Color Calibration of HDR Image under a Known Illumination for Measuring Reflectance Property of Materials

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SUMMARY High Dynamic Range Imaging (HDRI) refers to a set of techniques that can represent a dynamic range of real world luminance. Hence, the HDR image can be used to measure the reflectance property of materials. In order to reproduce the original color of materials using this HDR image, characterization of HDR imaging is needed. In this study, we propose a new HDRI characterization method under a known illumination condition at the HDR level. The proposed method normalizes the HDR image by using the HDR image of a light and balances the tone using the reference of the color chart. We demonstrate that our method outperforms the previous method at the LDR level by the average color difference and BRDF rendering result. The proposed method gives a much better reproduction of the original color of a given material.

key words: high dynamic range imaging (HDRI), color calibration, device characterization

1. Introduction

The main goal of computer graphics is to realistically represent an object. For many years texture mapping has been widely used to represent an appearance of the object in computer graphics. However, most materials require physical reflectance properties to appear more realistic, and many researchers have worked on measurement based appearance modeling [1], [2].

In order to measure the reflectance properties of an object, both a spectroradiometer and a conventional digital camera can be used to estimate the radiance. In recent studies, digital cameras have become more popular due to its reasonable price [1]–[3]. To estimate the radiance using a digital camera, a high dynamic range (HDR) image is required in order to represent a wide range of real world luminance. A conventional image captured by a digital camera is called a low dynamic range (LDR) image which includes a narrow luminance range. On the other hand, an HDR image is usually constructed from several images taken with different exposure times [4], [5]. Recently, the HDR cameras which can capture a wide range of real world luminance at once have been released recently [6].

Unfortunately, all devices dealing with color including a digital camera, a monitor, a scanner and a printer have a device-dependent color space. For example, the same red color can be represented by a different RGB value for a monitor, a printer, and a scanner. Therefore, the color space of a digital camera or an HDR camera must be transformed to a device-independent color space such as CIEXYZ and CIEL*a*b* for accurate color reproduction. This leads us to make a transformation model from a device-dependent color space to a device-independent one, which is called the device characterization [7], [8].

Kim et al. proposed an accurate characterization method of HDRI for unknown illumination condition [9]. Furthermore, their method can directly calibrate an HDR image from an HDR camera. However, it requires expensive equipment such as a spectroradiometer and a customized color chart that requires uniform backlighting.

In general, the reflectance properties of an object are measured under fixed illumination condition such as D50 and D65 in most existing systems. Therefore, the HDR image can be characterized by using the conventional color chart in this environment. Some researchers have calibrated the color of the HDR image by using a color chart under a known illumination condition [10], [11]. Michael et al. calibrated LDR images by using the ICC profile before creating an HDR image, then constructed an HDR image by using the color calibrated LDR images. We call this ‘LDR level method’ since actual calibration is performed at the LDR level while our method is performed at the HDR level. This LDR level method cannot maintain an accurate radiance because the pixel values of each LDR image have been changed before constructing the HDR image. It therefore cannot deal with an HDR image generated by the HDR camera either.

Chou et al. [12] presented a color calibration method to reduce color distortions during the tone mapping step after recovering an HDR image. To estimate color distortions of the color calibration matrix, LDR images with different exposure times are needed. It therefore cannot deal with an HDR image generated by the HDR camera. Akyuz et al. [13] have also addressed issues related to the color appearance in HDR imaging. They mentioned the disconnect problem between the illumination condition of the photographed environment and the one of the viewing environment. To solve the disconnect, they use color appearance models which have a number of key parameters to describe the environment. In the image preparation process, to handle an uncalibrated HDR image, they use sRGB conversion matrix under the assumption that most digital cameras use sRGB output standard. Because the assumption leads to a significant errors, we propose a color calibration method for an HDR image without an assumption.
In this study, we propose a new HDRI characterization method at the HDR level under a known illumination condition for the system that measures reflectance properties. In contrast to the LDR level method, our method constructs a HDR image first, then the calibration is performed. To achieve accurate characterization, two novel steps are proposed: the normalization and the tone-balancing. The main advantages of using the proposed method over existing methods are as follows:

- It calibrates the HDR image at the HDR level so that it can also be used for the HDR camera.
- No special equipment such as a spectroradiometer and a uniform backlighting system is needed.

2. The Proposed Method at the HDR Level

2.1 Overall Procedure

Figure 1 shows the overall procedure of the proposed method. For the characterization of color devices, we can define a function \( f \) which transforms the device dependent color \((r, g, b)\) of an HDR image to the device independent color \((x, y, z)\) in the CIEXYZ color space:

\[
f(\text{RGB}_{HDR}) = \text{XYZ}
\]

where \(\text{RGB}_{HDR}\) is a vector \([r, g, b]^T\) of the HDR image of the color chart taken by several LDR images with different exposure time or by the HDR camera at once, and \(\text{XYZ}\) is a vector \([x, y, z]^T\) in the CIEXYZ which is provided with the color chart as a reference.

