Improved Spectral-Reflectance (SR) Estimation Using Set of Principle Components Separately Organized for Each SR Population with Similar SRs

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Abstract

This paper proposes an algorithm that can reduce the estimation error of surface spectral-reflectance(SR) when using a conventional 3-band RGB camera. In the proposed method, the estimation error is reduced by using adaptive principle components(PCs) for each color region. To build an adaptive set of PCs, n SR populations are organized for n PC sets using the Lloyd quantizer design algorithm. The Macbeth ColorChecker is utilized for the initial representative SR values for 1485 Munsell color chips as the total color population, then the Munsell chips are divided into subsets with a set of corresponding adaptive PCs organized for each subset. To evaluate its performance, the proposed estimation method is compared with a conventional 3-band principle component analysis(PCA), 5-band Wiener estimation method, and another conventional 3-band PCA method in estimation experiments for randomly selected SRs from Munsell color chips. The proposed method exhibited a superior estimation performance compared to the two 3-band PCA methods and 5-band Wiener method.

Introduction

The input colors of a camera are stimuli that are multiplied by the spectral distribution of the ambient illuminant, the SR of an object, and the camera sensitivity. Accordingly, since SR is a significant factor indicating the color of an object, estimating the SR of an object using a multi-spectral camera system has already received widespread attention. If a photograph is taken using a camera system with many filters, estimating the SR of an object using a Wiener estimation method[1,2] or PCA method[3-8] can enable color reproduction based on the spectral distribution.

It has been previously reported that if more than five filters are used when estimating a natural color, the SR of an object can be estimated within the color difference that can be discriminated by human vision. However, the use of additive color filters and taking photographs additively when using a 5-band image acquisition system is difficult. Therefore, to produce an accurate estimate of the SR using an existing RGB camera, decreasing the color difference for each color by composing similar SR populations[10] and finding separate principle component vectors for each similar SR population has been suggested. However, since this method uses the Macbeth ColorChecker as a reference when dividing the total colors into regions, the short-coming is that the Macbeth ColorChecker cannot represent the total population. As such, the error variance for the estimation of the SR increases between the populations when estimating the SR of an object.

Accordingly, to solve this problem, this paper proposes a method for obtaining an optimal population, where the Lloyd quantizer design algorithm[9] is applied to identify similar SR populations, thereby reducing the estimation error and improving the cumulative distribution for each SR population.

SR Estimation Using Set of Principle Components Separately Organized For Each SR Population with Similar SRs

The SR curve of an object is relatively smooth in relation to the illumination and does not change suddenly. Therefore, several researchers, like Cohen,[3] Maloney,[4] and Pakkienen,[5] have estimated the SR of an object using a linear model composed of several principle components. The principle component or basis function is computed using spectral data on measured color chips from the color appearance system.[12] The estimation performance of a PCA method is determined by the number of principle component vectors used: i.e. the higher the number of principal component vectors used, the lower the estimation error. As such, the estimation of the SR of an object relative to the number of principle component vectors can be evaluated as a cumulative distribution ratio as follows:

$$p_m = 100 \times \frac{\sum_{i=1}^{m} a_i}{\sum_{i=1}^{n} a_i} \tag{1}$$

where n is the sample size of SRs and m is the number of principle components.

In this paper, the principle component vectors are obtained based on values measured at 1nm intervals within a range of 380-780nm using the Munsell system. Samples are then made from the value of each SR measured at 10nm intervals within a range of 400-700nm.

Therefore, to improve the cumulative distribution ratio when using a conventional RGB camera, the current study estimates the principle component vectors separately for each population after composing similar SR populations. A flowchart of the proposed method is shown in Figure 1.

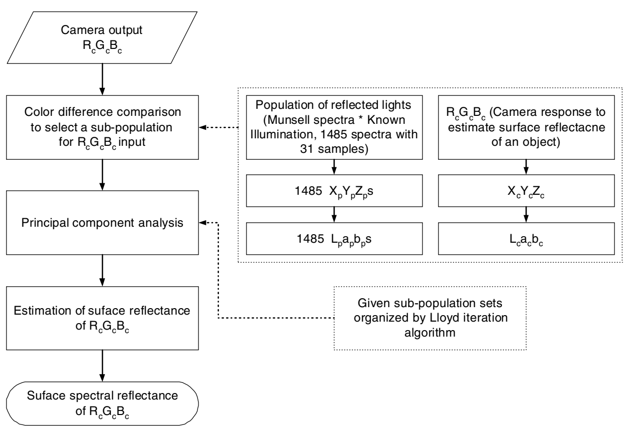

Figure 1. Flowchart of the proposed surface spectral estimation using set of principle components separately organized for each population of spectral reflectance.

