Imaging of Cosmetics Foundation Distribution by a Spectral Difference Enhancement Filter

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Abstract

The light reflected from an object contains a range of information about its physical and chemical properties. Changes in the physical properties of an object can sometimes be evident as barely detectable changes of the spectra. However conventional color sensors (e.g. human color vision or typical RGB camera) are not able to detect most of spectral differences because the spectrum information is mapped into three-dimensional RGB signal. This article proposes a method for designing an optical filter which optically performs discriminant analysis of incoming spectrum to enhance object's spectral difference. First, spectral transmittance of the filter is theoretically determined by minimizing the misclassification of two selected target colors by discriminant analysis. In this study, spectral datasets of human facial colors in the presence and absence of cosmetics foundation were used as these targets. A real optical filter was developed by vacuum deposition technology according to the theoretical design, and was applied to the detection of the presence of a cosmetics foundation on the human face. In the first experiment, a digital camera equipped with the developed filter was used to detect foundation on face. The result confirmed a clear enhancement of spectral difference between facial colors with / without foundation (misclassification rate for these two sets was 4.1%), which were difficult to discriminate by naked eyes. As the second experiment, a calibration curve between the discriminant score calculated from filtered image and the amount of applied cosmetics foundation was experimentally obtained and high estimation accuracy was established (decision coefficients were about 0.9). Finally, the optical filter was applied to visualize the spatial foundation distributions of a realistic made-up skin condition. Visualized foundation map clearly indicated the unevenness of foundation distribution even though the skin color looked uniform. Results confirm that the proposed filter can achieve to visualize the foundation distribution without any destructive inspection.

Introduction

The light reflected from an object contains a range of information about its physical and chemical properties. In human color vision, transformation from spectra to tristimulus signals results that the most of spectral information is lost (so called as metamerism). Recently, spectral imaging has received a lot of attention to detect or discriminate such spectral difference and visualize the object's property. However, often the non-destructive inspections based on the spectral imaging are still problematic in industrial applications because of its cost and measuring skill, etc.

In our previous works[1][2], we proposed a method for designing the spectral transmittance of the filter which allows the two colors from a pre-defined target spectra to be distinguished from each other with greater ease and accuracy than without filtering for human color vision (color discrimination enhancement[1]) and artificial camera system (michromatic scope[2]). Current study proposes a method to enhance the spectral difference between two target colors only by one filter which is equipped in front of lens of an RGB digital camera and perform discriminant analysis for incoming spectra optically. The filtering process in the spectral domain is expected to detect and enhance the spectral differences even for metameric color sets or colors.

This study focuses on human skin color as a target, especially difference of facial colors in the presence and absence of cosmetics foundation. Human skin color is attracting considerable attention in several fields of research because it is a rich source of information about health or mental conditions, etc. Color of the skin was considered to be associated with the chromophores, including melanin, carotene, and haemoglobin[3]. Optical absorption by hemoglobin appeared to have an effect on the reflectance of human skin mainly at wavelengths in the range of 545 to 575 nm the absorption property is considered to be affected by the presence or absence of cosmetic foundation. However it is difficult or almost impossible for our naked eyes to detect or discriminate its spectral differences.

In this study, the optical filter was applied to visualize the spatial foundation distributions of realistic condition by enhancing the spectral differences of facial skin colors in the presence and absence of cosmetic foundation. Next section outlines the research problem. The third section presents our general solution for the problem. The spectral measurement is described in the fourth section. The results from the experiments and the principled evaluation of the developed optical filter are presented in the fifth section. The calibration curves to estimate the amount of applied cosmetics foundation are established and they are applied to visualize the cosmetics foundation distribution in the sixth section. Finally, our conclusions are presented in the seventh section.

Problem Setting

The problem addressed in this study is how to define a filter that enhances the spectral difference between two spectral colors $I_1(\lambda)$ and $I_2(\lambda)$ (in practice, $I_1(\lambda)$ and $I_2(\lambda)$ represent spectral data sets for category 1 and 2). Thus, the target is as follows:

$$\mathbf{C}_i = \int \{T(\lambda) I_i(\lambda)\} S(\lambda) d\lambda \;\; (i = 1, 2) \qquad (1)$$

$$Min\{P_e(\mathbf{C_1}, \mathbf{C_2})\} \qquad (2)$$

$$P_e(\mathbf{C_1}, \mathbf{C_2}) = p_1 \cdot P(f_d(\mathbf{C_1}) \le 0) + p_2 \cdot P(f_d(\mathbf{C_2}) > 0) \qquad (3)$$

