Densely Sampled Light Probe Sequences for Spatially Variant Image Based Lighting

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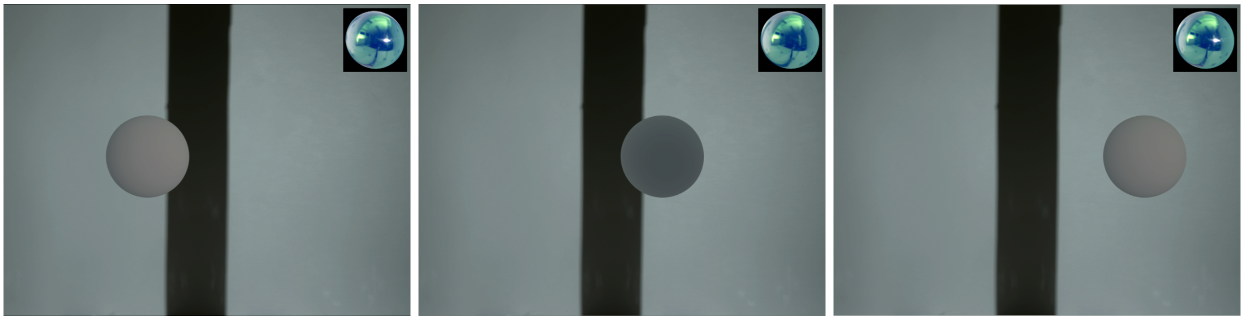

Figure 1: Three images from a rendered video sequence of 300 frames. The synthetic sphere is rendered as illuminated by real world lighting at many different positions, captured by a light probe HDR video sequence. The sphere is rendered in the traditional way using only one light probe for each frame.

Abstract

We present a novel technique for capturing spatially and temporally resolved light probe sequences, and using them for rendering. For this purpose we have designed and built a *Real Time Light Probe*; a catadioptric imaging system that can capture the full dynamic range of the lighting incident at each point in space at video frame rates, while being moved through a scene. The Real Time Light Probe uses a digital imaging system which we have programmed to capture high quality, photometrically accurate color images with a dynamic range of 10,000,000:1 at 25 frames per second.

By tracking the position and orientation of the light probe, it is possible to transform each light probe into a common frame of reference in world coordinates, and map each point in space along the path of motion to a particular frame in the light probe sequence. We demonstrate our technique by rendering synthetic objects illuminated by complex real world lighting, using both traditional image based lighting methods with temporally varying light probe illumination and an extension to handle spatially varying lighting conditions across large objects.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism; I.4.1 [Image Processing and Computer Vision]: Digitization and Image Capture;

Keywords: HDR, Video, Image Based Lighting

1 Introduction

It is well known that lighting is a key component in the process of rendering realistic imagery. This has led to the development of advanced methods for modeling and simulating the lighting in virtual scenes. However, it has proven difficult and time-consuming to realistically model the complex illumination found in most real world environments. Therefore, image based methods have been proposed where *light probes*, omnidirectional *high dynamic range* (HDR) images capturing real world lighting, are used for lighting synthetic objects.

In recent years, image based lighting techniques have been successfully incorporated in commercial renderers and production pipelines. However, existing methods are based on still images of static lighting at a single point in space, while most real world lighting conditions vary over both time and space.

Recent development of imaging hardware and computer technology has made it possible to perform rapid HDR image capture, and even streaming capture. We have programmed a powerful digital imaging system to capture high quality color HDR images at video rates. We use this device to capture images with a dynamic range of $10{,}000{,}000 : 1$ at 25 frames per second. The system performance is highly configurable in terms of frame rate, resolution, exposure times and covered dynamic range, and can be adapted for a wide range of applications. Using this camera hardware we have designed and built a light sampling device, a Real Time Light Probe. The HDR video imaging system is mounted on a rig, and records the environment through the reflection in a mirror sphere. The light probe can easily be moved around in a scene, and can rapidly capture the incident illumination at any position in space.

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We use the captured data to produce renderings of synthetic objects as illuminated by the lighting found in a real world scene. Using the light probe sequences instead of a static image we can render objects under complex lighting conditions with significant spatial and temporal variations.

