Linearization Curve Generation for CcMmYK Printing

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Abstract

The linearization curve generation is an important step in printer color characterization. The typical purpose of the linearization curves in conventional four ink printing is to compensate for dot overlapping and dot size variations and therefore to accommodate the non-linearity of the printing process. In CcMmYK "photo" printing, the introduction of light cyan and magenta inks presents new challenges for printer color characterization and linearization. In this paper we propose an alternative architecture for CcMmYK printer image processing in which the linearization curves also take responsibility for the separation of the light/dark inks. We address the importance of linearization, and propose strategies for how to best take advantage of the additional inks. The proposed methods are confirmed by experimental results.

Introduction

The ICC color management architecture[1] suggests that each color imaging device should be characterized by its ICC profile. The ICC profile specifies the relationship between the device dependent color space (typically RGB for scanners and monitors, and CMYK for printers) and a Profile Connection Space (PCS). The PCS is a device independent color space. In this study we have chosen to use the CIELAB color space[2] as the PCS, thus aligning with common industry practice. For each device, or for each class of devices, the associated ICC profile must be determined through a process of colorimetric device characterization, also known as profiling. For the case of printing, the subject of this paper, a great number of algorithms have been proposed in the past, we cite only a few here.[3-5] Several of the proposed methods have also been turned into commercially available software products.[6]

A typical ICC printer profile includes a three-dimensional look-up table (3D LUT), followed by a set of four 1D LUTs at the output. The 3D LUT determines the color conversion from CIELAB to the linearized printer color space C'M'Y'K, while each of the 1D LUTs specifies the conversion from C'M'Y'K' to the actual amounts of cyan, magenta, yellow, and black inks (CMYK), as shown in Figure 1. These 1D LUTs are commonly known as linearization curves. The application of these linearization curves is essential for good color reproduction.
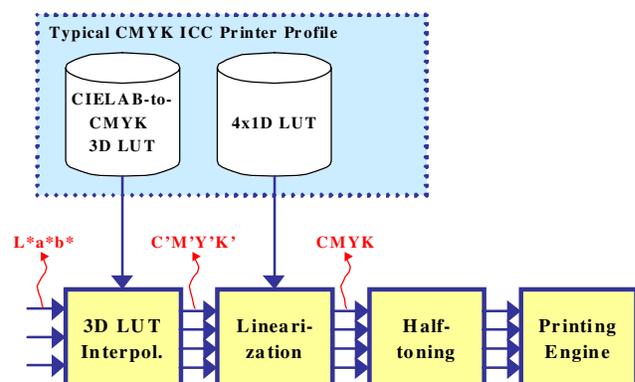

Figure 1. Typical CMYK printer image processing architecture.

In later years, the use of more than 4 inks for printing has become more and more common, not only in professional "HIFI color" printing devices, but also in more consumer-oriented devices, targeted towards printing amateur photographs, greeting cards, etc.[7-9] The most common method is to add diluted versions of the cyan and magenta inks to the traditional four-color ink set. This technique is commonly known as "inkjet photo printing." Using this technique, lighter colors can be created using these diluted inks instead of the regular ones, thus reducing the apparent graininess due to halftoning. The reduction in graininess has two main reasons. The first reason is that the contrast between the color of the halftone dot and the paper is reduced, and the other is that the spatial frequency of the dots on paper is increased. The human eye is less sensitive to higher frequencies. Even though the ICC specification allows arbitrary dimensions of the color data in a profile, the use of more than four inks brings new challenges to color characterization.

The remainder of this paper is organized as follows: First, we discuss why linearization of the CMYK values is important, and then we discuss to which reference the linearization should be performed. In the following section we propose an image processing architecture for CcMmYK printing. We then explain how to apply the proposed CMYK linearization techniques to CcMmYK printing, by

first determining the "photo ink" separation, and then applying the linearization techniques. Then we present some experimental results and finally the conclusions to our work.

Why Linearize?

The ultimate goal of printer color characterization is to convert color information from the profile connecting space (CIELAB) to CMYK. Since CIELAB and CMYK are not linearly related, a non-linear model is needed to perform the color space conversion from CIELAB to CMYK. Thus, in the following equation, the function *f()* needs to be determined.

$$(C, M, Y, K) = f(L*, a*, b*)$$

One way of solving the above equation is to minimize the error between the originally specified CMYK values and the modeled CMYK values. However, it needs to be noted that in order to obtain the best color conversion results, the distance in CIELAB space should be minimized. In other words, the printed patches using the modeled *C, M, Y, K* values should have similar measured *L*, a*, b** values compared to the original set. Linearizing the CMYK values to CIELAB will in many cases facilitate the task of color characterization.