Here, i (=1 or 2) corresponds to a category number, vectors of $\mathbf{C_1}$ and $\mathbf{C_2}$ contain the three-dimensional color signals for two pre-defined targets which are transformed from the spectral set $I_i(\lambda)$, $T(\lambda)$ is transmittance function of the filter and $S(\lambda)$ represents color sensitivity function of the camera. P_e is the misclassification rate, p_1, p_2 are prior probabilities of $I_1(\lambda)$ and $I_2(\lambda)$, respectively. In this study, linear discriminant analysis (LDA) was used for classifying the category 1 and 2. Discriminant score by LDA formula for two classes is as follow:

$$f_d(\mathbf{x}) = (\mathbf{\Sigma}^{-1}(\boldsymbol{\mu}_1 - \boldsymbol{\mu}_2))^t \left(\mathbf{x} - \frac{\boldsymbol{\mu}_1 + \boldsymbol{\mu}_2}{2} \right) - \log(p_2 / p_1) \quad (4)$$

where $\mathbf{x}$ is a color vector transformed from an observed spectrum, $\mathbf{\Sigma}^{-1}$ is a pooled variance-covariance matrix of color vector sets $\mathbf{C_1}$ and $\mathbf{C_2}$, and $\boldsymbol{\mu}_1$, $\boldsymbol{\mu}_2$ are mean of $\mathbf{C_1}$, $\mathbf{C_2}$. When $f_d(\mathbf{x})>0$, an observed spectrum is classified to category 1, otherwise category 2.

Design the Spectral Filter

This study aims to define a spectral transmittance function of the filter $T(\lambda)$ so as to minimize the misclassification rate between the two pre-defined spectral sets $I_1(\lambda)$ and $I_2(\lambda)$. LDA was performed on r-g chromaticity coordinates transformed from RGB color space as:

$$\begin{cases} r = \dfrac{R}{R+G+B} \\ g = \dfrac{G}{R+G+B} \end{cases} \quad (5)$$

The RGB color space was defined by the spectral sensitivities of a digital camera Nikon D70 as $S(\lambda)$ which was measured by a monochromators as shown in Fig.1.

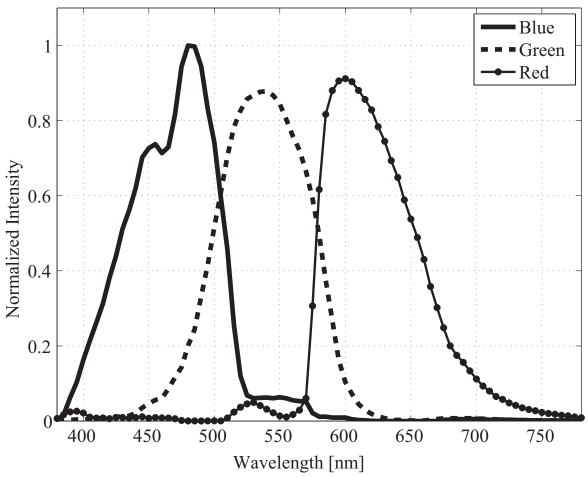


***Figure 1.** Spectral sensitivities of the RGB color filters for a digital camera Nikon D70. The spectral sensitivities were measured by a monochromators (Shimadzu, SPG-120). The measured wave-range was 380-780nm, 5nm steps.*

For decreasing the number of independent variables in optimization process, we introduce a model describing transmittance function $T(\lambda)$ by spline function $B_k(\lambda)$[4]:

$$T(\lambda) = \sum_{k=1}^{N} D_k B_k(\lambda)$$

$$B_k(\lambda) = \begin{cases} \{\omega^3 + 3\omega^2(\omega - |\lambda - \lambda_k|) + 3\omega(\omega - |\lambda - \lambda_k|)^2 \\ \quad - 3(\omega - |\lambda - \lambda_k|)^3\}/6\omega^3 \quad \text{for } |\lambda - \lambda_k| \le \omega, \\ (2\omega - |\lambda - \lambda_k|)^3/6\omega^3 \quad \text{for } \omega \le |\lambda - \lambda_k| \le 2\omega, \\ 0 \quad \text{for } 2\omega \le |\lambda - \lambda_k|. \end{cases} \quad (6)$$

where $k =1, 2, ..., N$, λ_k is the centre of the function, D_k is the weight of spline function $B_k(\lambda)$, and ω is the discrete step of the wavelength range. The computations in each iteration step of the optimization are as follows:

Step1: Compute the spectral transmittance according to Eq.6 with the independent variables.
Step2: Transform the spectral datasets to filtered RGB colors using the transmittance and spectral sensitivities.
Step3: Perform the linear discriminant analysis on r-g chromaticity coordinates to classify the datasets.
Step4: Calculate the misclassification rate of the LDA and modify the independent variables to minimize it.

