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Evaluation of high dynamic range photography as a luminance data acquisition system

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In this paper, the potential, limitations and applicability of the High Dynamic Range (HDR) photography technique are evaluated as a luminance mapping tool. Multiple exposure photographs of static scenes were taken with a commercially available digital camera to capture the wide luminance variation within the scenes. The camera response function was computationally derived by using Photosphere software, and was used to fuse the multiple photographs into an HDR image. The vignetting effects and point spread function of the camera and lens system were determined. Laboratory and field studies showed that the pixel values in the HDR photographs correspond to the physical quantity of luminance with reasonable precision and repeatability.

1. Introduction

It possible to measure the photometric properties of a scene by means of point-by-point measuring devices. However, these measurements take a long time, are prone to errors due to measurement uncertainties in the field and the obtained data may be too coarse for analysing the lighting distribution and variation. There is a need for a tool that can capture the luminances within a large field of view at a high resolution, in a quick and inexpensive manner.

Photography has the potential for this kind of data collection. Photograph based photometry is not a new approach; various researchers have utilized film based photographs and CCD outputs for luminance measurements. The common approach in early studies was to acquire the calibration functions for a certain camera and illuminant, which involved lengthy and complex physical measurements performed in laboratory conditions, accompanied with extended data analysis.[1,2] RGB values were converted to the CIE tristimulus values through the calibration functions. These early studies were based on single photographs, which provide a limited dynamic range of luminances. More recent techniques[3] employ multiple photographs, which allow a larger luminance range to be captured. Some of these techniques require expensive equipment. All of these studies require costly and tedious calibration processes, and yield calibration functions that are strictly device dependent.

In HDR photography, multiple exposure photographs are taken to capture the wide luminance variation within a scene. Camera response function is computationally derived through a self-calibration process from the multiple exposure photographs; therefore the HDR photography technique is applicable to all cameras that have multiple exposure capabilities. The camera response function is used to fuse the photograph sequences into a single HDR image. HDR photography is not

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Table 1 Camera settings

Feature	Setting	Feature	Setting
White balance	Daylight	Image size	2592 pixels × 1944 pixels
Best shot selector	Off	Sensitivity	100 ISO
Image adjustment	Normal	Image sharpening	Off
Saturation control	Normal	Lens	Fisheye
Auto-bracketing	Off	Noise reduction	Off

specifically developed for lighting measurement purposes. The objective of the present study is to evaluate the appropriateness (ie, accuracy, applicability, and limitations) of the technique as a luminance data acquisition system.

2. Equipment and softwares

2.1 Equipments

The multiple exposure photographs were taken with a Nikon Coolpix 5400 digital camera mounted on a tripod and fitted with a fisheye lens (Nikon FC-E9). The fisheye lens has a focal length of 5.6 mm and an angle of view of 190°. Reference physical measurements were taken with a calibrated hand held luminance meter with 1/3° field of view (Minolta LS110).

2.2 Softwares

The multiple exposure photographs were processed using the software called Photosphere.[4] All photographs were taken with the camera settings shown in Table 1. It is especially important to fix the white balance for achieving consistent colour space transitions. Changing either the aperture size (f-stop) or the shutter speed (exposure time) can vary the exposure values. Shutter speed is a more reliable measure than aperture size.[5,6] Therefore, exposure variations were achieved with a fixed aperture size (f/4.0), and varying only the shutter speed in manual exposure mode (2 s to 1/4000 s).

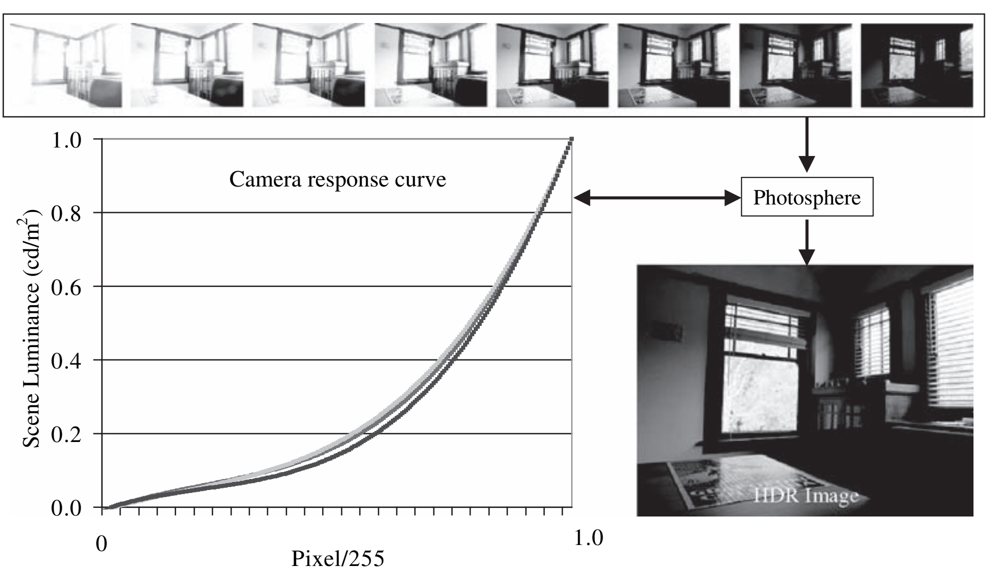

Figure 1 Camera response curve for Nikon 5400 as determined by Photosphere

An interior scene with daylight that had large and smooth gradients throughout the interior and exterior views was selected for determining the camera's natural response function.[7] Photosphere generated the camera response curve for the Nikon 5400 that was used in this study based on 10 exposure sequences in three channels (RGB) as follows (Figure 1):

$$R = 1.53994x^3 - 0.99492x^2 + 0.46536x - 0.01037$$
$$G = 1.31795x^3 - 0.69784x^2 + 0.38994x - 0.01005$$
$$B = 1.67667x^3 - 1.09256x^2 + 0.42334x - 0.00745$$

The curves are polynomial functions that model the accumulated radiometric non-linearities of the image acquisition process (such as gamma correction, A/D conversion, image digitizer, various mappings) without addressing the individual source of each non-linearity.[5,6] The technique, known as radiometric self-calibration,[5] is a computationally derived calibration process used to relate the pixel values to the real world luminances. Camera response curves vary considerably between different cameras, therefore radiometric self-calibration has to be applied to each camera. However, the only input to the process is a set of multiple exposure photographs.

