

# A Real Time Light Probe

J. Unger<sup>†</sup>, S. Gustavsson<sup>‡</sup>, M. Ollila and M. Johannesson<sup>1</sup>

Norrköping Visualization and Interaction Studio, Linköpings Universitet

<sup>1</sup> Integrated Vision Products AB, Sweden

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## Abstract

We present a novel system capable of capturing high dynamic range (HDR) Light Probes at video speed. Each Light Probe frame is built from an individual full set of exposures, all of which are captured within the frame time. The exposures are processed and assembled into a mantissa-exponent representation image within the camera unit before output, and then streamed to a standard PC. As an example, the system is capable of capturing Light Probe Images with a resolution of 512x512 pixels using a set of 10 exposures covering 15 f-stops at a frame rate of up to 25 final HDR frames per second. The system is built around commercial special-purpose camera hardware with on-chip programmable image processing logic and tightly integrated frame buffer memory, and the algorithm is implemented as custom downloadable microcode software.

Categories and Subject Descriptors (according to ACM CCS): I.3.1 [Computer Graphics]: Hardware Architecture  
Input devices, Parallel processing;

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## 1. Introduction and Previous Work

The use of HDR images is rapidly becoming more common in visual and special effects applications. In the computer graphics community HDR images are becoming a de-facto standard with new methods for capturing and rendering with real world lighting information emerging. Until now, all these techniques fundamentally required a set of separate single shot exposures over time to capture the full dynamic range, with rather extensive post-processing to generate the HDR image.

Research into high dynamic range radiance maps was performed [War91] [HS93] [Mad93] [RBS99][MP95] [DM97] [Sch94]. Mann and Picard demonstrated how to vary the exposure setting of a digital camera to obtain greater dynamic range [MP95]. Debevec and Malik later introduced a method for generating high dynamic range radiance maps using a series of photographs with different exposures [DM97].

[WD02] demonstrated a real-time high dynamic range light probe where a five facet prismatic multi-image filter was modified with neutral density filters to four of the five

facets to achieve light attenuation equivalent to 3, 6, 10 and 13 F-stops. The video frame was thus divided into five regions, with the center region capturing a direct view and the four outer regions stopped down to lower exposures. The frame rate was full video rate, but the quality and resolution of the final light probe image was low. Recently, Kang et al [KUWS03] developed a technique for HDR video using a digital camera where the exposure setting was changed rapidly back and forth between adjacent frames. Their resulting image was of high quality and high resolution, but the dynamic range was not huge, and the frame rate was only 7.5 FPS, half the frame rate of the digital camera used.

This paper describes work in progress for a real time HDR light probe. As our hardware platform, we use a commercial product, Ranger M50, an industrial inspection and range measurement camera with a "smart image sensor" designed, manufactured by Integrated Vision Products AB, www.ivp.se. Many years of research and development have been spent on hardware design [FIJ92] [JLMM03]. Our system is implemented as custom downloadable microcode software for this special purpose but off-the-shelf camera hardware. The current version of the camera is monochrome, but an extension to color is close at hand by moving to a 3-chip solution.

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<sup>†</sup> jonun@itn.liu.se

<sup>‡</sup> stegu@itn.liu.se

## 2. A Hardware HDR Algorithm

In order to assemble an HDR radiance map, a set of exposures covering the dynamic range in the scene is needed. Debevec et. al [DM97] presented a method where the HDR images are generated by taking a weighted mean of pixel values from a set of images with varying exposure time. Using their notation, the irradiance  $E_i$  on the sensor at a given pixel  $i$  at exposure  $j$  is given by:

$$E_i = \frac{f^{-1}(Z_{ij})}{\Delta t_j} \quad (1)$$

where  $f$  is the, in most cases non-linear, camera transfer function,  $Z_{ij}$  the digital pixel value and  $\Delta t_j$  the  $j$ :th exposure time.

In our case we have access to the linear A/D conversion output. This means that  $f$  vanishes and the irradiance seen at sensor pixel  $i$  can be found as:

$$E_i = \frac{Z_{ij}}{\Delta t_j} \quad (2)$$

The linear mapping has a constant resolution, so all values  $Z_{ij}$  from the black level to just below saturation could be used to compute the irradiance  $E_i$ . The limiting factors for the accuracy in the estimate of  $E_i$  are the increasing relative quantization error and decreasing SNR ratio in the lower range of  $Z_{ij}$ , near the black level. Thus, the lower range of values should be avoided where possible. For a set of exposures with different exposure times  $\Delta t_j$ , high pixel values  $Z_{ij}$  below saturation will always have a smaller relative quantization error than lower pixel values. For a certain pixel  $p$ , the highest non saturated value  $Z_{pj}$  from the set of exposures would give the most accurate irradiance value  $E_p$  seen by that particular sensor pixel. Under the assumptions that the scene to be captured is stationary during the full set of exposures and that the noise level is kept within reasonable limits, it is not necessary to compute a weighted mean from a set of different exposures. Instead, the irradiance  $E_i$  can be computed directly from the most reliable pixel value.