Spectral Measurement

The experimental data consisting of two target spectral datasets were measured by a multi spectral imaging system (Nuance™, Multispectral Imaging System, CRi, VIS). The first set $I_1(\lambda)$ contains naked skin spectra and the second set $I_2(\lambda)$ contains spectra from skin to which cosmetic foundation has been applied. The spectral range of the measurements varies from 420 nm to 720 nm in 5 nm steps. The cosmetics comprise two types of foundation (liquid, powder) and each of them contained three kinds of color. Most suitable one (subjects' favorite foundation) was chosen for each subject. All subjects were Japanese women who ranged in age from 20 to 60. Spectra from 30 subjects in total were measured. From the spectral image, datasets for designing the filter were extracted automatically. Totally, each of the datasets consists of 540 spectra from the subjects (with 9 spectra extracted from different facial positions for each image). Figure 2 shows the average spectra of each dataset. There was an only slight spectral difference between spectra of naked skin and skin with foundation. The cause of the difference is spectral absorbing characteristics of oxygenated hemoglobin as mentioned above.

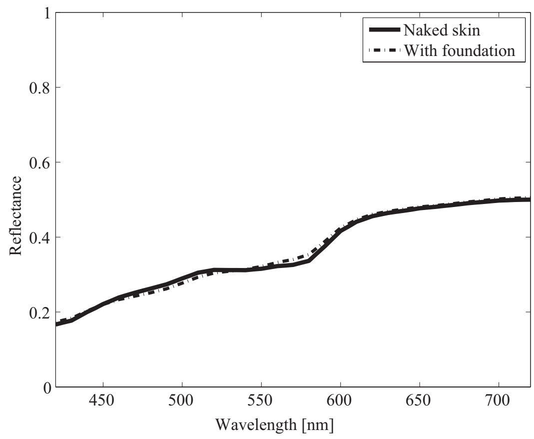


***Figure 2.** Average spectra of datasets, naked skin and skin with foundation. The slight spectral difference at wavelengths in the range of 545 nm to 575 nm is caused by spectral absorbing characteristics of oxygenated hemoglobin.*

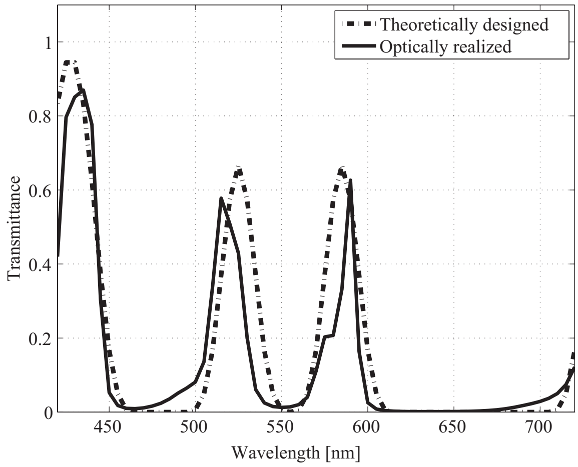
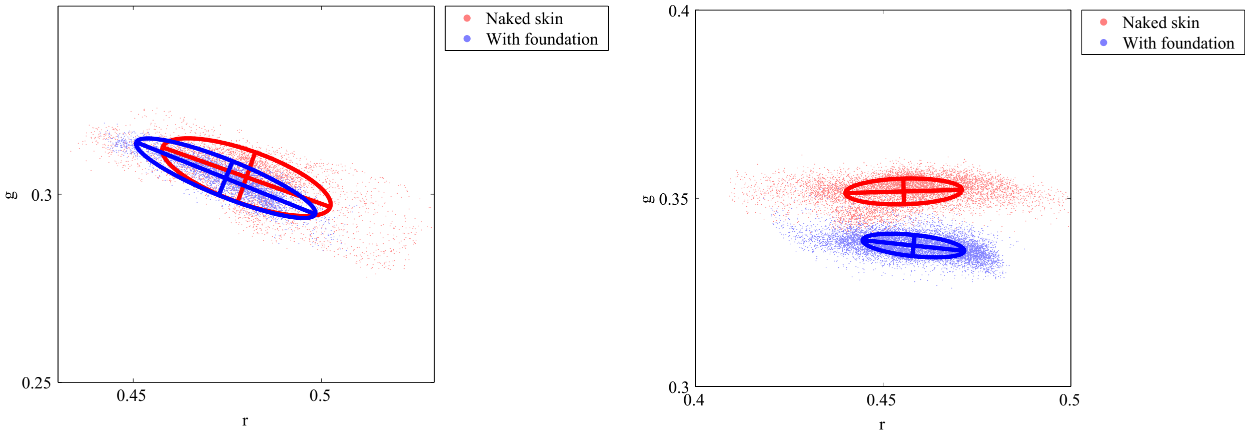


