

COLOR CALIBRATION OF SCANNERS USING POLYNOMIAL TRANSFORMATION

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ABSTRACT:

Digital imaging is a rapid growing area with the developments in computer technology. Digital color use has become a conventional tool in many disciplines, such as cartography remote sensing and photogrammetry. The need for better color quality enforces digital imaging industry to produce devices with less color distortions. Despite the today's advanced level of technology, it is known that input and output devices cause color distortions, which depends on the quality of the device itself. Scanners, being peripheral devices that capture the image of an object, are mostly used input devices in digital imaging. In this study color accuracy of desktop scanners is handled. A method based on polynomial transformation, which makes possible to map device dependent colors to device independent ones, is introduced. Tests on five different desktop scanners show the evident applicability of the method.

1. INTRODUCTION

Digital color usage has been rapidly growing with the developments of software and hardware technology. Color imaging has been involved with a variety of branches such as printing industry, graphic arts, photography etc. The need for better quality in color display and color output enforces the digital imaging industry to develop better products. Scanners have been used in many areas of digital imaging. These devices capture the digital image of an object and save it as an image file. The quality of the captured image depends on the scanner. Since scanners can have lost their quality from time to time, they have to be calibrated. The most simple and common way to calibrate them is to compare the scanned image with the original image. For this purpose certified calibration cards for color accuracy and test targets for geometric accuracy have been used. The colors and sizes of the certain objects on the cards have been calibrated according to an international standard. They can be used for color calibration or geometric calibration. The cards are scanned, and then the color values obtained by scanner are compared with the original color values of the card. The calibration methodology is actually to determine a transformation model between scanned values and original values. Linear or non-linear models are possible. If such a model is developed, every scanned image can be corrected. One of the transformation models used in scanner calibration is the polynomial transformation. In most applications polynomial transformations have been determined between the device dependent color space and one of the device independent color spaces defined by CIE (Commission Internationale de L'Eclairage). In this study, polynomial transformations with different orders are determined based on RGB (Red, Green, Blue) values of test cards and RGB values obtained by scanner. For five different desktop scanners polynomial transformations are compared with each other to find the most suitable degree of polynomial. The approach here can be applied for all kinds of scanners.

2. RESEARCH ON SCANNER CALIBRATION

Baltsavias and Waegli (1996) found the geometric accuracies of desktop publishing scanners used in photogrammetry and cartography between 4 and 7 micron. They performed the calibration in two steps. In the first step influences of lens deformation was modeled. In the second step, using all points as control points an affine transformation was performed.

Baltsavias (1996) concluded that the geometric accuracy of desktop publishing scanners was low. He suggested limiting cartographic scans to A3 size, checking and calibrating them regularly.

Vrhel and Trussel (1999) present the mathematical formulation of calibrating color scanners. They found that the mapping from scanned values to colorimetric values is nonlinear. They applied artificial neural network for calibration, then compared this method with other calibration methods based on a test performed with 264 samples.

Hardeberg et al (1996) propose an analytic method based on 3rd order polynomial regression techniques. They used CIE color space values and scanned values of 288 parts of the IT8.7/2 color calibration card. They found out that the polynomial regression delivers better results than other methods.

Finlayson and Drew (1997) mentioned that the color values measured by color devices (e.g. scanners, color copiers, and color cameras) must be transformed to colorimetric "tristimulus" values in order to characterize them in a device independent fashion. Two well-known methods for this transformation are the simple least squares fit procedure and Vrhel's principal component method. They propose a new constrained regression method based on finding the mapping which maps a single (or possibly two) basis surface(s) without error and also minimizes the sum of squared distances between the mapped RGB data and corresponding XYZ tristimuli

values. This method is particularly useful either when it is crucial to transform a particular color with great accuracy or when the calibration data is incomplete.

Ostromoukhov et al (1994) performed 3D-transformations between RGB and CIE XYZ color spaces in order to calibrate electronic display systems.

Mohd and Kirby (1997) tested geometric accuracy of desktop publishing scanners by using a calibrated grid plate. They applied affine transformation and polynomial regression between scanned Cartesian coordinates and the calibrated ones. They found out that 2nd and 3rd order polynomials are suitable for geometric improvement of scanned images. Higher order polynomials are no more useable. The order of polynomial depends on the scanner used.

