Color Temperature Estimation of Fluorescent Scene Illumination

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Abstract

Fluorescent light sources have spectral power distributions with strong spikes. This paper proposes an analysis method for examining the reliability of color temperature estimation of any scene illuminant including fluorescent light sources. We define a color-rendering index for evaluating any light source relative to the blackbody radiators reference illuminants. We show that the sensor correlation method can be used for estimating the color temperature of fluorescent scene illuminants with high color-rendering indices. Both the color-rendering index and the gamut correlation coefficients are useful for examining the reliability of illuminant color temperature estimates. The feasibility of the proposed method is demonstrated in experiments where the Macbeth Color Checker and a natural scene are illuminated with several real fluorescent lamps.

Introduction

Estimation of scene illumination from image data has important applications in many fields of color science, computer vision, image processing, color imaging, image reproduction, and image database retrieval. The theory of scene illuminant estimation has a long history, and a large number of estimation algorithms have been proposed. However, illuminants with spectral-power distributions including spikes, such as fluorescent illuminant, have been neglected as a target scene illuminant.

The spectral-power distributions of fluorescent light sources do not approximate those of natural daylight. The spectral distribution of a fluorescent lamp or a mercury arc lamp includes intense spectral lines and a weaker continuous spectrum. Because most estimation algorithms depend on strong physical constraints, such as low-dimensional linear models with smooth basis functions, such spikes are not well represented. Yet fluorescent sources are often used as indoor lighting.

Therefore we discuss illuminant classification for inferring scene illumination with spiky spectrum. Illuminant classification, in which the scene illumination is classified as belonging to one of several likely types, is a simple and stable computation. A typical case of illumination classification is to restrict the estimation to a set of blackbody radiators, say spaced every 500 degrees Kelvin (K). We previously presented the sensor correlation algorithm for classifying scene illuminations by color temperature of the blackbody radiators.[1-3] The color temperature was estimated by finding the best match between the image color gamut and the reference illuminant gamut.

Fluorescent light sources have spectral power distributions with strong spikes. Even though the color of two sources of the fluorescence and blackbody radiator types may match, the appearances of objects in a scene illuminated by these two sources can differ. This means that the illuminant gamut of a fluorescent source can differ from the illuminant gamut of the blackbody radiator with the same correlated color temperature. As the difference increases, the reliability of color temperature estimation decreases.

In this paper, we propose an analysis method for examining the reliability of color temperature estimation of any scene illuminant including fluorescent light sources. We define a color-rendering index for evaluating any light source relative to the blackbody radiators reference illuminants. We show that the sensor correlation method can be used for estimating the color temperature of fluorescent scene illuminants with high color-rendering indices. Both the color-rendering index and the gamut correlation coefficients are useful for examining the reliability of illuminant color temperature estimates.

Illuminant and Color Temperature

The sensor correlation method classifies scene illuminants according to their blackbody color temperature. The color temperature of a light source is defined as the absolute temperature (in Kelvin, K) of the blackbody radiator. For an arbitrary illuminant, the correlated color temperature is defined as the color temperature of the blackbody radiator that is visually closest to the illuminant. The equation of the spectral radiant power of the blackbody radiators as a function of temperature T (in K) is given by the formula[4]

$$M(\lambda) = c_1 \ \lambda^{-5} \ \{\exp(c_2/\lambda T) - 1\}^{-1}, \qquad (1)$$

where c_1 = 3.7418 x 10^{-16} Watts-m^2 and c_2 =1.4388 x 10^{-2} Watts-K and λ is the wavelength (nm). The spectral power distributions corresponding to color temperatures spanning 2500-8500K are shown in Figure 1.

Differences in color temperature do not correspond to equal perceptual color differences. Visually equally significant differences of color temperature correspond more closely to equal differences of the reciprocal color temperature. The unit on the scale of micro-reciprocal degrees ($10^6 K^{-1}$) is called "mired". This unit is also called "remek", which is the contraction for a unit of the International System of Units (SI), the reciprocal megakelvin ($M\ K^{-1}$). The blackbody radiators are written as a function of the reciprocal temperature T' as

$$M(\lambda) = c_1\ \lambda^{-5}\ \{\exp(c_2 T'/\lambda) - 1\}^{-1}, \qquad (2)$$

where c_1 = 3.7418 x 10^{-16} Watts-m^2 and c_2 =1.4388x 10^4 Watts/mired. In Figure 1, the spectral-power distributions of the blackbody radiators are represented at the reciprocal color temperatures, spanning *T'(1)*=118 mired (8500K) to *T'(13)*=400 mired (2500K) in 23.5 mired increments.

