# Limitation of Color Samples for Spectral Estimation from Sensor Responses in Fine Art Painting

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A new technique is proposed to improve the way of selecting samples used to estimate spectral reflectance from sensor responses in multi-band images. This technique limits the samples of reflectance spectra based on the spectral reflectance estimated by the conventional estimation method, and estimates it again using the limited samples. Vector angle and distance among reflectance spectra as the criteria for the limitation can be applied to improve the estimation of reflectance spectra.

**Key words**: high quality imaging system, spectral estimation, color samples, oil color painting, computer color mixture

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## 1. Introduction

With the blooming of the network society, it is expected that fine art painting can be appreciated at home by accessing the digital archives of fine arts. The archives also provide data on conservation and scientific analysis. A conventional photographic system using film and scanner has heretofore been used for image acquisition, digitization and recording. However, it is difficult to retain the accurate color reproduction because of the photochemical process. To solve this problem, high quality imaging systems[1-4] have been proposed and constructed for paintings using a digital camera without the photochemical process.

Color correction techniques based on an estimation of reflectance spectra were proposed[5-7] to reproduce the color of the original under an arbitrary illuminant. The reflectance spectra are estimated from the multi-band images based on samples of these spectra which are measured a priori. These techniques were applied to the high quality imaging system for paintings[8,9]. The estimated reflectance spectra also provide reliable information on the physics of the pigments used to cover the canvas. If the imaging system is specified, the accuracy of estimation depends on the estimation method used and samples of the reflectance spectra. The estimation method has been improved for more accurate color reproduction[10,11], however, the way of selecting samples of reflectance spectra has not been improved.

In this paper, we propose a technique to improve the selecting samples of spectral reflectance to assure accurate color reproduction. This method limits the number of samples of reflectance spectra based on the reflectance estimated by the conventional estimation method, and estimates it again using the limited samples. In the next section, we show the process to make samples of reflectance spectra for oil painting. In section 3, we will describe the Wiener estimation method as one of the conventional estimation methods. In section 4, the method to limit the samples is explained, and the estimation method using limited samples is compared with the conventional estimation method by computer simulation. In section 5, we will discuss and conclude our research.

## 2. Samples of Reflectance Spectra for Painting

We used 147 color samples (Holubein Artist's Oil Colors) painted on 4cm x 5cm film with the thickness of about 10μm. The spectral radiant power of the 147 samples on a standard diffusing reflector was measured by a spectrophotometer (Abesekkei Model 2706) at the angle of 45˚ viewing condition with 2˚ viewing angle. The color samples were set under D65 illuminant in a standard illumination booth., and data were measured at intervals of 5nm between 400nm and 700nm. The spectral reflectance was calculated by dividing spectral reflection of the color samples by the spectral reflection of the standard diffusing reflector. An x-y chromaticity diagram of the measured color samples under D65 illuminant is shown in Fig. 1.

In general, three oil colors are mixed on a palette, and the mixed colors are then applied to the canvas. To make appropriate samples for practical oil painting, the reflectance spectra of mixed oil colors are required. In this paper, we assumed that Lambert-Beer's Law holds in the mixed oil colors, and we mixed three of the fundamental 147 oil colors in the computer randomly according to the following equation.

$$r_m(\lambda) = 10^{-(-a_i \log_{10} r_i(\lambda) - a_j \log_{10} r_j(\lambda) - a_k \log_{10} r_k(\lambda))} \qquad (1)$$

where $r_m(\lambda)$ is the spectral reflectance of mixed oil color, $r_i(\lambda), r_j(\lambda)$, and $r_k(\lambda)$ are reflectance spectra of the fundamental oil colors, and $a_i$, $a_j$, and $a_k$ are coefficients proportional to the amount of the fundamental oil colors $r_i(\lambda)$, $r_j(\lambda)$, and $r_k(\lambda)$, respectively. The subscripts *i*, *j*, and *k* are randomly selected in the 147, and the coefficients $a_i$, $a_j$, and $a_k$ are also randomly but uniformly valued between 0 and 1. In this paper, 1000 mixed oil colors were calculated as samples, and they are shown in Fig. 2 as an x-y chromaticity diagram.

