Color Management Technology for Digital Film Mastering

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Abstract

While digital equipment and devices are rapidly gaining a considerable share in the film production process flow, it has been a subject for argument whether or not visualized image on a certain display device at any point in digital production process can be interpreted as an image representing the picture quality of finalized film to be projected on screen. We have applied the color management technology of our own development to encoding process of film-captured information. As a result, colors of direct prints from negative films are successfully reproduced on high-end digital projectors. This paper analyzes the densitometric transfer between camera negatives, intermediate and positive films. Then a practical calculation method for printing density, and a color conversion system from printing density to CIE XYZ values are proposed. The paper further discusses an encoding system of printing density as a suitable system to fit in the conventional film production flow, which can develop into a successful digital cinema mastering technique.

Introduction

The recent progress in display technologies has enabled us to reproduce on screen colors that are closer to print films. It is helpful in film production to use projectors with better, advanced color reproduction. However, unless the print films are electronically scanned, we must interpret and estimate the colors on print films from those obtained by scanning the camera negatives or intermediate films. Moreover, the flow of motion picture film printing complicates the interpretation when the original camera negatives are scanned, because colors and tones on the print film are decided by printer's settings, that is, exposure steps to print films via negatives assigned to each of R, G and B channels. These facts make us believe that, before discussing the technologies for digital cinema mastering, characteristics of films and every stage of film transfer functions in film laboratory processes must be clarified. This clarification can only assure the reliability of color management model based on printing density. Film labs have long been familiar with printing density and digital encoding systems in printing density was accepted in the film industry only a decade ago.[1-3] The color management model improves the accuracy of calibration of film I/O devices, and contributes to the creativity in film production. Accordingly, the image quality in film presentation is improved and a better reproduction of images on high-end digital projectors is made possible.

In the 1980s, we, at Imagica Corporation, developed a color negative analyzer for use at our own film lab facilities and in the mid-1990s we started to build and provide film scanners to film production companies in the worldwide film industry. The feedback from these activities motivated our study presented in this paper: namely, the frustration experienced by people in the field - poorly organized encoding system for film to video transfer and the unfavorably obvious difference in displayed image on CRT monitors and digital projectors from that of film presentation. We first analyzed the densitometric transfer between camera negatives, intermediate films and positives, and found that polynomial matrix convolution in density gives a good approximation of printing density. As a result, film I/O devices are now accurately calibrated. Secondly, we analyzed colorimetric transfer from printing density into the CIE XYZ values. The conversion method is implemented into a color conversion module using a 3-D look-up table (LUT). The conversion system was successfully applied in the mastering process for Super High Definition (with 3840x2048 Pixels) Digital Cinema System by NTT Network Innovation Laboratories.[4]

Film Production and Transfer

As shown in Fig. 1, the simplest film presentation in general movies is a direct print from camera negatives. When the camera negatives are printed onto positive print films, exposure steps, usually towards every cut of scenes, are preferably changed or set according to the decision by a skilled color expert, "color timer", in film labs or (in collaboration with) a cinematographer or director. Other steps of processes using intermediate films are required for traditional composite work with optical printing or for getting duplication masters to make some hundreds of distribution copies.

In recent film productions, however, digital composite and digital color correction works have replaced those traditional film works in the production flow. In such digital processes, film scanners digitize the camera negatives and film recorders put the images back to intermediate films or camera negatives with less granularity. For splicing with camera negatives of non-digital scenes, film recorders produce negative image films. But when entire scenes of a footage are digitized or entire scenes are shot by digital cameras, e.g. HD cameras, first negatives may be skipped and intermediate positives, so called inter-positive (IP) films are directly produced. The duplication (negative) masters are printed from the IPs. Apart from film production, for video release, such as DVD and broadcasting, one of available image sources, i.e. camera negatives, IPs, inter-negatives (IN) and teleprints (low contrast prints specifically prepared for telecine use) is chosen in telecine (film to video) conversion.

