Determining tone conversion characteristics of digital still cameras without a gray scale and its application to color management

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Fig. 1  Imaging with a digital still camera
Introduction

The use of digital still cameras is widespread but accurate color reproduction can be problematic. The imaging scheme for a digital still camera is shown in Fig. 1. The tone conversion characteristics of a digital still cameras are one of the most important characteristics of the camera and are also used for the transformation of raw red, green and blue digital values, $D_R$, $D_G$ and $D_B$ to colorimetric values $X$, $Y$ and $Z$ or $L^*$, $a^*$ and $b^*$. They are determined from measured digital values as a function of known luminance of an object from a gray scale included in the scene. They are called the characteristic curve in photography, the gamma characteristic in television, and the opto-electronic conversion function (OECF) in ISO 14524 [1].
There are many problems with the capture of images of gray scales such as the use of more gray patches to get precise tone conversion characteristics, non-uniform illumination and the decrease of the surrounding illumination with the 4th power of the cosine law and the vignetting factor.

We have developed a new method based on the exposure to the CCDs. The values are calculated on the basis of the digital values of two images of the same subject captured at two different levels of exposure whose ratio is known[2,3]. The obtained characteristic is a relationship between the relative exposures and the digital values, not an OECF. This is a relationship between luminance and digital values.
Fig. 2  Tone conversion characteristic curve and variables used in this study
Method of determining tone conversion characteristics

The gradient of a tone conversion characteristic curve of a digital still camera is defined as

$$ g = \frac{d\ D}{d\ \log H} $$  \hspace{1cm} (1)$$

where $D$ is the raw digital value of the camera, $D_R$, $D_G$ or $D_B$, and $H$ is the exposure to the CCD. Integrating this equation, the log exposure is expressed as

$$ \log H = \int \frac{d\ D}{g} + C $$  \hspace{1cm} (2)$$

where $C$ is the constant of integration.
In application of Eq. (2), assume that there are two images of a gray scale, images 1 and 2, and that each image has been produced under identical conditions except for exposure. If \( r \) expresses the exposure ratio of image 2 to image 1, then

\[
H_{2i} = r H_{1i}
\]

\((i = 1, 2, 3, \ldots, n)\)  \hspace{1cm} (3)

where \( i \) is the step level and \( n \) is the number of steps.

Digital values of the images corresponding to exposures \( H_{1i} \) and \( H_{2i} \) are \( D_{1i} \) and \( D_{2i} \), respectively. An average gradient between these digital values is expressed as

\[
g_i = \frac{D_{2i} - D_{1i}}{\log r}
\]

\( (i = 1, 2, 3, \ldots, n) \)  \hspace{1cm} (4)
A digital value $D_i$, at which the gradient is equal to the average gradient $g_i$, must exist in the range between $D_{1i}$ and $D_{2i}$, and is expressed as

$$D_i = \frac{w_{1i} D_{1i} + w_{2i} D_{2i}}{w_{1i} + w_{2i}}$$

(5)

where $w_{1i}$ and $w_{2i}$ are weighting coefficients. These coefficients are determined from the following equations.

$$w_{1i} = 2\Delta D_{1i} + \Delta D_{2i}$$

(6)

$$w_{2i} = \Delta D_{1i} + 2\Delta D_{2i}$$

(7)

The weighting coefficients are used in order to shift the digital value $D_i$ slightly from the midpoint of $D_{1i}$ and $D_{2i}$ towards the section of the curve having the higher gradient, since the gradient at the midpoint is virtually always slightly different to the average gradient $g_i$ [4].
The log exposure for step $i$, $\log H_i$, is then calculated from the following equation.

$$
\log H_i = \log H_{i-1} + \frac{D_i - D_{i-1}}{g_i}
$$

(8)

The digital value vs. log exposure curve can be calculated from the set of digital values from Eq. (5) and the log exposure from Eq. (8). In most cases, the constant $C$ in Eq. (2) can not be determined. It should be noted that, in turn, the actual values of $\log H$ also can not be determined because $\log H$ here has relative, but not absolute, significance.

For simplicity, the above explanations are based on stepwise images, such as images of a gray scale. In order to apply the method to pictorial images, digital values of corresponding pixels in images 1 and 2 may be used as the digital value pair $D_{1i}$ and $D_{2i}$ mentioned above.
The digital values of images 1 and 2 corresponding to the same cumulative frequency are used as the digital value pair $D_{1i}$ and $D_{2i}$.

The calculation steps for pictorial images are as follows.

(1) cumulative frequency distributions of two images are calculated,

(2) corresponding digital values of two images, $D_{1i}$ and $D_{2i}$ ($i = 1, 2, \ldots, n$), for the same cumulative frequency are determined,

(3) digital values $D_i$ between $D_{1i}$ and $D_{2i}$ are calculated as a weighted average,

(4) the log relative exposure, $\log H_i$, is integrated from digital values $D_{1i}$ and $D_{2i}$.

Thus, log relative exposures $\log H_i$ and corresponding digital values $D_i$ are calculated, i.e. tone conversion characteristics are obtained without a gray scale.
Elimination of flare

On the translation of scene luminances into the illuminances incident on the CCDs, the illuminance on each CCD consists of two parts. One part is the image-forming light, which is relative to the scene luminance, $L$, coming from the element being imaged by the lens. The other part is the nearly uniform flare light, $E_f$, reflected and scattered from the lens surfaces, the lens mount, the diaphragm and shutter blades, the inner surface of the camera body, and the surface of the CCD. The illuminance, $E$, on the CCD is the sum of these parts. Thus

$$E = cL + E_f$$

where $c$ is a constant.
The scene luminances are relative to reflectances, $r$, of patches included in a gray scale, and illuminances, $E$, are relative to exposures, $H$, which are calculated from digital values from the CCD using the tone conversion characteristics. From these variables, the following equation holds.

$$H = c' \rho + H_f$$  \hspace{1cm} (10)

where $H_f$ is the exposure for flare light, and $c'$ is a constant.

