Color Calibrated High Dynamic Range Imaging with ICC Profiles

Michael Goesele[1], *Wolfgang Heidrich*[2], *Hans-Peter Seidel*[1]

[1]*Max-Planck-Institut für Informatik Saarbrücken, Germany*

[2]*The University of British Columbia Vancouver, Canada*

Abstract

High dynamic range (HDR) imaging has become a powerful tool in computer graphics, and is being applied to scenarios like simulation of different film responses, motion blur, and image-based illumination. The HDR images for these applications are typically generated by combining the information from multiple photographs taken at different exposure settings.

Unfortunately, the color calibration of these images has so far been limited to very simplistic approaches such as a simple white balance algorithm. More sophisticated methods used for device-independent color representations are not easily applicable because they inherently assume a limited dynamic range. In this paper, we introduce a novel approach for constructing HDR images directly from low dynamic range images that were calibrated using an ICC input profile.

1. Introduction

Normal photographs have non-linear film response and are therefore not directly useful as input data for most computer graphics algorithms, as these require linearized radiance values. For example, in order to illuminate synthetic objects using photographs of a real environment (see e.g. [3]), we have to integrate over the incident radiance at every point on the synthetic object. If this information is to be taken from an image, then the limited dynamic range and the non-linear film response of the image has to be taken into account, or effects such as saturation of very bright image parts will show up as artifacts in the final rendering. The same is true for effects like motion blur [4], or for image-based measurements of reflection properties [6].

High dynamic range (HDR) imaging is a powerful tool for avoiding these problems. Using methods summarized in more detail in the next section, differently exposed photographs of the same scene are first used to estimate the non-linear film response curve, which can then be used to generate images with a high dynamic range and a linearized film response that do not saturate in the bright parts.

Unfortunately, the state of the art of color calibration in HDR imaging uses a very simplistic approach, based on a simple white balance between the red, green, and blue channels of the image. The use of more sophisticated techniques such as ICC profiles was so far not possible since these profiles are inherently tailored towards the case of images with limited dynamic range.

In this paper we propose a new method for constructing HDR images directly from low dynamic range images calibrated with an ICC input profile. This will not only allow us to have meaningful colors in image-based illumination and measurement, but also to simulate the effects of different camera/lens/film combinations with realistic colors.

The remainder of this paper is organized as follows: in Section 2 we briefly summarize the work related to HDR imaging. In Section 3 we analyze the theoretical foundations of HDR imaging in XYZ color space. We then describe how to use ICC profiles for HDR imaging (Section 4), and validate our assumptions about the resulting color space in Section 5. In Section 6 we summarize our algorithm before we conclude by presenting results for the proposed method (Section 7).

2. Previous Work

High dynamic range imaging was first introduced by Wyckoff [13] in the 1960s who invented an analog film with several emulsions of different sensitivity levels. His false color film had an extended dynamic range of about 10^8.

More recently, several authors proposed method to extend the dynamic range of digital images by combining multiple images of the same scene that differ only in exposure time. Madden [7] assumes linear response of a CCD imager and selects for each pixel an intensity value from the brightest non-saturated image. Mann and Picard [8] construct the response curve of the camera by observing the intensity values of single pixels in an exposure series. A more robust method to determine the response curve, which selects a small number of pixels from the images and performs an optimization with a smoothness constraint, was introduced by Debevec and Malik [4]. They also introduced a white balance step in order to determine the relationship between the channels of a RGB color image. Robertson et al. [11] improved on this by optimizing over all pixels in all images and using a different weighting function.

In addition, several methods have been proposed to alter the design of a digital camera in order to extend its dynamic range [9, 10]. Notably, Moriwaki [9] focuses on the correct capture of the ratios of the RGB color channels in the presence of high contrast for color segmentation algorithms. Furthermore, modern CMOS imagers have a higher dynamic range than the more commonly used CCD imagers.

The above methods for constructing a HDR image from an exposure series are either assuming a linear response of the imaging system or determine the response curve in a separate step, treating multiple color channels independently. If the relationship between the color channels is considered at all, it is only done for the final HDR image.