The objective is to find a transformation function \(f\) in:

\[
g = \arg \min_f \sum_{i=1}^{N_p} ||f(\text{RGB}_{HDR_i}) - \text{XYZ}_i||^2
\]

where \(N_p\) is the number of patches in the color chart, which can be solved by a least square method. Satisfying the condition of \(g\), we find a matrix \(M\) by using a polynomial regression.

A problem occurs in calculating the transformation matrix between the RGB of the HDR image and the reference XYZ of the color chart since the range of the RGB value is not fixed. Moreover, comparing the XYZ of a color calibrated HDR image with the reference XYZ requires balancing of the tone between them.

To solve these problems, we propose two novel processes: the normalization and the tone-balancing. After both processes are performed, we can compute the transformation matrix \(M\).

In the color reproduction stage, we can reproduce the original color of an HDR image from the camera by applying normalization, tone-balancing and the transformation matrix \(M\) to the HDR image.

2.2 Normalization of an HDR Image

Figure 2 represents various material samples (metallic paint coated, pearl coated, solid paint coated, non-coated etc.) we used for measuring the reflectance properties (BRDF). Each material uses a different exposure range of LDR images to make an HDR image. Figure 3 shows LDR images with different exposure times and the dynamic range used for an HDR image indicated by the arrow line.

The range of pixel value in an HDR image is not fixed.
and represents relative luminance. In other word, the same pixel value in two different HDR images does not represent the same radiance. Accordingly, the pixel values of HDR images by a diverse exposure range can be expressed as the same value but can represent different radiance. In this case, the transformation matrix $M$ from the characterization stage cannot be used directly for color reproduction because of the inconsistency in a dynamic range of HDR images between at characterization stage and at the color reproduction stage. Therefore, it is necessary to normalize every HDR image in order to keep the range of HDR images at both stages.

Fortunately, we can determine the maximum value of an HDR image which is constructed in our measuring environment since our illumination condition is known and all measurements are taken in the dark room. To determine the maximum value in this environment, we create an HDR image of a light source by using the same camera. For using the same environmental condition as creating the HDR image of a light source by using the same camera. For using the same environmental condition as creating the HDR image of a color chart, we put a mirror at the position of the chart and capture the mirrored light source at the same camera position as indicated in Fig. 1 (a).

Although the maximum pixel value of the HDR image of a light does not mean an absolute luminance, it can be considered as the maximum luminance in the measuring environment. Equation (3) represents the maximum pixel value vector $m$ of the HDR image of a light for each RGB channel.

$$m = \max(RGB_{LightHDR}), \quad j = 1 \sim P$$

where $RGB_{LightHDR}$ is a pixel value vector $[R \ G \ B]^T$ of the HDR image of a light, and $P$ is the number of pixels of the HDR image of a light.

Finally, considering $m$ as the maximum luminance, all HDR images created in the measuring environment can be normalized as follows:

$$RGB_{NormHDR} = \frac{RGB_{HDR}}{m}, \quad i = 1 \sim N_p$$

where $RGB_{NormHDR}$ is a pixel value vector of the normalized HDR image. For the characterization stage, $N_p$ represents the number of color patches in the HDR image of the color chart. For the color reproduction stage, $N_p$ is the number of pixels of the HDR image of materials.

### 2.3 Tone-Balancing

The main purpose of tone-balancing is to keep the same tone of HDR images before and after the calibration. To achieve this goal, it should be performed before constructing the transformation matrix $M$ in the characterization stage. Similarly, in the color reproduction step, it should be performed before multiplying the HDR image of a material sample by the transformation matrix $M$. To avoid confusion with tone mapping, we call this ‘tone-balancing’ in this study.

First, we compute the ratio of two values of the white patch from the reference XYZ and the HDR image of the color chart as shown in Fig. 1 (b). The ratio cannot be calculated directly since two values from the reference XYZ and the HDR image of the color chart in RGB are in different color spaces. Fortunately, we can easily obtain the sRGB value of the reference XYZ since we set the environment with fixed (D65) standard light and process all experiments in the dark room. Thus, we compute the ratio of the RGB value of an HDR image and the converted sRGB value of the reference color chart. Equation (5) is used to calculate the ratio $r$.

$$r = \frac{sRGB_{Ref}}{RGB_{NormHDR}}$$

where $sRGB_{Ref}$ is the converted sRGB of the white patch from the reference XYZ value. Applying the ratio to all color patches, tone-balanced reference values in sRGB space are computed as follows:

$$sRGB_{TBBRef} = sRGB_{Ref} \times r, \quad i = 1 \sim N_p$$

where $sRGB_{Ref}$ is a vector $[R \ G \ B]^T$ of the reference sRGB value for each patch $i$, and $sRGB_{TBBRef}$ is the tone balanced sRGB reference. Here, $N_p$ is the number of color patches of the chart. After obtaining the tone balanced sRGB reference, we can reconvert the sRGB into the XYZ, represented as the tone balanced reference XYZ, $XYZ_{TBBRef}$, by using the known transformation matrix [14].