Figure 3. *Spectral transmittance of the theoretically designed and the optically realized filter. The theoretical transmittance was designed by optimization. The optical filter was realized by vacuum deposition technology.*

Figure 4. *Developed optical filter. The optical filter was made of multi-layer thin film to realize the theoretical spectral transmittance shown in Fig. 3.*



(A) Without filtering ***(B) With filtering***

Figure 5. *Color (chromaticity) distributions extracted from RGB image taken with the digital camera. Figure (A) shows the color distributions without filtering, and (B) shows the distributions with filtering. The ellipses represent equiprobability ellipses which shafts were defined by the standard deviations. The misclassification rate in (A) was 36.0%, and 4.1% in (B).*

Experimental Result

A. Design and Development of the Optical Filter

We designed a spectral filter by optimization process using spectra of measured naked skin and skin with foundation. Wavelength range was 405-735 [nm], and the discrete step ω in Eq.6 was 15[nm], and in total 23 number of independent variables ($D_1, D_2, \ldots, D_{23}$) were optimized. For the optimization, the method of simulated annealing was applied[5]. The illumination function was defined as $E(\lambda) = 1$ over the whole spectral range in this optimization.

The spectral transmittance functions of theoretically designed and optically realized ones are shown in Fig.3, and picture of the realized optical filter is shown in Fig.4. According to the comparison between the 'theoretically designed' and 'optically realized', the optically realized filter had higher discrimination accuracy than theoretical one.

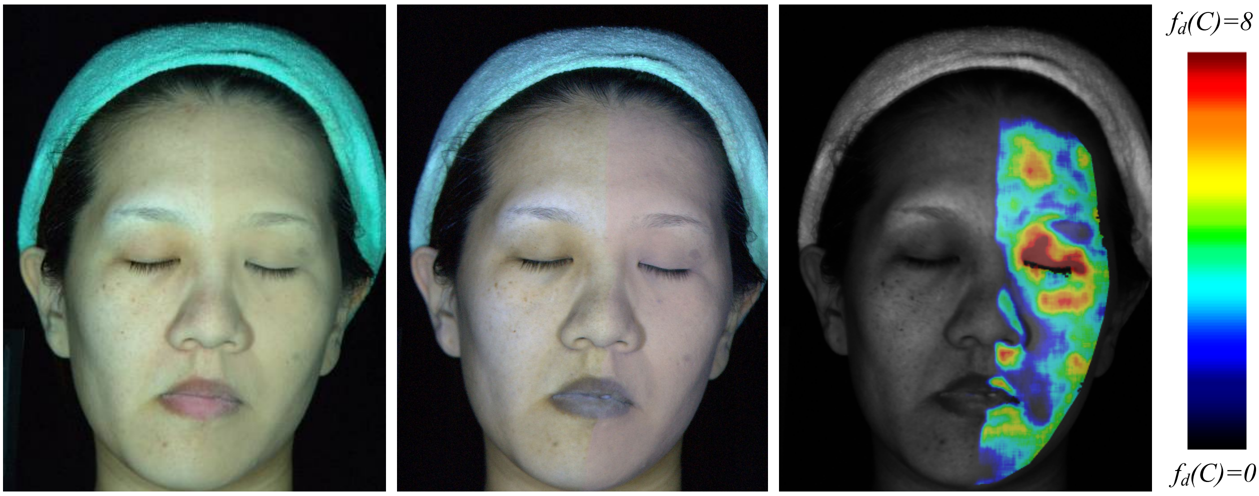
B. Color Coordinates Distributions

For evaluating the real optical filter, a measurement by an RGB digital camera with the developed optical filter was performed for three subjects. A measurement device was commercially available camera Nikon D70, and the illumination light sources were fluorescent light (Diva-Lite, 6500K). Polarizing films were installed on both the camera and the illumination light source for eliminating the specular light.

Figure 5(A) and (B) show color (chromaticity) distributions of two targets (naked skin and skin with foundation) with and without filtering. The ellipses in Fig.5 represent equiprobability ellipses which shafts were defined by the standard deviations. Color distributions with filtering are effectively separated for two targets. The misclassification rates for w/o filtering were 36.0% (Fig.5A), and 4.1% with filtering (Fig.5B).