In contrast to that we assume that colors are reconstructed correctly in each input image if the pixel under consideration is not saturated or underexposed. We use an ICC input profile [5, 12] describing the properties of our imaging system to capture accurate colors and to convert the input images into the CIEXYZ profile connection space (PCS). We assume and confirm with a measurement that the transformation into the PCS leads to a linear XYZ space[1], allowing us to calculate HDR values by a simple averaging operation.

3. High Dynamic Range Imaging in XYZ Color Space

The CIEXYZ color space is defined relative to the spectral power distributions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ of the CIE 1931 standard colorimetric observer [2]. The X, Y, Z tristimulus values are defined for secondary light sources (reflecting or transmitting objects) as

$$
\begin{aligned}
X &= k \int_\lambda \phi(\lambda)\bar{x}(\lambda) d\lambda \\
Y &= k \int_\lambda \phi(\lambda)\bar{y}(\lambda) d\lambda \\
Z &= k \int_\lambda \phi(\lambda)\bar{z}(\lambda) d\lambda \\
k &= \frac{100}{\int_\lambda S(\lambda)\bar{y}(\lambda) d\lambda}
\end{aligned}
$$

where $\phi(\lambda)$ is the spectral distribution of the light and $S(\lambda)$ is the relative spectral power distribution of the illuminant. Note that the tristimulus values are independent of the power of the illuminant and depend linearly on $\phi(\lambda)$.

If we are able to acquire color corrected photographs in CIEXYZ space (e.g. using ICC profiles, see Section 4), then this linearity relationship means that every pixel i in the color corrected image will get the following color value:

$$
\begin{aligned}
X_i &= lT \cdot \int_\lambda \phi_i(\lambda)\bar{x}(\lambda) d\lambda, \\
Y_i &= lT \cdot \int_\lambda \phi_i(\lambda)\bar{x}(\lambda) d\lambda, \\
Z_i &= lT \cdot \int_\lambda \phi_i(\lambda)\bar{x}(\lambda) d\lambda,
\end{aligned}
$$

where T is the exposure time and l is an unknown scaling factor. That is, the CIEXYZ color values are proportional to the exposure time and the scene luminance due to the linearity of the CIEXYZ color space.

3.1. Exposure Series

This property can be used to scale and average the pixel values for a set of images $\{I_j\}$ of the same scene with different exposure times T_j in order to create a HDR image of the scene according to the following formulas:

$$
\begin{aligned}
X_i &= T_n \frac{\sum_j X_{i,j} T_j^{-1} w(X_{i,j}, Y_{i,j}, Z_{i,j})}{\sum_j w(X_{i,j}, Y_{i,j}, Z_{i,j})} \\
Y_i &= T_n \frac{\sum_j Y_{i,j} T_j^{-1} w(X_{i,j}, Y_{i,j}, Z_{i,j})}{\sum_j w(X_{i,j}, Y_{i,j}, Z_{i,j})} \\
Z_i &= T_n \frac{\sum_j Z_{i,j} T_j^{-1} w(X_{i,j}, Y_{i,j}, Z_{i,j})}{\sum_j w(X_{i,j}, Y_{i,j}, Z_{i,j})}
\end{aligned}
\tag{1}
$$

T_n is a scaling factor to determine the exposure level of the HDR image. As the images $\{I_j\}$ have a limited dynamic range the weighting function w is used to ignore pixel values which are saturated or underexposed and therefore invalid. In addition it can be used to emphasize the contribution of pixel values in the medium part of the dynamic range, which are assumed to be more accurate.

The resulting HDR pixel values are now proportional to the luminance of the corresponding part of the scene. An absolute calibration can be achieved by capturing a target with known luminance. Alternatively the exposure formula given in [1] can be used to obtain an approximate calibration.

4. Using ICC Profiles

In order to calibrate the color of our individual photographs, we use ICC profiles that describe the color characteristics of devices such as digital cameras, monitors, or printers [5, 12]. A profile can be used to convert input data

[1] We use CIEXYZ to denote the CIE XYZ color space as defined in [2] and XYZ for any other, not necessarily well defined color space with similar properties.

from the color space of the input device into a common profile connection space (PCS) which is either CIELAB or CIEXYZ with a defined white point (illuminant D50). CIELAB values can be converted into CIEXYZ and vice versa. An output or monitor profile converts image data from the PCS to the color space of the output device before it is printed or displayed. These operations are usually performed by a color management system.