### 2.4 Transformation Matrix

Finally, the transformation matrix between the tone balanced reference XYZ and the normalized HDR image of the chart shown in Fig. 1 (c) can be calculated by polynomial regression. The transformation is represented as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

where the vector $[X \ Y \ Z]^T$ is from the tone balanced reference XYZ, $XYZ_{TBBRef}$, and $C$ is $[1 \ R \ G \ B \ RB \ GB \ R^2 \ G^2 \ B^2 \ RGB]^T$, where R, G, B is from the normalized RGB value of the captured HDR chart image, $RGB_{NormHDR}$. $M$ is the $3 \times 11$ transformation matrix we have to calculate. The HDR images in CIEXYZ space can be acquired by applying the matrix to the HDR images which is measured in the same environment as the one in creating the matrix.

### 3. Experimental Results

#### 3.1 Color Difference

We use a Canon EOS-1D mark II digital camera and the Digital ColorChecker SG chart that contains the color reference data in this experiment. We also used D65 light sources from GretagMacbeth.
To measure the error of the color calibrated HDR image, we calculate the average color difference $\Delta E$ between the color calibrated HDR image and the reference $L^*a^*b^*$ of the chart in the CIEL*a*b* space which has the uniform color space. The HDR image of the chart and the reference XYZ are changed to the CIEL*a*b* space, in which we calculate the color difference $\Delta E$ [4].

Figure 4 shows $L^*$, $a^*$, $b^*$ values of a color patch from the reference of the color chart, the color calibrated HDR image at the LDR level, and the color calibrated HDR image at the HDR level, respectively. For the LDR level method, we calibrate each LDR image by using the ICC profile before creating an HDR image, and we construct an HDR image by using the color calibrated LDR images. We acquire the ICC profile from the Eye-One Pro and Eye-One Match provided from GretabMacbeth.

The average $\Delta E$ of the HDR level color characterization, 10.2698, is much smaller than that of the LDR level color calibration, 22.8561. Figure 5 shows the uncalibrated HDR image (a) and the calibrated one (b) by using our proposed HDR level method. Figure 5(b) shows more clear colors than those of (a).

3.2 BRDF Rendering Results Using Color Calibrated HDR Images of Materials

We examine the BRDF rendering results by using the color calibrated HDR image. The BRDF rendering is one of the most popular techniques in comparing the results in appearance modeling. Our BRDF capturing system and the measured HDR images of gold metallic paint are shown in Fig. 6 (a). The capturing system consists of a material sample of spherical shape, a light source module, a rotary stage to rotate the light source and a digital camera as the detector. The system rotates the light source from 10 degree to 170 degree with 1 degree increment. It takes about 50 minutes to capture the data of one sample, in which the size of raw image data amounts to 7.7 GB. At each light source position, we capture 10 images with different exposure times to generate HDR images. In our experiment, we use metallic paint materials which are widely used in industrial products. Figure 6 (b) shows the BRDF rendering results using the HDR images of different metallic paint materials: gold, blue and silver. In Fig. 6 (b), the first column shows the original material images, and the second is the color calibrated material images. The rest three images show the BRDF rendering results. The images in the third column show the color calibrated HDR images at the LDR level by using the ICC profile, the fourth column shows the HDR images without color calibration and the last one shows the color calibrated HDR images at the HDR level.

As shown in Fig. 6, the HDR images without calibration show poor results - the gold metallic paint looks more
reddish, the blue one more greenish, and the silver one more yellowish. On the other hand, the results of the HDR images with calibration at the HDR level show the color very close to the original for each material.

4. Conclusion

A characterization method of HDRI under a known illumination at the HDR level is proposed. The proposed method normalizes the HDR image by using the HDR image of a light source and balances the tone. We demonstrate that the proposed method gives better results than the existing methods at the LDR level by comparing the average color difference. The average color difference of our method at the HDR level is smaller than that of the previous LDR level method. Also the BRDF rendering results using the proposed method reproduce the original color very close to the color of original material. In addition, our method can be applied to the HDR images from HDR camera and requires no special equipment such as the spectroradiometer and the uniform back-lit.

However, our method has a drawback. The color reproduction should be performed in the same environment as the one in which the characterization is performed.

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