The main contribution of this paper is the demonstration of image based lighting under temporally and spatially varying lighting conditions. This is made possible by our photometrically correct, high quality HDR color video capture methodology, which is presented first. Our methodology employs continuous exposure with a rolling shutter. This presents a significant improvement over previous sequential exposure methods.

2 Related Work

The work presented in this paper relates to work in two different areas. The design and implementation of the real time light probe relate to the field of high speed imaging, camera hardware and sensor technology, while the capture process, data processing and rendering application relate to the field of HDR imaging and image based lighting. The key concept relating the two fields in this context is the *Plenoptic Function*, or more precisely sampling the plenoptic function.

The plenoptic function $P(\phi,\theta,\lambda,x,y,z,t)$, [Adelson and Bergen 1991], describes the radiance of any wavelength λ arriving at any point in space (x,y,z) from any direction (ϕ,θ) at any time t. By fixing time and using one equation per spectral integral (R,G,B), three 5D functions $P(\phi,\theta,x,y,z)$ describe any possible omni-directional image seen from any fixed point in space.

Based on the idea of environment mapping [Blinn 1976], [Miller and Hoffman 1984] approximated the plenoptic function at a point in space by capturing environment maps by photographing a mirror sphere placed in a real world environment. Using the environment map they simulated both diffuse and specular materials, and showed how blurring of the map could simulate different reflectance properties. More recently [Debevec 1998] and [Sato et al. 1999] proposed methods for rendering synthetic objects into real world scenes. They sampled the plenoptic function by capturing panoramic HDR images [Ward 1991], *radiance maps*, of the incident illumination at one single point in space and used this 2D information, $P(\phi,\theta)$ for rendering synthetic objects and integrating them into photographs of the real scene. [Debevec et al. 2000] proposed a technique for image based relighting of reflectance fields of human faces captured using a *light stage*. Using this technique the subject could be accurately rendered into novel environments. To capture spatial variations in the lighting environment [Unger et al. 2003] used light field techniques, as presented by [Gortler et al. 1996] [Levoy and Hanrahan 1996], and captured omnidirectional HDR images of the incident illumination at evenly spaced points on a plane. The 4D captured real world lighting data, $P(\phi,\theta,x,y)$, was then used within a global illumination framework to render synthetic objects illuminated by spatially varying lighting such as spotlights, dappled lighting and cast shadows. [Masselus et al. 2003] demonstrated that such light fields were useful for image based relighting of captured reflection data. However, the capture time for such an HDR light field was very long, and the scene to be captured had to be kept stationary during the entire process. This made it impractical to perform a dense samplng of the lighting variation.

The difficulties of rapid and accurate HDR capture are largely due to the limited dynamic range of CCD and CMOS sensors. There are a number of commercial sensors and cameras with an extended dynamic range in the order of three to four orders of magnitude, some using sensors with a logarithmic response curve. A nice overview of available cameras and the field of HDR imaging can be found in [Reinhard et al. 2006]. However, the extreme dynamic range required for image based lighting can not yet be adequately captured with such systems.

The most common technique, today, for capturing HDR images is to use a series of images of a scene with varying exposure settings such that the full dynamic range of the scene is covered, [Madden 1993] [Mann and Picard 1995]. The set of low dynamic range images can then be combined into a high dynamic range image. Most digital cameras have an intrinsic non-linear response function f to mimic analogue film and to stretch the dynamic range in the digital, usually 8 bit, output image. This function maps the registered radiance E to pixel values Y, $Y = f(E)$. By recovering the camera response function,[Debevec and Malik 1997] [Robertson et al. 1999] [Mitsunaga and Nayar 1999], robust estimates of the radiance E can be computed as $E = f^{-1}(Y)$, and accurate HDR images can be assembled using the multiple exposure technique. [Nayar and Mitsunaga 2000] presented a technique for extending the dynamic range of a camera by placing a filter mask in front of the sensor, with varying transmittance for adjacent pixels.The values from differently exposed pixels could then be combined into an HDR image.

