Technical Trend

Variation of Calibration Factor over Time for High Dynamic Range Photography in a Single Daylit Interior Scene

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ABSTRACT

This paper describes a study on the variation of calibration factor over time for High Dynamic Range (HDR) photography in a single daylit interior scene. Field measurements were conducted in a classroom under stable sky conditions. The luminance of each color of the X-Rite ColorChecker chart measured with a calibrated luminance meter was compared with the luminance value of the corresponding pixels extracted from the HDR image fused with low dynamic range (LDR) photographs of multiple exposures taken using a consumer grade digital single-lens reflex camera fitted with an ultra wide angle lens. The ratio between the luminances obtained from these two methods was computed and defined as the calibration factor. It was found that for each color there was a weak and not significant correlation between the calibration factor and the daylight levels ranging from about 75 to 30,000 lx. Without any significant relationship with the daylight levels, the calibration factors of each color obtained in the measurements were averaged, so that for any daylit scene with a dominant color, the real luminance could be determined by multiplying the average calibration factor of that color to the HDR luminance. The calibration factor of a 'daylit scene' in which all the 24 colors were evenly distributed was also computed, and it was 0.53 with a standard deviation of 0.03. Having more understanding about the feasibility of applying HDR photography technique as a luminance data acquisition system, researchers can have more confidence in its application for the investigation of the relationship between various luminance-based parameters and interior daylighting performance.

KEYWORDS: calibration factor, color chart, daylit environment, high dynamic range photography

1. Introduction

Luminance is a commonly used parameter to describe interior daylighting performance. The ratios between task, wall and ceiling luminances have been claimed to have a strong influence on occupants' visual satisfaction¹⁾. Lighting guides¹⁾²⁾ give recommendations of luminance contrasts between task and immediate surround and between task and general background in the work place environment. Researchers have also carried out studies on subjective preferences towards different luminance-based parameters in the field of view, such as luminance variability³⁾, luminances in the horizontal band of width 40° and in the central circle of angular subtense 40°⁴⁾. There is undoubtedly a close relationship between the luminance in the field of view and subjective preferences to an interior daylit environment. In order to develop a comprehensive daylighting performance assessment method for interior spaces, it is necessary to have a fast and effective method for the measurement of luminance and its distribution in a space.

Luminance within the field of view can be obtained using point-by-point measurements with a spot

luminance meter. However, these studies suffer from random errors, need excessive measuring time, and the obtained data generally give luminances at too few points for researchers to analyze the overall light distribution. The improved digital imaging technology allows photography to become a technique not only capable of capturing a lighting environment realistically, but also having the potential to collect luminance data within the field of view. With the advanced technology of high dynamic range (HDR) photography, the luminance within the field of view could be obtained using a consumer grade digital camera with an ultra wide angle lens in a quick and inexpensive manner.

In HDR photography, low dynamic range (LDR) photographs of multiple exposures are taken to capture a wider luminance range of a scene⁵⁾ and using the computer software called *hdrgen* fused into an HDR image with pixel values extending over the luminance span of the human visual system. This is done by saving the HDR image in RADIANCE RGBE format, a common HDR image format allowing the luminance of every pixel of the HDR image to be computed.

A previous research studied the potential, limitations and applicability of the HDR photography technique as a luminance mapping tool by laboratory and field measurements to compare the luminance values shown in the HDR images with the luminance values physically measured by a calibrated luminance meter in different settings, from black painted rooms to general office spaces and outdoors, under different kinds of light sources, from fluorescent lamps, metal halide lamps to overcast and clear skies⁶⁾. The study reported that the luminances in the HDR images correspond to the physical quantity of luminance with reasonable precision and repeatability.

Despite the encouraging findings, there is a query about the degree of variation of the calibration factor for a single scene over time due to daylight variations. The calibration factor is determined by dividing the physically measured luminance values of a selected region in the scene by the luminance values of the same region in the HDR image. Then the 'real' luminance of a point within the scene can be found by multiplying the calibration factor and the luminance value of the corresponding pixel of the HDR image. The calibration factor would most likely be kept constant over time for a confined space with stable light output, but in dynamic scenes, such as an interior daylit environment, its change over time is still unknown. It is therefore necessary to take a look at the variation of calibration factor in a daylit scene under various indoor daylight levels.