Once the camera response curve is determined, Photosphere can fuse any photograph sequence into a HDR image. HDR images can be stored in image formats such as Radiance RGBE[8] and LogLuv TIFF,[9] where the pixel values can extend over the luminance span of the human visual system (from 10^{-6} to 10^8 cd/m^2).

2.3 Luminance calculation

For analysing the HDR images from Photosphere, computational procedures were implemented (referred to as HDRLab). The routines were written in Matlab® and they allow the user to extract and process per-pixel lighting data from the HDR images saved in Radiance RGBE format. CIE XYZ values for each pixel were quantified from floating point RGB values based on the standard colour space (sRGB) reference primaries,[10] CIE Standard Illuminant D_{65}, and standard CIE Colorimetric Observer with 2° field of view. The transformation process is performed as follows:

1) Floating point RGB is calculated from RGBE integer values.[8]

$$red = \frac{R}{255} * 2^{(E-128)}, green = \frac{G}{255} * 2^{(E-128)},$$

$$blue = \frac{B}{255} * 2^{(E-128)}$$

2) CIE chromaticities for the reference primaries and CIE Standard Illuminant D65 are as follows:[10]

$$R(x, y, z) = (0.64, 0.33, 0.03)$$
$$G(x, y, z) = (0.30, 0.60.0.10)$$
$$B(x, y, z) = (0.15, 0.06, 0.79)$$
$$D_{65}(x, y, z) = (0.3127, 0.3290, 0.3583)$$

3) RGB to XYZ matrix is constructed with the matrix of RGB chromaticities ('K'), which are differentially scaled to achieve the unit white point balance ('W'). Further information on RGB to XYZ conversion can be found in Wyszecki and Stiles[12] and Glassner.[13]

$$K = \begin{bmatrix} r_x & r_y & r_z \\ g_x & g_y & g_z \\ b_x & b_y & b_z \end{bmatrix} = \begin{bmatrix} 0.64 & 0.33 & 0.03 \\ 0.30 & 0.60 & 0.10 \\ 0.15 & 0.06 & 0.79 \end{bmatrix}$$

$$W = \begin{bmatrix} \frac{X_n}{Y_n} & 1 & \frac{Z_n}{Y_n} \end{bmatrix} = [0.9505 \quad 1.0 \quad 1.0891]$$

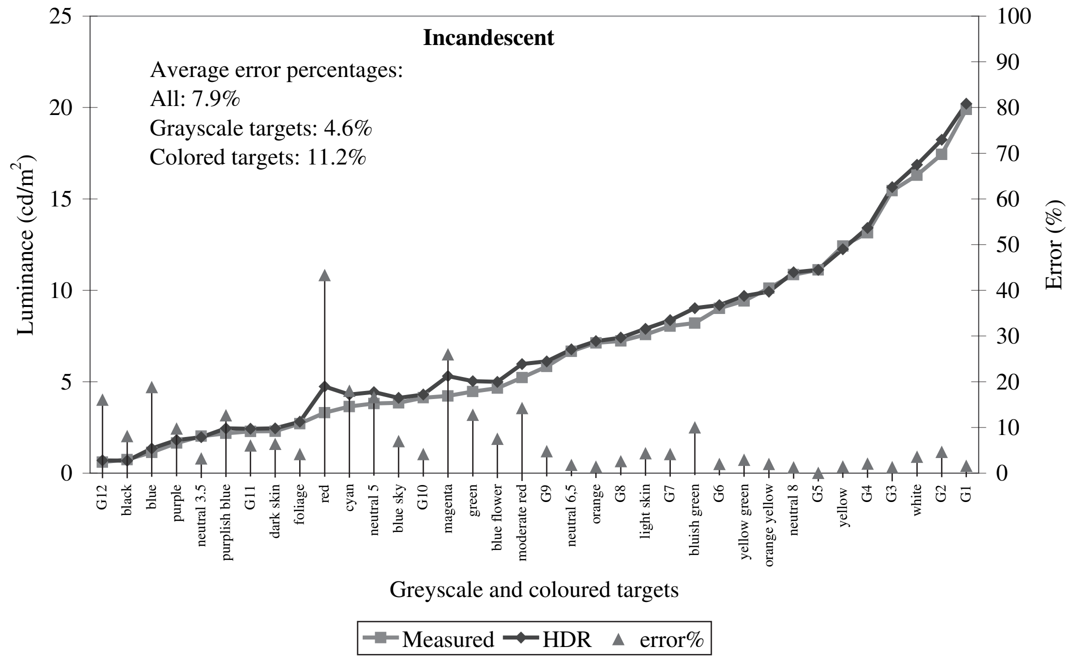

Figure 2 Dark room with greyscale and coloured targets, illuminated with an incandescent lamp

$$V = WK^{-1} = [0.6444 \quad 1.1919 \quad 1.2032] = [G_r \quad G_g \quad G_h]$$

$$G = \begin{bmatrix} G_r & 0 & 0 \\ 0 & G_g & 0 \\ 0 & 0 & G_b \end{bmatrix} = \begin{bmatrix} 0.6466 & 0 & 0 \\ 0 & 1.1919 & 0 \\ 0 & 0 & 1.2032 \end{bmatrix}$$

$$X = 0.4124 * R + 0.3576 * G + 0.1805 * B$$
$$Y = 0.2127 * R + 0.7151 * G + 0.0722 * B$$
$$Z = 0.0193 * R + 0.1192 * G + 0.9505 * B$$

