, \ldots, f_m]^T$ and matrix $\mathbf{H} = [\vec{H}_1, \vec{H}_2, \ldots, \vec{H}_m]^T$. Using these the following linear equation can be solved to obtain values of the hemispherical harmonic coefficients $\vec{c}$.

$$\mathbf{H}\vec{c} = \vec{f} \quad (2)$$

And the computed coefficients can be used with equation (1) to compute the pixel intensity under any novel lighting direction.

Note that the number of coefficients is based on the order of the HSH model (*# of coeffs.*$= (order + 1)^2$), and allows the flexibility to represent a reflectance function with a varying degree of complexity. This makes it more appropriate for our purposes than an analytical model because we can select the order depending on the type of object that is being photographed, as we will explore in section 4.3.

4. Monitor-based Acquisition

Monitors are much more flexible illumination sources than special purpose domes with fixed point lights. However monitors are not as bright, and they subtend a limited angular range. In this section we discuss our implementation, and give two brief examples of the advantages available by using a monitor. First, using low frequency area lighting, rather than point lighting reduces aliasing due to high frequency illumination effects. Second, adaptive sampling allows the number of lighting samples to be tuned to the complexity of the object being captured. We conclude this section with a comparison of accuracy between dome and monitor acquisition, showing that monitor capture can produce results comparable to those obtained using a traditional dome device.

Figure 2. A subset of the rectangular patch patterns displayed on the monitor

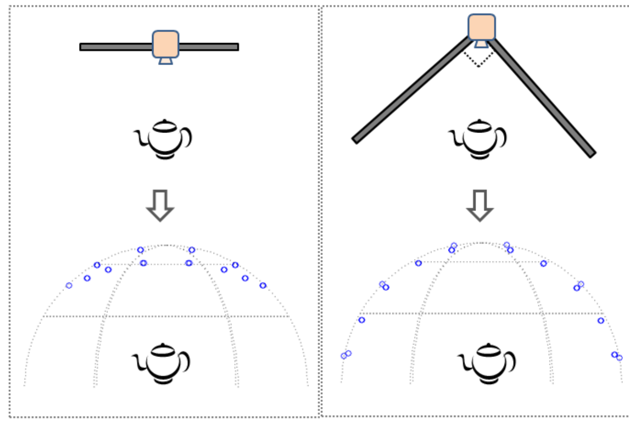


Figure 3. A cross-sectional illustration of the capture setup. *Left :* Single monitor setup showing the placement of the monitor, camera and the object(top), and the calculated directional lights relative to the object(bottom) *Right :* The Dual monitor capture setup with similar details

4.1. Implementation

Our capture system uses a single monitor (figure 1b) or a dual monitor setup (figure 1c). A sequence of white rectangular patchs are displayed on the monitor (figure 2), and the object is photographed under each illumination condition. The configuration of the capture setup showing the monitors, the camera and the object is illustrated in figure 3(top).

Since the illuminated surface patch is a near area light source, the directional lighting equivalent needs to be estimated. We use Clark's method to approximate a distant point light source given the coordinates of an illuminated patch and the distance to the object from the monitor (Figure 3) [3]. In addition to providing an equivalent illumination direction over the hemisphere, this also provides a relative brightness calibration for each illuminated patch on the monitor.

Since the luminance output of a patch on the monitor is lower than a typical illuminant (flash / halogen lamp) that would be used in a custom lighting rig, we use a longer exposure time (0.8s) and a dark environment for image ac-

Figure 4. Comparison of reconstructed images from capture under point light sources (left) and area light sources (right). Notice the cross-blended shadow near the tail of the cat

quisition.

We use both a single monitor setup and a dual monitor setup with 22" LCD displays. Most objects shown in this paper were photographed using a Canon Rebel XT DSLR camera. White balance correcting was done using a gray card.

To demonstrate the lowered barrier to entry and ease of capture enabled by using monitors as illuminants for relightable image capture, we also built an acquisition system implemented as a web application (using flash and PHP) which displays lighting patterns on the screen and captures images via a webcam. A user need only visit a web page to capture a relightable image from their desktop or laptop.

4.2. Point vs Area Light Sources

Point light sources are a high frequency lighting environment which induces high frequency shadow and specularity effects in sampled images. Since we take a limited number of lighting samples, proper signal processing would have us low-pass filter the lighting environment before sampling it. This can be approximating using area light sources.