This paper reports on a study about the variation of the HDR calibration factor over time in a single daylit interior scene. A chart of 24 standardized colors was used as the scene in this study. 29 field measurements of luminance values of each color of the chart were conducted in an interior with windows under stable sky conditions, with as little daylight variations as possible during each measurement set, directly with a calibrated luminance meter and indirectly by means of the HDR imaging approach using a digital camera fitted with an ultra wide angle lens. The calibration factor of each color was computed as the ratio between the luminances of that color obtained by the two methods. Their extents of change over time were tested by correlation analysis. It is believed that having answered the question about the variation of the HDR calibration factor over a wide range of daylight levels, it would be more confident for researchers to apply the HDR technique as a luminance data acquisition system.

2. Equipment

The X-Rite ColorChecker chart, as shown in Figure 1, was used as the scene in this study. There are 24 scientifically designed 4 cm×4 cm color squares, denoted by C1 to C24. The reflectance of each color is uniform across the entire square. The sRGB values of the 24 colors

are listed in Table 1. The measurements were conducted in a typical classroom of the Hong Kong Polytechnic University with all window blinds pulled up and all electric lights turned off under stable clear and overcast sky conditions. The color chart was placed on a vertical plane perpendicular to the windows. A consumer grade digital single-lens reflex camera (Canon EOS 350D) fitted with an ultra wide angle lens (Sigma 10-20 mm F4-5.6 EX DC HSM) was mounted on a tripod at a perpendicular distance of 300 mm from the centre of the color chart. The measurements were conducted with the lens fixed at focal length of 10 mm giving a 96° horizontal field of view. A calibrated hand held luminance meter (Minolta LS-100), with 1° field of view and spectral response matching the photopic vision of human eye $V(\lambda)$, was used to perform physical luminance measurements for each color of the chart at its centre with a diameter of 10 mm. A multi-point illuminance measuring system (Konica Minolta T-10M) with four sensor heads was used to measure the daylight illuminance at the four corners of the color chart.

Figure 1 The X-Rite ColorChecker Chart used in this study

Table 1 The 24 targets in the X-Rite ColorChecker chart

Code No.	Name	sRGB		
		<i>R</i>	<i>G</i>	<i>B</i>
C1	Dark skin	115	82	68
C2	Light skin	194	150	130
C3	Blue sky	98	122	157
C4	Foliage	87	108	67
C5	Blue flower	133	128	177
C6	Bluish green	103	189	170
C7	Orange	214	126	44
C8	Purplish blue	80	91	166
C9	Moderate red	193	90	99
C10	Purple	94	60	108
C11	Yellow green	157	188	64
C12	Orange yellow	224	163	46
C13	Blue	56	61	150
C14	Green	70	148	73
C15	Red	175	54	60
C16	Yellow	231	199	31
C17	Magenta	187	86	149
C18	Cyan	8	133	161
C19	White	243	243	242
C20	Neutral 8	200	200	200
C21	Neutral 6.5	160	160	160
C22	Neutral 5	122	122	121
C23	Neutral 3.5	85	85	85
C24	Black	52	52	52

3. Camera settings

In this study, a total of nine low dynamic range (LDR) photographs of exposures within the range from -4 EV to $+4$ EV of the metered exposure were taken for each color of the chart to capture a wide luminance variation, as shown in Figure 2. Although altering either the aperture size or the shutter speed could vary the exposure values, the camera was set to Aperture Priority mode with a fixed aperture size of $f/8.0$ so that exposure variations were achieved by varying the shutter speed in Automatic Exposure Bracketing (AEB) mode, which was reported to be more reliable. Automatic White Balancing was turned off, instead Daylight White Balancing dominated. More camera settings are listed in Table 2.

Figure 2 Multiple exposure photographs of the X-Rite ColorChecker chart (First row left to right: -4 , -3 , -2 EV; Second row left to right: -1 , 0 , $+1$ EV; Third row left to right: $+2$, $+3$, $+4$ EV)

Table 2 Features used by the camera and lens system

Feature	Setting	Feature	Setting
White balance	Daylight	Metering mode	Partial
ISO speed	100	Color space	sRGB
Size/Quality	Large/Fine	Focal length	10 mm
AF mode	One shot	Auto bracket	On
AE lock	Yes	Drive mode	Continuous
Exposure compensation	None	Aperture size	$f/8.0$

4. Camera response curve

The nine exposure LDR photographs were processed to make an HDR image using the computer software called *hdrgen*⁷⁾ with a camera response curve obtained by capturing multiple exposure photographs of an interior scene with very bright and dark, large neutral grey and white surfaces, providing smooth and continuous gradients for the software to sample. Figure 3 shows the camera response curve generated by *hdrgen* used in this study based on the exposure sequences in three channels

(*RGB*) and their formulae are as follows:

$$\begin{aligned}
 R &= 1.36713x^3 - 0.80178x^2 + 0.43657x - 0.00192 \\
 G &= 1.26970x^3 - 0.66162x^2 + 0.39597x - 0.00406 \\
 B &= 1.25264x^3 - 0.63439x^2 + 0.38028x - 0.00147 \quad \dots\dots(1)
 \end{aligned}$$

where x is normalized pixel value, i.e. pixel value/255.

