Development of Multi-Spectral Scanner by Using LEDs Array for Digital Color Proof

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Abstract

We have developed a multi-spectral scanner with LEDs array and photodiode array to measure the reflectance spectra for printing proof accurately. The system is composed of LEDs array with five different spectral radiant distributions and 2048 silicon photodiodes with SLA (Selfoc Lens Array) for imaging to measure printings. Five kinds of LEDs were selected from 40 kinds of LED with different spectral radiant distribution on the market to minimize the average color difference ΔE^*_{94} between the measured and estimated reflectance spectra of typical 81 color charts. The multiple regression method based on the clustering and polynomial regression algorithm was introduced for high accurate estimation of the spectral reflectance for printing. The result shows that the average and maximum color difference ΔE^*_{94} between the measured and estimated reflectance spectra of 2048 silicon and 2048 silicon and 2048 silicon method based on the clustering and polynomial regression algorithm was introduced for high accurate estimation of the spectral reflectance for printing. The result shows that the average and maximum color difference ΔE^*_{94} between the measured and estimated reflectance spectra of 2048 silicon printing. The result shows that the average and maximum color difference ΔE^*_{94} between the measured and estimated reflectance spectra of 2048 silicon printing. The result shows that the average and maximum color difference ΔE^*_{94} between the measured and estimated reflectance spectra of 928 color charts were 1.02 and 2.84, respectively.

The scanner can measure the reflectance of print with 0.5mm pitch resolution and 100 mm/s scanning speed. The FPGA (Field Programmable Gate Array) and DSP (Digital Signal Processor) were introduced to accelerate the calculation of sensor calibration and estimation of reflectance spectra of printing proof for practical and commercial use. As the result, the developed scanner could measure the reflectance spectra of printing proof within 20 seconds.

Keywords:

Multi-spectral, Scanner, LED, Optimization, Estimation, Polynomial regression, Clustering

1. Introduction

The color proof has been widely used to evaluate and refer the color reproduction in printing, which gives the guarantee to the customers for the quality of print based on the colorimetric color reproduction. In recent years, accurate digital color proof instead of conventional proof has been required to reduce the cost of transportation and saving the time by using the computer network¹⁻².

A color densitometry scanner is usually used to measure and digitize the color information of color proof into R, G, B densities³⁻⁵. As is well known, printing proof based on the densitometrical measurement is influenced by the condition of illuminant. For the colorimetrical color reproduction, it was necessary to compare the color proofs and prints under the illuminant D50⁶⁻⁷ in printing industry. In the approving process by customer, however, this condition of illuminant D50 is not always followed in the practical situation.

For the accurate digital color proof, a multi-spectral imaging⁸⁻¹⁵ has been developed for accurate color reproduction under the different illuminants recently. The reflectance spectra of the object are acquired in this imaging system for calculating the colorimetrical values under arbitrary illuminants. The multi-spectral imaging was usually performed by using five or more color filters for multi-band imaging. It is typically used that the rotating filters are mounted in front of the monochrome type of CCD camera⁸⁻¹¹. However, it requires a much time to rotate the filters with mechanical wheel. Instead of the rotating filters, the liquid crystal tunable filter (LFTF) was used in the multi-spectral imaging¹²⁻¹⁴. This is suitable for a high-speed measurement because the LFTF can change the spectral distribution of filter such as peak wavelength and bandwidth in several milliseconds. As the recent developed method for high-speed measurement, the CRISTATEL project¹⁵ uses the small cask with filters and linear CCD array detector, which achieved 10 milliseconds scanning for each filter. However, these methods need more than 30cm distance between the device and the object. This distance is not practical for the factory use, and **t** is necessary to satisfy the specifications of accuracy, compact and high-speed measurement to make the digital color proof at the print industry.

We developed a multi-spectral scanner by using LEDs array and photodiode array to measure the spectral characteristics of printing proof accurately. A compact scanner can be achieved by using LED illumination and optical element such as the Selfoc lens array. The conventional color filters are not necessary in this scanner because the LED emits the light which have a band-limited spectral radiant distribution. Since the LED response time is very fast, a high-speed measurement is possible by the timesharing control of each LED emission.

