SCIENTIFIC PAPERS
OF THE UNIVERSITY OF PARDUBICE
Series A
Faculty of Chemical Technology
17 (2011)

IMPROVEMENT OF ACCURACY OF ICC PROFILE BY MEANS OF ANALYSIS OF MULTIDOMAIN COLOUR SPACE

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Received September 30, 2011

The investigation focuses on development of colour information transformation model which takes into account different importance of different domains of colour space depending on the aim of the colour reproduction process and types of print production. The methods of creating the multidimensional colour look-up tables of colour imaging devices are proposed. Namely, the method for direct mapping device-dependent colour space to device-independent based on spline approximation of the data from original test chart taking into account the local non-uniformities in the colour space and criterion of the transformation accuracy. This method reduced the errors during reproduction memorable colours and important for scene colours. We also proposed a combined method of reverse mapping device-independent colour space to device-dependent device signals taking into account the decomposition of the space on the priority area of colour

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reproduction. Both these methods allow reducing error during the process of transformation of colour coordinates of images within the reproduction process.

Keywords: colour management, ICC profile, colour look-up-tables.

Introduction

Colour management is a part of the general process, which includes the calibration of all the elements of reproduction system, the creation and use of profiles of the input, output and display graphics devices, methods of control of the colour reproduction using colorimetry. All the colour management process can be divided into four main phases [1-3]: identification of a colour value — the description of the colour coordinates in a device-dependent colour space RGB or CMYK, or receipt of measurement results in device-independent space Lab; normalization of colours — bringing all elements to a uniform colour space; conversion to output colour space — receiving of a number of numerical values to print the desired colours; proofing — checking the correctness of colour reproduction for the final print.

One of the first steps in profile building involves measuring the colorimetry of a set of colours from some imaging media or display. If the imaging media or viewing environment differ from the reference, it will be necessary to adapt the measured colorimetry to that appropriate for the profile connection space. These adaptations account for such differences as white point chromaticity and luminance relative to an ideal reflector, viewing surround, viewing illuminant, and flare. Currently, it is the responsibility of the profile building software to do this adaptation. But still it is not fully investigated and optimized methods of creating CLUTs, which would take into account non-linear transformation of various areas gamut of input, display, and output colour reproducing devices [1,3]. Also, the standard software for building profiles (ProfileMaker, Monaco Profiler) does not provide the required accuracy of colour reproduction.

Therefore, if investigating all the factors and limitations, which have an influence on the graphic data workflow in the digital systems, it has become possible to create the methods of creating CLUTs which will provide the basis for improvement of accuracy digital colour data transformation for correct image processing.

Problem Definition

In this study, as the output device for the creating LUT-tables of profile has been chosen professional digital proof printer Epson Stylus Pro 4880. The source data for comparative analysis of the methods for creating LUT-tables is the test chart of 1728 patches representing a uniform sample of the RGB colour space for which the dependence between device-dependent coordinates and device-independent colour coordinates Lab has been established using spectrometric measurements (Fig. 1).

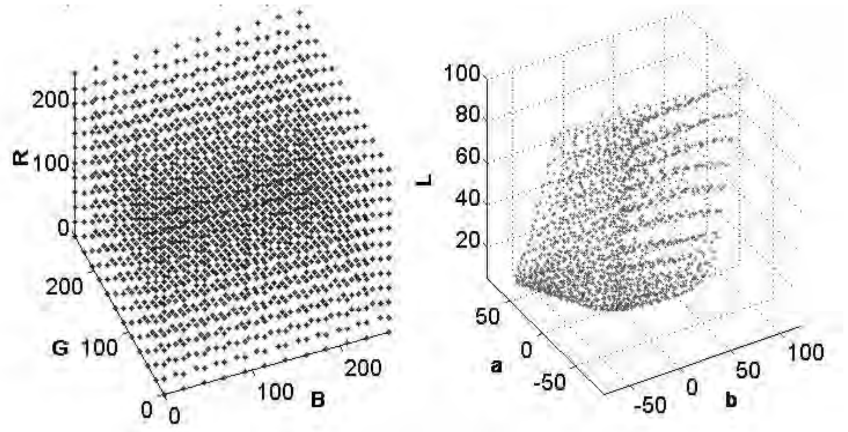

Fig. 1 Location of the coordinates of the test chart in the RGB colour space and Lab

To create a profile of the proofing device, it is necessary to establish connection between device-dependent RGB colour space and device-independent space Lab for all grid points of a multidimensional LUT-table.