Once the camera response curve was known, it could be used for *hdrgen* to fuse the photographs of multiple exposures of any scene into an HDR image using the RADIANCE RGBE format.

Figure 3 Camera response curve determined by *hdrgen*

5. Measurements

The digital camera fitted with the ultra wide angle lens was placed at 300 mm in front of the X-Rite ColorChecker chart which was the scene in this study such that the chart was in the middle of the camera's field of view. For each measurement set, nine LDR photographs of multiple exposures of the scene were taken for the production of an HDR image and the luminance values were then extracted from the pixels of that HDR image. The luminance at the centre of each color of the chart was also measured with the calibrated luminance meter LS-100 at the same location as the camera three times before and three times after taking the multiple exposure photographs. The measurement area by LS-100 was a circle of diameter 10 mm so that the luminance of each color was measured entirely within the color square. Meanwhile, the vertical illuminance of the color chart was estimated by averaging the four illuminance values measured by the illuminance meters placed at the four corners of the color chart. The mean illuminance value was regarded as the indoor daylight level received by each color square of the chart during one measurement set. The time taken for each measurement set was 10 minutes and was identical for all measurement sets.

The six physically measured luminance values of each color were averaged to compare with the pixel luminance values of that color in the HDR image having the same region size as that measured by the luminance meter. The luminance value of any pixel (L) was calculated by the

floating point *RGBs* stored in the image using the following equation⁸⁾:

$$L = 179 \times (0.265 \times R + 0.670 \times G + 0.065 \times B) \quad \text{.....(2)}$$

The ratio between the luminances obtained from these two methods in each measurement was computed and defined as the calibration factor. The calibration factors of each color under different daylight levels were then analyzed by the computer program 'statistical package for social sciences' (SPSS).

6. Vignetting effect

Vignetting effect is a major optical concern during the study. It occurs in different extents for different camera and lens combinations. Since in this study an ultra wide angle lens was applied to capture the field of view as what human could see in reality, considerable light falloff occurred from the optical centre of the scene to its perimeter in a radial form. Light reduced towards the corners of the photographs and this is the vignetting effect. Although a relatively small aperture, *f*/8.0, was used in this study to mitigate the vignetting effect, the luminance values towards the corners of the HDR image were still considerably reduced, and thus appropriate corrections were required to compensate for the luminance loss.

Figure 4 The 'digital filter' for luminance loss for vignetting effect

A simple experiment was carried out in advance to determine the vignetting effect of the lens used in this study. A white surface was vertically placed in front of the calibrated luminance meter. The luminances of nine points (3×3) on the surface were measured by the luminance meter. Since it was found that the luminance variation of these points in different directions was less than 5%, the surface was assumed to be matt. This white matt surface was then put perpendicularly in front of the digital camera at a distance of 300 mm, i.e. the same distance that the color chart in the later field experiments

would be placed, so that the whole field of view of the camera was covered by this surface. LDR photographs of multiple exposures were taken for this surface and an HDR image was then fused. The luminance of each pixel of the HDR image was found. Assuming the luminance of any point on this matt surface was the same, the luminance loss due to vignetting effect was calculated by dividing the luminance of any pixel by that of the centre pixel of the HDR image of this surface. Figure 4 shows the luminance loss factor (*LLF*) of the HDR images due to vignetting effect determined by the above experiment. This is called a 'digital filter' as the *LLF* was used to correct for luminance loss in the analysis of the field measurements by modifying equation (2) into the following one:

$$L = 179 \times (0.265 \times R + 0.670 \times G + 0.065 \times B) / LLF \quad \text{.....(3)}$$

7. Point spread effect

Point spread effect is another optical effect that might be of concern in this study. In theory, a narrow light beam from a small object (point) located very far from the camera covers less than one pixel area. In practice, however, the beam would be spread out and scattered by the lens so that a small amount of light would fall on a few pixels surrounding the pixel where the image of the point falls, resulting in a loss of luminance in the image pixel to its neighboring ones. Many factors, such as the aperture size, exposure time and distance from the optical centre, affect the point spread effect. In this study, the aperture size was fixed, but it was not yet feasible to quantify the general scattering of light due to this effect, and therefore, point spread effect was neglected in this study.