More recently [Kang et al. 2003] programmed a camera from Pt. Grey Research to alternately capture two different exposures at 15 fps, from which they could assemble final images with a slightly extended dynamic range at 7.5 fps. [Waese and Debevec 2002] demonstrated a real-time HDR light probe where neutral density filters with different attenuation levels were attached to four of five facets of a prismatic lens. By combining the five different images seen by the sensor, HDR frames were assembled and used as lighting information for a rendered sequence. The frame rate was full video rate, but the spatial resolution of the final light probe image was low. Another real-time light probe, based on multiple exposures, was presented by [Unger et al. 2004]. They used a highly programmable imaging system to capture HDR images covering 15 *f-stops* at 25 fps. However, the system was monochrome, and because of the time disparity between the different exposures, rapid camera and object motion in the scene could lead to ghosting artifacts in the final HDR image.

3 A Real Time Light Probe

The work presented here overcomes many of the problems with previous methods for rapid HDR imaging, and presents a significant improvement. It is now possible to perform spatial and temporal sampling of a 6D version of the plenoptic function of the form $P(\phi,\theta,x(t),y(t),z(t),t)$, i.e. space and time can be varied in an interdependent fashion. We capture panoramic HDR image sequences of incident lighting, using a catadioptric imaging system consisting of an HDR video camera and a mirror sphere.

3.1 Imaging Hardware

The HDR video camera, see Figure 2, is based on a commercially available camera platform, the Ranger C50 from the company SICK IVP[1]. The camera was originally designed for industrial inspection purposes, but its configurability makes it possible to re-program it to function as a high performance multiple exposure camera for HDR image capture.

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[1] http://www.sickivp.se

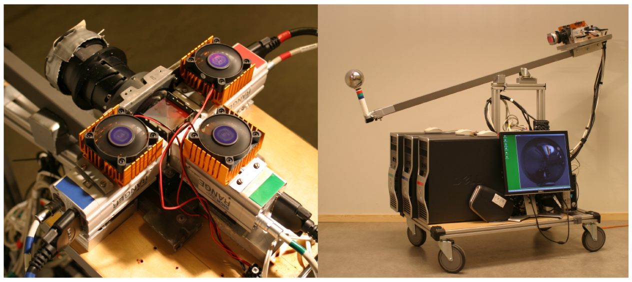

Figure 2: **Left**: The three camera units and the RGB beam splitter in the middle. **Right**:The HDR Light Probe system, rigged on a cart and aimed at a 10 cm diameter mirror sphere.

The large 14.6 by 4.9 mm CMOS sensor has a resolution of 1536 by 512 pixels and an internal and external data bandwidth of 1 Gbit/s. Each column on the sensor has its own A/D converter and a small processing unit. The 1536 processors working in parallel allow for real-time image processing. Exposure times can be shorter than a microsecond, and A/D conversion can be performed with 8 bit accuracy. It is also possible to A/D convert the same analogue readout twice with different gain settings for the A/D amplifier. By cooling the sensor, the SNR can be kept low enough to get two exposures from a single integration time without any significant amount of thermal noise.

The camera sensor is monochrome so color images are acquired by an externally synchronized three-camera system with RGB beamsplitter optics, see Figure 2. Each camera is connected via a Camera Link interface to a host PC, and attached to a rig with a mirror sphere. The three host PCs and the rig are mounted on a cart for mobile HDR capture.

3.2 HDR Capture Methodology

Our HDR capture methodology is similar to the multiple exposure algorithm used for still images but we have implemented a continuous rolling shutter progression through the image to avoid having the different exposures acquired at widely disparate instants in time, see Figure 3. This means that there is a set of rows in a moving window on the sensor, which are being processed simultaneously. As soon as an exposure is finished for a particular row, the value is A/D converted and the next longer exposure is started immediately. All rows are not imaged at the same time, which yields a slight curtain effect for camera and scene motion, but in return all exposures for one particular row of pixels are acquired head to tail within the frame time. A nice side effect is that almost the entire frame time is used for light integration and the longest exposure lasts almost the entire frame time. The camera units can be programmed to output assembled HDR frames in RGBE format, but in this experiment the raw A/D converted data for each exposure were streamed to the host PC for post-processing and off-line HDR assembly.