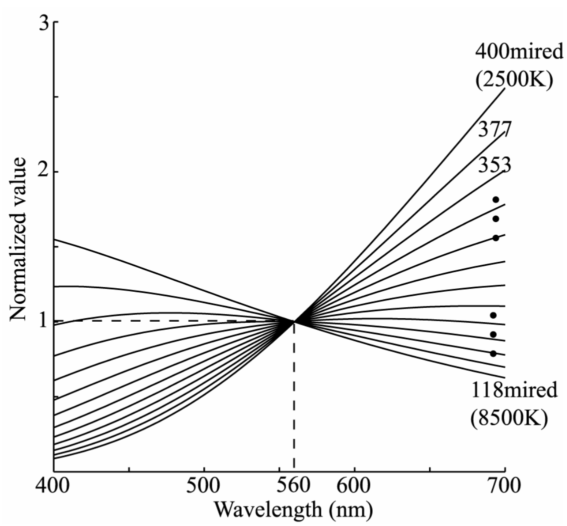

Figure 1. Spectral power distribution of blackbody radiators.

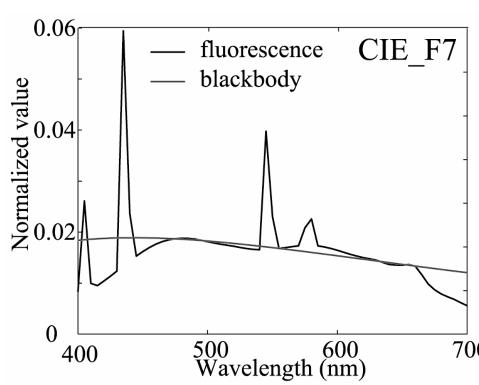

Figure 2. Spectral power distribution of a typical fluorescent lamp

The CIE defined the relative spectral power distributions of illuminants representing typical fluorescent lamps.[5] This set of illuminants consists of twelve light sources, including daylight fluorescence, cool white fluorescence, and tri-band fluorescence. For example, Figure 2 depicts the spectral power distributions of the illuminant F7. For comparison to blackbody radiators, the red curve represents the spectrum of the corresponding blackbody radiator with the same color temperature as the correlated color temperature of the fluorescent source.

Illuminant Gamuts

Illuminant classification algorithms use a set of reference illuminant gamuts to define the anticipated range of sensor responses. When we capture a color image of a natural scene under an unknown illuminant, a correlation between the image data and the illuminant gamuts with different color temperatures can be computed. A color temperate with the peak correlation is then selected as the estimate of illuminant color temperature.

In order to create these gamuts, we used a database of surface-spectral reflectances provided by Vrhel et al.[6] together with the reflectances of the Macbeth Color Checker. The image data were obtained using a Minolta camera (RD-175) with known sensor sensitivities. Hence, the sensor responses can be predicted using

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \int_{400}^{700} S(\lambda) M(\lambda) \begin{bmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{bmatrix} d\lambda, \qquad (3)$$

where $S(\lambda)$ is the surface-spectral reflectance function and $r(\lambda)$, $g(\lambda)$, and $b(\lambda)$ are the spectral sensitivities, and $M(\lambda)$ is the scene illuminant. The camera can be operated in one of tungsten mode and daylight mode. Operating with the high blue sensor gain improves the performance of the scene illuminant classification. Hence, all analyses throughout this paper were performed in the tungsten mode. The scene illuminants for classification are blackbody radiators spanning 118 mired (8500K) to 400 mired (2500K) in 23.5 mired increments, as shown in Figure 1.