Another reason for linearization is that the most common method to handle printer color management is via three-dimensional look-up-tables (3D LUT). Essentially a printer color profile contains a 3D LUT which defines the color transformation from CIELAB to CMYK for a subset of CIELAB colors, typically defined as a regularly spaced grid in CIELAB space. Then, for each pixel of the image that is to be printed, the color transformation is calculated by interpolating linearly between the values of the 3D LUT, using an interpolation scheme such as tri-linear or tetrahedral interpolation. Since the color conversion from CIELAB to CMYK is typically very non-linear, this interpolation may introduce significant errors, in particular if the 3DLUT is defined on a coarse grid. By linearizing the CMYK values to CIELAB space using four 1DLUTs, the conversion performed by the 3DLUT becomes more linear, thereby reducing interpolation errors.

Still another reason is that there are dot gain variations for different paper types in inkjet printing. The reason of the dot gain variation is that different type of paper absorbs ink differently therefore the actual dot size varies from paper to paper. In addition, the dot-overlapping behavior differs from paper to paper. All these variations are compensated in 1D LUT linearization curves. Linearization creates the impression that the printer is "well-behaved."

Which Variable to Use for Linearization?

It was mentioned in the previous section that linearization needs to be performed to CIELAB space. However, CIELAB is a three-dimensional space, the question is what variable should be used for linearization.

One candidate would be D = (L'2 + a'2 + b'2)1/2, where L' = max(L*)-L*, a' = max(a*)-a*, and b' = max(b*)-b*. The reason for using the maximum value minus the original value would be to ensure that L', a' and b' are in the same trend, so that they do not cancel each other after being added together. The problem with this approach is that human vision is more sensitive to luminance (L*) than to chroma (a* and b*). Therefore, summing the three components with the same weights may not produce visually linear results.

Another choice is to use *L** alone, since human vision is most sensitive to *L** and its dynamic range is all positive numbers, it is computational simple to use. *L** does indeed work well with black, cyan and magenta. However, *L** does not work well for yellow. Because the dynamic range of *L** for yellow patches is rather small, therefore, results based on *L** are not very reliable. On the other hand, since *b** has the largest dynamic range for yellow patches, *b** could be used to linearize yellow.

In summary, in order to determine what variable to use for linearization, we have considered dynamic range, human visual sensitivity, and computational complexity. We have chosen to use *L** for *C*, *M* and *K*, and *b** for *Y*.

Image Processing Architecture for CcMmYK Printing

A typical printer image processing pipeline consists of three steps: color conversion to linearized C'M'Y'K by interpolation in a 4-output 3D LUT, linearization by look-up in four 1D LUTs, and finally the process of halftoning.

For CcMmYK printing, however, there are two possible architectures. The most straightforward way would be to use a 6-output 3D LUT to convert from CIELAB space to linearized C'c'M'm'Y'K' space, followed by six 1D LUT linearization tables, as shown in the upper part of Figure 2. Alternatively, a modified architecture could be to use a 4-output 3D LUT to convert from CIELAB space to linearized C'M'Y'K' space, followed by six 1D LUTs, as shown in the lower part of Figure 2. These 1D LUTs would then not only be responsible for the linearization, but also for the photo-ink separation, that is, the derivation of light and dark magenta inks from *M'*, and light and dark cyan inks from *C'*, as summarized in the following expressions:

C=LUT_C1[C']; c=LUT_C2[C']; K = LUT_K[K'];
M=LUT_M1[M']; m=LUT_M2[M']; Y = LUT_Y[Y'];

We propose to use the second architecture because it has three advantages. The first advantage is that it is computational less expensive to perform 3D interpolation for four-channel than for six-channel. The second advantage of the modified architecture is that it requires less space to store the four-channel 3D LUT than six-channel 3D LUT for a given printer profile. The overall disk or memory space saving becomes significant when