4) It is possible to calibrate images and cameras in Photosphere with a physical luminance measurement of a selected region in the scene. This feature can be applied as a constant ('k') either to the pixel values in an image or to the camera response function. Luminance (L) is calculated as:

$$L = k*(0.2127*R + 0.7151*G + 0.0722*B) \ \ (\mathrm{cd/m^2})$$

3. Measurement setups and analyses

To evaluate the HDR technique, a suite of measurements and analyses were undertaken. Key sets of measurements involved the comparison of luminances of various surfaces as determined from HDR images and the luminance meter. The measurements were repeated in different settings, which varied from controlled laboratory environments (black painted room without daylight) to office spaces and outdoors. The interior settings

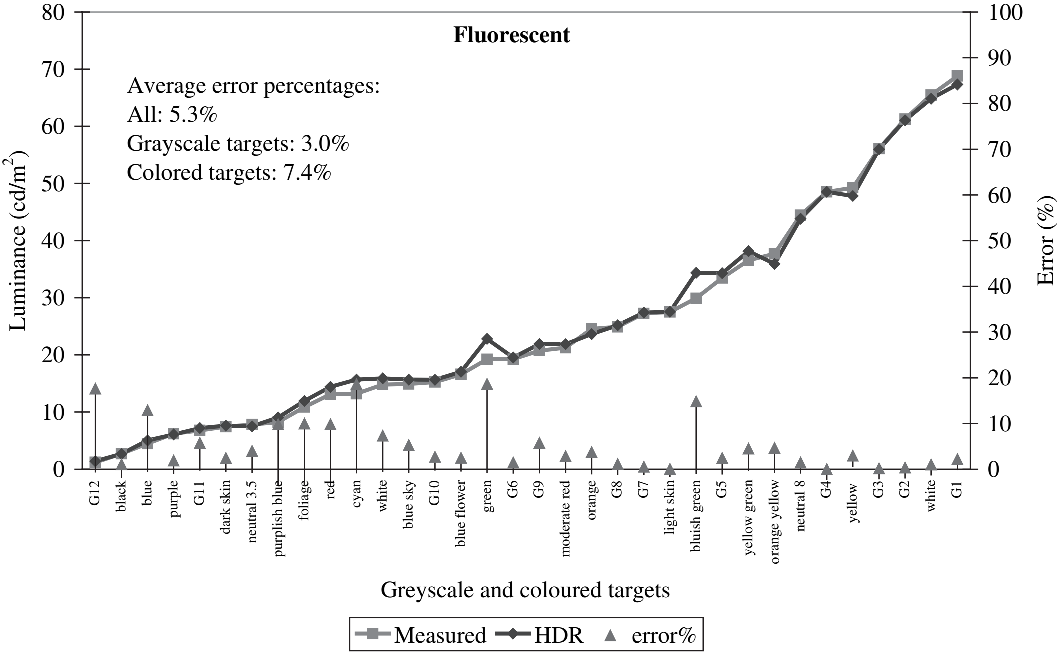

Figure 3 Dark room with greyscale and coloured targets, illuminated with a T5 fluorescent (3000K) lamp

had different light sources and different illuminances. Precautions were taken to ensure that the equipment and the people who made the measurements did not cast shadows on the targets. The measurements were made with five sets of paper targets: The first target consisted of 24 squares (two sets of 12 squares) which had reflectances ranging from 4% to 87%. The other four targets had a grey square target in the middle with a 28% reflectance. This square was enveloped by: a) white (87% reflectance); b) black (4%); c) white-then-black; d) black-then-white surroundings. The Macbeth ColorChecker® chart was also used as a target.

The centre of each target was measured with the Minolta luminance meter and each measurement setup was captured with the HDR images. When daylight was present in the setup, the physical measurements were made twice, before and after the multiple exposure photographs were taken. There was a time lag between the physical measurements and the multiple exposure photographs; therefore bracketing the photograph sequences with physical measurements allowed the variation of the lighting conditions to be characterized. A rectangular block of pixels (approximately corresponding to the size and location of the spot used for the luminance meter) was extracted from the digital images for each target. The selection area was fitted inside each target and excluded the borders, where the luminances could change drastically. The minimum, maximum, mean, and standard deviation of each block were studied to ensure that luminance within the selected region was uniform. This approach was considered to be more reliable than processing 1 or 2 pixel values.

3.1 Accuracy

A laboratory space was illuminated with different light sources such as an incandescent lamp, a projector (using a 500W tungsten lamp), fluorescent (T12, T8, and T5 lamps

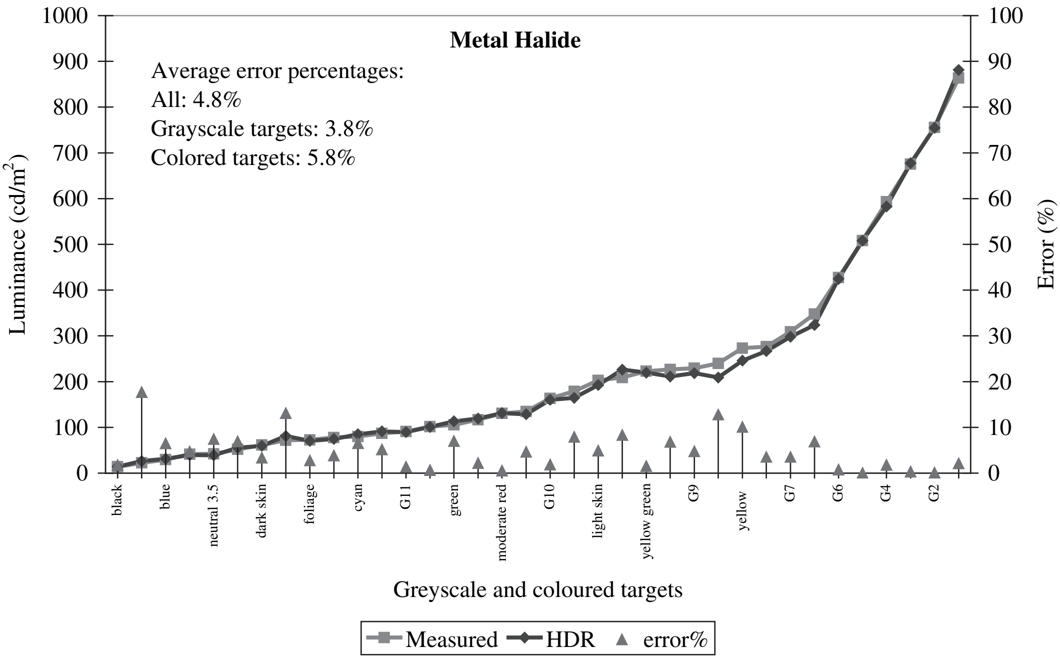

Figure 4 Dark room with greyscale and coloured targets, illuminated with a metal halide lamp