For designing the multi-spectral scanner with LEDs array, it is important to decide the number of LED and the spectral radiant distribution of each LED. The algorithm to decide the optimal combination of LEDs is explained in section 3. We develop the multi-spectral scanner by using the obtained optimal combination of LEDs and evaluate the accuracy of estimated reflectance spectra in section 4 and 5. To improve the accuracy of estimation, we also introduce an additional algorithms using the clustering method and polynomial regression method in section 6. Finally concluding remarks are described in section 7.

2. Compact multi-spectral scanner by using leds array

Figure 1 shows the schematic design of the proposed multi-spectral scanner. To satisfy the geometric conditions defined by ISO or DIN standard⁶ of 0-45 degrees method, the LED array is attached on the mount to illuminate the print from 45 degrees, and the detector array is set to detect the light to 0 degrees from the print. The SLA (Selfoc lens array) is inserted between the print and detector for compact structure.

Multiple color type of LED is used in this system for multi-spectral imaging. The each emission for color can be controlled independently in this multiple color type of LED. The analog responses of photo-detector from each color emission in LED are converted to the digital value, and the calibrated value $P_i(x,y)$ at position (x,y) illuminated by *i*-th LED is expressed by

$$P_{i}(x, y) = \frac{\int_{380}^{780} S(\mathbf{l}) \cdot L_{i}(\mathbf{l}) \cdot R(x, y, \mathbf{l}) \cdot d\mathbf{l} - D(y)}{\int_{380}^{780} S(\mathbf{l}) \cdot L_{i}(\mathbf{l}) \cdot W(y, \mathbf{l}) \cdot d\mathbf{l} - D(y)} \cdot \frac{1}{W_{r}} \qquad \dots (1)$$

where $S(\)$, $L_i(\)$ and $R(\)$ are spectral sensitivity of the photodiode, spectral radiant distribution of *i*-th LED and spectral reflectance of the print respectively. $W(y,\)$ are spectral reflectance measured on the reference white plate at position *y*. The value D(y)is measured under the condition which is switched the LEDs off. The coefficient W_r is used to compensate the difference between reference white plate and standard white. The above processes for scanner calibration are performed respectively for large amount of photodiodes in the multi-spectral scanner. In our system, we use the FPGA (Field Programmable Gate Array) for this calculation, since the FPGA has an ability to perform large number of simple and high speed calculation.

As is mentioned above, each color emission in the LED is controlled by the timesharing process, and the responses of photo-detector for color emissions are ordered and streamed in the time series. The stream of responses is stored in the memory for each set of color emissions in the pixel. Based on the stored set of color emissions, the spectral reflectance is estimated in the DSP (Digital Signal Processor). The DSP is superior to calculate vector-matrix operation at high speed for handling the stored response in the memories. In this paper, multiple regression method is used for the spectral estimation⁹. The estimation process for the method is simply expressed by the Eq. (2)

$$\begin{bmatrix} \widehat{R}_{380} \\ \widehat{R}_{390} \\ \vdots \\ \widehat{R}_{780} \end{bmatrix} = \begin{bmatrix} A_{380,1} & A_{380,2} & \cdots & A_{380,i} \\ A_{390,1} & \ddots & & & \\ \vdots & & & \vdots \\ A_{780,1} & & \cdots & A_{780,i} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_i \end{bmatrix} \qquad \dots (2)$$

where \widehat{R}_{I} is the estimated reflectance at the wavelength I, and $A_{I,i}$ are elements of the estimation matrix, which is determined from the relation between the scanner

response and the spectral reflectance of the samples. The sample should be chosen to stand for the target prints, and measured *a priori*.