Estimating the SR of an object from the RGB values, i.e. the output of the camera, requires the mean of the SR, the principal vectors, and the extension coefficient of each principle component based on the assumption that the camera's characteristics can be modeled. In the case of a conventional PCA, common principal vectors in a population are identified based on the assumption that the Munsell population includes the SR of every color. As shown in Fig. 1, the proposed method does not use the total Munsell population to find the principal vectors, but rather identifies separate principal vectors for each population after obtaining similar separate SR populations from a 1485 Munsell population. To find the color of arbitrary RGB values related to a certain population, the population, including the input values, is identified through comparing the color difference and finding the principal vectors using the total SR data included in that region. Then, the SR of an object can be estimated.

Lloyd Algorithm for Composing the Similar SR Population

The proposed method in Fig. 1 is similar to conventional methods in the sense of applying the principal vectors to SR populations composed of similar SRs. The method proposed in Ref. [10] uses 24 color chips from the Macbeth ColorChecker as center colors for dividing the total Munsell population into similar SR populations. That is, the most similar number N of Munsell color chips is identified using the color difference between about 24 color chips from the Macbeth ColorChecker, then similar SR populations are composed using the assigned 24 SRs. Yet, the colors in the Macbeth ColorChecker can not be center colors for the SRs of all the Munsell color chips, despite being spread relatively uniformly throughout CIELAB color space.

Therefore, to identify optimal color patches representing center colors, the SRs of the Munsell color chips are uniformly divided and similar SR populations optimized by composing principal vectors for the divided regions, thereby reducing the variance of the estimation error. The Lloyd quantizer algorithm is applied to divide the Munsell population uniformly. The Lloyd algorithm, based on K-means clustering as an optimal iteration algorithm, initially randomly selects K vectors for N input vectors in m-order vector space and minimizes the TSE(Total Squared Error), which is the error measure.

The error E between the quantization vectors and the input vectors is defined as follows:

$$E = \sum_{\lambda=400}^{700} \left| c_i(\lambda) - p_k(\lambda) \right| \tag{2}$$

where $c_i(\lambda)$ is the quantization vector, that is, one of the SRs from the Macbetch ColorChecker in the initial step and a new representative SR in each subsequent step, and $p_k(\lambda)$ is one of the SRs out of 1485 Munsell color chips. Each SR, i.e. the reflectance, consists of 31 ordered data sampled at 10nm intervals within a range of 400-700nm and is a value within a range from 0 to 1. 1485 Munsell SRs are mapped as representative SRs to minimize the vector errors E in each step. Since 24 initial quantization vectors are used, this divides 24 populations in each iteration step. The new representative SR is defined as the mean value of the total SRs included that population. The estimation error TE of the total SRs defined is calculated as follows:

$$TE = \sum_{n=1}^{1485} \sum_{\lambda=400}^{700} \left| c_r(\lambda) - p_n(\lambda) \right| \tag{3}$$

where $c_r(\lambda)$ is the representative SR of the population, including an arbitrary $p_n(\lambda)$, which are the SRs of 1485 Munsell color chips. The Lloyd algorithm is applied iteratively by calculating the TE for each step. Fig. 2 shows the process used to find similar SR populations.

After composing similar SR populations, the proposed method determines 3 principal vectors by applying the PCA method to each population. Then, the SR of an object can be estimated using principal vector sets based on the output of a 3-band camera, as shown in Fig. 1.

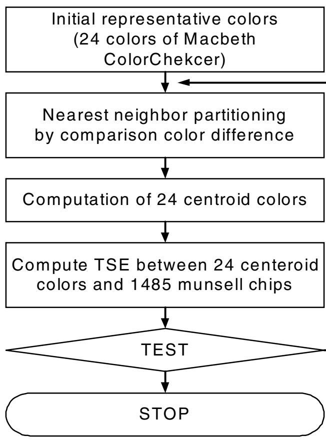

Figure 2. Application of Lloyd algorithm for building sub-populations of spectral reflectance.

Experiments

The estimation error for the SR and cumulative distribution ratio from the proposed method were compared with those from conventional methods. 120 patches of Munsell color chips were arbitrarily selected to estimate the SRs. A Toshiba IK-C41MK CCD camera was used in all the experiments. To evaluate its performance, the proposed method was compared with a conventional 3-band principle component analysis(PCA), 5-band Wiener estimation method, and another conventional 3-band PCA method.[10] 1485 Munsell color chips were divided into 24 similar SR populations using the Lloyd quantizer algorithm.