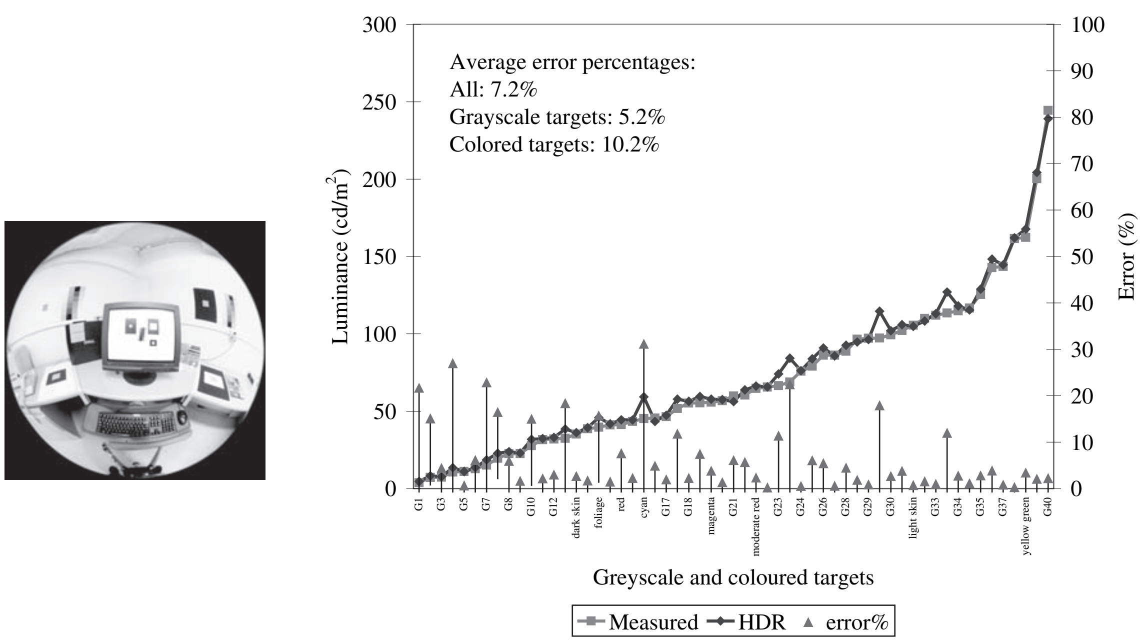

Figure 5 Coloured and greyscale targets in an office space illuminated with daylighting and electric lighting

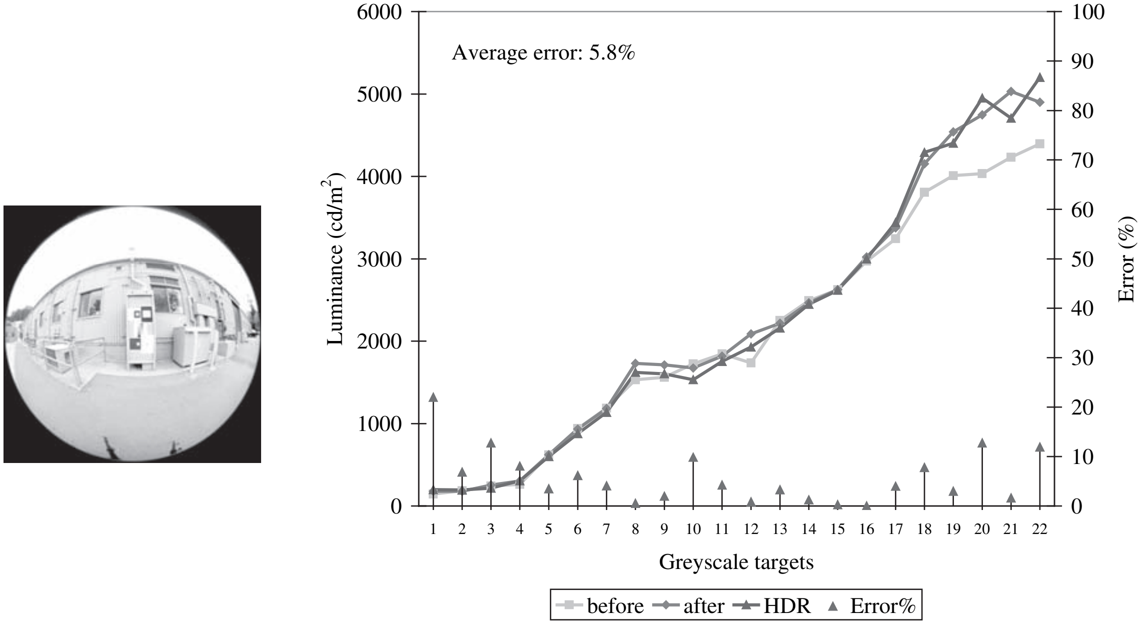

Figure 6 Outdoor scene with greyscale targets under overcast sky

with CCT of 6500K, 3500K, and 3000K, respectively), metal halide (MH), and high pressure sodium (HPS) lamps. The accuracy tests were carried out with Target 1 and a Macbeth ColorChecker® chart. Figures 2–4 show the accuracy obtained for incandescent,