C. Detection of Skin Area Applying Cosmetics Foundation

Figures 6 (A)-(C) show the results of filtered images. The foundation was applied only on left side of the face. Figure 6(B) shows the enhancement of the spectral difference as the enhancement of the color difference (shifted to be reddish). Figure 6 (C) shows the discriminant score $f_d(\mathbf{C})$ which is computed according to Eq.4 by r-g chromaticity for each pixel. Colored pixels in Fig.6 (C) were classified into the area



(A) Without filter ***(B) With filter*** ***(C) Score image***

Figure 6. *Results of filtered images using a digital camera. The foundation was applied only on left side of the face. Figure (A) shows an RGB-color image without filter. The filtered color image is shown in (B). The clear enhancement by the filter was on the image. Figure (C) shows the discriminant score which is computed according to Eq.4.*

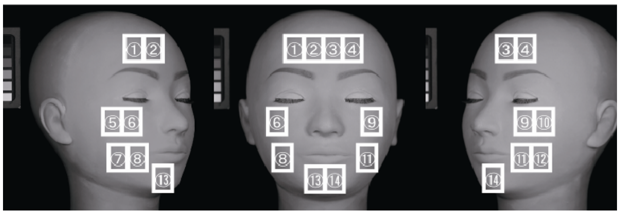


Figure 7. *Areas of cosmetics foundation application for the quantitative measurement. Totally cosmetics foundation was applied to 14 areas. The observation angles were -45, 0 and 45 degrees. The application areas indicated in each facial image were used for the analysis described below.*

applying foundation according to the classification rule. It shows that detection was performed accurately.

Estimation of Cosmetics Foundation Amount

A. Quantitative Measurement

This filter was developed based on linear discriminant analysis to discriminate between skins with/without cosmetics foundation. However the discriminant score shown in Fig.6 (C) was distributed in continuity. Such continual change might reflect amount of applied cosmetics foundation. To concern the correlation between amount of cosmetics foundation and discriminant score, a quantitative experiment was performed. Cosmetics liquid type foundation defined quantitatively was applied to the face. The size of applying area was 3cm x 2cm and there were 14 areas over the face. The application amounts were 0.5, 1, 1.5, 2, 3, 4, 5, 6, 8 and 10μL. They were strictly controlled by recoating using a micropipette. The observation angles were -45, 0 and 45 degrees. All measurement devices were fixed through the measurement, and the subjects turned sideway to take the profile images described as Fig.7. Discriminant scores were extracted from the numbered areas in the figure manually. As shown the figure, several application areas were used for multiple observation angles. Thus the estimation error coming from the observation angle will be also discussed using the cross over. The measurement protocol of the camera, the foundation and the illumination light were the same as previous experiment (described in B. Color Coordinates Distributions). The measurement was carried out for four Japanese females who ranged in age of 18 to 40. The subjects chose a favorite color of cosmetics foundation their own.

B. Results of the Measurement

Figure 8 shows the discriminant scores which were extracted from measured images manually. The error bars show the standard deviations. Obviously, there are strongly positive correlation with logarithmic character between the amount and the discriminant score. In reference.6, the reflectance spectra of made-up skin were estimated by Kubelka–Munk theory[7], and good estimation results were described. Actually, the reflectance estimated by the theory showed quite similar relationship to the result shown in Fig.8.

Figure 9 shows the estimation error coming from the observation angle. The solid lines show the discriminant scores of forehead jaw observed in 0 degree angle. The scores of same positions observed in -45 and +45 degrees are shown as broken lines. There are few estimation errors between observation angles. Thus the estimation of foundation amount will be less-restricted to the observation angle of skin surface.

C. Calibration Curve Fitting

Cleary logarithmically relationship between discriminant score and applied foundation amount was concerned by the quantitative measurement. Thus the foundation amount may be estimated from the score with high accuracy. In this study, we proposed two kinds of the amount estimation formula described as follows:

$$y = a\ln(x + c) + b \qquad (7)$$

$$y = a\{\ln(x + by_0 + c) - \ln(by_0 + c)\} - y_0 \qquad (8)$$

Here an output variable y means discriminant score, an input variable x means the applied foundation amount and the variable y_0 is the discriminant score of naked skin. The other parameters a, b and c are coefficients and constant terms. Thus these inverse functions can be used as the estimation formulas. Eq.7 is based on simple logarithmic function. It may be able to transform a discriminant score to foundation amount with high