3. Selection of LEDs

At the development of multi-spectral scanner by using LED array, it is important to decide a number of LED and the spectral radiant distribution of LED. In the conventional multi-spectral imaging by using the color filters, it is possible to optimize the spectral distribution of filters⁹ and to make the optimized filters in the industry. However, the spectral radiant distribution of LED has been already decided by epitaxy process of LED. It is not practical to optimize the spectral radiant distribution of LED for designing the imaging system. In this paper, we select the LED combination from 40 kinds of LEDs on the market to minimize the error between the original and estimated reflectance. Figure 2 shows the spectral radiant distributions of the LEDs, which are normalized by the peak power and are from the specifications of the LED. However, the peak wavelength of each LED is usually shifted by the fluctuation Therefore, it is necessary to take into account this fluctuation to select the LEDs for robust designing in the imaging system.

Next, we will explain a flow of LED selection for the optimized robust imaging system. In this flow, a number of LED to be selected is set as number *i*, and this flow is repeated by changing the number *i* from 3 to 7 to decide the optimal number of LED. The number of combination $n=_{40}C_i$ is calculated, and the evaluation process is repeated *n* times by changing the combination of LEDs. In this evaluation, the responses for reflectance sample illuminated by the current LEDs combination are obtained by the computer simulation of the imaging system, and the calibrated responses are obtained by Eq. (1). The spectral reflectance is estimated from the calibrated responses by using the multiple regression method as Eq. (2). The estimated reflectance is evaluated in comparison with the original reflectance of the sample. In this paper, eighty-one samples for reflectance are examined for each evaluation of the LEDs combination.

Figure 4 shows reflectance spectra of 81 color samples which are printed on the coated paper and measured by the portable spectral photometer (Gretag-Machbeth Spectro-Eye).

The criteria for the evaluation should be set to meet the criteria used in the practical application. For the criteria in this paper, we used the color differences ΔE^*_{94} in CIE L*a*b* color space¹⁶ under A, C, D50, D65 illuminants and 2 degree viewing angle. From our preliminary experiments, we found the selected optimal combination of LEDs is same for A, C, D50 and D65 illuminations respectively. For the ease of explanation, therefore, we will first present the results for the selected optimal combination of LEDs under D50 illuminants, which is defined by ISO 13655⁶ and ICC standard in graphic industry⁷ in the conventional method. Then, the selected optimal combination is examined under other conditions for illuminant and type of paper, to show the effectiveness for the practical application.

It is also necessary to consider the fluctuation of the peak wavelength for the criteria at the evaluation. Therefore, we add ± 10 nm variation to the peak wavelength for each LEDs in the process of simulation. This degree of variation ± 10 nm is decided with enough range from the measurements of LEDs as is shown in Fig. 3. Since the variation $-10, 0, \pm 10$ nm should be applied at each LED, we have 3ⁱ kinds of variation for *i* pieces of LEDs. It is noted that the estimation process in Eq. (2) was designed without the variation of the peak wavelength. The color differences for the 3ⁱ kind of variation are calculated, and maximum color difference $\Delta E^*_{94Flutuation}$ is used for the evaluation of the current combination of LEDs. The maximum color difference $\Delta E^*_{94Flutuation}$ indicate the worst case of color difference for estimation when the LEDs have ± 10 nm variation at peak wavelength.

Figure 5 shows the results of calculation according to changing the number of LEDs. In this figure, the triangles and line show the result of the maximum ΔE^*_{94} without ±10nm fluctuation of peak wavelength, and the squares and line show the result of the maximum ΔE^*_{94} which apply the robust assessment of ±10nm fluctuation. Both results show that the accuracy of estimation is improved as the number of LEDs increases. It is clear that the five LEDs are necessary to estimate the spectral reflectance

less than the maximum $\Delta E^*_{94}=2$ which is calculated between original and the estimated reflectance spectra. Figure 6 shows the spectral radiant distributions of the best combination for each 3,4,5 and 6 number of LEDs.

As is mentioned above, it is preliminary investigated that the selected five LEDs is effective for various printed papers and illuminant conditions, although the best selection is obtained by the evaluation for only D50 illuminant. We will evaluate this effectiveness in detail as follows. Table 1 shows the printed paper and illuminant condition that is used for the verification of the influence.