The system is highly configurable, and there are trade-offs possible between the dynamic range and the number of exposures, the image resolution, and the frame rate. The hard limiting factors are the maximum data output rate of 1 Gbit/s, the A/D conversion time of 9.6 μs per exposure for each row of pixels and the total sum of all exposure times. Because of the rolling shutter methodology, A/D conversion can be performed simultaneously with exposure. If the number of exposures is N, their exposure times are T_i, and the image resolution is H rows of W pixels each, the resulting minimum frame time is

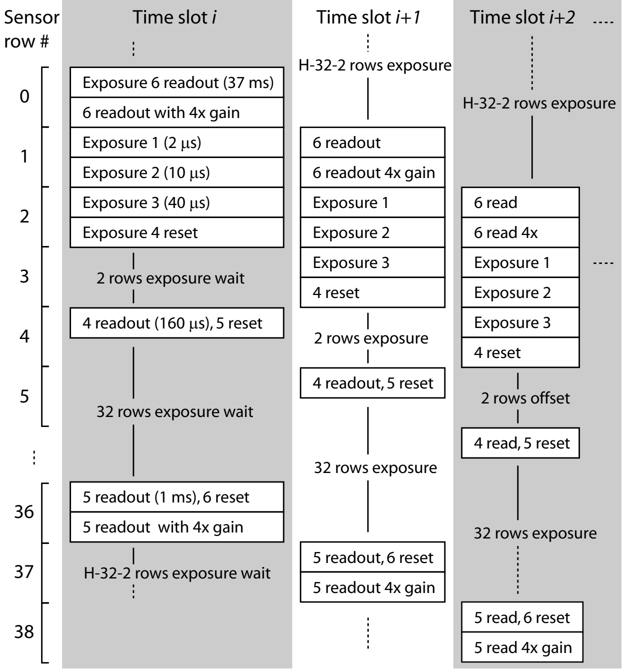

Figure 3: The progressive image exposure and readout from a rolling shutter algorithm effectively removes any significant time disparity between subsequent exposures within each HDR frame. For each time slot several exposures and readouts are performed. One full frame is exposed in H time slots, one for each row. In our example $H = 512$.

$$\begin{aligned}
T_c &= H \cdot 9.6 \cdot 10^{-6} [s] \\
T_p &= max(T_c, T_i) \\
T_d &= (H \cdot W \cdot 8 \cdot 10^{-9}) [s] \\
T_f &= max(\sum_{i=1}^{N} T_p, N \cdot T_d) \qquad (1)
\end{aligned}$$

The processing time, T_p, is the maximum of the A/D conversion time, T_c, for one full frame of H rows and the exposure time, T_i, for exposure i. The frame time, T_f, is the maximum of the processing time and the data transfer time, T_d, the time it takes to transfer all i exposures over the 1 Gbit/s data link.

For this real-time light probe we use eight exposures taken 2 to 3 f-stops apart, an image resolution of 512 x 512 pixels and a frame rate of 25 frames per second, which is well within the capabilities of the hardware. The exposure times and gain settings are indicated in Figure 3. This particular choice of parameters makes the frame time bounded by the A/D conversion time, so a somewhat larger image resolution would be possible.

3.3 System Evaluation

With 8 bit A/D conversion with a variable gain of 1x to 4x, and exposure times ranging from 2 μs to 37 ms, the dynamic range of the composite HDR image is comparable to a linear A/D conversion of $8 + log_2(4 \cdot 37{,}000/2)$ bits, or more than 24 bits.