8. Analysis and results

The experiments were carried out on six days at different times in a typical sidelit classroom of the Hong Kong Polytechnic University under stable overcast and clear sky conditions to investigate the variation of the calibration factor of a single daylight scene with the use of the X-Rite ColorChecker chart. 29 measurements were taken in this study under a wide range of daylight levels with the mean vertical illuminance of the color chart varying from about 75 lx to about 30,000 lx. Direct sunlight on the color chart was avoided throughout all the measurements. Table 3 lists the mean vertical illuminance (*E*) within the measurement period of each measurement set and its standard deviation (*SD*).

The data obtained was tested by correlation analysis of SPSS for investigating whether there is any correlation between the calibration factor of each color and the daylight levels. The results of the Pearson correlation coefficient (*R*) and probability value (*p* value) are tabulated in Table 4. A value of *R* closer to either -1

(negative correlation) or 1 (positive correlation) means a stronger correlation between the variables. For a 99% confidence level, the relationship is said to be statistically significant if the probability of occurrence by chance, which is expressed as p value, is less than 0.01.

In this study, there was lack of sufficient evidence to show that a strong and significant correlation exists between the calibration factors of each color and indoor vertical illuminances. It was concluded that different daylight levels would most probably not exert any influence on the variation of HDR calibration factors of any color.

Table 3 The mean vertical illuminance of color chart with a standard deviation (SD) provided for each measurement set

Measurement set	E (lx)	SD
1	74	8
2	232	18
3	239	21
4	340	13
5	343	6
6	358	25
7	365	16
8	366	7
9	395	40
10	464	18
11	487	14
12	536	21
13	559	13
14	673	73
15	682	57
16	795	59
17	820	51
18	2963	99
19	2966	110
20	4022	426
21	4306	108
22	4410	63
23	4446	16
24	4449	40
25	4502	41
26	4507	50
27	27704	701
28	28644	1134
29	29911	316

Since it was found that the change of indoor vertical illuminance levels is not a reason for the variation of calibration factors of any of the 24 colors, researchers have attempted to simply take average of the calibration factors obtained from the 29 measurements of each color, as the calibration factor CF_{color} of each color, which are tabulated in Table 4 together with the standard deviation SD . For any scene with a dominant color, calibration from HDR luminance to real luminance could be achieved by multiplying the HDR luminance by CF_{color} of that color.

In order to simplify the application of HDR photography for luminance measurement of a daylight scene, a single calibration factor across the daylight scene (CF_{scene}) was calculated for each measurement set. Assuming that the 24 colors are evenly distributed in the scene, CF_{scene} is the simple arithmetic mean of the calibration factors of the 24 colors of the chart and the calculated CF_{scene} for all the 29 measurement sets are tabulated in Table 5. The mean of the CF_{scene} of the 29 measurement sets, CF_{mean} , was found to be 0.53 with a standard deviation of 0.03. This shows that the general variation of the calibration factor of such a 'scene' within the normal indoor daylight levels investigated in this study was reasonably steady at 0.53 with an error of 5.7%. This error is within the accuracy criterion suggested by Inanici⁹ that the calibration factor across the scene should assure accuracy with a 10% error margin. The calibration factor of this 'daylit scene' was again tested by correlation analysis for confirmation to examine whether it has any close relationship with the indoor vertical illuminance levels and it was still found none ($R = -0.122$, $p = 0.529$), as shown in Table 5.

Table 4 Results of correlation analysis for the calibration factors of each color and the indoor vertical daylight illuminance levels, and the average calibration factor of each color (CF_{color})

Code No.	R	p value	CF_{color}	SD
C1	0.251	0.189	0.44	0.05
C2	-0.116	0.548	0.53	0.03
C3	0.163	0.397	0.48	0.03
C4	-0.380	0.042	0.61	0.06
C5	-0.281	0.139	0.55	0.06
C6	-0.194	0.313	0.56	0.05
C7	-0.116	0.549	0.53	0.04
C8	0.002	0.992	0.42	0.04
C9	0.110	0.569	0.45	0.03
C10	-0.279	0.143	0.52	0.06
C11	-0.337	0.074	0.63	0.05
C12	-0.254	0.184	0.61	0.06
C13	0.027	0.888	0.39	0.05
C14	0.120	0.536	0.54	0.05
C15	0.164	0.395	0.44	0.03
C16	-0.111	0.566	0.63	0.04
C17	-0.027	0.891	0.47	0.03
C18	0.032	0.871	0.47	0.04
C19	-0.171	0.375	0.59	0.06
C20	0.006	0.974	0.59	0.06
C21	0.137	0.479	0.57	0.05
C22	-0.175	0.365	0.60	0.05
C23	-0.171	0.376	0.62	0.09
C24	0.046	0.814	0.59	0.10