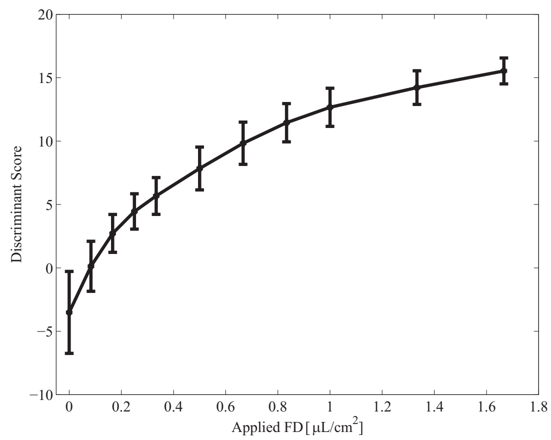


Figure 8. *Discriminant scores which were extracted from measured images manually. The error bars show the standard deviations. Obviously, there are strongly positive correlation with logarithmic character between the amount and the discriminate score.*

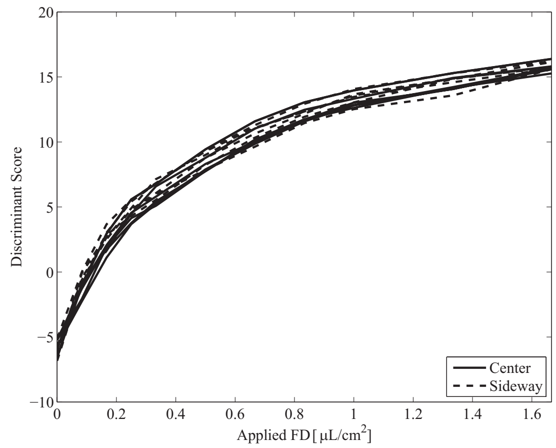
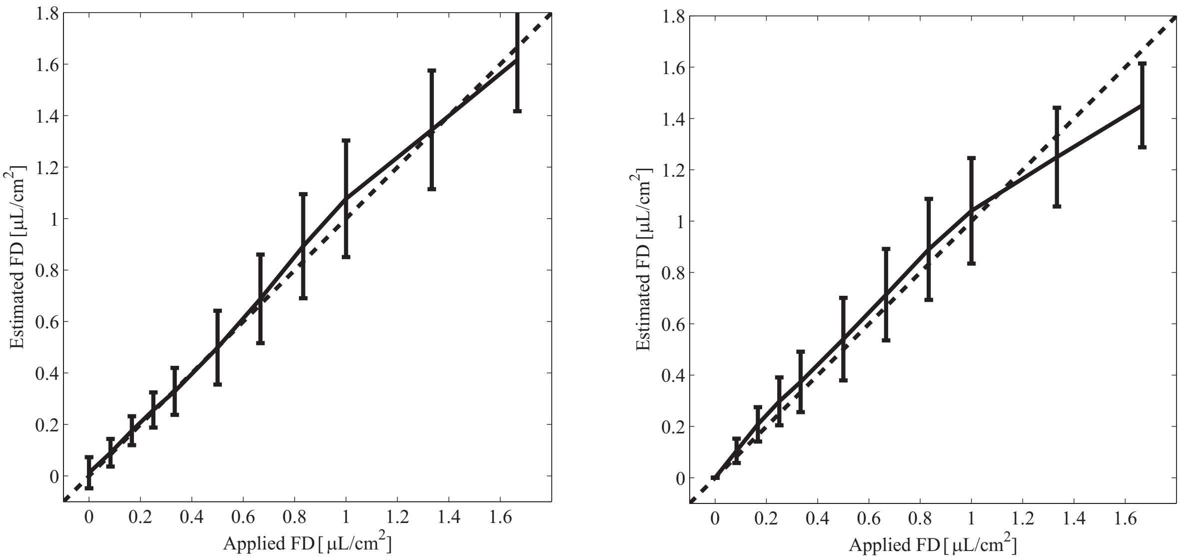


Figure 9. *Estimation errors coming from the observation angle. The solid lines show the discriminant scores of forehead and jaw (No. 1-4, 13 and 14 shown in Fig.7) observed in 0 degree angle. The scores of same positions observed in -45 and +45 degrees are shown as broken lines.*