## 3. Conventional Estimation Method: Wiener Estimation

The reflectance spectra are estimated from the sensor responses of a multi-band imaging system based on the samples of reflectance spectra. Several methods have been proposed for the estimation[5-7,9-11]. Among conventional methods, the Wiener estimation method is simple and gives highly accurate estimations[9]. We model the imaging system and introduce the Wiener estimation method as follows.

The response $v_i(x,y)$ at position (x,y) of the digital camera with *i*-th color filters is expressed by

$$v_i(x,y) = \int_{400}^{700} t_i(\lambda) E(\lambda) S(\lambda) r(x,y;\lambda) d\lambda, \quad i = 1, \ldots m. \qquad (2)$$

where $t_i(\lambda)$, $E(\lambda)$, $S(\lambda)$ and $r(x,y;\lambda)$ are transmittance of *i*-th filter, radiance of illuminant, sensitivity of the camera and reflectance of the painting, respectively. For commercial use, three band filters are often used to capture the color images, thus we assumed that *m* is equal to three in this paper. We also assumed that noise is negligible because of wide band filters.

For mathematical convenience, we express the spectral characteristic by vector or matrix. The number of elements, $l$, for discrete spectral data becomes 61 as the data is obtained at interval of 5nm from 400nm to 700nm. Using vector matrix notation, Eq. (2) can be expressed as,

$$\boldsymbol{v} = \mathrm{F}\boldsymbol{r}, \tag{3}$$

where $\boldsymbol{v}$ denotes a column vector with $m$ elements representing the camera responses and $\boldsymbol{r}$ denotes a column vector with $l$ element representing the spectral reflectance of the painting. We omitted (x,y) from $\boldsymbol{v}$ and $\boldsymbol{r}$ for simplicity. These two vectors are related by a linear acquisition system matrix $\mathrm{F}$ with $m \times l$ components. The matrix $\mathrm{F}$ is expressed as

$$\mathrm{F} = \mathrm{TES}, \tag{4}$$

where

$$\mathrm{T} = [\boldsymbol{t}_1, \quad \boldsymbol{t}_2, \quad \cdots, \quad \boldsymbol{t}_m]^t. \tag{5}$$

The vector $\boldsymbol{t}_i$ denotes a column vector representing the transmittance of $i$-th filter and $[\ ]^t$ represents transposition. The matrices $\mathrm{E}$ and $\mathrm{S}$ denote $l \times l$ diagonal matrices corresponding to the spectral radiance of illuminant and spectral sensitivity of the camera, respectively. The purpose here is to solve Eq. (3), which is very ill-conditioned. The Wiener estimation method is applied to this problem as follows.

The solution of Eq. (3) by the Wiener method is given by the following linear operation,

$$\boldsymbol{r}_{est} = \mathrm{G}\boldsymbol{v}. \tag{6}$$

The estimation matrix $\mathrm{G}$ is determined to minimize the ensemble average of the square error between the original $\boldsymbol{r}$ and estimated spectral reflectance $\boldsymbol{r}_{\mathrm{est}}$, i.e.,

$$e = \left\langle \left\| \boldsymbol{r} - \boldsymbol{r}_{est} \right\|^2 \right\rangle \rightarrow \min. \tag{7}$$

Here, $\langle\ \rangle$ represents the ensemble average for samples of spectral reflectance. The estimation matrix $\mathrm{G}$ is explicitly expressed by

$$\mathrm{G} = \mathrm{R}_{rv}\mathrm{R}_{vv}^{-1}, \tag{8}$$

where $\mathrm{R}_{rv}$ and $\mathrm{R}_{vv}$ denote correlation matrices defined as,

$$\mathrm{R}_{rv} = \left\langle \boldsymbol{r}\ \boldsymbol{v}^t \right\rangle,\ \mathrm{R}_{vv} = \left\langle \boldsymbol{v}\ \boldsymbol{v}^t \right\rangle. \tag{9}$$

Explicitly, Eqs. (6) and (7) show that the accuracy of estimation depends on the selection of color samples. With the conventional method in this paper, these correlation matrices are calculated using the simulated 1000 mixed color samples shown in Fig. 2 and corresponding camera outputs. In the next section, we propose a method to improve the way of selecting samples of spectral reflectance for accurate estimation.