Nearly all domes make use of lights with limited area, usually a small bulb. In contrast, illuminating patches on a monitor provides area light sources. Since the monitor illumination is easily changed, the light area can be easily adapted to match the sampling frequency. Practically speaking, point lights can produce a crossblending effect in reconstructed images, rather than the appearance of smooth lighting. Figure 4 illustrates this issue. The left image, which was reconstructed from a capture under a dome of lights, shows cross-blending near shadow areas (inset). On the right side, where the images were captured under area light sources (a monitor), the cross-blending artifacts are absent.

4.3. Scene Dependent Adaptive Capture

Not all objects require the same number of lighting samples for accurate reconstruction. With a dome, it is difficult to arbitrarily add more physical lights if they are required for a particular object. Monitors provide the flexibility to adaptively change the number of samples, depending on the needs of the object.

Objects should be captured using the minimum number of samples needed for the reconstruction. This will reduce the capture time, and also allow the use of a less complex model (i.e. fewer terms on the polynomial). We carry out a real-time iterative capture process that fits a model, estimates the error, and decides whether more samples need to be captured. We can illuminate smaller patches on the monitor to acquire more samples. Our algorithm is simple and meant to demonstrate that a monitor allows adaptive capture.

The steps for the algorithm are as follows,

0. *Initialize* $n = 1$*, and the set of captured images to the empty set*

1. *Capture enough new images under new lighting conditions to fit a model of order* n*, and add them to the set of captured images*

2. *Do an* n*-th order Hemispherical Harmonics model fit to the set of captured images*

3. *Calculate reconstruction error (by comparing captured and reconstructed images)*

4. *If reconstruction error is larger than the threshold, a more detailed model is needed. Increase* n *and go to step 1*

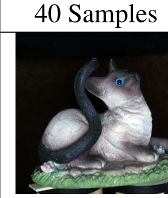
	20 Samples	RMSE	40 Samples	RMSE
White Cat		7.1		5.9
Silver Box		19.4		15.2

Figure 5. Adaptive capture results comparing reconstructions using different numbers of samples for objects with simple (i.e. white cat) and complex (i.e. silver box) reflectance. Note the high initial reconstruction error for the silver box and the relatively large reduction when extra images are added.

Figure 5 shows two examples of objects with different degrees of complexity and their acquisition result using the adaptive method. The reconstruction error used is the pixel-wise RMSE which compares the captured images and reconstructed images under given lighting conditions. A mostly matte object (white cat) can be represented with a lower-order HSH and requires fewer lighting samples to be captured. The reconstruction error is relatively small even after fitting a first order HSH (4 coefficients). Given such a low reconstruction error, the adaptive algorithm would have terminated the capture. Adding additional lighting samples does not change the detail of object nor reduce the reconstruction error significantly. On the other hand, with a complex object (silver box), the lower order fit results in a large reconstruction error. Once we acquire more images and carry out a higher order fit, we can see a decrease in the reconstruction error. Additionally the reconstruction shows more high-frequency lighting detail visually.

4.4. Comparison of Relighting Results

In order to verify that high accuracy capture is possible using a monitor, we compared directly against a dome. The dome had 24 incendiary flash lights and used a Canon 20D DSLR camera. The monitor based capture used 24 rectangular patches, matching the number of captured samples on the dome. White balance correcting was done using a gray card.

Figure 6 shows side-by-side comparisons for 4 objects captured using a lighting dome and the monitor. In each dataset, the reconstructions are lit from the same incident lighting angle for visual comparison. Reconstruction errors were calculated for each approach using a test set of sampled images that were not included in the model fitting. Since the test images were sampled within the limits of the measurements span, these reconstruction errors represent interpolation errors in both cases.

The reconstruction errors were observed to be less than a dome based setup in all the cases. We hypothesize that the reduced error comes from using area lights as well as sampling lights only over the reduced angular range of the monitor. This leads to a better approximation via HSH in the interpolated regions. Finally, as we can observe from the rendered images, both the acquisitions produce similar perceptual results.

5. Extrapolation Using Analytical Models

An obvious disadvantage of a typical monitor is that the small and flat display area leaves us with a limited span of incident lighting angles compared to a hemispherical dome. While this can be overcome using a dual monitor capture setup as presented in figure 1c, in this section we present an extrapolation technique which can be used to generate novel views outside of the sampled incident lighting angles.

We would like to be able to reconstruct the scene under any novel lighting condition over the entire upper hemisphere. However, measuring samples from only a limited span of angular lighting directions (Figure 7) constrains the domain over which we may accurately interpolate with a parametric function.