(A) Simple logarithmic function ***(B) With baseline correction***

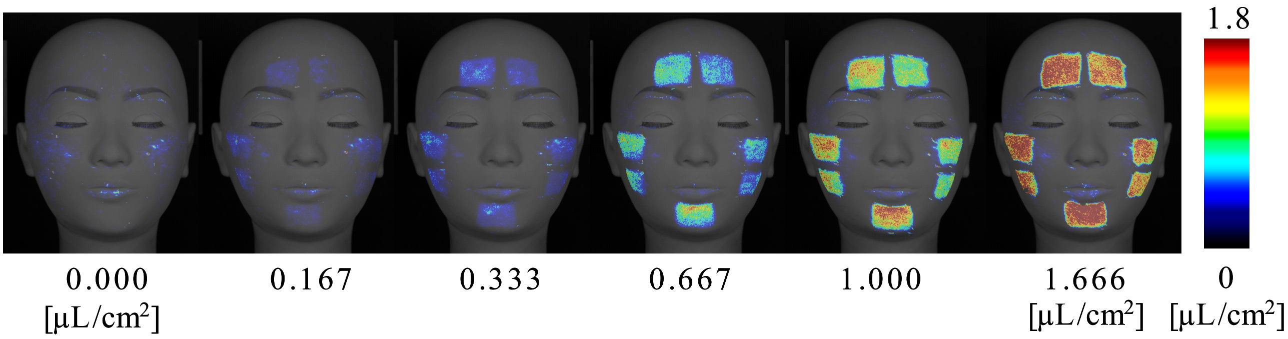
Figure 10. The relation of applied foundation amount and estimated amount. The error bars mean standard deviations. About Fig.(A), decision coefficient is 0.915 and SEP is 0.156. About Fig.(B), decision coefficient is 0.898 and SEP is 0.165. The estimation accuracy is higher for Fig.(A) than Fig.(B). However Fig.(B) has no error when the applied foundation is zero.

accuracy because of relationship between them as indicated in above section. However, the output image using Eq.7 will have a continuity distribution even if no foundation is applied over a face. Because the discriminant scores of naked skin are not constant. It is undesirable when a slight amount of cosmetics foundation should be detected and be weighed out. Therefore, we proposed another formulation which included image processing to meet above-mentioned requirement. In this formula, the estimated foundation amount (variable x in Eq.8) is constantly zero when the naked skin is observed. However, the naked skin image measured under the same measurement environment is required as the baseline image. And also, the image transformation should be applied to adjust position of facial features of two images to visualize the distribution of cosmetics foundation.

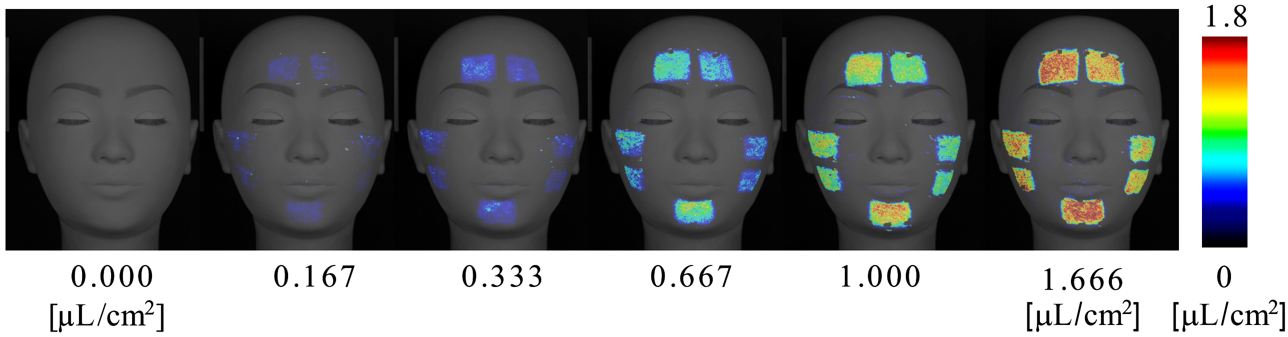
In this study, steepest descent method and least square method were used for solving undefined parameters a, b and c. The estimated parameters, decision coefficients and SEP (standard error of prediction) are described in Table I. Figure 10 shows the relation of applied foundation amount and estimated amount. The error bars mean standard deviations. As described in Table I, both of estimation formulas indicate high accuracy of estimation of applied cosmetics foundation. Decision coefficient and SEP show a bit higher accuracy on the simpler formula. However, as shown in Fig.10 (B) the estimation with baseline correction achieved better result in range of slight amounts.

Table I: Parameters and evaluated values of the calibration curve

	a	*b*	*c*	R^2	SEP
Simple logarithmic function	7.221	11.59	0.121	0.915	0.156
With baseline correlation	9.806	0.029	0.364	0.898	0.165



(A) Simple logarithmic function



(B) With baseline correction

Figure 11. *The comparison of foundation maps computed with different calibration curves. These are results of one subject. The computed images are put on the make-up doll image using image transformation method 'local weighted mean method[8].*

D. Visualization of Foundation Amount Map

Both of two proposed calibration curves showed sufficient estimation accuracy described as Table I, Fig.10 (A) and (B). For the comparison of these two formulas, the foundation maps of the images which measured in quantitative measurement were computed. Figure 11 shows the computed foundation amount maps of one subject. They are put on the image of make-up doll using image transformation method 'local weighted mean method[8]'.