We calculate the illuminant gamuts for fluorescent light sources with the CIE spectral power distributions for $M(\lambda)$ in Eq.(3). First, the illuminant gamuts are calculated on the rb-chromaticity plane by using the transformation r=R/(R+G+B) and b=B/(R+G+B). Figure 3 shows the chromaticity gamuts for 12 fluorescent illuminants F1, F2, ..., F12. There is very little separation between illuminants. Therefore the chromaticity correlation method fails in classifying the fluorescent light sources.

In our sensor correlation method, the illuminant gamuts are defined on the RB-plane. The boundary of the illuminant gamut is obtained from the convex hull of the set of (R, B) points. Figure 4 shows the illuminant gamuts of the blackbody radiators for 13 successive temperatures in the RB-plane. In the figure, gamuts are depicted at equal spacing in reciprocal color temperatures. For example, the illuminant gamuts for CIE F3 and F7 are depicted in red bold lines in Figure 4. The correlated color temperatures of F3 and F7 are 3445K and 6493K, respectively. In the figure, the ranges depicted with red dotted lines indicate the illuminant gamuts for the corresponding blackbody radiators with the same color temperatures. A comparison between the red bold polygon and the red dotted polygon suggests that a good coincidence is obtained between the fluorescent gamut F7 and the corresponding blackbody gamut, while the fluorescent gamut F3 is included in another blackbody gamut with different color temperature.

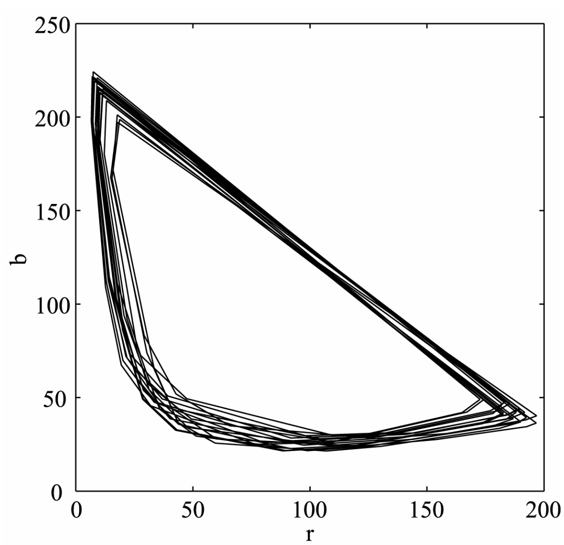

Figure 3. Illuminant gamuts for CIE fluorescent light sources in the rb-chromaticity plane.

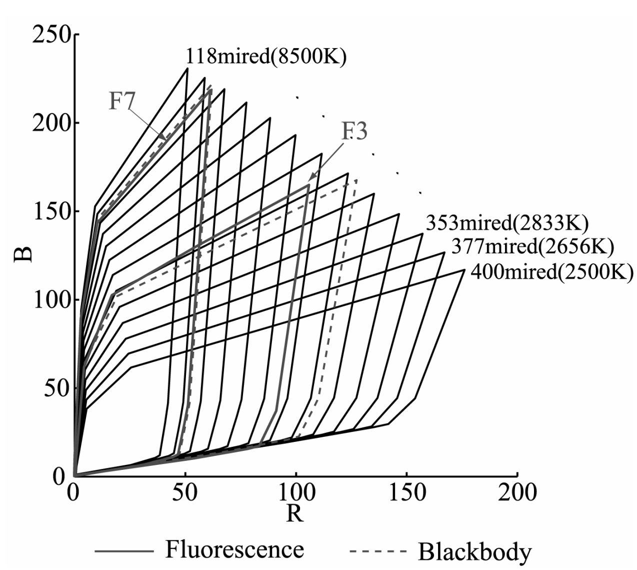

Figure 4. Illuminant gamuts for black body radiators. and CIE F3 and F7 in the RB-sensor plane.

Color-Rendering Index

Color rendering of a light source is the subject of predicting effect the source has on the color appearance of objects in comparison with their appearance under a reference source. A fluorescent light source has a different effect on color rendering than a blackbody radiator. Therefore, a color-rendering index for a given light source is useful as a measure of the degree to which the perceived colors of objects illuminated by the source conform to those of the same objects illuminated by a standard source.