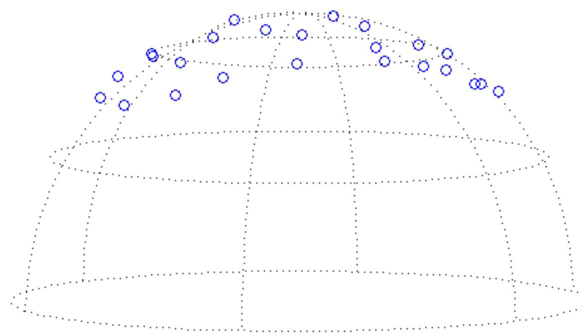


Figure 7. The range of angles covered by monitor illumination (indicated by the blue points)

Parametric functions such as hemispherical harmonics are not useful for relighting when extrapolating far beyond measured samples. If we fit an HSH model to a set of samples, and simply reconstruct an image under a novel lighting condition outside the sampled range, it often shows significant artifacts (Figure 8-top). On the other hand, analytical reflectance models, such as Lambertian, Phong or Ward, are less prone to such severe extrapolation artifacts, since they are constrained to a physical model. However, simply using an analytical model would result in the loss of detail captured by the higher order hemispherical harmonics model inside our sampling range. Our proposed method is a merging of the two models, effectively capturing detail where we have samples and falling back to the simpler analytical model in the extrapolated areas.

Given the measured samples $f(\theta, \phi)$, using equation (2) we can obtain the hemispherical harmonic coefficients $\vec{c}$. Photometric stereo can be used to calculate the surface normal N and albedo ρ. The relighting result can then be computed by blending equation (1) and the Lambertian reflectance model as follows.

$$I(\theta, \phi) = \alpha\rho N.L(\theta, \phi) + (1 - \alpha) \sum_{l=0}^{n} \sum_{m=-l}^{l} c_l^m H_l^m(\theta, \phi) \tag{3}$$

where α is a cross blending term linearly varying from $0..1$ when (θ, ϕ) moves outside the sampled region.

Figure 8 shows the rendered images with plain hemispherical harmonics and our extrapolation algorithm. In each case, the plots on the left show the computed intensity (in red, green and blue channels) for a *single* pixel in the scene under a light moving from left to right over the hemisphere. The measured samples are indicated by cross marks for each color channel. It is evident from the top plot that naive extrapolation of the hemispherical harmonic results in unpredictable behavior outside the measured data region, with all three channels being quickly saturated. The

	Dome	RMSE	Monitor	RMSE
White Cat		8.5		3.4
Elephant		7.9		5.0
Sea Shells (Dual Monitor)		11.5		9.9
Red Bowl (Dual Monitor)		10.1		7.9

Figure 6. Comparison of Dome and Monitor based capture results

bottom row of images shows the results of using the extrapolation algorithm. As can be observed by the plots all the color channels behave reasonably and gradually get less bright as the light moves to a grazing angle.

To compare the effectiveness of extrapolated models against real data, we first collected input images using a lighting rig with 90 lights spanning the full hemisphere. Then we selected the inner set of lights falling within 45 degrees of angle from the zenith, similar to the span of incident illumination from a single monitor setup. Different reflectance models were fit to this limited span of lights, and relit images reconstructed under lighting angles from $0°$ (zenith) to $90°$ (horizontal plane).

Figure 9 shows the RMSE of reconstructed results compared to the ground truth. Since the range of input samples span ≈ 45 degrees from the zenith, the reconstruction error up to that point represents interpolation errors. Similarly reconstruction errors for lighting angles > 45 repre-

