Adaptive Colorimetric Characterization of Camera for the Variation of White Balance

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SUMMARY The RGB signals generated by different cameras are not equal for the same scene. Therefore, cameras are characterized based on a CIE standard colorimetric observer. One method of deriving a colorimetric characterization matrix between camera RGB output signals and CIE XYZ tristimulus values is least squares polynomial modeling. Yet, this involves tedious experiments to obtain a camera transfer matrix under various white balance points for the same camera. Accordingly, the current paper proposes a new method for obtaining camera transfer matrices under different white balances using a 3 x 3 camera transfer matrix under a specific white balance point.

key words: camera characterization, colorimetric characterization, camera transfer matrix, camera calibration

1. Introduction

A camera is a useful acquisition tool in image processing and color communication. However, the RGB signals generated by a camera are generally device-dependent, i.e., different cameras produce different RGB responses to the tristimulus XYZ for the same scene. Furthermore, such RGB signals are not colorimetric, as they do not directly correspond to device-independent tristimulus values based on CIE color-matching functions (CMFs). The reason for this is that the spectral sensitivity of the color sensors used in cameras does not correspond to device-independent tristimulus values based on CIE CMFs [1]. Plus, the spectral sensitivity of the sensors used in different cameras varies significantly from one another. Therefore, a transform that defines a mapping between camera RGB signals and a device-independent color space, such as XYZ or CIELAB, is essential for high-fidelity color reproduction.

The transform derivation process is known as camera characterization [2]. The conventional camera characterization methods can be divided into two general categories: spectral sensitivity based [3] and color target based [4]–[8].

With spectral sensitivity-based characterization, the camera spectral sensitivity needs to be measured using specialized apparatus, such as a mono-chrometer and radiance meter. A relationship needs to be found between the camera spectral sensitivity and CIE CMFs. This relationship can then be used to transform the camera RGB values into XYZ values. As such, the basic concept of color target-based characterization is to use a reference target that contains a certain number of color samples. These color samples are then imaged by a camera and measured by a spectrophotometer to obtain the RGB values and their corresponding XYZ values. Methods such as three-dimensional lookup tables with interpolation and extrapolation [4]–[6], least squares polynomial modeling [7], and neural networks [8] are typically used to derive the transformation between the camera RGB values and the XYZ values. However, color target-based characterization is more widely used, as it only requires a known target, which makes it more practical. Plus, polynomial regression is adopted for model derivation.

Device characterization by polynomial regression with least squares fitting has already been adequately explained by many other researchers [2], [9], [10]. In particular, Hong et al. [2] studied camera characterization using variable polynomial regression with least squares fitting and found that camera characterization accuracy is reliable when the number of training samples is over 60. But, a camera has the different white balance points by the photographing conditions and it will have a different colorimetric camera characterization according to the white balance points. And the tedious experiments are required to obtain a camera transfer matrix using over 60 training samples under various white balance points for the same camera [2]. Also, the training samples must be uniformly spread within the camera’s color gamut. Therefore, a simple and flexible method is required for the colorimetric characterization of a commercial camera.

In the current paper, we propose a new camera colorimetric characterization method for obtaining camera transfer characterization matrix under different white balances using a camera transfer matrix under a specific white balance point. In experimental results, we confirm that the proposed method can produce a 3 x 3 linear transfer matrix under any other white balance with a reasonable degree of accuracy when compared with the transfer matrix obtained by the conventional method.

2. Camera Characterization of Ideal Color Camera

The intension of an ideal color camera is to provide RGB channel voltages suitable for a display with specified primary chromaticity coordinates and a specified reference white. As such, the RGB channel voltages required for the camera to produce perfect color fidelity with a specified set
of display primaries and normalizing white illuminant can be calculated for a linear system as follows [11], [12]:

\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = K^{-1} \begin{bmatrix}
x_p \\
y_p \\
z_p
\end{bmatrix} = \begin{bmatrix}
x_R \\
y_R \\
z_R
\end{bmatrix}
\]

(1)

where \(xyz\) represent the tristimulus values of the objects, the matrix \(K\) represents the tristimulus constant matrix and \(\begin{bmatrix} x_p & y_p & z_p \end{bmatrix}^T\) represents the reference white illuminant chromaticity coordinate matrix. Matrix \(K\) can be determined by requiring that the output be the desired \(XYZ\) coordinate matrix, and \(\begin{bmatrix} x_p & y_p & z_p \end{bmatrix}^T\) represents the phosphor primaries chromaticity coordinate matrix, and \(\begin{bmatrix} x_w & y_w & z_w \end{bmatrix}^T\) represents the reference white illuminant chromaticity coordinate matrix. Matrix \(K\) can be determined by requiring that the output be the desired normalizing white illuminant for equal channel voltages.

3. Proposed Camera Characterization Method

This paper proposes a new method for obtaining a camera transfer matrix under different white balances using a 3×3 camera transfer matrix under a specific white balance point. A process of the proposed method is shown in Fig. 1.