The CIE recommended a technique for calculating the color-rendering index.[4,7] The reference illuminants are defined to be the CIE daylight D for correlated color temperatures greater than or equal to 5000K and blackbody radiators for correlated color temperatures less than 5000K. The CIE technique defines a special color-rendering index as $R_i = 100 - \Delta E_i$, where the color difference ΔE_i is based on the Euclidian distance between the color of the sample under the test and reference sources in a uniform color space. A general color-rendering index is defined as the average of the special color-rendering indices for eight specified Munsell color samples.

We found that the color-rendering index is closely related to the performance of our scene illuminant classification algorithm by the color temperature of the blackbody radiators. The eight test-color samples recommended by the CIE represent colors around the hue circle of moderate saturation and equal lightness. These color samples form an illuminant gamut in a proper color space for a specific light source. Then the average color difference between the color samples illuminated by the test source and those illuminated by the reference blackbody radiator corresponds to a shift of the illuminant gamut in the color space as the illuminant changes from the test to the reference. The color-rendering index is inversely proportional to the average color difference. Therefore, if a test illuminant has a high value of the color-rendering index, the shift of the illuminant gamut is small, that is, the gamut of the test illuminant is closely located to the one of the reference illuminant. Thus, the color-rendering index can be used a measure of how closely a test illuminant gamut is to the corresponding blackbody radiator's gamut, so that it can be used as a performance measure of illuminant classification based on blackbody radiators.

We define a new color-rendering index that specializes the illuminant classification based on blackbody radiators. The reference illuminants are blackbody radiators only. The test-color samples are all surfaces in the database used for determining the illuminant gamut. The color-rendering index R_a is defined as

$$R_a = 100 - c\,\overline{\Delta E}\,, \qquad (4)$$

where

$$\overline{\Delta E} = \frac{1}{N}\sum_{i=1}^{N} \Delta E_i\,. \qquad (5)$$

The average $\overline{\Delta E}$ represents the arithmetic mean of the color difference ΔE_i over all the surfaces, where ΔE_i is calculated in a uniform color space by using the surface-spectral reflectance of each sample and both spectral-power distributions of the test illuminant and the corresponding blackbody radiator. In this study, the constant c is chosen so that the color-rendering index becomes equal to 50 when the fluorescent lamp CIE F4 is used as a test source.

The values of the color-rendering indices for the CIE fluorescent light sources are plotted in Figure 5, where the color difference was calculated using the CIE-U*V*W* color space (see p. 828, Ref. [6]). The black line marked with triangles in the figure suggests that F6 has the lowest value of around 50, and F8 has the highest of around 90.

The color-rendering index is closely related to the degree of conformity between the two illuminant gamuts of a test source and the corresponding reference source. Therefore, it is appropriate to compute a correlation coefficient between the two illuminant gamuts because the illuminant classification algorithm is based on correlation between the observed image gamut and the reference illuminant gamut. The gamut correlation coefficient is computed from the area of the gamuts in the RB plane as

$$r = S_{\mathrm{TR}} / \sqrt{S_{\mathrm{T}} S_{\mathrm{R}}} \,, \tag{6}$$

where S_{T} and S_{R} are the areas of test and reference gamuts, and S_{TR} is the area of overlap between the two gamuts. In Figure 5, the red line marked with circles shows the correlation coefficients between the fluorescent light sources and the corresponding blackbody radiators with the same correlated color temperatures. Note that the variation of the correlation coefficients is similar to the one of the color-rendering index.