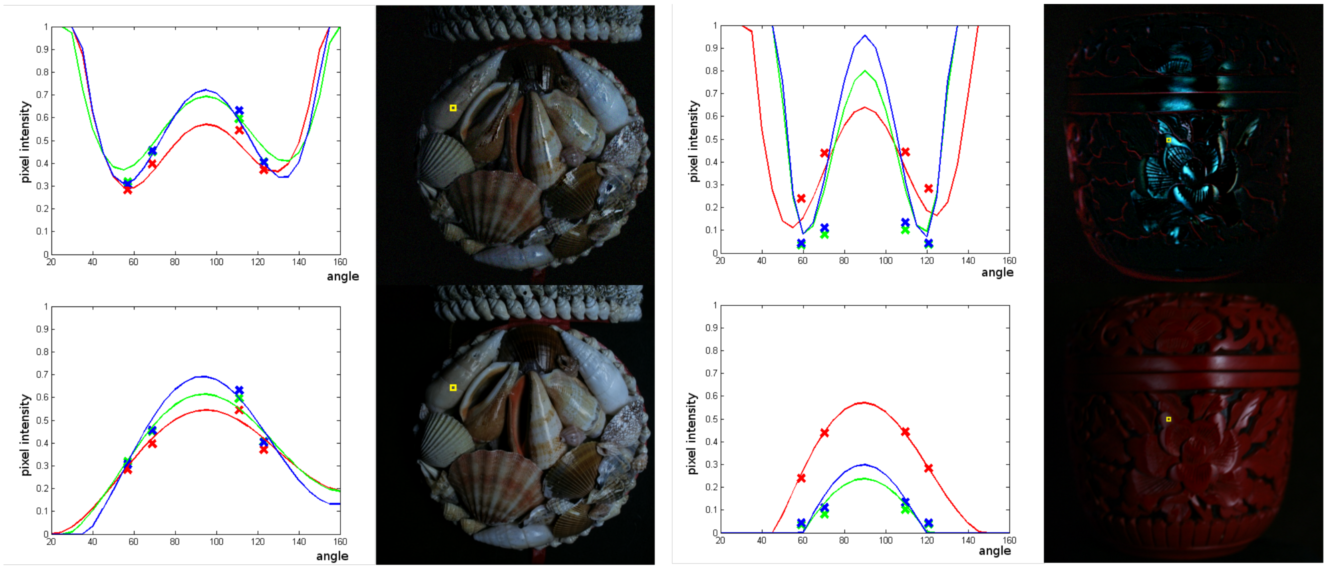


Figure 8. Two examples comparing reconstructed images with (bottom row) and without (top row) extrapolation correction. The plots on the left show the intensity variation for R,G,B channels of a single pixel (indicated in yellow) under the changing lighting directions from left to right over the hemisphere

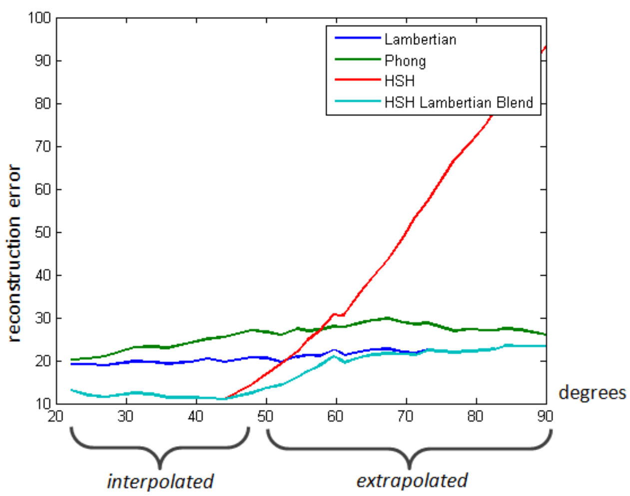


Figure 9. Plot showing reconstruction error vs angle of lighting from zenith for different reflectance models. When interpolating between measured samples, the HSH model has significantly lower error than the analytic Lambertian or Phong models. When extrapolating beyond the sampled region, the Lambertian model performs best. We use a linear blend between these two models, using the more-detailed HSH model while interpolating and smoothly shifting to the Lambertian model when extrapolating.

sents extrapolation errors. In the interpolated region (indicated in the plot), we can see that the plain Hemispherical Harmonics model performs best. However it immediately breaks down upon extrapolation. Phong and Lambertian models perform reasonably well even under extrapolation. Our method generates lower reconstruction error upon extrapolation than the other methods, and in the case of extreme extrapolation performs no worse than the Lambertian model.

We chose a simple Lambertian model instead of a more complex analytical model such as Phong or Ward since given the sparseness of our input samples, a non-linear solve with a high number of unknown parameters may result in a noisy fit. For example in figure 9 even for interpolation, Phong fares worse than Lambertian in most cases. With dense, complete samples theoretically a more complex model would be a better choice, but the limited and sparse sampling that we have does not make a complex analytical model suitable for extrapolation.

Combining a parametric HSH model with an analytic Lambertian model provides the benefits of both models.

6. Conclusion

In this paper, we demonstrated the capture of relightable images using regular monitors as illuminants. We have shown that the results are comparable in quality to an expensive, custom-built lighting rig while providing additional flexibility. We also demonstrate a reduction in high frequency lighting artifacts, and that adaptive capture can determine the appropriate number of lighting samples to capture for a given object. We addressed the main limitation of monitor based capture by presenting a simple but effective extrapolation method that can be used in re-rendering images from directions outside the sampled lighting set.