A suitable input profile can be used to convert input data from a digital camera into the linear CIEXYZ color space of the PCS and corresponds therefore to the response curve that is traditionally used in HDR imaging. However, in contrast to the response curve it not only linearizes the input data but converts it into the well defined CIEXYZ color space.

Many algorithms which use HDR images should be able to directly use a XYZ HDR image instead of a RGB HDR image as the two color spaces are related, others have to be adapted to the new color space. If all operations that are applied to an XYZ HDR image preserve the linearity of the CIEXYZ space it is possible to apply an ICC output profile to the HDR image in order to have a complete color management chain.

This approach depends on the assumption that the input profile converts the input images into a linear XYZ space. Depending on the properties of the input device this might be difficult and a tradeoff between good color representation and linearity has to be made during the creation of the input profile. In addition, an input profile can be generated for a preferred reproduction, e.g. to emphasize shadow regions, so that the resulting profile might perform a desired but not necessarily faithful conversion into CIEXYZ space which changes the actual color. Due to these reason it is necessary to check how linear the resulting XYZ space is (see the next section). The impact of the remaining nonlinearities on the resulting images is analyzed in Section 7.

5. Linearity Measurements

To test our approach we acquired an exposure series of an IT8 target with a Kodak DCS 560 digital camera and HMI metal halide lighting. The series consists of 13 images with exposure times between $\frac{1}{30}s$ and $\frac{1}{500}s$ in $\frac{1}{3}$ f-stop increments. A custom ICC input profile was generated for a correctly exposed image from this series using the Linotype CPS ScanOpen ICC DCam software. The images of the exposure series were then converted into 16 bit per channel XYZ color space with our own implementation of a color management system using the generated profile. Pixels for which at least one channel was saturated or for which all channels were underexposed, were marked invalid and excluded from further processing.

We implemented the approach of Robertson et al. [11] for 16 bit images and calculated the response curves for all color channels. Figure 1 shows a plot of the computed response curves and a linear response curve for comparison. Note that no smoothing operation is applied during the computation. The recovered response curves confirm

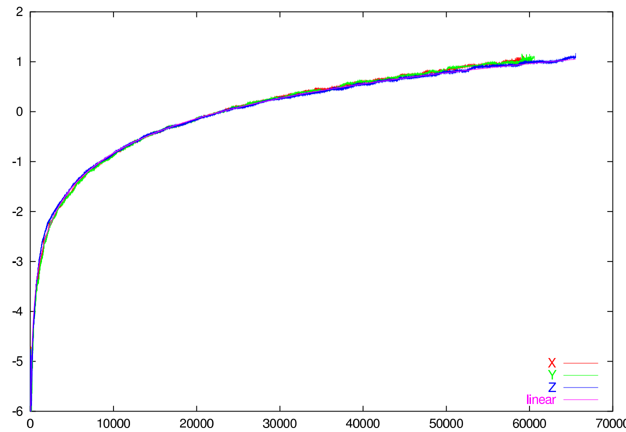

Figure 1: *Logarithmic plot of the response curve of the X, Y, and Z channels for the IT8 target exposure series. The horizontal axis shows 16 bit digital units. For comparison a plot of a linear response curve is included.*