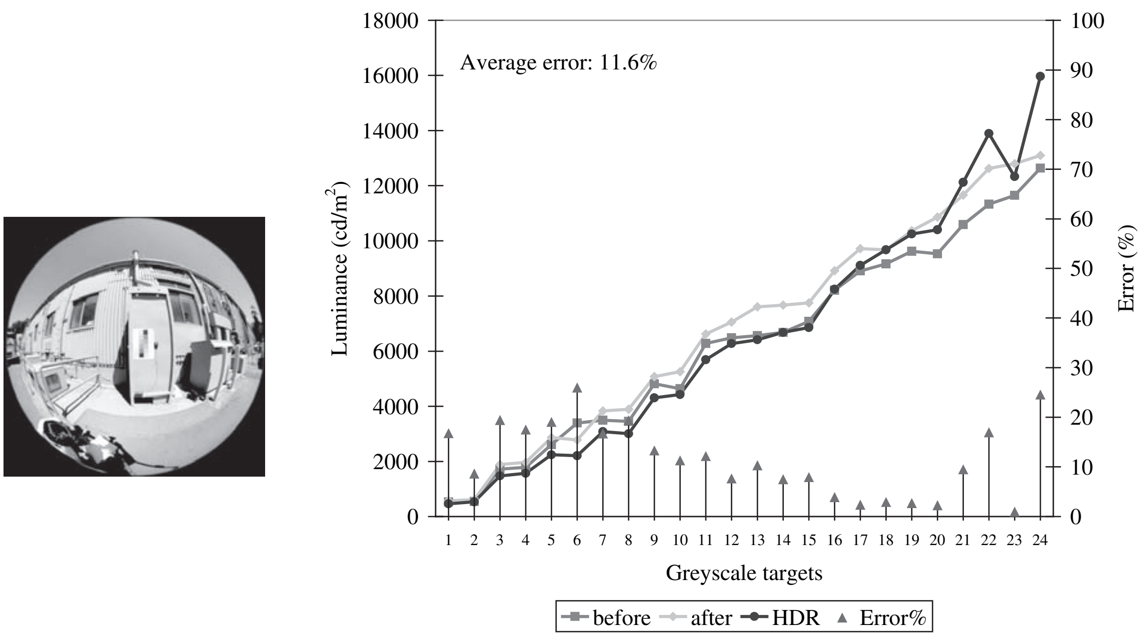

Figure 7 Outdoor scene with greyscale targets under clear sky

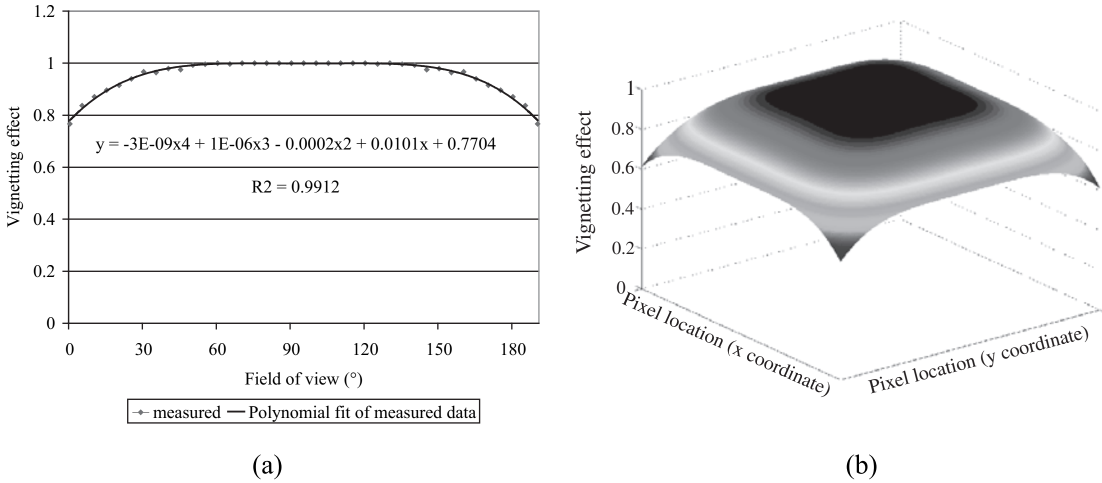

Figure 8 The vignetting function of Nikon FC9 fisheye lens. a) Measured data points and the vignetting function derived to fit the measured points; b) digital filter developed based on the vignetting function

fluorescent, and MH light sources. Although the spectral properties of the light sources were quite different, the accuracy proved to be reasonable (error margin within 10%) for all targets. The error margins for greyscale and coloured targets varied depending on the spectral power distribution of the light sources. Figure 5 shows an office space illuminated with daylight and electric lighting. Figures 6 and 7 illustrate outdoor scenes with dynamic lighting conditions. The measurement setups shown here are chosen to provide a wide spectrum of luminous environments. Additional setups have been measured and the results reveal similar error margins.[11]

3.2 Vignetting—Light fall off

The Nikon FCE9 fisheye lens uses equidistant projection to produce an image (ie, the distances between two points are projected by a constant scaling factor in all directions). The equidistant fisheye lenses exhibit noticeable light fall off (which will be referred to as vignetting) for the pixels far from the optical axis. It is therefore necessary to address and correct this aberration. The approach adopted was to determine the vignetting function of the Nikon FCE9 fisheye lens and use this function to devise a 'digital filter' in HDRLab to compensate for the luminance loss.

The camera was rotated with respect to the target in increments of 5° until the camera field of view was covered. The luminance of a target was determined from HDR photographs for each camera position and compared with the physical measurement. Figure 8 (a) illustrates the normalized data points and the polynomial function derived to fit these points. The square of the correlation (r^2) between the measured points and the derived vignetting function is 99.12%. As it can be seen from the figure, vignetting effects are insignificant in the centre of the image and the maximum effect is at the periphery with 23% luminance loss.