## 4. Limited Samples Method

Figure 3 shows a schematic diagram of the proposed technique to improve the way of selecting samples of spectral reflectance. As the first step of the estimation, the conventional method is applied to estimate the spectral reflectance from sensor responses. We call this estimated spectral reflectance the first estimated spectral reflectance. Secondly, samples of the reflectance spectra are limited using the first estimated spectral reflectance, and the spectral reflectance is again estimated using the limited samples. Samples are limited based on the angle or distance criteria between the first estimated spectral reflectance and sample vectors used in the first estimation. The reflectance spectra with smaller angle or distance compared with first estimated spectral reflectance are gathered as $N_2$ pieces of samples.

A computer simulation was carried out to determine the limitation number $N_2$. For the evaluation of the resultant estimation matrix, 100 mixed oil color samples were calculated according to Eq.(1). As described, three band filters were considered. D65 illuminant and spectral sensitivity of Kodak DCS420m were used for system matrix. Figure 4 shows the resultant relationship between the limitation number $N_2$ and performance of the proposed technique using the vector angle as the criterion for limitation. The RMS (root mean square) error among 100 reflectance spectra for evaluation and estimated reflectance spectra are shown in Fig. 4(a). Averaged and maximum color differences in CIE L* a* b* color space[12)] are shown in Figs. 4(b) and (c) respectively. From the results of the simulation, we can conclude that 100 limited samples are appropriate for limitation using the vector angle as the criterion. Similar simulation is performed for limitation using the vector distance as the criterion. Figures 5(a),(b),(c) show the resultant relationship between the limitation number $N_2$ and RMS, averaged, maximum color differences, respectively. From the results of the simulation, we can also conclude that 100 limited samples are appropriate for the limitation using the vector distance as the criterion. It is noted that the appropriate number of limited samples should be examined again if the samples of the first step estimation are changed.

The resultant performances where the number for limitation was set to be the appropriate limitation number 100 were examined further in comparison with the first estimated spectral reflectance. Figure 6(a) show the color differences between the original and first estimated spectral reflectance for evaluation, and Figs. 6(b),(c) show the difference between the original and second estimated spectral reflectance using vector angle and distance as the criterion respectively. In general, it is known that the just noticeable color difference is about 2.5 in CIE L* a* b* color space. We can conclude that our proposed technique greatly improved the estimation for accurate color reproduction.

The limitation of samples can be repeated based on the second estimation, however, this repetition did not improve the estimation in our 1000 color samples.

## 5. Discussion and conclusion

In the proposed technique where the samples of reflectance spectra are limited based on the spectral reflectance estimated by the conventional method, angle and distance among the vectors of reflectance spectra were considered to be the criteria for the limitation. We found that the estimation was well improved in 100 limited samples from among our simulated 1000 color samples. The shortcoming of the technique is the processing time because samples are limited at each point in the image. To overcome this shortcoming, the each estimation matrix should be determined in advance for each categorized spectral reflectance, and the first estimated spectral reflectance should be classified into the category speedily.

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## Captions of figures

Fig. 1. An x-y chromaticity diagram of the 147 measured color samples of oil painting under D65 illuminant.

Fig. 2. An x-y chromaticity diagram of 100 simulated mixed color samples of oil painting under D65 illuminant.

Fig. 3. Schematic diagram of limited sample method to improve the way of selecting color samples of spectral reflectance.

Fig. 4. Resultant relationship between the limitation number $N_2$ and performance of the proposed estimation technique using the vector angle for limitation. (a)RMS error, (b) averaged color difference and (c) maximum color difference in CIE L* a* b* color space.

Fig. 5. Resultant relationship between the limitation number $N_2$ and performance of the proposed estimation technique using the vector distance for limitation. (a)RMS error, (b) averaged color difference and (c) maximum color difference in CIE L* a* b* color space.

Fig. 6. Color differences between the original spectral reflectance for evaluation and (a) first estimated spectral reflectance, (b) second estimated spectral reflectance using vector angle for limitation, (c) second estimated spectral reflectance using vector distance for limitation.