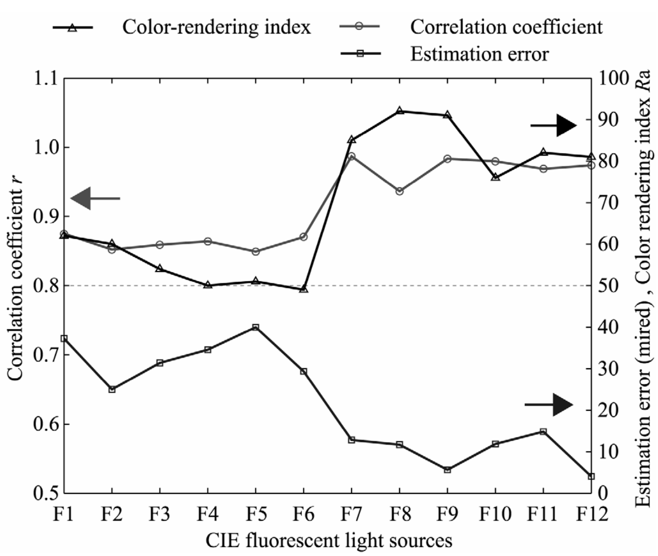

Figure 5. Variations of the color-rendering index, the correlation coefficient, and the estimation error for the CIE fluorescent lights.

The color-rendering index provides an effective measure for predicting the performance of color temperature estimation by the illuminant classification algorithm. We can demonstrate this fact in a simple simulation based on the CIE fluorescent light sources. First, the correlation values are computed between the illuminant gamut of each fluorescence and all illuminant gamuts of 13 blackbody radiators shown in Figure 4. Second, the illuminant color temperature with the peak correlation is selected as a color temperature estimate for the fluorescent illuminant. Third, the estimation error is computed as the difference between the estimated color temperature and the original correlated color temperature in the reciprocal color temperature unit (mired). The errors are depicted by the blue line marked with rectangles in Figure 5. Note that the estimation error varies in inverse proportion to the color-rendering index. That is, the two curves of the error and the index are symmetrical with respect to the horizontal line.

Experiment

The sensor correlation algorithm is applied to color temperature estimation of fluorescent scene illumination from image data. The proposed color-rendering index can then be used for predicting the estimation reliability

Six real fluorescent lamps of White, Mellow 5D, Test Color D65, Meat Display, Museum (bulb), Museum (daylight), and Plant Lighting were used in our experiments. First we illuminated the Macbeth Color Checker with these light sources, and captured six images of the color checker scene. For example, Figure 6 shows the plot of the (R, B) pixel values on the illuminant gamuts for the Museum (bulb) lamp, where the red curves represent the image gamuts, and the black bold curves represent the correctly classified illuminant gamuts. Good estimates of color temperature are obtained in this case. Figure 7 depicts the estimation errors for all images. The color-rendering indices and the correlation coefficients are also plotted in the figure.

Large estimation errors occur in the cases of Meat Display and Plant Lighting that have very low values of the color-rendering index. These are not general-purpose, but special-purpose light sources for enhancing specific spectral regions. From these results, we can obtain a reliable estimate of color temperature for any light source with $R_a \geq 60$ without exception. Note that even though $R_a < 60$, a good performance is obtained for White.

Moreover, the proposed analysis method was applied to a natural scene. The scene of the left in Figure 8 was photographed under the three illuminants of White, Mellow 5D, and Test Color D65. The (R, B) pixel values and the image gamut of images under Mellow 5D are depicted in Figure 9. Table 1 summarizes the estimation accuracy for the Macbeth Color Checker and the natural scene. The measurement values of color temperature were obtained from direct measurements using a spectro-radiometer. The estimation error is then defined as the difference between the estimated color temperature and the direct measurement.

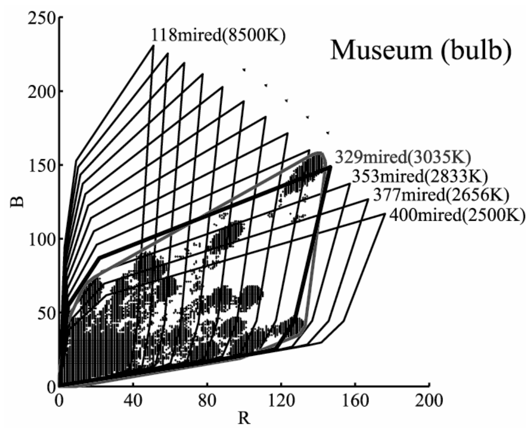

Figure 6. Plot of the (R, B) pixel values for the Museum lamp.