Compared to currently available logarithmic sensors, this system has significantly better image quality and accuracy. It should be

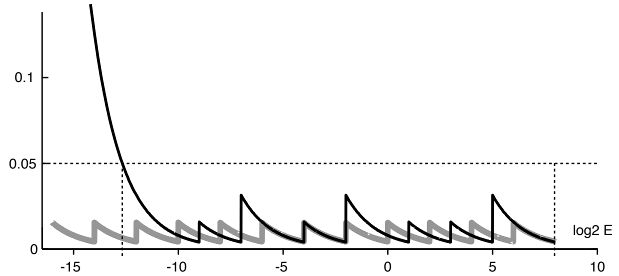

Figure 4: **Black curve**: The relative quantization error with our particular choice of exposure times is within a few percent over a wide dynamic range. **Grey curve**: The relative quantization error for a wider range of exposures including very long exposure times, taken 2 f-stops apart using 8 bit linear A/D conversion. This is comparable to what could be achieved using high quality still images.

noted that a hypothetical ideal logarithmic sensor with a similar dynamic range and 10 or 12 bits A/D conversion would exhibit about the same relative quantization error. However, logarithmic sensors of today have problems that are still limiting their practically attainable accuracy for absolute radiometric measurements [Krawczyk et al. 2005].

This system also compares favorably to traditional multiple exposure techniques. Our final HDR image has a dynamic range comparable to a multiple exposure acquisition with exposures covering as many as 16 f-stops, in effect a dynamic range of 10,000,000 : 1, and a relative quantization error within a few percent at all except for the lowest exposure values. Capture of one such HDR frame can be performed in 40 milliseconds. Thus the system is capable of capturing color HDR images, with an extreme dynamic range and a spatial resolution similar to standard digital video, at video frame rates. If a frame rate of 24 or 30 fps is desired the system can be reconfigured accordingly.

Thermal noise is low for the relatively short exposures used, so our main source of error is the 8 bit quantization. The relative quantization error as a function of irradiance, E, is displayed in Figure 4. For comparison we also display the quantization error for a capture using several more exposures taken only 2 f-stops apart with 8 bit linear A/D conversion. This is similar to what would be practical using a standard digital SLR camera. Towards low radiance values our quantization error peaks because we cannot use exposure times longer than the frame time. However, the sensor has a high light sensitivity and our longest exposure time of 37 ms gives good images even in regular fairly dim indoor lighting so longer exposure times are not really needed.

The rolling shutter methodology greatly reduces the potentially serious problem with camera or scene motion during capture. The worst case scenario is a camera or scene motion in the vertical direction in the image. Very small objects that cover only a single sensor pixel must not move distances close to the full image height within the frame time or else they will have the wrong intensity or be entirely missed in the shot. This is not a severe constraint. 25 frame heights per second corresponds to a very rapid scene motion or camera panning which is generally not seen in video footage, and objects so small that they are imaged as a single pixel are not very common. If this problem arises, it can be alleviated by bringing the camera slightly out of focus, thereby making the problematic object cover more pixels in the captured image. Moreover, in this particular application, the image is a panoramic view through a mirror sphere in a fixed position relative to the camera. In terms of angular velocity the critical speed for object motion in the scene would be several full revolutions per second around the sphere. For direct imaging applications it might still be a problem and should be investigated further.

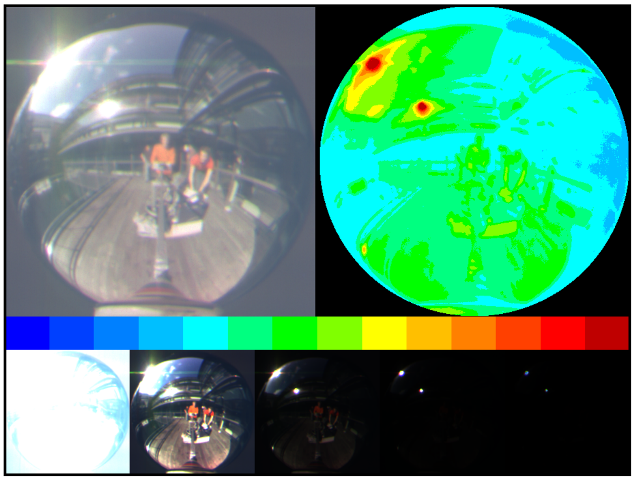

Figure 5: A gamma mapped HDR image, a color coded log_2 exponent image, and five different linear mapped images 3 f-stops apart from a light probe sequence captured in an outdoor environment.