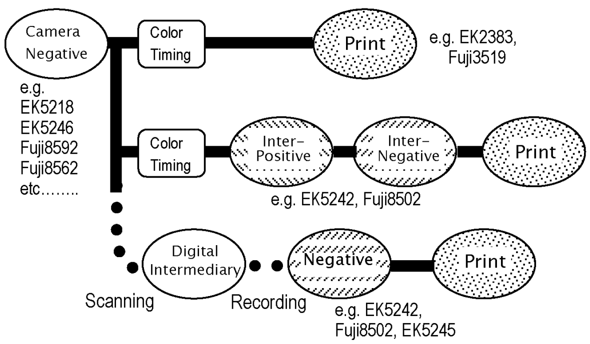

Figure 1. Motion Picture Work

Meanwhile, film labs and post-production facilities have been heavily equipped with electronic and digital tools to support their film production works. Color film analyzers are used to monitor camera negatives in positive image format. The color timer decides the printer setups that consist of step numbers to be assigned to R, G and B channels for each scene of the footage. Then the printer makes positive prints according to these settings. Signal processor circuits are built in the color analyzer to reproduce the printing system, so that the color film analyzer has three knobs that simulate the given settings for R, G and B. But the reproduced image on monitor screen was not good enough for everybody involved to share the final look. Only skilled color timers are able to give the right setup with the negative analyzer.

Recently, the use of digital daily prints is getting more and more popular. Traditionally daily prints are made as work prints in editorial, with which the cinematographer and director can check their vision. Digital daily is useful to preview the look and to share the information in the frame at an even remote location. Also it is digitally conformed by editorial list, and then the conformed image is shown by digital projector. However, the color reproduction is not well managed yet. Thus, an appropriate encoding system in film production must take account of characteristics of respective film types and the printing systems. We examine how the encoding system in printing density applicably works for digital film I/O systems.

Encoding Systems in Printing Density

In the early 90s, film production flow for visual effect (VFX) purposes evolved with addition of digital composite systems featuring the film scanner, film recorder and graphic workstation. The composite system has been widely accepted because not only various special effects by computer graphics were made possible, but also the image quality was well managed by an encoding method called the ‘Cineon’ system established by Eastman Kodak.[5] Its calibration basis is density reproduction where 10-bit codes, 0 to 1023 steps, are approximately assigned to a negative density range of 2.0. Precisely, Cineon codec is on printing density, which is a sort of integrated density depending on some transfer factors such as the spectral transmittance of negative films, spectral distribution of printer illuminant, spectral sensitivity of positive films, and, possibly on spectral transmittance of print films and spectral distribution of projector’s illuminant.

Note here that printing density has dependency on spectral transmittance of negative films. An important aspect of this fact is that, with two different film stocks, EK5242 and EK5218, for example, that have the same status M densities over lowest density (D-min) for R, G and B, the values of printing density are not necessarily the same. The EK5242 is a typical intermediate film often used for laser film recording. The EK5218 is one of camera negatives. Although some similarity may be found among characteristics of some of the camera negatives, we should make a profile on every single motion picture film before using them. Consequently, the encoding system in printing density is introduced to solve the problems in interpretation of film types. The prospective benefits using the encoding system are as follows:

1. Compatibility with the conventional film production process
2. Complete calibration possible on total film I/O devices, from the film scanner to recorder
3. Seamless presentation of digital (VFX frames) and non-digital hybrid sequences
4. Printer setups commonly shared with digital timing
5. Predictable CIE XYZ values

Densitometric Analysis

Densitometric analysis was performed on a film transfer from five types of camera negatives to a positive print, and another from an inter-negative to a positive print. Assuming Lambert-Beer’s law and proportional secondary absorption, a reproduction equation [6 7] is given as:

$$\begin{pmatrix} Dri \\ Dgi \\ Dbi \end{pmatrix} = \begin{pmatrix} f00 & f01 & f02 \\ f10 & f11 & f12 \\ f20 & f21 & f22 \end{pmatrix} \begin{pmatrix} Drc \\ Dgm \\ Dby \end{pmatrix} \qquad \text{Equation 1}$$

where Dri, Dgi and Dbi denote integral densities derived from the concentration of C, M and Y dyes, and Drc, Dgm and Dby denote analytical densities for C, M and Y dyes. The reproduction rule may be applied to analysis of spectral sensitivity of film scanners and interimage effects. However this simple matrix does not practically interpret the density transform for entire density range. Instead, polynomial regression was introduced and transfer matrix (3x13) **T** from status M density to status A density was obtained (Eq. 2).