The accuracy of estimation is examined by using the "art paper" and "matte paper", which are used well in print industry. The estimation matrix is calculated by using 81 color samples of "coat paper" print under the illuminant D50 as is mentioned above, and the spectral reflectance is estimated from the response of multi-spectral scanner for art and matte color samples. The accuracy of estimation is also examined under A, C, D50 and D65. Figure 7 shows the result of maximum ΔE_{94} between the original reflectance and estimated reflectance in 81 color samples for each paper and illuminant.

The black bar in this graph shows the result of maximum ΔE^*_{94} without ±10nm fluctuation of peak wavelength and the gray bar in this graph shows the result of maximum ΔE^*_{94} with ±10nm fluctuation of peak wavelength. It is interesting in Fig. 7(a) that the estimation accuracy for art and matte paper are higher than that of coat paper, even if the estimation matrix was designed for coat paper. This is because the gamuts of 81 color samples for art and matte paper are included in the gamut of coat paper. Figure 7(b) shows that the result of the maximum color difference ΔE^*_{94} by using the coat paper under A, C, D50 and D65. It is noted that the estimation matrix was designed for coat paper under A, C and D65. Based on the Fig. 7(a) and (b), therefore it was empirically confirmed that the estimation matrix for coat paper and D50 illuminant is also effective for other kind of paper and illuminant.

As a conclusion of results, we found that the number of the best LED combination is five, and peak wavelength of LEDs was obtained as 450nm, 470nm, 530nm, 570nm, and 610nm respectively.

4. Development of multi-spectral scanner

We developed the multi-spectral scanner by using the best combination of five LEDs. Figure 8 shows a proto-type multi-spectral scanner which can measure 1024mm × 800mm print sample. The scanner consists of a sensor head with detector, LED illuminations and processing circuit. The detector has 2048 photodiode array and SLA is inserted between print and detector. The surface-mount type of LED is used in the scanner to make it more compact for practical use.

Thirty-two sets of three LEDs in the selected five LEDs are aligned to illuminate the print from the angle of +45 degree. We could not align five kinds of LED as one linear array since the power of each LED is not enough for aligning sparsely for each kind of LED. Therefore, the rests of selected LEDs are aligned to illuminate the print from the angle of -45 degree.

In the system, the print is scanned twice; forward and backward. In the forward scan, the three kinds of LED from +45 angles are used for illumination, and two kind of LED from -45 angles are used for illumination in the backward. Each emission of LED is controlled by the timesharing process to illuminate the print by one kind of LED at each time. Figure 9 shows the timing chart of the timesharing process. For effective output level setting, the time of measurement at each line is divided by the ratio of LED power to determine the duration time for each LED.

The scanner is capable of sampling at 2048×1600 pixels to measure the image with 1024mm×800mm in a 0.5mm pitch. The analog response of photo-detector from each LED illumination is converted to 16 bits with A/D converter, and the amount of digital data becomes about $2048 \times 1600 \times 5 \times 2 = 33$ MB which is acquired by all the numbers of pixels for each LED. The digital data are sent from the multi-spectral scanner to the processing circuit with high speed transmitter. The processing circuit performs the

calculations of the calibration and multiple regression method expressed by Eqs. (1) and (2).

Figure 10 shows the processing circuit which is composed of FPGA, the memory and DSP. The calibration of digitized responses by Eq. (1) is performed at FPGA in the time series, and the stream of responses is stored in the memory at once. The calculation of multiple regression method by Eq. (2) is performed at DSP which is superior to handle to the stored response in the memories. In this calculation expressed in Eq. (2), we adopt the distributed computing by using the six DSPs, where each 342 pixels are assigned each six DSPs.

The scanning speed is designed to be 4000 microseconds per 0.5mm pitch based on the architecture of hardware in the developed multi-spectral scanner. The total number of the scanning becomes 1600 times to measure the proof with 800mm width in a 0.5mm pitch. In this system, it takes about 16 seconds for the multi-spectral measurement since the color proof is scanned forward and backward. Therefore the total measuring time is within 20 seconds including the calculation and display in practical examination.