Going from short to long exposure times allows us to discard old values  $Z_{ij}$  in favor of later, non-saturated values  $Z_{i(j+n)}$ . Thus, the algorithm breaks down into a simple comparison and possible update of a value. This is a very hardware friendly algorithm: it is strictly sequential, it requires temporary storage only for a single frame of pixel data, and the computations involve no multiplications.

## 3. Implementation

The camera chip consists of a large sensor area and a somewhat smaller area of processing logic. The 14.6 by 4.9 mm sensor area contains 1536 columns of 512 CMOS photodiodes, with a high light sensitivity, low blooming and bleeding, excellent pixel response uniformity and low noise, particularly if the camera is cooled to keep it at room temperature.

Pass	Exposure time(s) $\Delta t$	Gain	A/D bits
1	1, 4, 16 $\mu s$	1x, 1x, 1x+4x	7 bits
2	128 $\mu s$	1x+4x	8 bits
3	1024 $\mu s$	1x+4x	8 bits
4	8192 $\mu s$	1x+4x	8 bits

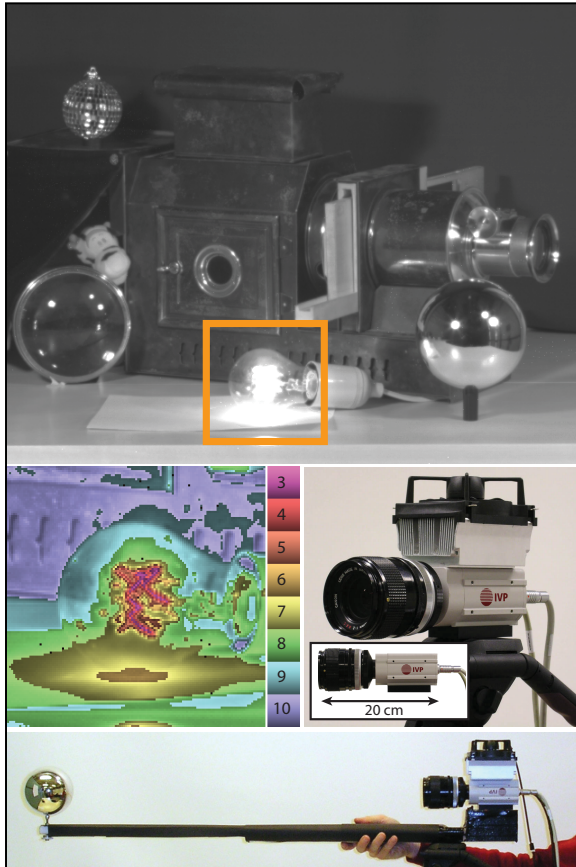
**Table 1: The exposure time, gain and A/D conversion settings used for generating the final HDR image. The 16, 128, 1024 and 8192  $\mu s$  exposures is A/D converted twice with 1x and 4x amplification.**

For each of the columns, there is an 8-bit ramp A/D converter and a simple processor along with some memory. The column processors are bit-serial (data is processed 1 bit at a time) and operate in a strict SIMD fashion (all processors execute the same instructions, but on different data). The 1536 units operating in parallel makes the processor array a very powerful device for real time image processing.

The CMOS photodiodes have a high light sensitivity, which is useful because a fast sequential HDR capture is limited to exposure times less than one frame time (40 ms at 25 FPS). We use exposure times ranging from 1 to 8192  $\mu s$ , where 8192 $\mu s$  exposure can actually yield a good image for reasonably lit indoor scenes. In our implementation we exploit that a single analog readout may be A/D converted more than once, with different gain settings for the A/D amplifier. The gain settings available are 1x and 4x. A/D converting twice with different amplification makes it possible to get two exposure values from one single integration time without loss in numerical precision. There will be some more analog noise in the amplified conversion, but the SNR ratio is still good enough for 8 bits A/D conversion.

Each HDR frame is captured in four passes with readouts of all sensor rows. Using the double A/D conversion and multiple short exposures for the first pass, 10 exposures are captured in total. In the first pass the A/D conversion precision is set to 7 bits, due to the fact that it is twice as fast as an 8 bit conversion. The details of the four passes are displayed in Table 1. The HDR frame is assembled, using the algorithm described in section 2, and streamed over a live feed to a host PC as an 8 bit mantissa and a 4 bit exponent. The camera is capable of capturing and streaming 512x512 HDR frames covering 15 f-stops at up to 25 FPS. The main limitations are bandwidth within the camera unit and to the host PC.

In our light probe application, Figure 1, the camera is mounted on a mobile rig facing a 10 cm diameter reflective sphere. The light probe capture device can easily be moved around in the scene to be captured.

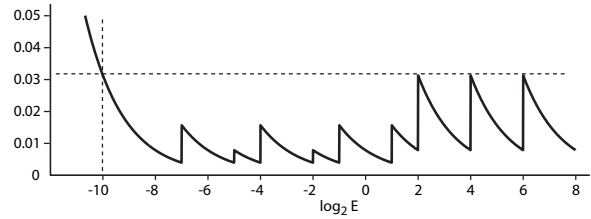


**Figure 1:** Top: One HDR frame acquired without the light probe setup tone mapped for presentation. Middle left: Detail of the pixels in the orange square, with the mantissa value mapped to intensity and the color hue denoting which exposure was picked. Middle right: The HDR acquisition camera unit, with a heat sink attached. Bottom: The light probe setup.