$$\begin{pmatrix} Ar \\ Ag \\ Ab \end{pmatrix} = \begin{pmatrix} kr0 & kr1 & kr2 & kr3 & kr4 & kr5 & kr6 & kr7 & kr8 & kr9 & kr10 & kr11 & kr12 \\ kg0 & kg1 & kg2 & kg3 & kg4 & kg5 & kg6 & kg7 & kg8 & kg9 & kg10 & kg11 & kg12 \\ kb0 & kb1 & kb2 & kb3 & kb4 & kb5 & kb6 & kb7 & kb8 & kb9 & kb10 & kb11 & kb12 \end{pmatrix} \begin{pmatrix} 1 \\ Mr \\ Mr^2 \\ Mr^3 \\ Mr^4 \\ Mg \\ Mg^2 \\ Mg^3 \\ Mg^4 \\ Mb \\ Mb^2 \\ Mb^3 \\ Mb^4 \end{pmatrix}$$

Equation 2

where Mr, Mg and Mb denote the status M densities for negatives and Ar, Ag and Ab denote the status A densities for positive print films. Status M densities were measured on more than 400 color exposures for the negatives, i.e. EK5218, EK5246, EK5248, EK5274, EK5279 and EK5242 respectively, and status A densities were measured on printed positive films (EK2383) respectively.

The measurements were performed by an X-rite 310 densitometer. Then the regression was carried out on the restricted colors that have positive density 0.30 to 3.30 in status A. In printing process, printer illuminant was controlled of the status M density, R 0.7 G 0.8 B 0.8, over D-min to make the status A density, R 1.08 G 1.06 B 1.03 for camera negatives' transfer.

In terms of internegative's transfer, printer illuminant was controlled of the status M density, R 0.94 G 1.45 B 1.53 to make the status A density, R 1.08 G 1.06 B 1.03. Actually, illuminant control of printer has a little variance. One step of illuminant control is equivalent to 0.025 logarithmic exposures. For the compensation of the variance, assuming the matrix **T** functions for smaller displacement of densities dMr, dMg and dMb, status M densities Mr, Mg and Mb are substituted with Mr + dMr, Mg + dMg and Mb + dMb respectively. Note dMr, dMg and dMb are constant. This printing criterion might be assuming a half-stop (square root 2) overexposure than the standard Eastman Kodak process.[8] Errors in regression for 300 to 400 test colors are shown in Table 1. The maximum error was 0.051 (D) to 0.076 (D) in status A and R.M.S. error was estimated around 0.025 (D) for respective film types. Film gamma of print film near gray is estimated as high as 4 for mid gray (around 0.5 status M density over D-min).[9] Measurement error of 0.01 in status M density is converted to 0.04 in the positive density in this case. We conclude this polynomial matrix model accurately represents the density transformation.

Certain compound negative densities of R, G and B in status M make visually neutral density. Note here that a typical combination of negative and positive films is not necessarily to produce colorimetric grays overall. Therefore, practically, a sensitometric strip does not necessarily turn to an overall gray in colorimetry.[1] Filmmakers, cinematographers and audiences accept this nature of film as cinematographic. For the comparison of tone reproduction on each negative, status A density was calculated by polynomial matrix **T** for parallel increments of status M densities (Mr = Mg = Mb) in Fig. 2. Again, for the compensation of the variance in printing, assuming the matrix **T** functions for smaller displacement of densities dMr, dMg and dMb, status M densities Mr, Mg and Mb are substituted with Mr + dMr, Mg + dMg and Mb + dMb respectively. Of camera negatives, except for type EK5274, four types, EK5218, EK5246, EK5248 and EK5279, have a similar characteristic in tone curves, and also the curve of intermediate film EK5242 is different from those of camera negatives.