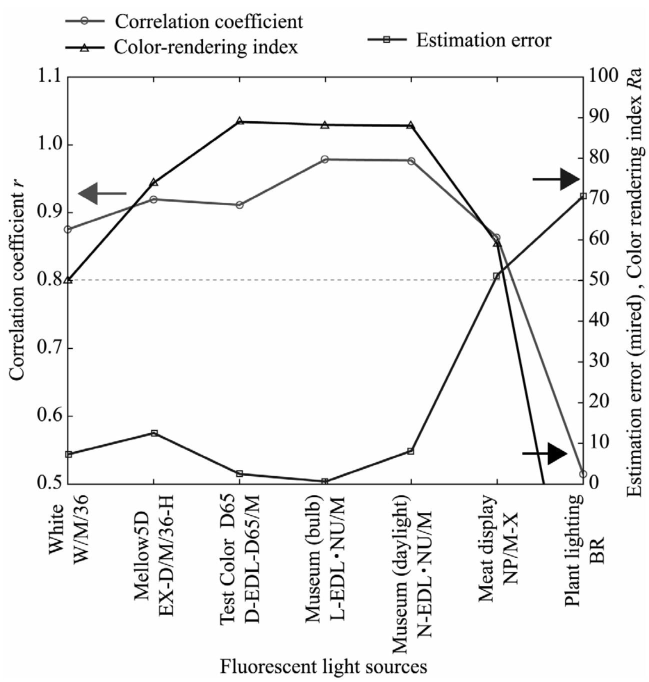

Figure 7. Estimation errors, color-rendering indices, and correlation coefficients for all images of the Macbeth Colors.

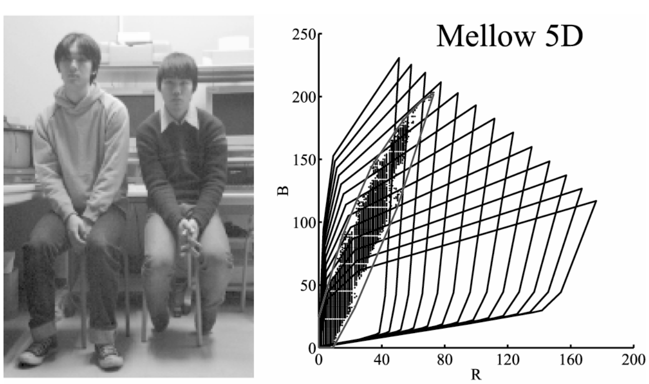

Figure 8. Application to a natural scene under fluorescent lights.

Thus, the sensor correlation method can be used for estimating color temperature of fluorescent scene illuminants with relatively high color-rendering indices. Both the color-rendering index and the gamut correlation coefficients are useful for examining the reliability of illuminant color temperature estimation.

Table 1. Estimation accuracy for the real scenes.

Light sources	Macbeth Color Checker	Natural scene
	Difference (mired)	Difference (mired)
White	7.43	10.11
Mellow5D	2.59	8.08
Test Color D65	12.65	0.30
Meat display	51.27	
Museum (bulb)	0.65	
Museum (daylight)	8.07	

Conclusion

This paper has proposed an analysis method for examining the reliability of color temperature estimation of any scene illuminant including fluorescent light sources with strong spikes. A color-rendering index was defined for evaluating any light source relative to the blackbody radiators reference illuminants. We have shown that the sensor correlation method can be used for estimating the color temperature of fluorescent scene illuminants with relatively high color-rendering indices. Both the color-rendering index and the gamut correlation coefficients are useful for examining the reliability of illuminant color temperature estimates. The feasibility of the proposed method was demonstrated in experiments where the Macbeth Color Checker and a natural scene are illuminated with several real fluorescent lamps. Thus, the sensor correlation method is available for most fluorescent scene illuminants used in our everyday lives.

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Biography

Shoji Tominaga received the B.E., M.S., and Ph.D. degrees in electrical engineering from Osaka University, Toyonaka, Osaka, Japan, in 1970, 1972, and 1975, respectively. Since 1976, he has been with Osaka Electro-Communication University, Neyagawa, Osaka, where he is currently a Professor with the Department of Engineering Informatics, and a Dean of the Faculty of information Science and Arts. His research interests include computer graphics, color image analysis, reflection modeling, and color vision. He is a senior member of IEEE and a member of OSA, IS&T, SID, SPIE, and ACM.