Figure 8 (b) is the digital filter developed in HDRLab based on the vignetting function. This filter is a matrix that has the same resolution as the fisheye image and it compensates for the vignetting effect based on the pixel locations. The vignetting function shown in Figure 8 (b) is generated for an aperture size of f/4.0. Note that vignetting is strongly dependent on the aperture size, and increases dramatically with wider apertures. Therefore,

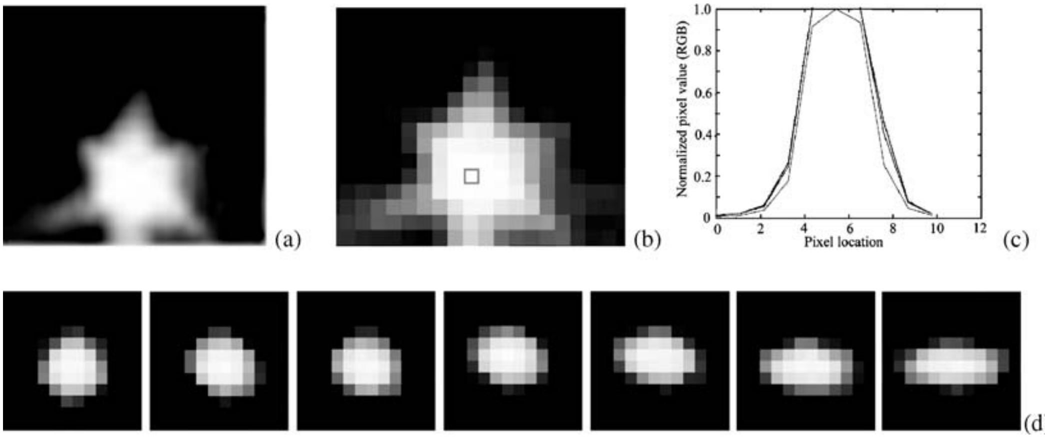

Figure 9 a) Close-up view of point spreading; the square in (b) shows the pixel that corresponds to the actual light source. c) PSF as quantified from the HDR image; d) PSF as a function of eccentricity (distance from the optical centre) in the camera field of view from 0 to 90° in 15° intervals

it is recommended that smaller apertures are used so as to reduce vignetting effects while capturing the calibration sequence which determines the camera response curves.[7]

3.3 Point spread function

It would have been very convenient to interpret each pixel in the photograph as a luminance measurement, but unfortunately, in most optical systems some portion of the pixel signal comes from surrounding areas. Light entering the camera is spread out and scattered by the optical structure of the lens, which is referred to as the point spread function (PSF).[14]

A point light source is used to quantify the PSF. The source is located far enough from the camera to ensure that theoretically it covers less than one pixel area. Without any point spread, the image of the light source should fit onto one pixel. The point spreading is illustrated in Figure 9 (a) and (b) as close-up views.

The aperture size, exposure time and eccentricity (distance from the optical centre) affect PSF. The aperture size was kept constant

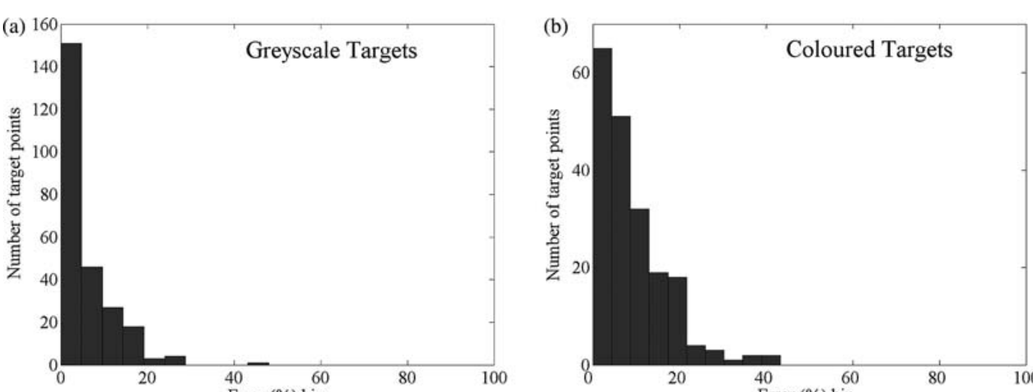

Figure 10 Histograms for error percentages between the measured and captured luminances for a) greyscale targets; b) coloured targets

throughout the capturing processes; therefore it was not a parameter affecting the luminances. The effects of exposure time and eccentricity were recorded and they were plotted in RGB channels. The PSF of the HDR image is shown in Figure 9 (c). The effect of the eccentricity was studied at 15° intervals and it is illustrated in Figure 9 (d). The spread affected a limited number of the neighbouring pixels. For most architectural lighting applications, it seems to be a small effect. However, it is important to note that the general scattering of light is such that the cumulative effect of a bright background surrounding a dark target can lead to larger measurement errors. This is indeed evident in the measurement results for darker targets shown in Section 3.1. Unfortunately, it is not feasible to quantify the general scattering. Consequently, point spread is one of the accumulative factors in the error margin, which was quantified as less than 10% on average in Section 3.1.

4. Discussion

The HDR images used in this paper were generated with the camera response functions shown in Figure 1. The luminances were calculated with the transformation functions given in Section 2.3. The calibration feature of Photosphere was used for fine-tuning the luminances with a grey target in each scene. The vignetting effect was corrected by utilizing the function shown in Figure 8.

The luminances extracted from the HDR images indicate reasonable accuracy when compared with physical measurements. Figure 10 presents a histogram for error percentages for 485 coloured and greyscale target points under a wide range of electric and daylighting conditions. The minimum and maximum measured target luminances are 0.5 cd/m^2 and 12870 cd/m^2, respectively. The average error percentages for all, greyscale, and coloured targets were 7.3%, 5.8%, and 9.3%, respectively. The square of the correlation (r^2) between the measured and captured luminances was found to be 98.8%. There is an increased error for the darker greyscale targets. As mentioned in Section 3.3, the general scattering in the lens and sensor affect the darker regions of the images disproportionately. The consequence of this scattering is an over-estimation of the luminances of the darker regions. Since the luminance is quite low for these targets, small differences between the measured and captured values yield higher error percentages.