Noriega et al (2001) determined some properties of scanners by using negative and positive density measurements on the scanned RGB values and the CIE XYZ color space values. They used standard observer color matching functions to transform the density values into CIE XYZ values. They concluded that the inaccuracies of the colorimetric values by scanner depend on the properties of the device and the related color management system.

In the models based on polynomial regression, including more samples in this part of the colorant space could reduce the errors at the gamut boundary. Common test targets such as the ISO 12640 and 12641 have only a limited number of patches at the gamut boundary. Therefore, Green (2000) proposes a new target for defining media gamut boundaries. He used 2nd order polynomial regression in his application.

Kang (1997) mentioned that many scientists have successfully applied regression method for transformation of scanned RGB values to colorimetric values. He determined polynomial equations of different order that convert the RGB values to CIE XYZ and CIE Lab color space values. He used IT8.7/2 calibration card and Sharp JX 450 scanner. He compared the results obtained by different order of polynomials and different standard illuminants.

Berns and Shyu (1994 and 1995) proposed a color mixing method based on theories of Beer-Bouger and Kubelka-Munk and scanner signals. They also applied polynomial regression.

Hardeberg (1999) developed methods based on linear regression, polynomial regressions of 2nd and 3rd order. He applied these methods to AGFA Arcus 2 scanner with AGFA IT8.7/2 calibration card.

Yilmaz (2002) applied conformal, affine, projective and polynomial transformations for reducing color inaccuracies. He examined five different scanners. He found out that the polynomial regression of 3rd order delivers the best results in general.

3. SCANNERS

A scanner is an electronic device that captures the image of any object and converts it into a computer format. It includes an array of cells that are optically sensitive. These cells called CCD (Charge Coupled Device) are connected with a detector that measures the intensity of coming light and converts it to electrical signals. The reflecting light from the object is

projected to the detector via an optical system. The electrical signals generated by the detector are then converted to digital information. Any of the information represents a pixel, and its size is a number of bits that are saved per pixel. If the number of bits per pixel increases, the quality of image becomes better. According to usage areas, scanners can be classified as follows (Baltsavias & Bill, 1994):

- Photogrammetric scanners
- Scanners of large documents
- Microdensitometers
- Desktop publishing scanners
- Other scanners such as scanners of 3-D objects, slide scanners, text document scanners, multiple purpose scanners, etc.

According to working principle two types are distinguished: Drum scanners and flat bed scanners. Drum scanners can process large format documents and delivers accurate images. The most common type of flat bed scanners is desktop publishing scanners.

The reliability of scanners depends on the certain tests. Four types can be performed (Yakar, 2002).

1. Geometric accuracy: With this test geometric distortions are investigated. Calibration targets with maximal positional error of 2-3 micron are required.
2. Geometric resolution: This is the test of optical scanning system. A variety of calibration targets are used.
3. Radiometric accuracy: This is the test of the sensibility of scanner to gray tones.
4. Color accuracy: In this test the original colors and the scanned colors are compared. Calibration cards or targets with standardized colors are required.

After these tests it is decided if the tested device is suitable for certain tasks.

4. COLOR CALIBRATION CARDS

Color calibration cards used for scanner calibration and test for color accuracy have been known as Q-60 calibration cards. They are mainly used in printing industry, photography, and for calibration of monitors, printers and scanners. The main purpose is to have best color outputs on reflection and transmission materials. They are also used for color calibration of scanners. Most of the cards, which are based on the Kodak's Q-60 color calibration card, are produced according to ANSI and ISO standards.