Because the short exposure times are so extremely short, there will be a problem with flickering light sources. Direct views of fluorescent tubes will not, by default, be measured correctly by the shorter exposures. If it is important to capture fluorescent tube lighting correctly, the frame time should be synchronized to the mains AC frequency and the aperture setting for the optics should be adjusted so that one of the longest exposure times gives a valid A/D reading for direct views of the fluorescent lights. This is perfectly possible but it requires some extra care. To avoid such problems in our experiments, we used only daylight and incandescent lighting with no significant amount of flicker.

4 Data Processing

In order to produce lighting data that is useful for rendering, we need to process the raw output stream from each camera and assemble the HDR image sequence. We also need to know the physical light probe position and orientation in the scene for each frame so that they can all be transformed into world coordinates. Tracking could be performed by either physical or image-based tracking methods, even directly from the spherical light probe image data, but in this experiment we used an external video camera mounted on the HDR camera rig to track feature points in the scene.

4.1 HDR Image Assembly

The output from each camera unit is a data stream with a data rate of around 1 Gbit/s. The high data rate makes it impractical to perform any extensive data processing on the fly. Instead, the raw data is streamed to disk, and the HDR image is assembled in a post-processing step. The HDR assembly algorithm is very similar to the one traditionally used for still images [Debevec and Malik 1997], and is only simpler because the A/D converted data from the camera represents a strictly linear response curve so there are no gamma corrections or lookup tables involved which need to be characterized and compensated for. The radiance, E, seen by a certain pixel

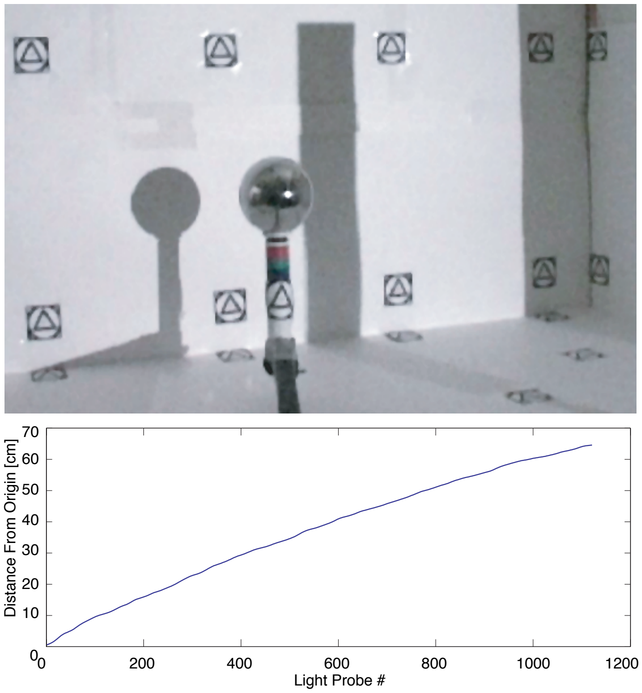

Figure 6: The background used for camera tracking. The position and orientation of each light probe were estimated by camera tracking of the regular video camera mounted jointly with the HDR camera on the rig. The tracked position along the main direction of motion is shown at the bottom.

is estimated from the N exposures with exposure time, T_i, and pixel value, Y_i, as a weighted mean

$$E = \frac{\sum_{i=0}^{N} \frac{g(Y_i)}{T_i}}{\sum_{i=0}^{N} g(Y_i)} \tag{2}$$

where g is the weight function. If the $(1x, 4x)$ dual gain functionality is used for a certain exposure, $i+1$, then $T_{i+1} = 4T_i$.

White balancing and radiance calibration was performed in relation to a standard digital SLR camera used for reference capture of HDR still images of the same scenes. Figure 5 displays an example image from a light probe sequence captured in a high contrast environment.

4.2 Light Probe Tracking and Transformation

To spatially relate the light probe images to each other and to the scene, we track the probe position and orientation through the sequence. For the experiments presented here, we used an ordinary digital video camera, attached to the light probe rig facing in the same direction as the HDR camera. The light probe was then tracked using traditional camera and feature point tracking. Figure 6 shows the view seen from the tracking camera during capture. The tracking information from the capture was used to rotate the light probe to a consistent world space orientation between frames.