#### 4. Results

As our results we present a sequence of HDR images, see Figure 3, color coded similar to Figure 1. The images are extracted from a light probe video sequence captured along a camera motion path in an indoor environment. To display the high dynamic range captured the exponent is mapped to hue, and mantissa to intensity, so that different exposures are displayed in different hues, and the intensity represents the value within that exposure. Because the exposures are acquired in four separate passes for each frame, the motion in the scene yields a small disparity between images from short and long exposures. The problem is not severe in the reflected light probe image but will be investigated in future research.

Figure 1 shows an example HDR image to the left, tone



**Figure 2:** The maximum relative quantization error is within a few percent. The maximum error depends on the number of bits used in the A/D conversion. Because also lower values are used for the longest exposure time, the relative error grows to the low end of the scale.

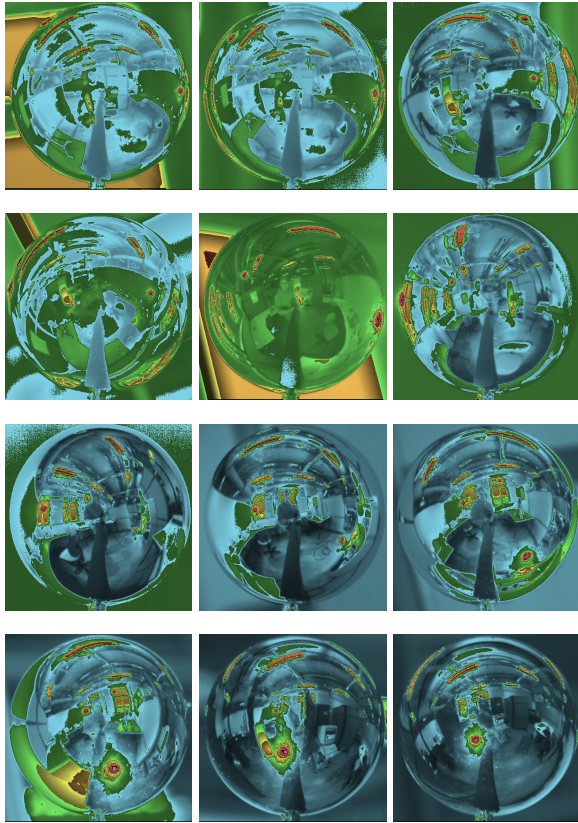
mapped for presentation. The aperture setting used was f4. There was not enough light in this indoor scene to make any use at all of the  $1 \mu\text{s}$  and  $4 \mu\text{s}$  exposures, not even for the direct view of the light bulb filament. To show the details more clearly, a small part of the image with an extreme dynamic range is shown in a version color coded as described above. The images show that the image quality is very good and that the system is able to capture a great dynamic range.

The maximum relative quantization error in our final HDR images is dependent on how close in f-stops the exposures are, and the resolution for each A/D conversion. The maximum relative quantization error in the system with our choice of parameters, Table 1, is plotted in Figure 2. Our light probe camera outputs a final HDR image with a maximum relative quantization error of within a few percent over a dynamic range of  $2^{18}$ , with reasonably useful values over the range of  $2^{20}$ , or a million to one.

#### 5. Future Work

Since this is work in progress, the capabilities and limitations of the system presented suggests some improvements for future versions. The major area to improve is to be able to capture color images. This could be accomplished by moving to a three chip solution or placing a pixel-interleaved RGB color filter array on the actual sensor. A three chip solution could consist of three separate synchronized cameras connected to the same host PC. By placing a bandpass filter in front of each camera they could capture the red, green and blue channels respectively.

Because the camera software is not yet running at precisely 25 Hz, the 50 Hz flickering from indoor lighting will cause interference. This will be solved by optimization of the micro code. Another important thing for future work is to investigate the misalignment between the different exposures. Kang et al [KUWS03] investigated techniques for compensating for this and many video processing, robot vision and image compression algorithms have been designed to address very similar problems with motion compensation.



**Figure 3: An HDR image sequence.** The images are extracted from an HDR light probe video sequence captured in an indoor scene. The images are color coded to show which exponent is used. Some strong light sources were placed in the scene to show that the light probe can capture HDR lighting information at video speed.

Capturing real world lighting along camera motion paths would make it possible to render synthetic objects moving through very complex lighting environments. Therefore we are also pursuing a file format and software tools to store, display and process HDR video sequences.

## 6. Acknowledgements

We would like to thank Johan Melander and Anders Murhed at IVP for help, discussions and ideas regarding the camera hardware and firmware. We also thank Ken Museth and Anders Ynnerman at NVIS for their insightful suggestions. This project was supported by the Science Council of Sweden through grant VR2002 621-2001-2623.

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