Cleary the foundation amount maps were visualized in both ways with high estimation accuracy. However, when a cosmetics foundation was not applied, slight amount errors were appeared on the foundation map computed by the simple logarithmic function. Thus the estimation formula with baseline correction will be more suitable when the foundation amount of estimation target is less than about 0.167[μL/cm^2]. On the other hand, the results of simple logarithmic function showed better estimation accuracy for range of much cosmetics foundation amount. Thus better estimation method should be selected depending on the visualization target.

E. Foundation Map of Realistic Made-up Skin

Until the previous section, the calibration curves for estimating the cosmetics foundation amount were established based on the quantitative measurement, and the visualization results of training data clearly showed the foundation application areas with high estimation accuracy. Thus, next, this method was applied to visualize the realistic made-up skin.

In this experiment, cosmetics foundation was applied uniformly over face so that the color of facial skin looks uniform. Fifty microliter liquid foundations were applied to each of forehead and around the cheeks, and about twenty-five microliter was applied to other areas, eyelids, nose, above the mouth. The measurement instruments were same as previous measurements. We used the simple logarithmic function (Eq.7) as the calibration curve.

Figure 12 shows the estimated foundation maps. As shown in Fig.12, the cosmetics foundation was distributed unevenly even though the skin color looked uniform in human eye. Therefore, this will be effective to evaluate the foundation distribution of various made-up skin conditions such as the evaluation of finish by cleansing or foundation deterioration with the passage of time.

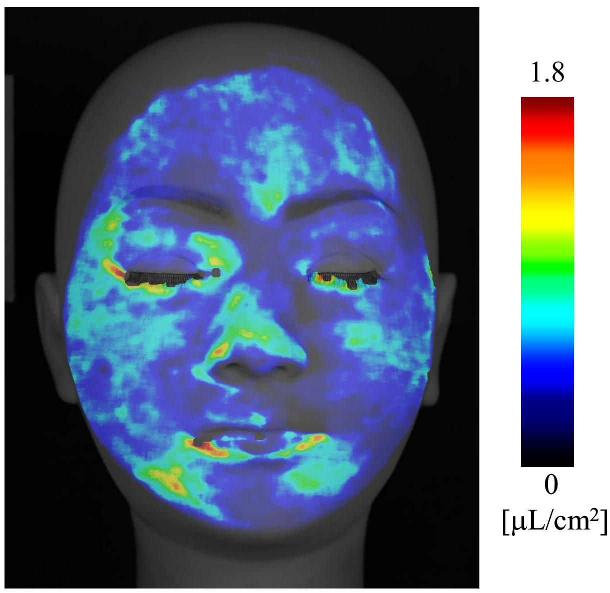


Figure 12. *Foundation maps of test data. It shows the foundation distribution of realistic made-up skin. Cosmetics foundation was applied uniformly over face so that the color of facial skin looks uniform.*

Conclusion

This study proposed a spectral filter to enhance spectral difference by performing discriminant analysis on incoming spectra to conventional RGB camera, and applied it to visualize the foundation distribution of realistic facial condition.

The spectral transmittance of the filter was designed so as to perform the linear discriminant analysis for two pre-defined spectral datasets. The designed theoretical spectral transmittance was optically realized as the multi-layer thin film filter. The color distributions of obtained RGB images taken with a digital camera equipping the filter showed clear enhancement of the spectral differences between two spectra sets which were even invisible to human.

In addition, there were strongly positive correlation between amount of applied foundation and discriminant score. Therefore two calibration curves were established described as Eq.7 and Eq.8. Eq.8 includes baseline correction by a naked skin image. Both of them showed high estimation accuracy described in Table I. Also, the visualization results in Fig.11 showed high estimation accuracy in both ways. Specifically, the calibration curve with baseline correlation (Eq.8) achieved better estimation in range of slight amounts, while the decision coefficient of simple logarithmic function (Eq.7) was higher.

The visualization result of cosmetics foundation amount map in realistic made-up skin showed the uneven foundation distribution as shown in Fig.12. The cosmetics foundation had been applied to make skin color uniform over face. This result suggests that the optical filter and the calibration curves are very powerful for evaluating various made-up conditions.

Our method is not restricted to cosmetic fields, rather for other application: food inspection, medical imaging or other target that need non-destructive inspection. Proposed system can be implemented as part of an on-line measuring system with compact and inexpensive way.

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