The camera characterization is determined as the product of the phosphor primaries chromaticity coordinate matrix and tristimulus constant matrix, as shown in Eq. (1). Here, the tristimulus constant matrix \(K\) is changed according to a change in the camera white balance point. Therefore, once the phosphor primaries chromaticity and reference white point of the camera are estimated, a camera characterization matrix can be easily obtained under any other white balance.

Thus, to obtain a camera transfer matrix under any other white balance according to the proposed method, the 3×3 linear transfer matrix under a specific white balance point is assumed to be equal to Eq. (1). Thereafter, the proposed method obtains the phosphor primaries chromaticity and reference white point of the camera as follows: First, \(R=1\) and \(G=B=0\) are substituted in Eq. (1) to estimate the \(R\) phosphor primary chromaticity coordinates.

\[
X = x_R K_R, \quad Y = y_R K_R, \quad Z = z_R K_R
\]

(4)

\[T = X + Y + Z = x_R K_{Rc} + y_R K_{Rc} + z_R K_{Rc} = (x_R + y_R + z_R) K_{Rc} = K_{Rc}
\]

(5)

\[
x = \frac{X}{T} = x_R, \quad y = \frac{Y}{T} = y_R, \quad z = \frac{Z}{T} = z_R
\]

(6)

The \(G\) and \(B\) phosphor primaries chromaticity coordinates are also estimated in the same way. Second, \(R=G=B=1\) is substituted to estimate the reference white chromaticity coordinates. Here, the value 1 means the normalized maximum \(RGB\) camera output. Third, the tristimulus constant matrix \(K\) can be calculated using the colorimetric coordinates estimated for the phosphor primaries and reference white point.

Therefore, a camera transfer matrix under any other white balance can be obtained using the estimated phosphor primaries chromaticity coordinate matrix and tristimulus constant matrix.

4. Experiments and Results

We have tested the performance of the proposed method with a Sony DVCAM DSR200 and the test color samples that are consisted of GretagMacbeth ColorChecker’s colors and 59 free colors. The 59 free colors covered a large color gamut in XYZ color space. The schematic diagram of camera characterization is shown in Fig. 2. The test color samples were displayed on the Sony G500 monitor, and the reference white of this monitor is fixed and not changed during test process. The camera \(RGB\) values for each test color sample calculated by averaging the \(RGB\) values of 80% of the pixels in the sample, excluding the boundary pixels. If the white balance point of camera is \(D_{65}, 5800K, 3200K,\) and \(A\) respectively, then we can calculate the camera transfer matrix \(M_{D_{65}}, M_{5800}, M_{3200},\) and \(M_A\) respectively and subscription means the white balance point of camera.

With STEP-1 of the proposed method, 2 kinds of 3×3 transfer matrix were obtained by the conventional color-target based characterization method under a specific white balance point \(D_{65}\), where \(M_{D_{65}}\) was generated by least squares fitting the camera \(RGB\) values to \(XYZ\) values using red, green, and blue samples, and where \(M_{D_{65}}\) was gen-
erated using all test samples. The camera transfer matrices \( M_{D65-\text{RGB}} \) and \( M_{D65-\text{GIM}} \) are shown in Table 1. Although the two transfer matrices were unequal, they did show a similar tendency.

With STEP-2 of the proposed method, the chromaticity coordinates for the phosphor primaries of the test camera were estimated using the camera transfer matrix \( M_{D65-\text{RGB}} \) and \( M_{D65-\text{GIM}} \). The estimated chromaticity coordinates for the phosphor primaries are shown in Table 2.

With STEP-3 and STEP-4 of the proposed method, the camera transfer matrixes under any other white balance were calculated using the estimated chromaticity coordinates for the phosphor primaries and each reference white point of the test camera. Table 3 shows the estimated transfer characterization matrices under each reference white point when using \( M_{D65-\text{RGB}} \) and \( M_{D65-\text{GIM}} \). Here, \( M_{E5,5800-\text{RGB}} \), \( M_{E5,3200-\text{RGB}} \), and \( M_{E5,\text{A}-\text{RGB}} \) mean the estimated transfer matrix under each reference white point when using the chromaticity coordinates for the phosphor primaries obtained by \( M_{D65-\text{RGB}} \). Also, \( M_{E5,5800-\text{GIM}} \), \( M_{E5,3200-\text{GIM}} \), and \( M_{E5,\text{A}-\text{GIM}} \) mean the estimated transfer matrix when using the chromaticity coordinates for the phosphor primaries obtained by \( M_{D65-\text{GIM}} \).

Finally, the performance of the camera transfer matrix was compared when using the proposed method and the conventional method under each reference white point. Table 4 shows the chromaticity errors of the proposed method and the conventional method.