An image of a mirror sphere is actually a multiple-viewpoint panorama of the environment, [Swaminathan et al. 2006]. Because we have densely sampled data, it is a possible to perform a resampling between different frames to obtain something much closer to a single-viewpoint panorama. However, for our experiments so far we have chosen to ignore that and regard a mirror sphere image as a reasonable approximation of a single-viewpoint panorama.

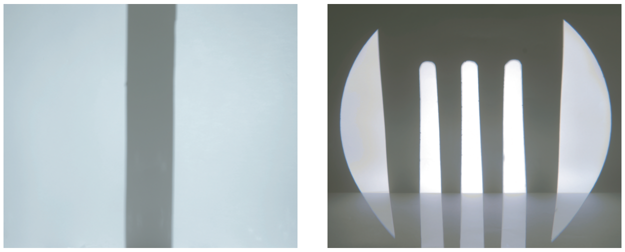

Figure 7: The two lighting environments used in the experiments were created using a projector spotlight to create the projected pattern. We also used two flood lights aimed at the ceiling on the right and left side of the box to provide some soft ambient lighting. The single shadow in the center of the first scene (left) was cast from an occluder placed in front of the projector, and the striped pattern (right) was cast from a fork placed in the gobo holder of the projector.

5 Rendering

Densely sampled sequences of real world illumination opens the door to a whole new area of rendering techniques using image based lighting with high frequency variations either spatially or temporally. Here we demonstrate two types of renderings making use of light probe sequences captured along a tracked 1D path in space.

First we show renderings of a diffuse object of about the same size as the physical light probe, moving along the captured path. In this case the object is rendered in the traditional way using only one light probe for the entire object. Second, we display renderings where the object is significantly larger than the physical light probe, elongated in the direction of the captured path. In this case we use one of several hundred light probes to render each object point, depending on the position of the point in world space. For clarity in the renderings, the light probe was moved along linear path in the scene shown in Figure 7.

5.1 Traditional Rendering

The traditional image based lighting method is to use one light probe captured at one single point in space as an approximation of the 2D plenoptic function $P(\phi, \theta)$. Using a light probe sequence, we can render an object at each sampled point along the captured path illuminated by the corresponding light probe. Figure 1 shows frames from an animated sequence where the object is illuminated by one single light probe image at different positions along the captured path in the first lighting example.

This type of rendering might be sufficient for small objects under low frequency spatial variations in the lighting. However, under real lighting conditions the illumination can vary rapidly even across small objects, and there will often be significant variations in lighting over the extent of larger objects. The traditional rendering technique cannot capture such effects.

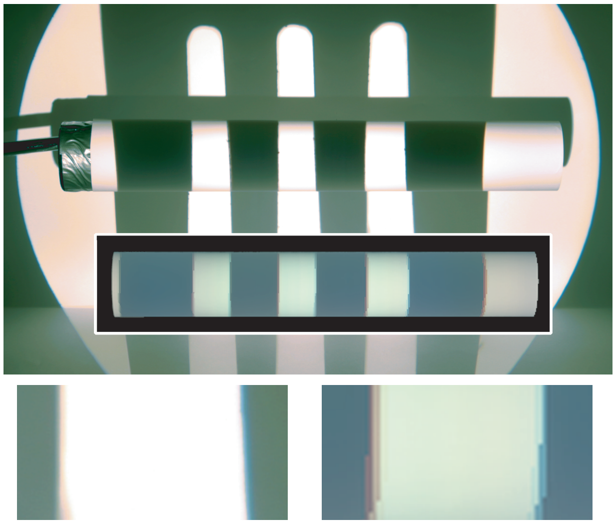

Figure 8: Still image of a cylinder in a spatially variant light field. Top: The background is a digital photo of the real scene with a cardboard cylinder, the inset shows a rending of a diffusely reflecting synthetic cylinder of about the same size. The inset was lit with image based lighting from a tracked sequence of over 1000 light probes. Bottom: close-ups of the millimeter-scale color fringes at the shadow edges. Real photo left, rendering right.