Figure 3 presents the variation transition of the total error when updating the SR representatives of 1485 Munsell color chips by applying the Lloyd algorithm iteratively. The reduction in the total error was very small after about 10 iterations. To confirm this, the populations were composed after 20 iterations in the experiments.

Table 1 shows the mean values and maximum values for the estimation error when using the above 4 methods. To calculate the mean and maximum, 120 patches were selected at the same interval from the total 1485 Munsell color chips. As a result, the mean and maximum of the estimation error was smaller for the proposed method than for the other conventional methods. In particular, the proposed method was better than the conventional methods as regards finding the optimal representative colors, because the former estimated the SRs by using the principle components adaptively.

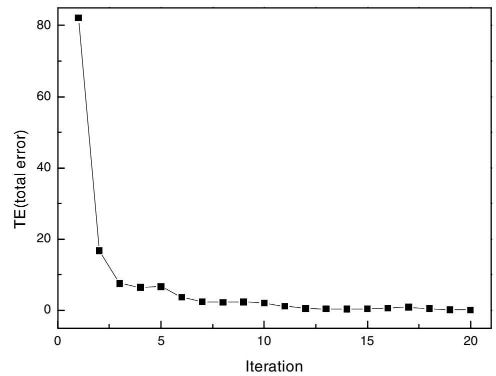

Figure 3. Total error in Lloyd algorithm according to the iteration.

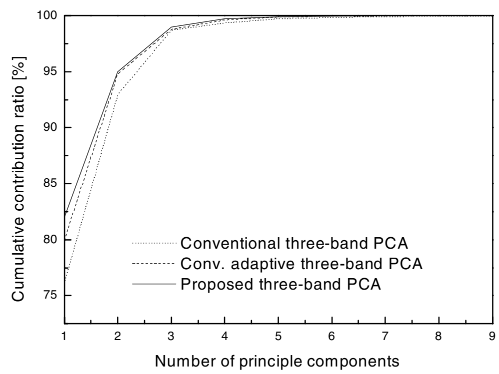

Figure 4. Comparison of cumulative distribution ratio according to estimation method of spectral reflectance.

The cumulative distribution ratio was also calculated. If the ratio is 100 % in Eq. (1), theoretically, this means that the SR of the population can be estimated perfectly by the linear composition of the principle components.

In a conventional 3-band PCA, the cumulative distribution ratio is only determined once. Therefore, to compare the methods fairly, the mean of the coefficients of the principle components were calculated for the other methods. The results shown in Table 2 and Fig. 4 confirm that the proposed method produced a better performance.

Table 1. Experiment result of spectral reflectance estimation for 120 selected colors from 1485 Munsell color chips.

	3-band PCA	5-band Wiener	Adaptive 3-band PCA	Proposed 3-band PCA
Mean of estimation error	0.00093	0.00052	0.00085	0.00032
Maximum or estimation error	0.0065	0.0037	0.0077	0.0023

Table 2. Comparison of cumulative distribution ratio according to estimation methods [%].

	1	2	3	4	5	6	7	8	9
Conventional 3-band PCA	77.112	92.963	98.701	99.353	99.721	99.843	99.912	99.943	99.972
Conv. Adaptive 3-band PCA	79.937	94.797	98.772	99.625	99.883	99.959	99.985	99.994	99.997
Proposed 3-band PCA	82.023	94.991	99.005	99.742	99.921	99.969	99.987	99.994	99.997

Conclusion

This paper proposed a method for reducing the estimation error of SRs by using adaptive principle components according to the color. Munsell color chips are divided to estimate the SRs, thereby enabling adaptive estimation according to the SRs of the input colors. The Lloyd algorithm is applied to create the new representative SRs when dividing the total Munsell SRs into populations. Based on considering optimal center color patches, the estimation error for the SR with the proposed method is smaller that that with other conventional methods and the cumulative distribution ratio is also increased when a PCA is applied. In the case of a 3-band PCA using a set of similar SR populations, the estimation error usually increases for a certain color when determining a similar SR population, however, the proposed method is able to reduce the variance in the estimation error according to the color.

Accordingly, when the proposed algorithm was used to estimate SRs, the variance in the estimation error of the SRs was decreased due to accurate modeling of the 3-band camera's characteristics and spectral power distribution of the illumination.

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Biography

Oh Seol Kwon received his B. S. degree in the school of Electrical Engineering and Computer Science from Kyungpook National University, Taegu, Korea, in 2002. He is currently pursuing the M. S. degree. His research interests include color image processing and color reproduction.