Kodak's Q-60 calibration cards, having all colors of the CIE Lab color space, are in accordance with the ANSI IT8 7.1 and IT8 7.2 and ISO 12641 standards. In general there are two types: IT8 7.1 (transmission) and IT8 7.2 (reflection). IT8 7.1 is printed on "Ektachrome Professional" films, with the size of 4x5 inch. IT8 7.2 is printed on "Ektachrome Professional" cards. Its dimensions are 5x7 inch. Both consist of 240 color parts, 24 gray parts and a human face. The colorimetric values of the cards are given by the manufacturer in a text file. In these files, CIE XYZ color space values, CIE Lab color space values, Sx, Sy, Sz (standard deviations of CIE XYZ values), average density (D) and SD (standard deviation of average density) are given. In this study Kodak's IT8 7.2-1993 2001:02 calibration card was used.

5. 3D POLYNOMIAL TRANSFORMATION

General form of a polynomial of n^{th} order with three variables can be given as follows.

$$f(x, y, z) = \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^n a_{ijk} x^i y^j z^k \quad (1)$$

$i + j + k \leq n$

where,

a_{ijk} : Coefficients x, y, z : Coordinates
 n : Order of polynomial

A 3D polynomial transformation for scanner calibration can be defined using three polynomials as follows.

$$\begin{aligned} R &= f_1(R_S, G_S, B_S) \\ G &= f_1(R_S, G_S, B_S) \\ B &= f_1(R_S, G_S, B_S) \end{aligned} \quad (2)$$

where,

R, G, B : calibrated values (device independent color space)
 R_S, G_S, B_S : scanned values (device dependent color space)

R, G, B values can be calculated from the CIE XYZ color space values of the calibration card. R_S, G_S, B_S values are obtained by scanning the calibration card. In case of Q-60 card there are 240 colors. This makes possible to determine the coefficients of polynomials in (2) by regression. If we select polynomials of 1st order in (2), the coefficients can be determined as follows. The polynomials:

$$\begin{aligned} R &= f_1(R_S, G_S, B_S) = a_0 + a_1 R_S + a_2 G_S + a_3 B_S \\ G &= f_1(R_S, G_S, B_S) = b_0 + b_1 R_S + b_2 G_S + b_3 B_S \\ B &= f_1(R_S, G_S, B_S) = c_0 + c_1 R_S + c_2 G_S + c_3 B_S \end{aligned} \quad (3)$$

If there are m known colors in device color space (scanned RGB values) and device independent color space (e.g. RGB values calculated from CIE XYZ values), we have $3*m$ equations ($3*240=720$ equations).

Because the number of known color values are more than required, the coefficients can be determined with least square adjustment. After adjustment the RMS (root mean square error) is also obtained.

$$\underline{L} = \begin{bmatrix} R_1 \\ G_1 \\ B_1 \\ \vdots \\ R_m \\ G_m \\ B_m \end{bmatrix} \quad \underline{A} = \begin{bmatrix} 1 & R_{S_1} & G_{S_1} & B_{S_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & R_{S_1} & G_{S_1} & B_{S_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & R_{S_1} & G_{S_1} & B_{S_1} \\ \vdots & \vdots \\ 1 & R_{m_1} & G_{m_1} & B_{m_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & R_{m_1} & G_{m_1} & B_{m_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & R_{m_1} & G_{m_1} & B_{m_1} \end{bmatrix} \quad \underline{x} = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ b_0 \\ b_1 \\ b_2 \\ b_3 \\ c_0 \\ c_1 \\ c_2 \\ c_3 \end{bmatrix}$$

$$\begin{aligned} \underline{L} + \underline{v} &= \underline{Ax} \Rightarrow \underline{x} = (\underline{A}^T \underline{A})^{-1} \underline{A}^T \underline{L} \Rightarrow \underline{v} = \underline{Ax} - \underline{L} \\ \Rightarrow RMS &= \sqrt{\frac{\underline{v}^T \underline{v}}{3m-12}} \end{aligned} \quad (4)$$

The relationship between the number of coefficients (q) and the order of polynomial (n) can be expressed as follows.

$$q = 3 \left(\sum_{k=1}^n \binom{k+2}{k} + 1 \right) \quad (5)$$

Table 1 shows the number of coefficients according to order of polynomial.

	Order of 3D polynomial					
	1	2	3	4	5	n
Number of coefficients	12	30	60	105	168	q

Table 1. The number of coefficients

In order to find the most suitable polynomial for a certain device, starting from the 1st order several polynomials have to be determined with least square adjustment. The polynomial with the smallest RMS can be considered to be the most suitable one.

