Recent Developments towards Control-Based Color Profiling Technology

Lalit K. Mestha, Alvaro E. Gil, Yao Rong Wang, Marty S. Maltz and Raja Bala; Xerox Research Center, Webster, NY 14580

Abstract

In this paper we describe the advances made in high accuracy, high performance destination color profiling technology for use in digital printers. A profiling technology, configured to produce (a) an initial estimate in the factory of a fine tuned GCR strategy and gain matrices as starting LUTs, and (2) a runtime profiling technology for adjusting colors before production run by the customer on a drifted print engine. Key new algorithms presented are: Co-operative Neighbor Driven Gray Component Replacement (GCR) algorithm and control-based inversion. These algorithms are used with other known suite of algorithms to make a complete practical profiling technology.

Introduction

A profile contains a multidimensional color correction look up table (LUT) comprising a series of nodes in input color space (*L*a*b* or XYZ*), and device-specific (*CMYK*) output values stored at each node. When the input pixels to be corrected coincide with the nodes of the LUT, the corresponding device specific color values are retrieved directly from the LUT. If the pixels are not on the node, then they are derived via interpolation of neighboring nodes using a standard technique such as tetrahedral interpolation.

In general, the first step in building a profile is to derive a forward model that maps a device-specific (*CMYK*) representation to a visual (*L*a*b**) color representation. Numerous modeling techniques have been used. Some are based on experimentally generated data, some are based on a first principle approach such as a spectral cellular Yule-Nielsen-corrected Neugebauer model (SCYNN), and some are a combination of both. The next step in the profiling process is to invert the aforementioned printer model to produce a mapping from a visual (*L*a*b**) representation to a device-specific (*CMYK*) representation that produces smooth, contour-free, noise-free and pleasing color prints.

Our approach towards creating high accuracy color profiling involves two steps; (a) the creation of an initial estimated LUT in the factory with a well tuned GCR strategy for a pre-selected number of nodes and gain matrices for each node and (b) a run-time (in-field) profiling technology with control-based inversion, gamut mapping and black point compensation algorithms. The in-factory profile allows developers to tune the GCR at the expense of reasonably long computational time. Whereas, the run-time profile involves little or no operator intervention to create and update profiles based on the measured color output of the device at the time of creating profile updates. Next we will present a brief overview of the algorithms and make references, as required, to published documents.

In-Factory Profiling

In this section we describe how new algorithms were integrated to generate a fine tuned ICC profile with no or limited formulation jumps for a four color printing system. A key output from this section is the well-tuned halftone screen specific starting LUTs comprised of GCR and gain matrices.

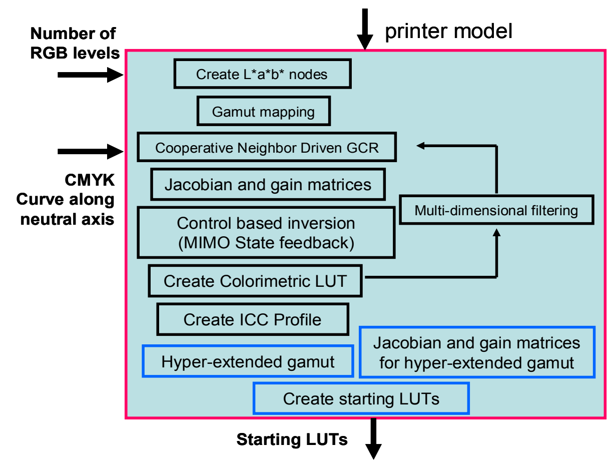

Figure 1: Block diagram view of the in-factory profiling technology

Figure 1 shows the block diagram view of various algorithms used in the in-factory profiling technology. Figure 2 shows the components within the ICC profile that translates color information from the Profile Connection Space (PCS) to the device-specific *CMYK* space. For the creation of a colorimetrically accurate destination ICC profile, we generate a dense RGB grid with node levels defined as inputs (e.g., 17 cube grid). These RGB nodes are then converted to *L*a*b** using a suitable color space (e.g., ProPhot RGB). These RGB nodes (colors) are then separated into in-gamut and out-of-gamut nodes (colors). The out-of-gamut colors are mapped to the gamut surface using any known gamut mapping algorithm (e.g., cusp gamut mapping). There is no need to select the optimal (best) gamut mapping for in-factory profiling function, since the starting LUTs do not carry this information. They contain *CMYK* values only for in-gamut colors. The in-gamut colors are now subjected to GCR constrained inversion.