The problem of determining the relationship between RGB signals and CIE Lab values for creating LUT-table of ICC RGB-output profile could be formulated as follows: suppose there is defined the set of N three-dimensional device-dependent colour patches $\{R_i, G_i, B_i\} \in RGB$, $i = 1,\dots, N$, obtained during the characterization of the device, and a corresponding set of three-dimensional device- independent samples $\{L_i, a_i, b_i\} \in Lab$, $I = 1, \dots, N$. It is necessary to find the form of analytic dependence describing the direct conversion RGB-Lab (AtoB) as well as inverse transform Lab-RGB (BtoA)

$$\begin{cases} L = \psi_L(R, G, B) \\ a = \psi_a(R, G, B) \\ b = \psi_b(R, G, B) \end{cases}, \qquad \begin{cases} R = \varphi_R(L, a, b) \\ G = \varphi_G(L, a, b) \\ B = \varphi_B(L, a, b) \end{cases} \tag{1}$$

A test sequence consisting of 1728 patches whose colour coordinates are located between the grid points, as well as 61 patches representing a sample of memorable colours (colour of human body, vegetable greens and sky), has been used for evaluation of the accuracy of the transformation.

Development of a Method for Creating the Multidimensional LUT-tables for Direct Conversion (AtoB)

The problem of approximation is solved for direct conversion RGB – Lab. Based on a uniform grid with the step equal to 23 $\{R_i, G_i, B_i\} \in RGB$ it is necessary to form a uniform grid of LUT-table containing 35937 values with a smaller step — 7.97.

For tabulated functional dependencies, we compared the effectiveness of such approximation methods as polynomial approximation, approximation using neural networks, spline approximation, spline interpolation (including linear), and using smoothing splines.

Polynomial Approximation

In this paper we consider the approximation of data by polynomials by means of the least squares method. Polynomial regression is a special case of multiple regression

$$\mathbf{y} = \mathbf{X} \cdot \boldsymbol{\beta} + \boldsymbol{\varepsilon} \tag{2}$$

where **y** is column vector size of values $n \times 1$ of one of the output variable L, a, b; n is number of patches; $\boldsymbol{\beta}$ is the vector of the model; **X** is a numerical matrix; $\boldsymbol{\varepsilon}$ is a vector of random disturbing factors. Dimension of the matrix is $\mathbf{X} = n \times p$, where p is number of the model coefficients, for example, the quadratic one has 10 coefficients R, G, B, RG, RB, GB, R^2, G^2, B^2, 1.

Approximation Using Neural Networks.

In the present work we have chosen the generalized regression neural GRNN (Generalized Regression Neural Network) network, which is designed to solve the problems of regression and is characterized by a high rate of learning [5]. To create a GRNNs, we have used the following functions of the MATLAB Neural Network toolbox:

- net = newgrnn (X_train, y, sp) is a network with learning. Where X_train values of R, G, B coordinates of the training samples (1728 patches); y – output values of L, a, b coordinates of the training samples; *sp* – smoothing coefficient;
- Y_Lab = sim (net, X_test) is network simulation. Where X_test values of R, G, B coordinates for the test sequence (1789 fields); Y_Lab are the results of approximation for the test samples.

We studied the dependence of the standard deviation for the training and test samples from the values of the smoothing coefficient. For calculations, we selected the value $sp = 10$ in which the standard deviation for the training and test samples is less than the minimum perceptible colour difference.

Spline Approximation.

Piecewise-polynomial spline approach has several advantages for the problems of data approximation in the case of complex nonlinear dependence of colour coordinates. They can take into account local changes in different parts of the colour space.