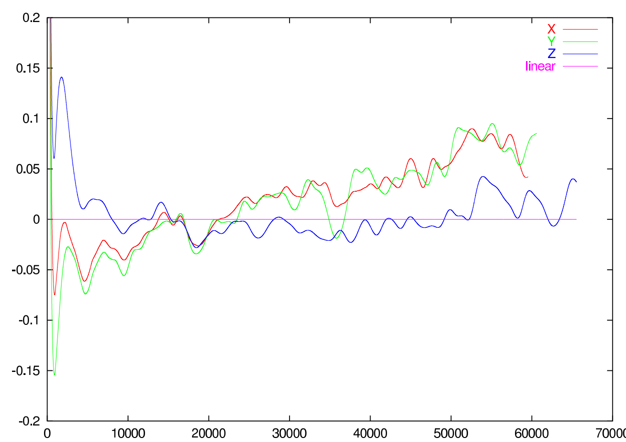

Figure 2: *Plot of the linearity of the response curve for the X, Y, and Z channels (same data as in Figure 1). The horizontal axis shows 16 bit digital units, the vertical axis shows the relative deviation from the linear response curve. A smoothing operation was applied to the curve in order to emphasize the global behavior. For comparison a plot of a linear response curve is included.*

that the resulting color space is approximately linear (see Figure 2. But they also show several problems:

- The response curves are not smooth and show a bias in the brighter regions (especially in the X and Y channel).
- In the very dark regions, the signal is strongly nonlinear and noisy. This can be due to several reasons, especially the limited signal-to-noise ratio of

the camera, quantization artifacts in the intermediate image representations, and problems with the generated profile.

- In the very bright regions the response curve has a high variance.

The weighting function w should take these problems into account and suppress values at both ends of the dynamic range. Further experiments have shown, that the local variations throughout the dynamic range depend on the scene content. Including them into the weighting function is therefore not appropriate.

The largest problem is the bias in the X and Y channel. This could be dealt with by manually linearizing the response curve which directly compromises the integrity of the profile connection space. Alternatively, combining several images can also reduce the error without explicitly changing the PCS. This approach has the advantage that it is unbiased, i.e. it leads to a correct result if the exposure series consists of a single image.

Taking these considerations into account, we decided to leave the response curve unmodified and to use a simple weighting function w with a linear ramp at both ends and a constant value inbetween. Due to the different behavior of the three channels, the widths of the ramps are different for each channel. As shown in Section 7 this choice worked well for our setup. However, depending on the individual setup used, a different weighting function may be appropriate.

6. Algorithm

Given a suitable input profile, the generation of a HDR image from an exposure series is not difficult. First the images have to be converted into CIEXYZ color space using the profile. Pixels for which at least one color channel is saturated or for which all color channels are underexposed in the original image should be marked invalid and excluded from the HDR calculation.

The contributions of the images to the final HDR image are summed up according to Equation 1 using the weighting function w. The resulting HDR image can then be arbitrarily processed as long as the linearity is preserved. Finally, the image has to be converted back to the PCS by correcting all pixels for which the value of Y is > 100. As these pixels are "overexposed" they can e.g. be set to the tristimulus values of the light source. The resulting image can then be used in the color management workflow without limitations.

7. Results and Conclusion

We described in this paper how the ICC profile mechanism can be used to acquire HDR images in CIEXYZ space with calibrated colors. As long as further processing steps (e.g. image-based rendering algorithms) preserve the linearity of the CIEXYZ color space, it is possible to return to the PCS and apply suitable output profiles to the images leading to an integration of HDR imaging with traditional color management systems.

Figure 3 shows a normal image, which was obtained with our method by generating a HDR image from the exposure series described in Section 5. The image was normalized (i.e., the intensity was scaled so that the largest pixel value equals 100) in CIEXYZ space, converted to CIELAB and finally to sRGB. For comparison, an original input image was also normalized in CIEXYZ space and converted to LAB. The Euclidean distance ΔE^*_{ab} between the two images has been calculated for all pixels and is shown together with a histogram of the color patch part of the target in Figures 4 and 5. The match between the images is very good. The results become only slightly worse, if less images (e.g., a series separated by a full f-stop) are used.