Table 1. Densitometric errors in status A density for six negatives (0.30 (D) to 3.30 (D))

Neg	Pos	# of Patches	Total Errors (r.m.s.)			Maximum Errors		
			R	G	B	R	G	B
EK5242	EK2383	309	0.021	0.013	0.032	-0.076	-0.051	-0.073
EK5218	EK2383	411	0.020	0.016	0.025	-0.060	0.063	0.069
EK5246	EK2383	401	0.021	0.018	0.025	0.065	-0.064	-0.070
EK5248	EK2383	401	0.023	0.021	0.025	-0.067	0.064	0.072
EK5274	EK2383	428	0.022	0.022	0.023	-0.067	-0.063	-0.059
EK5279	EK2383	401	0.022	0.023	0.027	-0.069	0.072	-0.074

Matrix **P** (3x3) is derived to give least square error towards the curves obtained by polynomial matrix **T**. For the regression, the status A density area of 0.9 to 3.0 was used. This region was assumed to have linearity in the density domain.

$$\begin{pmatrix} PDr \\ PDg \\ PDb \end{pmatrix} = \mathbf{P} \begin{pmatrix} Mr \\ Mg \\ Mb \end{pmatrix} \qquad \textit{Equation 3}$$

where PDr, PDg and PDb denote printing densities. As a result of experiment, matrix $\mathbf{P}_{5218\text{-}2383}$ for EK5218 to EK2383 and matrix $\mathbf{P}_{5242\text{-}2383}$ for EK5242 to EK2383 are derived as follows.

$$\mathbf{P}_{5218-2383} = \begin{pmatrix} 4.049 & 0.303 & 0.072 \\ 0.472 & 3.090 & 0.191 \\ 0.248 & 0.397 & 2.913 \end{pmatrix} \quad \textit{Equation 4a}$$

$$\mathbf{P}_{5242-2383} = \begin{pmatrix} 4.478 & 0.291 & 0.039 \\ 0.561 & 3.106 & 0.197 \\ 0.325 & 0.350 & 2.947 \end{pmatrix} \quad \textit{Equation 4b}$$

This paper assumes equal values of printing density set on PDr = PDg = PDb give identical curves in status A with a small offset, in other words, the parallel curves with a small offset in status A density instead of log(Xn/X), log(Yn/Y) and log(Zn/Z). This is because it is found that the mixture ratio of status A density R 1.08 G 1.06 B 1.03 gives approximately D55 (reflective) illuminant from screen by Xenon projector as a result of spectral analysis described below. When the camera negative EK5218 is scanned with calibration by matrix $\mathbf{P}_{5218\text{-}2383}$, and then the data is recorded onto EK5242 with calibration by matrix $\mathbf{P}_{5242\text{-}2383}$, the status M density on recorded negative is described as:

$$\begin{pmatrix} Mr' \\ Mg' \\ Mb' \end{pmatrix} = \mathbf{P}^{-1}_{5242-2383} * \mathbf{P}_{5218-2383} \begin{pmatrix} Mr \\ Mg \\ Mb \end{pmatrix} \quad \textit{Equation 5}$$

where $\mathbf{P}^{-1}_{5242\text{-}2383}$ is the inverse matrix of $\mathbf{P}_{5242\text{-}2383}$. Using polynomial matrix **T**, the status A density on the print film in this calibration model is estimated as:

$$\begin{pmatrix} Ar \\ Ag \\ Ab \end{pmatrix} = \mathbf{T}_{5242-2383} \begin{pmatrix} Mr' \\ Mg' \\ Mb' \end{pmatrix} \quad \textit{Equation 6}$$

Meanwhile, most film recorders currently used in the industry do not embed such a matrix process, but, instead, employ gamma management equation shown in Eq. 7.

$$\begin{pmatrix} Mr \\ Mg \\ Mb \end{pmatrix} = \begin{pmatrix} b00 & 0 & 0 \\ 0 & b11 & 0 \\ 0 & 0 & b22 \end{pmatrix} \begin{pmatrix} PDr \\ PDg \\ PDb \end{pmatrix} \quad \textit{Equation 7}$$

In short, this model only maintains the neutral grays. For accurate color reproduction and compensation of secondary absorption, at least a 3x3 matrix should be implemented. Thus, current film I/O devices will be more accurately calibrated using printing density.