The $r$ and $H$, values of $c'$ and $H_f$ are determined from the experimental gray scale data. Exposure excluding flare is then calculated as the difference in exposure from the exposure caused by the flare light, $H_f$.

The shading of the exposures excluding flare is corrected by the exposure of white objects.
Application to color management

The corrected exposures are evaluated by the sensitivity of the CCDs.

\[ R = \int E(\lambda) S_R(\lambda) \, d\lambda \]  \hspace{1cm} (11)

\[ G = \int E(\lambda) S_G(\lambda) \, d\lambda \]  \hspace{1cm} (12)

\[ B = \int E(\lambda) S_B(\lambda) \, d\lambda \]  \hspace{1cm} (13)

In these equations, \( E \) is the spectral energy of the light coming from the subject in the original scene, and \( S_R \), \( S_G \) and \( S_B \) are the spectral sensitivities of the three color components of the CCDs used in the camera.
If the Luther condition holds, tristimulus values $X$, $Y$ and $Z$ are related linearly to $R$, $G$ and $B$.

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix} M_L \end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]  \hspace{1cm} (14)

In the equation, $M_L$ is a $3 \times 3$ matrix. If the relationship between $R$, $G$ and $B$ and $X$, $Y$ and $Z$ is nonlinear, a higher order must be included in the transform equation. Quadratic terms are used in the following equation.

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix} M_Q \end{bmatrix} \begin{bmatrix}
R & G & B & R^2 & G^2 & B^2 & RG & GB & BR & 1
\end{bmatrix}^t
\]  \hspace{1cm} (15)

In the equation, $M_Q$ is a $3 \times 10$ matrix.
Experiments and results

Two different exposure images for a scene including a GretagMacbeth Color Checker DC were captured using a Minolta Dimage RD-3000 digital still camera. One of the two images, image 1, is shown in Fig. 3.

Cumulative frequency distributions for digital value $R$ of the two images are shown in Fig. 4.

The calculated tone conversion characteristics of digital value $D_R$ is shown in Fig. 5 as a curve. In Fig. 5, the relationship between luminances and digital values is plotted as dots. A comparison of the two tone conversion characteristics demonstrates that they are almost identical except in the region of lower luminance where flare is effective.
Fig. 3 One of the images used in this study
Fig. 4  Cumulative frequencies of digital value $D_R$ for two images
Fig. 5 Calculated tone conversion characteristics for digital values $D_R$ (curve) and measured digital values from a gray scale (dots)
Fig. 6  Cumulative frequencies for red, green, blue and Total digital values
Application to color management

Colorimetric values for color patches were calculated using both the proposed and conventional processes with a gray scale using the analytical model. The tone conversion characteristics obtained with the conventional process are shown in Fig. 5, in which eight gray patches in the test chart for digital still cameras published by The Institute of Image Electronics Engineering of Japan were captured using the RD3000 camera, and spline interpolation was used to smooth the curve.

Calculation was performed using two processes. In the proposed process, the tone conversion characteristics were determined with the new method and flare was eliminated. In the conventional process, the tone conversion characteristics were determined with a gray scale in the scene and spline interpolation, and flare was not eliminated.
The following calculation steps were used.

1) digital values $D_R$, $D_G$ and $D_B$ were linearized to exposures $R$, $G$ and $B$ using the tone conversion characteristics,
2) flare was eliminated from exposures in the new process and shading of the exposures corrected in both processes,
3) tristimulus values $X$, $Y$ and $Z$ were calculated from exposures using Eqs. (14) and (15),
4) $L^*$, $a^*$ and $b^*$ were calculated from $X$, $Y$ and $Z$
5) color differences between calculated and original values of $L^*$, $a^*$ and $b^*$ were calculated

The color differences for the two processes are shown in Table 1. Mean and maximum color differences for the new process were less than those for the conventional process.
Table 1  Color differences for the two processes

<table>
<thead>
<tr>
<th>Combination</th>
<th>Process</th>
<th>Proposed</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>mean</td>
<td>4.1</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>24.4</td>
<td>29.5</td>
</tr>
<tr>
<td>Quadratic</td>
<td>mean</td>
<td>2.2</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>6.3</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Proposed process: calculated, excluding flare
Conventional process: using gray scale, including flare
Discussion

With regard to the importance of the accurate reproduction of gray levels, the identification of the three tone conversion characteristics of digital values $R$, $G$ and $B$ was confirmed. The cumulative frequencies of digital values $R$, $G$ and $B$ were summed and the cumulative frequency of the total digital value was obtained. Tone conversion characteristics of total digital value were calculated and compared to those of digital values $R$, $G$ and $B$. The characteristics of total digital values approximated the average of the digital values $R$, $G$ and $B$.

In Table 1, the mean and maximum color differences for the new process were less than those by the conventional process. It was assumed that the error in the tone conversion characteristics and the nonlinearity between $R$, $G$ and $B$ and $X$, $Y$ and $Z$ decreased.