multiple printer profiles are needed for different paper types. Memory space saving is a very important system consideration, particularly for embedded imaging systems. The third advantage of the modified architecture is that most commercially available color profiling tools only provide 3D LUT from a PCS space to CMYK space. Therefore, the proposed architecture enables using commercially available profiling tools to create the 3D LUTs.
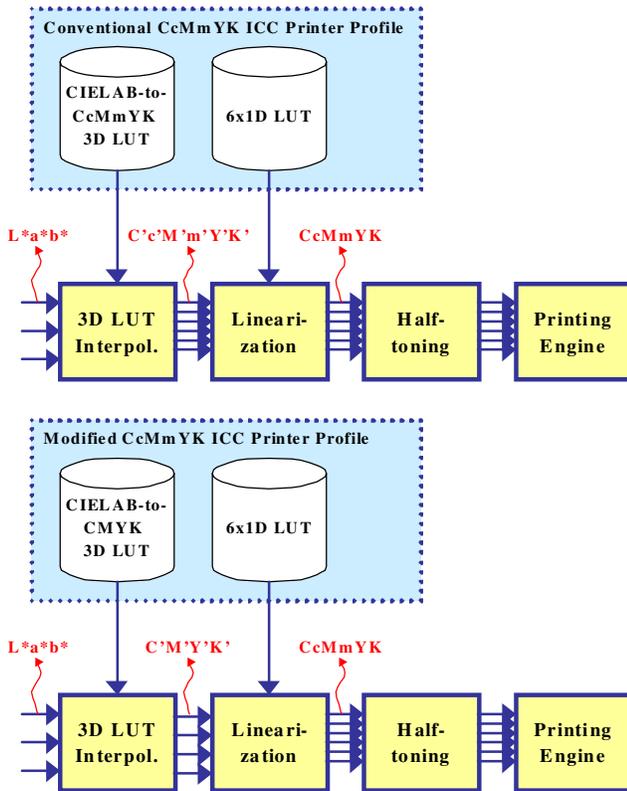

Figure 2. Two image processing architectures for CcMmYK printing: conventional (top) and the proposed (bottom).

Photo-ink Separation Process

The first step in the linearization curve generation for CcMmYK printing is to define a scheme for the photo-ink separation process, that is, how to generate dark and light ink combinations for the cyan and magenta channels, respectively. We have identified several criteria for choosing this separation path: to avoid objectionable dot patterns, to have smooth curves, and to avoid using too much ink. Based on these criteria, we have designed a separation path as illustrated in Figure 3.
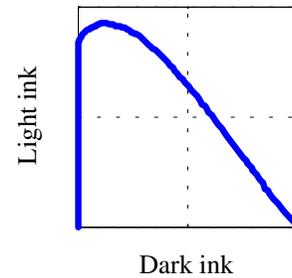

Figure 3. Proposed photo-ink separation path

After the dark/light ink combination path is established we need to choose the specific dark/light ink combinations for each ink density level. The determination of these values has to ensure that the printed color is linearized against CIELAB space. This is achieved using the CMYK linearization presented in previous sections.

Experimental Results

The results presented in this section are based on experiments work done using a Lexmark 3200 ink-jet printer with Hewlett-Packard Premium Inkjet Paper. Figure 4 shows the linearization curves for cyan ink. We see that in order to avoid bad dot patterns, only light cyan is used for low ink density levels. As the ink density increases, the dark ink amount is increased and the light ink is decreased and the transition is smooth. For yellow and black inks, since there is no dark/light ink combination, it is only needed to determine the values for all ink density levels such that the printed colors using these values are linearized to CIELAB space. Figure 5 shows the linearization curves for black and yellow ink.
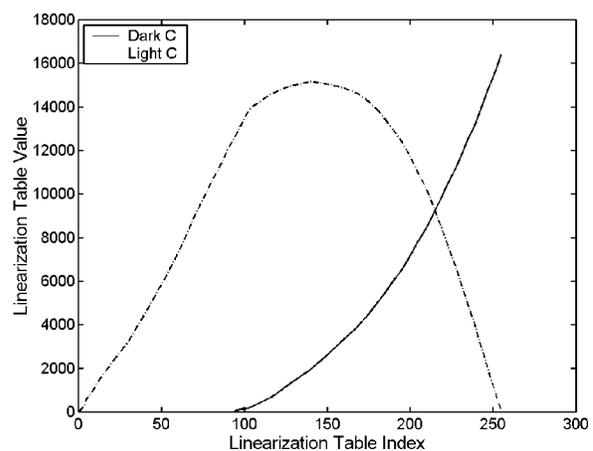