Interpretation into Colorimetry

Another subject that is more difficult to define is transformation from status A density to CIE XYZ values. Here CIE XYZ values must be discussed in the reflectance on a screen projected by Xenon projector.

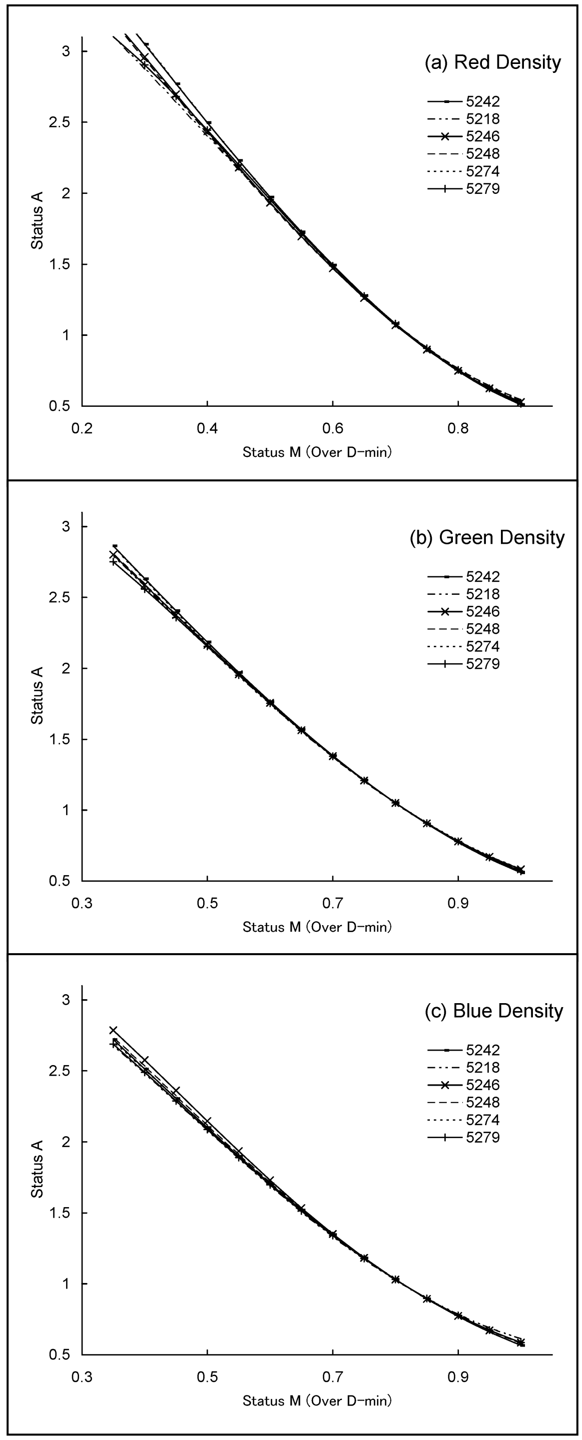

Figure 2 Status M density to status A density of six negatives for red densities (a), green densities (b) and blue densities (c)

Spectral transmittance of five hundreds (500) colors on EK2383, and spectral distribution of the native illuminant of Xenon projector and its reflection on screen were sampled by a Photo Research PR-650, then CIE XYZ values were computed. The reflected illuminant with open-gate on screen was x 0.330 y 0.351, which is approximately 5500K. Several models of high order polynomial matrices were attempted. However, we were not able to find a matrix that fit the interpretation from status A density to CIE XYZ. Instead, with the 500 samples, a 3-D LUT was made for the interpretation. In simulation for the identical color samples used for regression, as colorimetric errors, the total ΔE*ab of 0.956 and the highest ΔE*ab of 5.75 were obtained for the density range of 0.20 to 3.80 in status A. Note all the calculations of ΔE*ab were under D55.