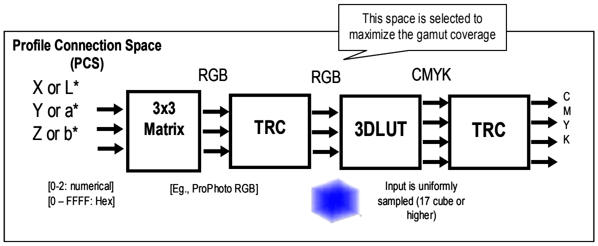

Figure 2: Block diagram view of theICC profile components

Gray Component Replacement (GCR)

For high quality color printing, image separations should not be noisy. One source of noise is large changes in formulation between neighboring nodes. This can arrise because most colors can be made with a wide range of CMYK formulations, and thefore the formulations for neighboring nodes can be very different. These formulation jumps and can appear as noise or contours. For example, neutral colors can be produced with an infinity of *CMYK* recipes.

The GCR approach gives a smooth transition between every neighboring node in *CMYK* space. The smoothness is preserved by using two novel algorithms; (1) a MIMO control algorithm and (2) a neighbor detection algorithm in *L*a*b** space. Neighboring pairs cooperate mutually by exchanging information in order to provide a smooth transition between them in the *CMYK* space. This work differs from other approaches in the sense that both nodes' accuracy and smoothness are controlled in one step. If the smoothness is not preserved, which may occur in some cases (e.g., when the printer is highly nonlinear or when the nodes are sparse), a multi-dimensional filtering algorithm is used to further refine the formulations.

Cooperative Neighbor Driven GCR Algorithm

While deriving the GCR algorithm, we assume that the $CMYK_A$ values of a particular node *A* or a set of neighboring nodes are known. Figure 3 shows an example of the known input *CMYK* values for the nodes along the neutral axis. This could be obtained from a computer generated curve fed as input to the in-factory profiling technology as indicated in Figure 1. Using this information, the printer model, and the right inversion algorithm, it is possible to estimate the "closest" $CMYK_B$ values of the "closest" node *B*, with respect to node *A*, in terms of a distance metrics in the *L*a*b** space. When multiple *CMYK* solutions are present, as in a four color *CMYK* printer, at the moment of deciding a *CMYK* recipe for a particular node (node *B*), this approach offers the possibility of selecting the one *CMYK* which is closest to the *CMYK* recipe of the neighboring node.

In order to create smooth *CMYK* recipes for all the nodes, starting from say the *CMYK* values for colors near the neutral axis, we define two groups that contain set of *L*a*b** values of the nodes. The first group is called the "recruiting set" that contains one or more *L*a*b** values with their respective *CMYK* values. The second group is called the "candidate set" that contains only their *L*a*b** values without the knowledge of their *CMYK* values. The goal of the recruiting set is to determine potential nodes from the candidate set that could become part of the recruiting set. The goal of the candidate set is to market themselves before the recruiting set in order to be recruited. This approach is described in detail in the upcoming book chapter [4]. The algorithm steps are shown next:

1. Define a recruiting set $R = \{1,2,\ldots,N\}$ that contains $N>=1$ *L*a*b** nodes. The location of these nodes in the *L*a*b** space could be decided by the designer. One option is to allocate one or more nodes along the neutral axis as in Figure 3. Thus, we are forcing these colors to behave the way we want along the neutral axis since the profile that will be built will inherit the *CMYK* values for this set.
2. Compute the *CMYK* values of all the nodes in the recruiting set. If these points are along the neutral axis, use the curve shown in Figure 3 for the initial estimate.
3. Define a candidate set $C = \{1, 2,\ldots,M\}$ that contains *M* number of *L*a*b** nodes. This list comes from all the nodes in the LUT.
4. Determine the candidate node to be recruited next. This can be done by gradually increasing the radius of a cylinder from 0 all the way until all the nodes in the LUT are recruited.

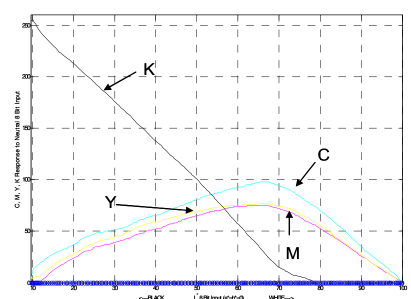

Figure 3: CMYK response of GCR along the neutral axis. X-axis has the range from L=0 to L*=100 and y-axis ranges from 0 to 255.*

5. Compute the *CMYK* values for the closest node using the *CMYK* value of the node in the recruiting set as a starting point. The recruiting process is neighbor driven since it always selects the nodes with the minimum distance between any recruiting and candidate nodes. Once a pair of nodes has been identified, the cooperation takes place since the *CMYK* values of the recruiting set is shared with the candidate set. The candidate node uses a MIMO controller of Figure 4 to iterate several times and converge to a new *CMYK* value that is close to its closest neighbor.