3D spline by means of B-splines is the tensor product of splines each of the variables R, G, B

$$y(R, G, B) = \sum_{u=1}^{U} \sum_{v=1}^{V} \sum_{w=1}^{W} a_{u,v,w} B_{u,k}(R) B_{v,l}(G) B_{v,m}(B) \tag{3}$$

where y is column vector of one of the output variable L, a, b; $B_{u,k}$, $B_{v,l}$, $B_{v,m}$ are 1D splines; k, l, m are the power of splines by the R, G, B; $a_{u, v,w}$ are the unknown model coefficients.

We investigated the influence of the number of pieces of the spline and the power of the basis B-splines on the value of complex criterion of quality of data approximation, and we obtained the values of criterion for all possible combinations of pieces of splines in three directions. The maximum number of pieces is connected to the number of grid points of the source data and the maximum power of the basis splines.

With increasing of the power of the basis splines from linear to cubic approximation the error decreases and then it begins to increase. Thus, based on the results of the calculations, we chose cubic splines, as well as the optimal number of pieces of B-splines in each direction: the L-7, at a-2 and b-4.

Interpolating Splines

Standard software ProfileMaker for building profiles uses a three-dimensional interpolation to transform colour information between the spaces RGB and Lab. Thus, to solve the problem of creating the LUT-table, we considered the methods of approximations based on interpolating splines. The task was to find three-dimensional splines S_l, S_a, S_b, for which the interpolation conditions are fulfilled

$$S_L(R_i, G_i, B_i) = L_i,\ S_a(R_i, G_i, B_i) = a_i,\ S_b(R_i, G_i, B_i) = b_i,\ i = 1, 2, ..., 1728 \tag{4}$$

It was found that the minimum value of complex criterion is reached at the follow power of the bases splines by coordinates: L – quadratic, a – linear and b – linear.

Smoothing Cubic Splines

In this case we solve the problem of smoothing of the experimental data as a minimization problem of some special functional (5) under the constraint on the deviation of the spline from the set of values

$$\min_{f}\left\{p\sum_{i=1}^{n}\left(y_i-f(x_i)\right)^2+(1-p)\int_{x_1}^{x_n}\left(f''(x)\right)^2\mathrm{d}x\right\} \tag{5}$$

where p is the parameter that determines the value of smoothing. If $p = 0$, it is calculated interpolating cubic spline [6].

In order to estimate the accuracy of conversion by using various methods of approximation of the colour data it is developed integrated criterion which takes into account:

- average colour difference ΔE between measured and calculated colour coordinates in the device-independent colour space Lab;
- the maximum colour difference of all the colours of the sample E_{max};
- colour difference ΔE_p in areas of a memorable colours (colours of human skin, greenery and colours of the sky);
- average colour difference ΔE_a of the achromatic colours because the human eye is most sensitive to colour shifts in shades of gray;
- colour difference ΔE_0 of sample of the colours on the gamut boundary. The sample consists of highly saturated colours that are often used to create a brand identity, as well as tints of blacks that are responsible for the details in the deep shadows.

The final value of the criterion is calculated from the ratio value of each component

$$K = k_1\Delta E + k_2 E_{\max} + k_3\Delta E_p + k_4\Delta E_a + k_5\Delta E_o \tag{6}$$

The values of k_1, k_2, k_3, k_4, k_5 are set by the group of experts and depend on the purpose of the reproduction process. The values of coefficients for printed advertising are 0.4, 0.05, 0.3, 0.1, 0.15.

Method of spline approximation for creation of LUT-tables (AtoB) of the profile of output device is selected on the basis of comparative analysis of the above mentioned models. The results of comparison of the measured and expected

Table I Errors in calculating the colour coordinates $L^*a^*b^*$

Method of approximation	Test samples					
	ΔE	$E_{\max}$	ΔE_p	ΔE_a	ΔE_o	K
Polynomial approximation. (Using quadratic polynomial)	1.76	6.76	1.95	2.88	2.03	2.2218
Approximation using neural networks GRNN	0.73	4.48	1.73	0.91	0.70	1.2352
Spline approximation	0.81	3.11	1.10	1.17	0.77	1.0452
Interpolating splines	0.74	3.17	1.29	0.94	0.71	1.0479
Smoothing cubic splines	0.74	3.71	1.35	0.91	0.70	1.0864

coordinates $L^*a^*b^*$ for all the investigated methods are given in Table I.