Practical Application of Printer Illuminant Control

As mentioned above, the encoding system needs to manage color timing process in printing. Using a panel printer of BHP Co., print films were printed. The setup was varied in 3-step increments from normal to +9 steps on each of R, G and B channels. Here, normal illuminant is defined to control the status M density, R 0.7 G 0.8 B 0.8, over D-min to make the status A density, R 1.08 G 1.06 B 1.03. The camera negative was EK5274 and the print film EK2383. The response of the print film was estimated according to the polynomial matrix **T** for EK5274 vs. EK2383. In this estimation, 3-step increment of printer's illuminant in each channel was compared by the combination of status M densities to be decremented, R 0.072 G 0.003 B 0.002 for red, R 0.008 G 0.0751 B 0.003 for green and R 0.004 G 0.000 B 0.0840 for blue channel. Table 2 shows the errors between measured densities and estimated densities for the sampled 15 colors. According to these status A densities, colorimetric difference ΔE*ab were estimated by 3-D LUT regression (shown in Table 2).

Table 2. Densitometric (status A) and colorimetric errors by printer illuminant controls for 15 colors

Printer Setup			Density Errors (r.m.s)			ΔE*ab	ΔE*ab
R	G	B	R	G	B	(r.m.s.)	(Max)
initial	initial	initial	0.018	0.024	0.019	1.48	3.60
+3	initial	initial	0.020	0.020	0.026	1.41	2.30
+6	initial	initial	0.026	0.020	0.021	1.54	2.77
+9	initial	initial	0.036	0.019	0.025	1.59	4.00
initial	+3	initial	0.024	0.022	0.026	1.43	3.08
initial	+6	initial	0.022	0.022	0.031	1.96	4.69
initial	+9	initial	0.028	0.028	0.028	1.87	5.75
initial	initial	+3	0.026	0.015	0.020	1.60	2.46
initial	initial	+6	0.031	0.021	0.023	2.04	3.31
initial	initial	+9	0.016	0.027	0.026	1.55	2.94