### Table 1
Camera transfer matrices obtained by the conventional color-target based characterization method under D65.

<table>
<thead>
<tr>
<th>White balance point of camera</th>
<th>( M_{D65-\text{RGB}} )</th>
<th>( M_{D65-\text{GIM}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>D65</td>
<td>0.6135 0.2584 0.1748</td>
<td>0.5750 0.2240 0.1663</td>
</tr>
<tr>
<td></td>
<td>0.3131 0.6915 0.0764</td>
<td>0.2837 0.6589 0.0765</td>
</tr>
<tr>
<td></td>
<td>0.0306 0.1188 1.0330</td>
<td>0.0088 0.1099 1.0046</td>
</tr>
</tbody>
</table>

### Table 2
Chromaticity coordinates for phosphor primaries estimated by the proposed method.

<table>
<thead>
<tr>
<th>Using camera transfer matrix</th>
<th>Estimated chromaticity coordinates for phosphor primaries</th>
</tr>
</thead>
</table>
| \( M_{D65-\text{RGB}} \)    | \begin{align*}
R & : 0.6410 \quad 0.2418 \quad 0.1361 \\
G & : 0.3271 \quad 0.6471 \quad 0.0595 \\
B & : 0.0320 \quad 0.1111 \quad 0.8045 \\
\end{align*} |
| \( M_{D65-\text{GIM}} \)    | \begin{align*}
R & : 0.6628 \quad 0.2256 \quad 0.1333 \\
G & : 0.3271 \quad 0.6637 \quad 0.0613 \\
B & : 0.0101 \quad 0.1107 \quad 0.8205 \\
\end{align*} |

### Table 3
Estimated transfer characterization matrices under each reference white point when using the proposed method and the conventional color-target based characterization method.

<table>
<thead>
<tr>
<th>Estimated camera transfer matrix by the proposed method</th>
<th>Camer transfer matrix by the conventional method</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{E5,5800-\text{RGB}} )</td>
<td>0.8014 0.2706 0.1918</td>
</tr>
<tr>
<td>( M_{E5,3200-\text{RGB}} )</td>
<td>0.4089 0.7241 0.0838</td>
</tr>
<tr>
<td>( M_{E5,\text{A}-\text{RGB}} )</td>
<td>0.0400 0.1224 1.1371</td>
</tr>
<tr>
<td>( M_{E5,5800-\text{GIM}} )</td>
<td>1.2587 0.2728 0.0940</td>
</tr>
<tr>
<td>( M_{E5,3200-\text{GIM}} )</td>
<td>0.6423 0.7550 0.0411</td>
</tr>
<tr>
<td>( M_{E5,\text{A}-\text{GIM}} )</td>
<td>0.0628 0.1254 0.5559</td>
</tr>
<tr>
<td>( M_{E5,\text{A}-\text{RGB}} )</td>
<td>0.1122 0.2463 0.0438</td>
</tr>
<tr>
<td>( M_{E5,\text{A}-\text{GIM}} )</td>
<td>0.5165 0.6592 0.0191</td>
</tr>
<tr>
<td>( M_{E5,\text{A}-\text{RGB}} )</td>
<td>0.0505 0.1132 0.2587</td>
</tr>
</tbody>
</table>

### Table 4
Chromaticity errors of the proposed method and the conventional method.

<table>
<thead>
<tr>
<th>The proposed method</th>
<th>The conventional method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer matrix</td>
<td>( \Delta \mu' \nu' )</td>
</tr>
<tr>
<td>( M_{E5,5800-\text{RGB}} )</td>
<td>0.0066 6.74</td>
</tr>
<tr>
<td>( M_{E5,3200-\text{RGB}} )</td>
<td>0.0091 7.74</td>
</tr>
<tr>
<td>( M_{E5,\text{A}-\text{RGB}} )</td>
<td>0.0068 18.80</td>
</tr>
<tr>
<td>Average</td>
<td>0.0075 11.09</td>
</tr>
<tr>
<td>( M_{E5,5800-\text{GIM}} )</td>
<td>0.0084 10.20</td>
</tr>
<tr>
<td>( M_{E5,3200-\text{GIM}} )</td>
<td>0.0136 9.07</td>
</tr>
<tr>
<td>( M_{E5,\text{A}-\text{GIM}} )</td>
<td>0.0093 14.20</td>
</tr>
<tr>
<td>Average</td>
<td>0.0104 11.16</td>
</tr>
</tbody>
</table>

### 5. Conclusions
This paper proposed a new method for obtaining camera characterization matrices under different white balances based on a camera characterization matrix under a specific white balance point. As such, the proposed methods enables a camera transfer matrix under any other white balance to be obtained using the colorimetric coordinates for the phosphor primaries derived from a \( 3 \times 3 \) linear transfer matrix under a certain white balance point.

In experimental results, we confirm that the proposed method produced a \( 3 \times 3 \) linear transfer matrix under any other white balance with a reasonable degree of accuracy.
compared with the transfer matrix obtained by the conventional color-target based characterization method. That is, we can see that the average $\Delta u'v'$ of the proposed method is about 0.002 more efficient than that of the conventional method. And this chromaticity errors of the proposed method are excellent because these errors are smaller than the threshold value that two separated color patches can be distinguished. We also confirm that the proposed method is a simple and flexible solution for obtaining commercial camera characterization without the need for tedious experiments using over 60 training samples under various white balance points for the same camera.

References