6. APPLICATION

The aim of the application is to find answers to following questions. Are 3D polynomials applicable for color calibration? If yes, what kind of polynomial is the most suitable for this purpose? Polynomial transformations are applied between device dependent color space (scanned color values) and device independent color space (original color values of the test card). In the application Kodak's IT8 7.2-1993 2001:02 calibration card is used.

The original color space for the test card is the CIE XYZ color space. Prior to transformation mentioned above a device independent RGB color space is required. It is obtained from CIE XYZ color space by using D65 standard illuminant and 2° standard observer (ITU-R BT.709-2).

The device color space is constructed by scanning the calibration card. 228 color parts of the card (A1-L19) are used. For each part 100 pixels are selected, and the average of them is calculated. With these average color values 228 colors are determined. If we consider these colors like points in geometrical sense, they are control points for 3D transformation. 228 control points make easily possible to realize polynomial regression until 4th order.

The scanners selected for the application were flat bed desktop publishing scanners. Their models and specifications are given in Table 2. Color calibration card was scanned at the optical resolution of each scanner. No improvements of the scanned image were undertaken. The tests were made at the same conditions (illumination, room temperature, etc.).

Scanner	Scanning method	Color depth	Gray depth	Optical resolution (dpi)	Size
HP ScanJet 5p	single pass	24 bit	8 bit	300	A4
Mustek A3 Sp	single pass	36 bit	12 bit	300	A3
Acer Prisa 310p	single pass	30 bit	8 bit	300	A4
HP ScanJet 5470c	single pass	48 bit	16 bit	2400	A4
Mustek Sp Plus	single pass	30 bit	8 bit	600	A4

Table 2. Scanner models and specifications

The criterion for determining the best fitting polynomial for each scanner is the RMS error obtained after least square adjustment. The polynomial transformation with smallest RMS error can be considered as the best fitting function that maps the device dependent color space to device independent color space. For each scanner in Table 2, bilinear, 2nd, 3rd, and 4th order polynomials are determined by least square adjustment. General equations of these polynomials are as follows.

Bilinear polynomial with 21 coefficients:

$$\begin{aligned} R &= a_1 + a_2 R_S + a_3 G_S + a_4 B_S + a_5 R_S G_S + a_6 R_S B_S + a_7 G_S B_S \\ G &= b_1 + b_2 R_S + b_3 G_S + b_4 B_S + b_5 R_S G_S + b_6 R_S B_S + b_7 G_S B_S \\ B &= c_1 + c_2 R_S + c_3 G_S + c_4 B_S + c_5 R_S G_S + c_6 R_S B_S + c_7 G_S B_S \end{aligned} \quad (6)$$

Polynomial of 2nd order with 30 coefficients:

$$\begin{aligned} R &= a_1 + a_2 R_S + a_3 G_S + a_4 B_S + a_5 R_S^2 + a_6 R_S G_S \\ &\quad + a_7 G_S^2 + a_8 R_S B_S + a_9 G_S B_S + a_{10} B_S^2 \\ G &= b_1 + b_2 R_S + b_3 G_S + b_4 B_S + b_5 R_S^2 + b_6 R_S G_S \\ &\quad + b_7 G_S^2 + b_8 R_S B_S + b_9 G_S B_S + b_{10} B_S^2 \\ B &= c_1 + c_2 R_S + c_3 G_S + c_4 B_S + c_5 R_S^2 + c_6 R_S G_S \\ &\quad + c_7 G_S^2 + c_8 R_S B_S + c_9 G_S B_S + c_{10} B_S^2 \end{aligned} \quad (7)$$