6. The closest node identified in 5 above now becomes part of the recruiting set, i.e., $R = R + \{j^*\}$, and no longer belongs to the candidate set, i.e, $C = C - \{j^*\}$.

7. Repeat algorithm steps from 4 to 7 until the set C is empty. That is, until there are no more candidate nodes to recruit.

MIMO Controller

The sharing of information, combined with the feedback control system approach, is used to compute the closest *CMYK* value of the selected color in the candidate set to the *CMYK* value of the color in the recruiting set. We design a MIMO state-feedback controller and operate on the printer model to update the *CMYK* recipe that will accurately reproduce the given target $L^*a^*b^*$ value. The feedback system shown in Figure 4 modeled in Reference [2] is expressed as a state equation of the form $x(k+1) = Ax(k) + Bu(k)$ where $x(k)$ represents the vector containing output $L^*a^*b^*$ values at iteration k, A is the identity matrix and B is the Jacobian matrix for the node color computed around the initial *CMYK* value, and $u(k)$ is the control law applied to the input of the printer.

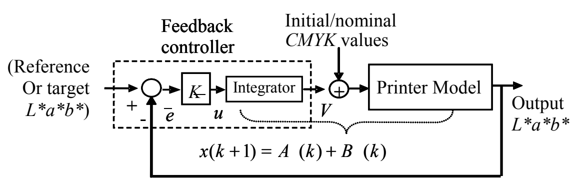

Figure 4: A MIMO state-feedback loop used (a) to obtain new CMYK recipe for neighboring nodes and (b) in the in-field profiling technology (Figure 6)

The control law is designed using MIMO state-feedback theory. Thus, $u(k) = -Ke(k)$, where $e(k)$ is the error between the target $L^*a^*b^*$ and the output $L^*a^*b^*$ value from the printer model at iteration k for each node. The gain matrix, K, is obtained from the Jacobian matrix using the pole-placement algorithm discussed in detail in Reference [2]. The Jacobian and controller parameters of the closest candidate node are computed using local information of the recruiting node. Due to the nonlinear response of the printer, the transformation to $L^*a^*b^*$ can lead to under sampling in some areas with high curvature and over sampling in other areas with less curvature. As a result, the Cooperative Neighbor Driven GCR Algorithm can give formulation jumps. This can be avoided by increasing number of nodes and/or by filtering the CMYK values using multi-dimensional filtering algorithms [2] and then by rerunning the GCR algorithm with new *CMYK* values until a desired smooth formulation is obtained (Figure 1). Once this process is finished, we have the *CMYK* values for all the in-gamut nodes. It is to be noted that the gamut we have constructed for the printer model shown in Figure 4 is extended slightly outside the gamut of the normal printer (see Figure 5). The starting LUTs should contain *CMYK* values not only for the in-gamut nodes of the normal printer, but should also contain *CMYK* values for the nodes inside the extended part of the gamut. This is required while building profiles in the field on a drifted printer.

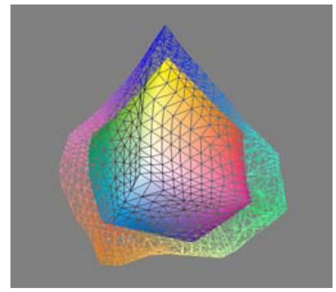

Figure 5: A hyper-extended gamut used to produce CMYK and gain matrices in the starting LUTs (Wired mesh: hyper-extended gamut produced using a printer model; solid: normal printer gamut)

In-Field Profiling

Components of algorithms used inside the in-field profiling technology is shown in Figure 6. This uses node levels, starting LUTs and the updated printer model as inputs to produce ICC profile with colorimetric and perceptual rendering LUTs.