When we use spline approximation, the average error of all the colours of a space is greater than in other methods of approximation, but by using this approximation we can increase the accuracy in areas of memorable colours that require more accurate colour reproduction (see Table I). The use of the approximating cubic B-splines with different number of pieces at each direction: for L-7, a-2 and b-4, gives an approximation with the minimum value of complex criterion.

Thus, it was determined that the most appropriate method for direct transformation (AtoB) is the use of the approximating B-splines with optimal values of the power and the number of pieces of the spline for each direction.

Development of a Method of Creating Multidimensional LUT-tables for Reverse Transformation (BtoA)

For reverse transformation Lab-RGB it is necessary to solve the more complex problem of constructing a uniform grid for the table-defined functions. $R = \varphi_R(L, a, b)$, $G = \varphi_G(L, a, b)$, $B = \varphi_B(L, a, b)$. The input data, non-uniform grid in device-independent space Lab, represents the body of complex shape. Due to differences in the form of gamuts, the linear transformation from one colour space to another is impossible. Therefore, the mathematical transformations are nonlinear and introduce significant distortions into the process of reproduction.

The location of points does not allow to create uniform grid on the whole space. Therefore, it was proposed to use methods of local approximation of the data for creating LUT-tables (BtoA). That is why, based on data for the direct conversion RGB-Lab dense grid (with step of 2 units) was built on hole space. Then the colour space was divided into several parts to build more flexible and accurate analytical dependence of the conversion of each region of colour space.

We defined the region with achromatic colours, the colours on the boundary of the gamut, the points lying inside the gamut and the memorable colours. For each point of all the regions we found nearby points, i.e., the neighbourhood. Experimentally, we found out the number of neighbourhood points involved in the approximation.

For the local polynomial approximation of the data when forming LUT-tables (BtoA) it was considered to compare linear, quadratic, incomplete quadratic and cubic regression models. To find the model coefficients, we used: least-squares method, robust algorithm and the method of minimax.

Polynomial Regression

We calculated the point estimates of the model by using least-squares method for each output variable R^*, G^*, B^*. The linear, quadratic, cubic and incomplete quadratic models without absolute term are compared. To calculate the regression coefficients, we used the function regress from Statistics Toolbox MATLAB. The results of calculations are presented in Table II.

Table II Errors in calculating the colour coordinates $R^*G^*B^*$ to construct regression model using least squares method

Regression model	Region of colour space											
	Colours inside gamut			Memorable colours			Achromatic colours			At boundary of gamut		
	ΔR	ΔG	ΔB	ΔR	ΔG	ΔB	ΔR	ΔG	ΔB	ΔR	ΔG	ΔB
Linear	2.6	2.4	3.8	2.1	2.3	4.8	4.1	3.0	3.1	5.4	5.8	7.6
Quadratic	2.7	2.5	4.1	2.1	2.5	5.4	3.4	2.4	2.6	5.6	5.7	7.4
Incomplete quadratic	*2.6*	*2.3*	*3.8*	2.0	2.2	4.6	3.8	3.0	3.1	5.1	5.5	7.3
Cubic	2.7	2.7	4.2	2.1	2.4	5.1	3.4	2.5	2.6	5.7	6.2	7.5

Robust Regression

The method of an iterative reweighted least squares method is used. Use of this algorithm allows to set lower values of the weights for the cases with greater deviation from the regression model to the rest. The task is to minimize each output function

$$S = \sum_{i=1}^{n} w_i \left(y_i - f(x_i, \boldsymbol{\beta})\right)^2 \tag{7}$$

where w_i – weights, that at the current iteration are calculated using biquadratic weighting function of the vector residuals, calculated at the previous iteration. In this case, the weights are determined as

$$w_i = \left(|R_i| < 1\right)(1 - r_i^2)^2 \tag{8}$$

r_i – the distance from i to the point of the regression line obtained in the previous iteration. The value of r_i is defined as

$$r_i = \frac{res}{ts\sqrt{1 - h}} \tag{9}$$

where $res = \mathbf{y} - \mathbf{X}\boldsymbol{\beta}$ – the vector of residuals from the previous iteration; t – matching constant; $\mathbf{h}$ – vector of diagonal elements of a matrix $\mathbf{H} = \mathbf{X}(\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathrm{T}}$; s – estimation of the standard deviation of the regression.