References

[1] P. N. Belhumeur and D. J. Kriegmant. What is the set of images of an object under all possible lighting conditions. *IEEE Computer Vision and Pattern Recognition (CVPR)*, pages 270–277, 1996. 2

[2] Y.-Y. Chuang, D. E. Zongker, J. Hindorff, B. Curless, D. H. Salesin, and R. Szeliski. Environment matting extensions: towards higher accuracy and real-time capture. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, SIGGRAPH '00, pages 121–130, New York, NY, USA, 2000. ACM Press/Addison-Wesley Publishing Co. 2

[3] J. J. Clark. Photometric stereo using LCD displays. *Image and Vision Computing*, 28(4):704 – 714, 2010. 2, 3

[4] P. Debevec, T. Hawkins, C. Tchou, H.-P. Duiker, W. Sarokin, and M. Sagar. Acquiring the reflectance field of a human face. In *SIGGRAPH*, 2000. 2

[5] P. Y. A. Epstein, R. Hallinan. 5±2 eigenimages suffice: an empirical investigation of low-dimensional lighting models. *Proceedings of the Workshop on Physics-Based Modeling in Computer Vision*, June 1995. 2

[6] M. Fuchs, V. Blanz, H. P. Lensch, and H.-P. Seidel. Adaptive sampling of reflectance fields. *ACM Transactions in Graphics*, 26, June 2007. 2

[7] M. Fuchs, H. P. A. Lensch, V. Blanz, and H. P. Seidel. Superresolution reflectance fields: Synthesizing images for intermediate light directions. *Comp. Graph. Forum*, 2007. 2

[8] N. Funk and Y.-H. Yang. Using a raster display for photometric stereo. In *Proceedings of the Fourth Canadian Conference on Computer and Robot Vision*, pages 201–207, 2007. 2

[9] P. Gautron, J. Křivánek, S. N. Pattanaik, and K. Bouatouch. A novel hemispherical basis for accurate and efficient rendering. In *Rendering Techniques*, pages 321–330, 2004. 1, 3

[10] A. Ghosh, S. Achutha, W. Heidrich, and M. O'Toole. BRDF acquisition with basis illumination. *IEEE International Conference on Computer Vision (ICCV)*, 0:1–8, 2007. 2

[11] A. Hertzmann and S. M. Seitz. Example-based photometric stereo: Shape reconstruction with general, varying BRDFs. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 2005. 2

[12] T. Malzbender, D. Gelb, and H. Wolters. Polynomial texture maps. In *SIGGRAPH*, 2001. 1, 2

[13] W. Matusik, H. Pfister, A. Ngan, P. Beardsley, R. Ziegler, and L. McMillan. Image-based 3D photography using opacity hulls. *ACM Trans. Graph.*, 2002. 2

[14] G. Müller, J. Meseth, M. Sattler, R. Sarlette, and R. Klein. Acquisition, synthesis and rendering of bidirectional texture functions. *Computer Graphics Forum*, 2005. 2

[15] P. Peers, D. K. Mahajan, B. Lamond, A. Ghosh, W. Matusik, R. Ramamoorthi, and P. Debevec. Compressive light transport sensing. *ACM Transactions in Graphics*, 28:3:1–3:18, February 2009. 2

[16] W. Z. R. A. Kennedy and T. D. Abhayapala. Spherical harmonic analysis and model-limited extrapolation on the sphere: Integral equation formulation. *The 2nd International Conference on Signal Processing and Communication Systems*, 2008. 2

[17] R. Ramamoorthi and P. Hanrahan. Frequency space environment map rendering. In *SIGGRAPH*, 2002. 1

[18] I. Sato, T. Okabe, Y. Sato, and K. Ikeuchi. Using extended light sources for modeling object appearance under varying illumination. In *Proceedings of the Tenth IEEE International Conference on Computer Vision (ICCV'05) Volume 1 - Volume 01*, ICCV '05, pages 325–332, Washington, DC, USA, 2005. IEEE Computer Society. 2

[19] Y. Y. Schechner, S. K. Nayar, and P. N. Belhumeur. Multiplexing for optimal lighting. *IEEE Transactions on Pattern Analysis and Machine Intelligence*. 2

[20] G. Schindler. Photometric stereo via computer screen lighting for real-time surface reconstruction. *International Symposium on 3D Data Processing, Visualization and Transmission (3DPVT)*, 2008. 2

[21] P. Schröder and W. Sweldens. Spherical wavelets: efficiently representing functions on the sphere. In *SIGGRAPH*, 1995. 1

[22] P. Sen and S. Darabi. Compressive Dual Photography. *Computer Graphics Forum*, 28(2):609 – 618, 2009. 2

[23] K. H. Shim and T. Chen. Efficient representation of lighting patterns for image-based relighting. In *Picture Coding Symposium 2004*. 2

[24] D. E. Zongker, D. M. Werner, B. Curless, and D. H. Salesin. Environment matting and compositing. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, SIGGRAPH '99, pages 205–214, New York, NY, USA, 1999. ACM Press/Addison-Wesley Publishing Co. 2