5. Evaluation of developed system

We evaluate and discuss the performance of the developed multi-spectral scanner in this section. Multiple regression matrix for estimation is determined from 81 colors samples on coat paper, and the spectral reflectances are estimated from responses for 928 colors in the ISO12642 IT8/3 chart. Figure 11(a) and (b) show the examples of estimated reflectance spectra compared with the original reflectance spectra. The best estimation shown in Figure 11(a) achieves an acceptable accuracy on the whole wavelength. On the other hand, the worst estimation shown in Figure 11(b) fails to fit the spectral reflectance in the region except for the center wavelength of used LEDs. It is not enough for five LEDs in this case to represent the spectral pattern.

Figure 11(c) shows the color difference between the original and estimated reflectance spectra of 928 colors charts using the developed multi-spectral scanner. The

average color difference ΔE^*_{94} is 1.23 and the maximum color difference ΔE^*_{94} is 4.07. In general, it is empirically said that the acceptable average color difference is about 2.5 and the maximum is about 3.0 in CIE L*a*b* color space in printing industry. Therefore, we can conclude that the developed multi-spectral scanner by using LEDs has enough accuracy on the aspect of average color difference. However, the maximum color difference exceed to the value of $\Delta E^*_{94} = 3.0$. In the next section, we will improve the estimation method to reduce the maximum color difference.

6. Clustering and polynomial regression

The clustering method¹⁷⁻¹⁸ and polynomial regression method¹⁹ are applied to improve the accuracy of estimation on the aspect of maximum color difference in this section. Figure 12(a) shows the CIE a*b* diagram of estimated color for 928 samples which is printed on coat paper and observed under the D50 illuminant. The estimated color is obtained by using the multiple regression method. The triangles show the color samples whose color difference is more than $\Delta E*_{94}=2.5$ and the dots show the other color samples. It is interesting in this diagram that the triangles are appeared in the red and green hue regions. Therefore, we apply the clustering method in these regions, which is performed empirically in this paper to improve the estimation accuracy as follows.

The red hue region is within the angles of -5° to 40° in hue angle, and the green hue region is within the angles of 145° to 175° in hue angle. It is noted that each cluster use each multiple regression matrix for the estimation of spectral reflectance. Figure 12(b) shows the color difference of 928 color samples based on this clustering method. The average color difference is improved to be $\Delta E^*_{94}=1.04$ and maximum color difference is $\Delta E^*_{94}=3.89$. From these results, the clustering method is effective to improve the accuracy of estimation for spectral reflectance. However, we could not reduce the maximum color difference by using the clustering method effectively.

The polynomial regression method is expected to improve the accuracy of estimation because the error of estimated reflectance is caused by the nonlinear characteristic which is not expressed by multiple regression method in Fig. 11(b). The polynomial regression method is performed to add the squared response P_i^2 in the calculation of multiple regression matrix. The higher order terms of the sensor response is effective for the nonlinear characteristic.

Figure 13(a) shows a comparison of the estimated reflectance spectra calculated by the polynomial regression method and the multiple regression method. This example is the same sample in Fig. 11(b), which is the worst sample by using the multiple regression method. It is shown that the spectral pattern is fit better to the original reflectance than that of the multiple regression method, and the color difference between estimated and the original reflectance is improved by using the polynomial regression method.

Figure 13(b) shows the color difference of 928 color samples by using the polynomial regression method. The result shows that the average and the maximum color difference are improved to $\Delta E^*_{94} = 1.02$ and $\Delta E^*_{94} = 2.84$, respectively.

7. Conclusion

We have developed the multi-spectral scanner by using LEDs array to make the accurate digital color proof. For designing the system, a robust technique was proposed to select LED from the combination of 40 LEDs on the market to minimize the color difference ΔE^*_{94} between measured and estimated reflectance. In this selection of LED, the fluctuation which was caused by manufacture epitaxy process was taken into account. As the result of LED selection, we found that the five LEDs are necessary to estimate the spectral reflectance less than $\Delta E^*_{94}=2$. The peak wavelength of LEDs was selected as 450nm, 470nm, 530nm, 570nm, and 610nm, which was not dependent on the change of illuminant conditions.