Polynomial of 3rd order with 60 coefficients:

$$\begin{aligned} R &= a_1 + a_2 R_S + a_3 G_S + a_4 B_S + a_5 R_S^2 + a_6 R_S G_S \\ &\quad + a_7 G_S^2 + a_8 R_S B_S + a_9 G_S B_S + a_{10} B_S^2 + a_{11} R_S^3 \\ &\quad + a_{12} R_S^2 G_S + a_{13} R_S G_S^2 + a_{14} G_S^3 + a_{15} R_S^2 B_S \\ &\quad + a_{16} R_S G_S B_S + a_{17} G_S^2 B_S + a_{18} R_S B_S^2 \\ &\quad + a_{19} G_S B_S^2 + a_{20} B_S^3 \\ G &= b_1 + b_2 R_S + b_3 G_S + b_4 B_S + b_5 R_S^2 + b_6 R_S G_S + b_7 G_S^2 + \dots \\ B &= c_1 + c_2 R_S + c_3 G_S + c_4 B_S + c_5 R_S^2 + c_6 R_S G_S + c_7 G_S^2 + \dots \end{aligned} \quad (8)$$

Polynomial of 4th order with 105 coefficients:

$$\begin{aligned} R &= a_1 + a_2 R_S + a_3 G_S + a_4 B_S + a_5 R_S^2 + a_6 R_S G_S + a_7 G_S^2 \\ &\quad + a_8 R_S B_S + a_9 G_S B_S + a_{10} B_S^2 + a_{11} R_S^3 + a_{12} R_S^2 G_S \\ &\quad + a_{13} R_S G_S^2 + a_{14} G_S^3 + a_{15} R_S^2 B_S + a_{16} R_S G_S B_S + a_{17} G_S^2 B_S \\ &\quad + a_{18} R_S B_S^2 + a_{19} G_S B_S^2 + a_{20} B_S^3 + a_{21} R_S^4 + a_{22} R_S^3 G_S \\ &\quad + a_{23} R_S^2 G_S^2 + a_{24} R_S G_S^3 + a_{25} G_S^4 + a_{26} R_S^3 B_S + a_{27} R_S^2 G_S B_S \quad (9) \\ &\quad + a_{28} R_S G_S^2 B_S + a_{29} G_S^2 B_S + a_{30} R_S^2 B_S^2 + a_{31} R_S G_S B_S^2 \\ &\quad + a_{32} G_S^2 B_S^2 + a_{33} R_S B_S^3 + a_{34} G_S B_S^3 + a_{35} B_S^4 \\ G &= b_1 + b_2 R_S + b_3 G_S + b_4 B_S + b_5 R_S^2 + b_6 R_S G_S + \dots \\ B &= c_1 + c_2 R_S + c_3 G_S + c_4 B_S + c_5 R_S^2 + c_6 R_S G_S + \dots \end{aligned}$$

The RMS errors after least square adjustment are shown in Table 3. It is evident from Table 3 that the RMS errors of 4th order polynomials are the smallest ones for each scanner. Higher order polynomials cannot easily be determined because the coefficients matrix A is getting ill conditioned (see Eq.4).

Scanner	2 nd order	3 rd order	4 th order	bilinear
HP ScanJet 5p	3.813920	3.385246	2.621954	4.326551
Mustek A3 Sp	5.278431	3.774867	3.237716	10.313035
Acer Prisa 310p	4.342248	3.296468	2.970317	9.013698
HP ScanJet 5470c	3.988234	3.646822	2.812947	4.858807
Mustek Sp Plus	5.899126	5.939940	4.674509	9.852291

Table 3. RMS errors after adjustment

7. CONCLUSION

In digital color imaging it should be known how accurate the scanners are. It considers the geometric accuracy and color accuracy. Employing mathematical methods can reduce the color distortions. In this study 3D polynomial transformations are applied for this problem. The tests show evident applicability of this transformation method for reducing color distortions of desktop publishing scanners. The transformations make possible to map device dependent color space to device independent color space. The results for a certain scanner model can be generalized, and a device profile for a color managing system can be defined. In the application the 4th order polynomial transformation is found to be most suitable for each scanner. In the appendix, original colors, scanned color and transformed colors (by 4th order polynomial) are shown. Based on the RMS errors in Table 3, the tested scanners can be ordered according to color accuracy; HP ScanJet 5p, Mustek A3 Sp, Acer Prisa 310p, HP ScanJet 5470c, Mustek Sp Plus. The colors in figures in the appendix confirm these ordering.

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APPENDIX