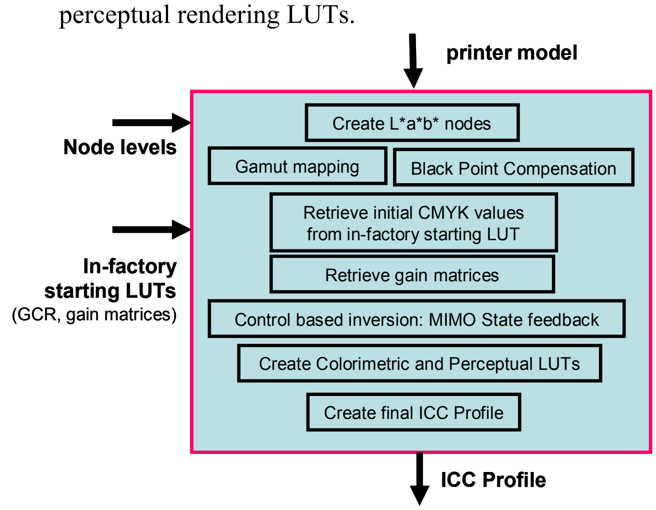

Figure 6: Block diagram view of the in-field profiling technology

The gamut mapping algorithm we have used is a combination of cusp, where colors are mapped to the gamut surface in the direction towards a neutral color whose lightness matches that of the cusp color, which is the most chromatic color of the same hue [5]. One of the issues with this method is that in dark regions, it can result in excessive shifts in lightness. It can also result in objectionable chromatic noise when dark colors span a wide range of hues. To address these issues, a modified mapping has been developed, which begins with cusp mapping for light colors, and gradually blends towards a lightness-preserving mapping for dark colors. This method has been shown to successfully alleviate both the aforementioned problems.

A similar control-based inversion algorithm as shown in Figure 4 with initial/nominal *CMYK* values from the starting LUTs is used to find the final *CMYK* recipe for each node. The inversion approach can also be implemented by iterating directly on the printer or by iterating on the updated printer model. Iterating on the printer can be an architecturally challenging task in high end production printers.

Black Point Compensation

RGB images often contain colors that are darker than the darkest color a printer can make. Minimum color error could be obtained by mapping the out of gamut colors to the darkest color the printer can make. However in that case, all details in these shadow regions would be lost. They often contain information the viewer knows should be there (the folds of a dark coat, the strands of dark hair), and their absence is very disturbing. We have adopted a technique for black point compensation in the perceptual LUT that retains these details, though at reduced contrast, and at the cost of lightening some of the darkest colors. In one version of the technique the compensation curve tracks the darkest color the printer can make, while in another version, it is fixed. The curve is an input L^* to output L^* function. The parameters of the curve are the lightening at an input L^* of 0, and the amount of contrast in the shadows (the slope of the curve at $L^* = 0$). The curve is parabolic in the shadows, and goes smoothly to an identity transform for lighter colors.

Conclusions

RGB and *CMYK* images have been converted to produce pleasing color with emphasis on accuracy, image quality and processing speed. In this paper we describe new algorithms that resulted in round trip inversion accuracy of nearly zero at the nodes, which combined with good gamut mapping and black point compensation algorithms, produced improved image quality when compared to previously known technology. These solutions are now being integrated in variety of forms in several digital production class printers using inline and offline spectral sensors.

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Biography

__Lalit. K. Mestha__, a Principal Scientist at Xerox, received his PhD from the University of Bath, England in 1985 and his BE in 1982, from the University of Mysore, India, all in EE. He has led & worked on sensing and control of several large scale engineering systems since 1987. He holds 68 US Patents and has a total of 198 publications including journal articles, conference papers, patents & patent filings. Prior to joining Xerox, Mestha was at the SSC Laboratory in Dallas. He is a Senior Member of IEEE and teaches at RIT as an Adjunct Professor in his spare time.

__Alvaro E. Gil__ received his B.S. and M.S. degrees in electrical engineering from Instituto Universitario Politécnico, Barquisimeto, Venezuela, in 1990 and 1998, respectively, and the Ph.D. degree in electrical engineering from The Ohio State University, Columbus, in 2003. From 1990 to 1999, he held engineering positions in the Automation Department at Petróleos de Venezuela (PDVSA) in Maracaibo, Venezuela. From 2002 to 2003 he was a research associate at the Department of Electrical Engineering, The Ohio State University. He worked as a postdoctoral researcher at Ohio State University between 2003 and 2005. He is now with Xerox Corporation, Webster, NY.

__Yao Rong Wang__ received his PhD from Purdue University in physics in 1986 and his BS from Shanghai Jiao Tong University in 1982. He joined Xerox in 1986 and has worked in material physics, xerographic controls, optical MEMS, and profiling technology. He holds 27 patents and has 71 publications.

__Martin S. Maltz__, a Principal Scientist at Xerox, received his PhD in solid state physics from the Massachusetts Institute of Technology in 1968 and his BSEE from the Rensselaer Polytechnic Institute in 1962. He has worked at Xerox Research since 1968, initially on marking and display technologies, and has lead and participated in the development of various color management technologies since 1990. He holds 25 US patents, and has a total of 50 publications, including patents, papers, and conference presentations.

__Raja Bala__ received the Ph.D. degree from Purdue University in 1992 in Electrical Engineering. Since then, he has been employed at Xerox Corporation, where he is a Principal Scientist conducting research in color imaging. His research interests include color management, device characterization, image-adaptive rendering techniques, optimization of color transformations for efficient color communication, security printing, and image personalization. Raja holds over 55 patents and over 65 publications in the field of color imaging. He is a Fellow of IS&T.