For the practical verification in printing industry, we constructed the proto-type multi-spectral scanner by using the LED array. In the sensor head, the photodiode array which has 2048 pixels was used as detector, and Selfoc lens array were inserted for imaging between object and detector. In the processing circuit, the FPGA and DSP were

used to accelerate the calculation for sensor calibration and spectral reflectance estimation. The scanner has 0.5mm pitch resolution and 100 mm/s scanning speed. In the practical examination, we found that the measurement was completed within 20 seconds including calculation and display.

The spectral reflectance of 928 color chart is used to evaluate the accuracy of measurement and estimation. The estimation procedure was determined by measuring the spectral reflectance of 81 typical color charts. By using the multiple regression method, the average color difference was $\Delta E^*_{94}=1.23$ and maximum color difference was $\Delta E^*_{94}=4.07$. The clustering method and the polynomial regression method were also introduced to improve the accuracy of estimated reflectance spectra in comparison with the multiple regression method. From the evaluation among these method, the polynomial regression method was effective for the practical use in printing industry, since the average color difference was $\Delta E^*_{94}=1.02$ and maximum color difference was $\Delta E^*_{94}=2.84$. In this study, we believe that the developed multi-spectral scanner system was very significant for the accurate digital color proof.

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Figure captions

Figure 1 Schematic illustration of multi-spectral scanner by using LEDs array

Figure 2 Spectral radiant distribution of commercially available LEDs

- Figure 3 Example for the shift of peak wavelength generated in manufacture epitaxy process
- Figure 4 Reflectance spectra of 81 color samples printed on coated paper
- Figure 5 Result of simulation with changing the number of LEDs (D50 illuminant)
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- (c) Color difference of 928 colors in the IT/8 chart between the original and estimated spectral reflectance

Figure 12 Improved result of estimation accuracy using the clustering method

- (a) Result of estimated spectra in CIE a*b* space,
- (b) Color difference of 928 colors in the IT/8 chart
- Figure 13 Improved result of estimation accuracy using the polynomial regression method
- (a) Example of spectral reflectance estimation,
- (b) Color difference of 928 colors in the IT/8 chart

Table caption

Table 1Condition of calculation which is verified by the influence of the printed paperand illuminant using LEDs array



Figure 1 Schematic illustration of multi-spectral scanner by using LEDs array



Figure 2 Spectral radiant distribution of commercially available LEDs



Figure 3 Example for the shift of peak wavelength generated in manufacture epitaxy process



Figure 4 Reflectance spectra of 81 color samples printed on coated paper



Figure 5 Result of simulation with changing the number of LEDs (D50 illuminant)



Figure 6 The spectral radiance distribution of LEDs obtained by simulation using LEDs array





Figure 7 Result of $\Delta E *_{94}$ for each kind of paper and each illumination



Figure 8 Proto-type multi-spectral scanner



Figure 9 Timing chart of the timesharing process for each LED





Figure 10 Block diagram and picture of processing circuit





Figure 11 Result of estimation accuracy using the multiple regression method

- (a) The best examples of spectral reflectance by estimation
- (b) The worst examples of spectral reflectance by estimation (? Center wavelength of used LEDs)
- (c) Color difference of 928 colors in the IT/8 chart between the original and estimated spectral reflectance





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(a)Result of estimated spectra in CIE a*b* space,
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 Table 1
 Condition of calculation which is verified by the influence of the printed paper and illuminant using LEDs array

Condition 1

LED Number	Printed Paper	illuminant
5	Coat	D50
5	Art	D50
5	Matte	D50

Condition 2

LED Number	Printed Paper	illuminant
5	Coat	А
5	Coat	С
5	Coat	D50
5	Coat	D65