The results also revealed increased errors for the saturated colours (Figure 10b). In Photosphere, a separate polynomial function is derived to fit to each RGB channel. However, it is important to note that the RGB values produced by the camera are mixed between the different red, green, and blue sensors of the CCD. The CCD sensors have coloured filters that pass red, green, or blue light. With the large sensor resolution, it was assumed that enough green (red, blue)-filtered pixels receive enough green (red, blue) light to ensure that the image would yield reasonable results. The sensor arrays are usually arranged in a Bayer (mosaic) pattern such that 50% of the pixels have green and 25% of the pixels have red and blue filters. When the image is saved to a file, algorithms built within the camera employ interpolation between the neighbouring pixels.[15] The HDR algorithm assumes that the computed response functions preserve the chromaticity of the corresponding scene points.[5] In an effort to keep the RGB transformations constant within the camera, the white balance setting was kept constant throughout the capturing process. The camera response functions were generated with these constraints. Likewise, the luminance calculations were approximated based on sRGB reference primaries, with the assumption that sRGB provides a reasonable approximation to the camera sensor primaries.

This work shows that the HDR photography technique is a useful tool for capturing luminances over a wide range, within 10% accuracy. It is worth mentioning that luminance meter measurements also have expected errors: $V(\lambda)$ match (3%), UV response (0.2%), IR response (0.2%), directional response (2%), effect from the surrounding field (1%), linearity error (0.2%), fatigue (0.1%), polarization (0.1%), and errors of focus (0.4%). The percentage values are published by the CIE,[16] they correspond with representative errors that are collected from the best available commercial instruments.

It is not suggested that HDR photography is a substitute for luminance meter measurements. It requires calibration against a point or area of a reliable standard target with a reliable luminance meter to have absolute validity. Yet, it provides a measurement capability with the advantage of collecting high resolution luminance data within a large field of view quickly and efficiently, which is not possible to achieve with a luminance meter. It uses equipment that is within the budgets of lighting practitioners and researchers. Additionally, the self-calibration algorithm in Photosphere provides quick and easy camera response functions compared to the lengthy calibration measurements required in prior research.

The HDR technique requires stable conditions over the period of the capturing process. Dynamic lighting conditions resulting in significant light changes between differently exposed photographs can compromise the accuracy of the end result. It is strongly advisable to measure a single target in the scene, to be used as a calibration feature. Finally, as with any measurement and simulation tool, the user should be aware of the limitations and expected errors to be able to interpret the results meaningfully.

HDR imagery provides data for qualitative and quantitative lighting analysis since HDR images can be studied for visual analysis by adjusting the exposure to different ranges, and post-processed to:

- extract photometric information on a pixel scale; this information can be utilized for statistical and mathematical analysis;
- generate false colour images (a range of colours is assigned to represent a range of luminances), iso-contour lines (coloured contour lines are superimposed on an image to demonstrate the distribution of the luminances), and calculate glare with automated analysis tools.[17,18]

Acknowledgements

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5. References

1 Uetani Y. Measurement of CIE tristimulus values XYZ by color video images: development of video colorimetry. *J. Arch. Planning. Env. Eng.* 2001; 543: 25–31.

2 Belia L, Minichiello F, Sibilio S. Setting up a CCD photometer for lighting research and design. *Building Env.* 2002; 37: 1099–1106.

3 Coutelier B, Dumortier D. *Luminance calibration of the Nikon Coolpix 990 digital camera: Proceedings of the CIE Conference*. San Diego: International Commission on Illumination, 2003.

4 Ward G. Photosphere. <http://www.anyhere.com/>.

5 Mitsunaga T, Nayar SK. *Radiometric self-calibration: Proceedings of IEEE Conference on Computer Vision and Pattern Recognition*. Fort Collins: Institute of Electrical and Electronics Engineers, 1999.
6 Debevec PE, Malik J. *Recovering high dynamic range radiance maps from photographs: Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques*. Los Angeles: SIGGRAPH, 1997.
7 Ward G. Photosphere Quick-start. <http://www.anyhere.com/>
8 Ward G. Real pixels. In Arvo J, editor. *Graphics gems II*. Academic Press, 1991: 80–83.
9 Ward G. The LogLuv Encoding for full gamut, high dynamic range images. *ACM Journal of Graphics Tools* 1998, 3: 15–31.
10 Stokes M, Chandrasekar S. Standard color space for the internet –sRGB. <http://www.w3.org/Graphics/Color/sRGB>.
11 Inanici MN, Galvin J. *Evaluation of High Dynamic Range photography as a luminance mapping technique*. LBNL Report No. 57545, Berkeley: Lawrence Berkeley National Laboratory, 2004.
12 Wyszecki G, Stiles WS. *Color science: concepts and methods, quantitative data and formulae*. John Wiley and Sons, 2000.
13 Glassner AS. *Principles of digital image synthesis*. Morgan Kaufman Publishers, 1995.
14 Du H, Voss KJ. Effects of point-spread function on calibration and radiometric accuracy of CCD camera. Applied Optics 2004; 43: 665–70.
15 Busch DD. *Mastering digital photography*. Muska & Lipman Publishing, 2004.
16 International Commission on Illumination (CIE). *Methods of characterizing illuminance meters and luminance meters: performance, characteristics, and specification*. Vienna: CIE, 1987.
17 Ward G. Radiance Visual Comfort Calculation, 1992. <http://radsite.lbl.gov/radiance/refer/Notes/glare.html>.
18 Wienold J, Reetz C, Kuhn T. *Evalglare3: International Radiance Workshop*, Fribourg, Switzerland, 11–12 October 2004. <http://www.radiance-online.org/radiance-workshop3/cd/Wienold_extabs.pdf>.