The use of this algorithm allows to set lower values of the weights for cases with greater deviation from the regression model to the rest. For calculations are used the function robustfit — Statistics Toolbox MATLAB. The calculation results are less sensitive to accidental releases into the sample than when we use the method of least squares. The results of calculations are presented in Table III.

Table III Errors in calculating the colour coordinates $R^*G^*B^*$ to construct regression model using robust algorithm

Regression model	Region of colour space											
	Colours inside gamut			Memorable colours			Achromatic colours			At boundary of gamut		
	ΔR	ΔG	ΔB	ΔR	ΔG	ΔB	ΔR	ΔG	ΔB	ΔR	ΔG	ΔB
Linear	2.7	2.4	3.8	2.1	2.2	4.6	4.1	3.1	3.1	5.6	5.9	7.8
Quadratic	2.8	2.6	4.1	2.1	2.4	5.4	*3.3*	*2.4*	*2.6*	5.7	5.8	7.4
Incomplete quadratic	2.6	2.3	3.8	*2.0*	*2.1*	*4.4*	3.8	3.0	3.0	5.2	5.6	7.4
Cubic	2.9	2.8	4.3	2.1	2.4	5.0	3.3	2.5	2.6	5.9	6.4	7.6

Minimax Regression

The minimax method is also used to estimate the regression coefficients. This method is minimizing the maximum absolute deviation of the experimental data from the regression line

$$\min_{\boldsymbol{\beta}} \max_{i} \left| y_i - f(x_i, \boldsymbol{\beta}) \right| \tag{10}$$

Function fminimax — Optimization Toolbox MATLAB — was used to solve the problem of minimax (10). The linear, quadratic, and cubic incomplete quadratic regression models are compared. However, the approaches based on linear and cubic models provide significantly greater error, so the results of calculations are presented only for the quadratic and incomplete quadratic model (Table IV).

Table IV Errors in calculating the colour coordinates $R^*G^*B^*$ to construct regression model using minimax method

Region of colour space	Regression model					
	Quadratic			Incomplete quadratic		
	ΔR	ΔG	ΔB	ΔR	ΔG	ΔB
Colours inside gamut	2.7842	2.5294	4.5019	2.8156	2.4803	4.4965
Memorable colours	2.1026	2.3942	5.4073	2.0264	2.1411	4.3853
Achromatic colours	3.3197	2.4270	2.5786	3.8295	3.0208	3.0867
At boundary of gamut	4.2408	4.9529	6.2477	*4.0879*	*4.7643*	*6.0217*

Based on the analysis of errors of calculation of colour coordinates of R^* G^* B^* by different methods (Tables II-IV) it was proposed to use a combined method of creating the LUT-table. It involves the various methods of approximation for different regions of the colour space; detailed information is given in Table V.

Table V Methods of local approximation of data for creating reverse transformation (*BtoA*)

Region of colour space	Regression model	Method for identification of model parameters
Colours inside gamut	Incomplete quadratic	Least squares method
Memorable colours	Incomplete quadratic	Robust
Achromatic colours	Quadratic	Robust
At boundary of gamut	Incomplete quadratic	Minimax method

The proposed method can reduce the error of conversion of colour coordinates from the device-independent to device-dependent colour space and it is needed for proper creation of profiles colorimetric LUT-tables.

Conclusion

We proposed effective methods of forward and reverse colour transformation for creating colorimetric LUT-tables of RGB-output profile of proofing device. This profile gives a smaller colour difference between colour samples as compared with the profile created by standard software (Profile Maker). Also it provides more accurate and predictable colour reproduction. To obtain the accuracy of colour reproduction, we used an integrated criterion which takes into account local nonuniformities in colour space.

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