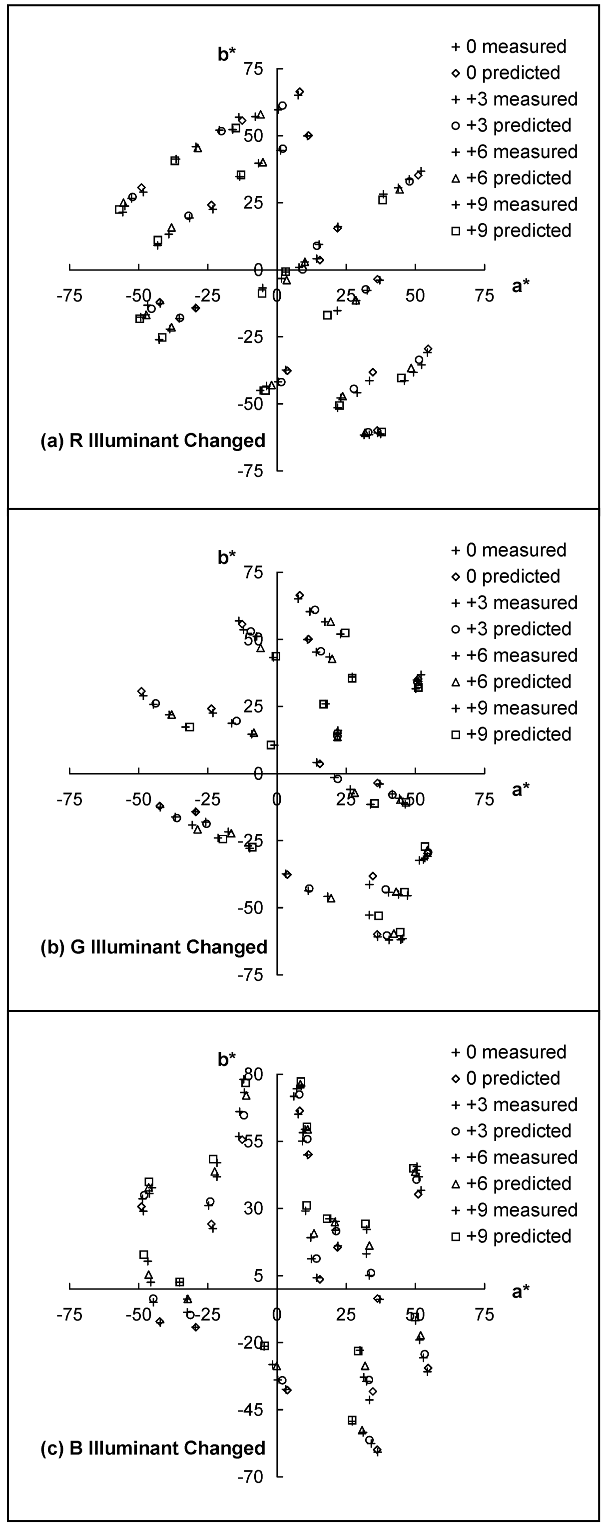

*Figure 3. Comparisons between measured results and predicted results (CIE a*b*), (a) for red illuminant changed, (b) for green illuminant changed and (c) for blue illuminant changed*

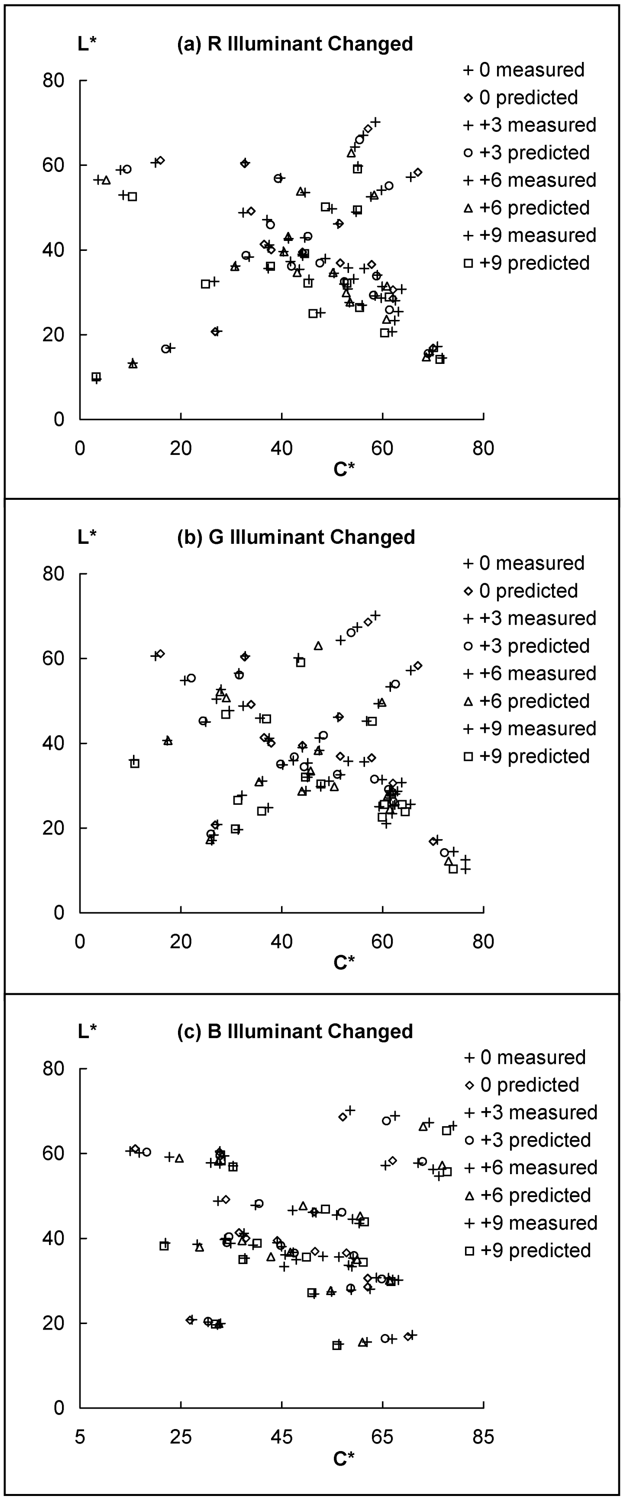

*Figure 4. Comparisons between measured results and predicted results (CIE C*L*), (a) for (a) for red illuminant changed, (b) for green illuminant changed and (c) for blue illuminant changed*