Discussion

Comment 1 on 'Evaluation of high dynamic range photography as a luminance data acquisition system' by MN Inanici

J Mardaljevic (IESD, De Montfort University, The Gateway, Leicester, UK)

The appearance of this paper is very timely as I suspect that many of us in the lighting research community are still unfamiliar with HDR imaging and the possibilities that it offers. I think it is fair to say that this work presents a significant advance over the techniques described by Moore *et al* in 2000.[1] The queries that follow are prompted by a desire to anticipate the practicalities involved in using the technique for experimental work. In particular, how much of the work described here would need to be repeated to achieve reliable results. It is noted in Section 4 that the calibration feature of the Photosphere software was applied 'in each scene'. It would be instructive to know the degree of the variation in the calibration factors across the scenes. Related to this, could Dr Inanici comment on what would be the likely impact on estimated luminance if the camera was calibrated just once against a spot measurement, and then used for long-term monitoring? The FCE9 lens that was used is described as a 'Fisheye Converter'. Is it the case that vignetting is likely to be greatest using such a lens, and are more moderate wide-angle and telephoto lenses less prone to this effect? It should be noted that Ward's Photosphere software (which runs under Mac OS X) is freely available from the URL given in the references.

Reference

1 Moore TA, Graves H, Perry MJ, Carter DJ. Approximate field measurement of surface luminance using a digital camera. *Lighting Res. Technol.* 2000; 32: 1–11.

Comment 2 on 'Evaluation of high dynamic range photography as a luminance data acquisition system' by MN Inanici

RH Simons (23 Oaklands Park, Bishops Stortford, Hertfordshire, UK)

The HDR photography system investigated by Mehlika Inanici seems principally aimed at measuring the luminances of interiors. I see no reason why this method could not be applied to recording the luminances of the road in road lighting installations.

I mention this because the last time I had to measure the luminance distribution of a road surface I was thwarted by the weather. I had to do this on a motorway which was closed for repairs and was going to be opened the next day to traffic. This then was a good opportunity for making the luminance measurements the client required. These had to be taken with a Spectra Pritchard Luminance Meter mounted on a special tripod which allowed the meter to be pointed accurately at the 30 measuring points on the road. As it might be imagined this was a time consuming business. When it came to measuring the last row of points there was a slight sprinkling of rain; slight but enough to change the reflection properties of the road completely. As the road could not be closed on the next day because of the expense and the disruption caused to the traffic, the measurements were never done.

This is a situation where HDR photography would have been a boon. I wonder whether you have had any experience of using it for road lighting measurements. I did use photography for this application in the 1950s, when I used a large plate camera. The system was crude and I would not like to hazard a guess at the accuracy. At that time we were dogged by the formation of ghost images of the road lighting luminaires diametrically opposite the images of the luminaires. We ended up using one element of a Rapid Rectilinear lens (which has two elements each consisting of cemented doublets), which certainly eliminated the ghost images. I imagine that the modern zoom lenses, with as many as eight components separated by air spaces, are very prone to give ghost images and to degradation of the image because of scattered light in the lens. Have you any advice on choice of lens?

Author's response to J Mardaljevic and RH Simons

MN Inanici

The HDR photography technique presented in this paper is a camera independent, low cost, and accessible solution for high resolution and large field of view luminance data acquisition. As Dr Mardaljevic points out, the software is freely available from the URL given in Ward[4] and it is user-friendly. Most of the work presented in this paper was done to evaluate the technique as a luminance measurement tool; hence it is not necessary to repeat the whole study to adopt the technique. Nevertheless, some of the steps have to be repeated when a different camera is employed.

It is necessary to generate a new camera response curve for each camera that is going to be used as a luminance data acquisition system. It is an easy process and the resultant camera response curve can be used for generating the subsequent HDR images. HDR photography technique has been tested with a few different camera models; and the error margins with different models were similar to the values reported in this paper. Yet, as with any measurement device, it is recommended that a few test measurements are performed to verify the accuracy.

Dr Mardaljevic enquires about the degree of variation in the calibration factors among the scenes. The calibration factors for the scenes presented in this paper vary between 0.87 and 2.09. The calibration factor is determined by dividing pixel values of a selected region in the scene by the physical luminance measurement (Minolta luminance meter) of the same region. A calibration value of ‘1’ obviously means that no calibration would be necessary. A calibration value of ‘2’ means that the pixel value of a selected region in the scene is twice the value measured by a luminance meter. The calibration factors for Figures 2–7 are given as follows: Figure 2 (laboratory space illuminated with incandescent lamp): 0.87; Figure 3 (fluorescent lamp): 0.95; Figure 4 (metal halide lamp): 0.86; Figure 5 (office space): 0.98; Figure 6 (outdoor scene with overcast sky): 1.9; and Figure 7 (outdoor scene with clear sky): 2.09. The utilization of a calibration factor becomes especially important with high dynamic range scenes such as daylit and sunlit interiors and exterior environments. Therefore, it is necessary to use the calibration factor across the scenes to assure accuracy with a 10% error margin. Yet, it would be interesting to look at the variability of a calibration factor for a single scene over time.

The author agrees with Dr Mardaljevic that vignetting is higher with fisheye lenses; and wide-angle and telephoto lenses should be expected to be less prone to vignetting. It is also important to note that aperture size has a significant effect on vignetting, and it is recommended that smaller apertures are used for reducing the vignetting effects.

Due to the limited scope of the project, the author did not attempt to evaluate it for road measurements. One of the advantages of HDR photography technique as luminance mapping tool is its ability to offer fast data collection. Therefore, as Mr Simons indicates, HDR photography technique has a great potential in recording the luminances of the road in road lighting installations.

The author thanks the discussants for their comments that serve to further describe the practicality and applicability of the HDR photography technique as a luminance data acquisition system. The author also thanks the anonymous discussant, who has pointed to the following as additional references:

References

1 Rea MS, Jeffrey IG. A new luminance and image analysis system for lighting and vision: equipment and calibration. *J. Illumin. Eng. Soc. N. Am.* 1990; 9: 64–72.
2 Illuminating Engineering Society of North America (IESNA). *IESNA approved method for digital photographic photometry of luminaires and lamps.* New York: IESNA LM-77-05, 2005.
3 Reinhard E, Ward G, Pattanaik S, Debevec P. *High dynamic range imaging: acquisition, display, and image-based lighting*. Morgan Kaufmann Publishers, 2005.