9. Conclusion

In order to comprehensively verify the feasibility of using HDR photography as a reliable luminance data acquisition system, field measurements were conducted to investigate the variation of the HDR calibration factor

under a wide range of daylight levels with the aid of a consumer grade digital single-lens reflex camera and an ultra wide angle lens. The X-Rite ColorChecker chart was used in this study as the single daylit interior scene. The calibration factor, i.e. the ratio between the physically measured luminance and the luminance extracted from an HDR image, of each color of the chart was analyzed with correlation analysis. A Pearson correlation was computed. It was found that the calibration factors of all the 24 colors of the chart did not have any strong and significant correlations with the interior vertical illuminance levels measured on the chart.

Table 5 The calibration factor of a 'scene' (CF_{scene}) with all the 24 colors evenly distributed and the results of correlation analysis tested with the indoor vertical illuminance levels

Measurement set	E (lux)	CF_{scene}
1	74	0.49
2	232	0.52
3	239	0.48
4	340	0.53
5	343	0.54
6	358	0.55
7	365	0.55
8	366	0.50
9	395	0.57
10	464	0.53
11	487	0.50
12	536	0.51
13	559	0.52
14	673	0.55
15	682	0.56
16	795	0.53
17	820	0.55
18	2963	0.52
19	2966	0.51
20	4022	0.57
21	4306	0.54
22	4410	0.57
23	4446	0.55
24	4449	0.59
25	4502	0.58
26	4507	0.56
27	27704	0.54
28	28644	0.50
29	29911	0.51
CF_{mean}		0.53
SD		0.03
R		-0.122
p value		0.529

In view of the fact that there is statistically no correlation with the indoor daylight illuminances, the calibration factors of each color over the investigated range of daylight levels were averaged, so that for any

scene with a dominant color the same as one of the 24 colors of the chart, calibration from HDR luminance to real luminance could then be achieved by multiplying the calibration factor of that color. It was also interesting to look into the calibration factor of a 'daylit scene' with all the 24 standardized colors evenly distributed on it, and it was found to be 0.53 with a standard deviation of 0.03. About 70% of the measurement results fell within this range.

10. Discussion

This study not only answers the question about the variation of the HDR calibration factor under a wide range of daylight levels, but also increases the researchers' confidence in applying HDR photography as a luminance data acquisition system. However, there are still some remarks from the study. Firstly, the calibration factor of 0.53 came from a 'daylit scene' made up of the 24 colors in the X-Rite ColorChecker chart, and thus, the calibration factor may slightly differ in other scenes in practice. Secondly, the experiments were only performed with one digital camera fitted with one lens. If other combinations of cameras and lens are applied, the calibration factor of 0.53 should no longer be valid, and besides, it would yet be an unknown whether a reasonably steady calibration factor exists over a wide range of daylight levels which represent changes over time of a daylit environment, like the results in this study. Lastly, the vertical illuminances investigated in this study were solely within the range of the common indoor daylight levels, and the variation of the calibration factor for HDR photography has not yet been investigated beyond this extent.

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References

- (1) Chartered Institution of Building Services Engineers: Code for Lighting (2002).
- (2) Baker, N., Fanchiotti, A. and Steemers, K.: Daylighting in Architecture: A European Reference Book, Commission of the European Communities, James & James Ltd., London, UK (1993).
- (3) Parpairi, K., Baker, N.V., Steemers, K.A. and Compagnon, R.: The luminance differences index: a new indicator of user preferences in daylit spaces, Lighting Res. Technol., 34(1), pp. 53-68 (2002).
- (4) Loe, D.L., Mansfield, K.P. and Rowlands, E.: Appearance of lit environment and its relevance in

- lighting design: experimental study, *Lighting Res. Technol.*, 26, pp. 119-133 (1994).
- (5) Reinhard, E., Ward, G., Pattanaik, S. and Debevec, P.: *High Dynamic Range Imaging: Acquisition, Display and Image-based Lighting*, Morgan Kaufmann, San Francisco, US (2006).
 - (6) Inanici, M.N.: Evaluation of high dynamic range photography as a luminance data acquisition system, *Lighting Res. Technol.*, 38(2), pp. 123-136 (2006).
 - (7) WebHDR: <http://luxal.dachary.org/webhdr/example.shtml>
 - (8) [HDRI] Calibrating HDR pictures with real world luminance. <http://www.radiance-online.org/pipermail/hdri/2006-September/000139.html>

*Figure 1 appears in color on J-STAGE; <http://www.jstage.jst.go.jp/browse/jlve/>