Additionally colorimetric comparisons are shown in Fig. 3 for CIE a*b* and in Fig. 4 for L*C*. The estimation shows a fairly good agreement between the measurement and conversion. This result shows that the encoding system based on printing density applicably interprets the density reproduction on every film transfer, including printer's illuminant control.

The proposed system is shown in Fig. 5. In Fig. 5, a basic encoding method is described. In scanning, 3x3 matrix **Ps** is applied to obtain printing density at the beginning. Digital timing is then performed, which is an additive or subtractive operation in log code. For positive's density, a combined process of inverse matrix $\mathbf{Ps}^{-1}$ and polynomial matrix **Ts** is applied. These matrices are created according to the regression technique mentioned above. The matrices depend on spectral sensitivity of the scanner (e.g. Imager XE), spectral transmittance of the specific negative (EK5274 in this case), spectral distribution of the printer's illuminant (e.g. BHP printer) and spectral sensitivity of the print film (EK 2383 in this case).

The film recorder can produce a negative (EK5242 in this case) from printing density by using a 3x3 matrix $\mathbf{Pr}^{-1}$. And, if inverse conversion of **Tr** is possibly defined, where **Tr** is derived by polynomial regression from status M density on negative film EK5242 to status A density on print film EK2383, the film recorder can also produce a negative (EK5242 in this case, too) from status A density. Then, finally, CIE XYZ values are obtained by transform function **M**. No polynomial matrix was found that satisfies the transformation. As mentioned before, instead, a 3-D LUT was built. This encoding system was applied to actual data mastering processes for high-end digital projectors. In the process, a 3-D LUT was introduced for the color conversion from printing density ("Cineon" code) to CIE XYZ values. Digital timing (printer illuminant control) as evaluated above was applied as well.

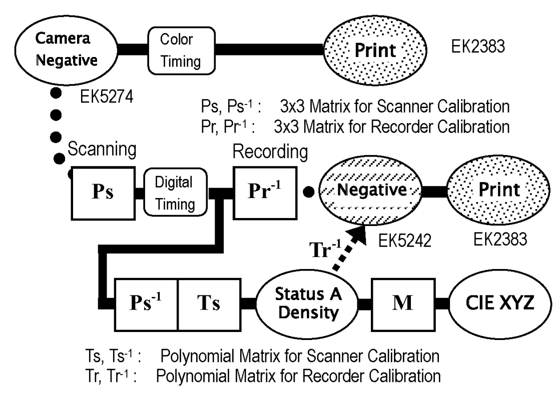

Figure 5. Proposed Encoding System

Conclusions

Our color management technology was systematically applied to digital film production flow. The film transfer (printing) process was analyzed. As a result, it has been determined that the proposed encoding system yields a high-fidelity color reproduction on high-end digital projector. In other words, profiling densitometric transformation between a specific negative film and positive film by polynomial matrices, we can interpret the densities into CIE XYZ values. We believe the proposed system enhances the function in post-production and encourages the creativity of film producers. More study must be carried on regarding interpretation techniques from status A density to CIE XYZ values. In terms of profiling, we will have more discussions on chemical control in film development, standard illuminant of printers, film emulsions to film types, and the nature of faded negatives.

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Biography

Ado Ishii is a senior R&D engineer at Imagica Corp., Tokyo, Japan, developing color management technologies for input and output devices for use in post-production facilities. He received his BE degree in electrical and information engineering from Yokohama National University, Japan, in 1987. In the same year, he joined Imagica Corp. and has since worked on hardware design of image processors for HD video and high resolution film scanner. He is a member of IS&T.