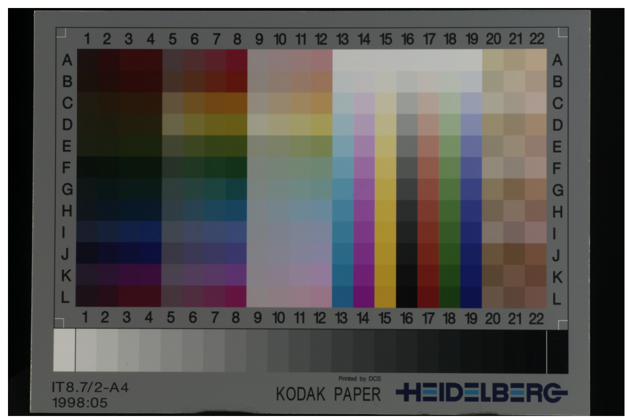

Figure 3: *Image generated from the HDR image of the IT8 target.*

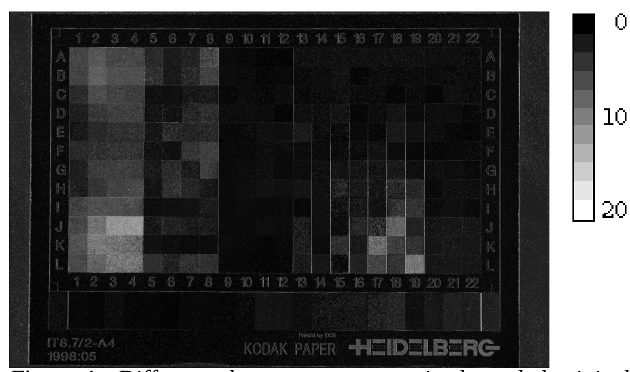

Figure 4: *Difference between an appropriately scaled original input image and Figure 3 calculated using the ΔE^*_{ab} metric. Most colors are reproduced very well, the largest error is in the patches J3 and J4 with $\Delta E^*_{ab} \sim 12$.*

Once the linearity of the XYZ space is established, the proposed method is easy to implement and requires only

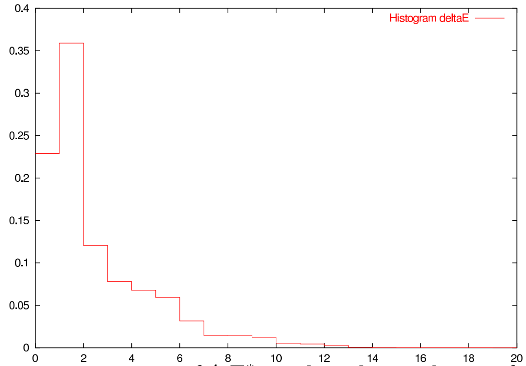

Figure 5: Histogram of ΔE^*_{ab} in the color patch part of the IT8 target (see Figure 4). The horizontal axis shows ΔE^*_{ab}, the vertical axis shows the corresponding fraction of pixels.

a small amount of memory as the images can processed sequentially. The quality of the results depends mainly on the input profile and the precision of the input images is not limited to a certain number of bits per channel.

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9. Biographies

Michael Goesele is a PhD student in the computer graphics group of the Max-Planck-Institut für Informatik in Saarbrücken, Germany. He studied computer science at the University of Ulm, Germany, and at the University of North Carolina at Chapel Hill, USA, and received his Master in computer science from the University of Ulm in 1999. His interests include color science, acquisition techniques for computer graphics, and image-based rendering.

Wolfgang Heidrich is an Assistant Professor at the University of British Columbia, Canada. Previously he was a Research Associate at the computer graphics group of the Max-Planck-Institut für Informatik in Saarbrücken, Germany, where he chaired the activities on image-based and hardware-accelerated rendering. He received a PhD in computer science from the University of Erlangen, Germany, in 1999, a Master in mathematics from the University of Waterloo, Canada, in 1996, and a Diploma in computer science from the University of Erlangen, Germany, in 1995. His research interests include hardware-accelerated and image-based rendering, global illumination, and interactive computer graphics.

Hans-Peter Seidel is the scientific director and chair of the computer graphics group at the Max-Planck-Institut für Informatik and a professor of computer science at the University of Saarbrücken, Germany. He is an adjunct professor of computer science at the University of Erlangen, Germany, and at the University of Waterloo, Canada. Seidel's research interests include computer graphics, geometric modeling, high-quality rendering, and 3D image analysis and synthesis. He has published some 150 technical papers in the field and has lectured widely on these topics.