5.2 Rendering Large Objects

To demonstrate our ability to capture high frequency spatial variations in the illumination over a larger object, we used a full sequence of light probes for rendering a single object. For each object point being rendered, the light probe closest to that point was used to compute the lighting. Although this nearest neighbor sampling was used, the result is good because of the dense sampling. Around 1000 light probes were captured along the 55 cm long cylinder and used in the rendering. Because the light probe sequence was acquired along a straight 1D path, a long and narrow object was chosen. The light field was also deliberately chosen to have its main variation along the direction of the path. It would be perfectly possible to capture a light field with variation in two or even three dimensions in reasonable time. However, the 1D path demonstrates the fundamental principle, and the rendering shown in Figure 8 shows an accurate rendering of the spatially varying real world lighting. The spatial resolution of the sampling is very high - even a millimeter-scale color aberration at the edges of the fork tines was captured correctly.

The plots in Figure 9 show that the match is not only a visual likeness, but that there is also a detail correspondence. It also shows that the color synchronization between the Canon EOS 30D used for capturing the backdrop image and our HDR camera isn't perfect and needs improvement. The main culprit is the high near-IR sensitivity of our HDR camera, unfortunately we did not use an IR blocking filter for the acquisition. Another cause of error is the non-standard spectral responses of the particular RGB filters we used for the HDR camera. Our beamsplitter optics is a research prototype, not a color calibrated system ready for production use.

Rendering with spatially variant light probe data is currently not supported in commercial renderers. Our final rendering, see Figure 8, is a composite of several hundred rendered images rendered in Pixar's PRMan, one for each of the light probes in the sequence. The final compositing blend was performed using additional pixel data with the spatial position of the object point in world coordinates. This method is impractical for production use, as it does a lot of unnecessary work. However, proper sampling of a spatially variant light field is not significantly more complex or time-consuming than sampling a static light probe, and can be implemented as extensions to most renderers.

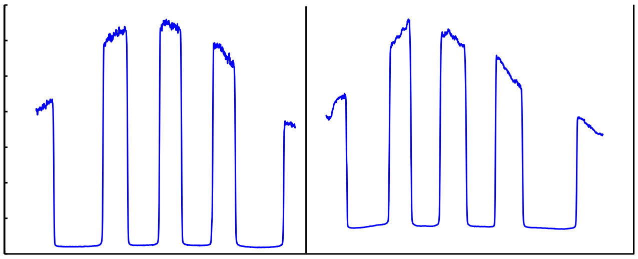

Figure 9: Horizontal traces of pixel intensities along the main axis of the cylinders. Left: real photo. Right: synthetic rendering. The detail correspondence is very good. Deviations can be attributed to different spectral responses of the cameras used and a high near-IR content in the ambient lighting.

6 Conclusion

We have presented a technique for capturing video sequences with an extreme dynamic range. The technique is not limited to the particular imaging hardware used, and could be implemented in similar programmable camera units. The application in this paper was rapid capture of light probes in high frequency spatially varying illumination. We displayed renderings illuminated by such captured real world lighting, and showed that it is now possible to rapidly capture such illumination in a practical way. Although this paper did not focus on high quality rendering and the lighting was only captured along a 1D path, it is evident that spatially variant light field illumination provides a powerful and useful extension to image based lighting.

7 Future Work

The successful results obtained with the real time light probe system opens up new research questions in several areas. Spatially variant light fields in more than one dimension can easily be captured. Rendering methods using such data are an interesting area that we will investigate further. In the experiments presented here the tracking was performed on a video stream captured by an external camera. Given the large number of omni-directional images and that features such as light sources easily can be detected in the data, tracking could be done directly on the light probe images.

Although the artifacts introduced by scene and camera motion are not a problem in the light probe setup the issue should be investigated for direct imaging applications. The prototype RGB beamsplitter optics used do not have standard spectral responses, and color synchronization against commercial cameras needs to be improved.

8 Acknowledgments

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