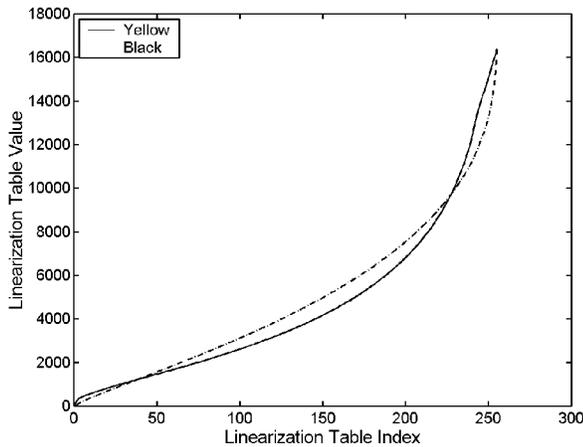*Figure 4. Linearization curves for dark/light cyan.*

Figure 5. Linearization curves for black and yellow.

Figure 7. Plot of measured b value versus yellow ink density.*

The next set of figures show the results after linearization for *C, M, Y,* and *K,* respectively. For each color of *C, M, Y,* and *K,* a series of 25 patches were printed after applying the linearization curves. The first five patches within a color ramp have 0% to 5% ink density with 1% increments, after that each patch has a 5% increment in ink density. Then each of the printed patches was measured using a GretagMacbeth SpectraScan/ SpectroLino spectrophotometer. Figure 6 shows the plot of the measured *L** values versus the ink density for *C, M,* and *K,* respectively. Figure 7 displays the plot of measured b* versus yellow ink density. We see from these figures that the designed linearization tables did indeed produce results that are very well linearized to CIELAB space.
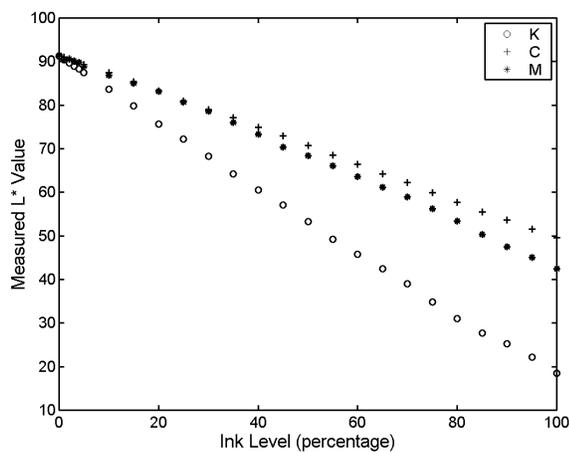
Discussion and Conclusion

The proposed CcMmYK printer image processing architecture, which uses a four-channel 3D LUT rather than a six-channel 3D LUT has several advantages. It reduces the computational complexity and memory requirements, and it allows using existing CMYK printer profiling tools to create the 3D LUT for CcMmYK printing.

In order to be able to use the proposed architecture in an ICC Color Management architecture, minor modifications of the standard would be required.

In our approach, the linearization curves are not only responsible for the linearization but also for the definition of the dark and light ink separation for each ink density. Therefore, generating a good set of linearization curves is even more important and challenging for CcMmYK printing than for CMYK printing.

Our proposed algorithms for generating the linearization curves take into consideration important factors such as data dynamic range, sensitivity to human vision system, computational intensity, smoothness of blends, interpolation errors, max ink coverage, etc. The experimental results indicate that the proposed methods produce good results.

Figure 6. Plot of measured lightness (L) versus ink density for black (K), cyan (C), and magenta (M), respectively.*

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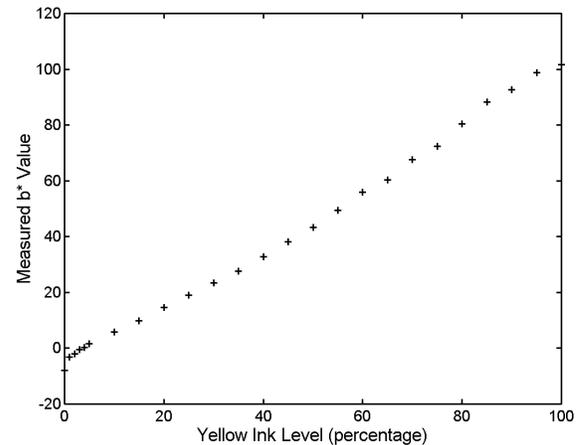1. International Color Consortium, *File format for color profiles*, ICC.1:1998-09, 1998, http://www.color.org/
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Biography

Ying X. Noyes received her Ph.D. degree in Physical Chemistry from Clarkson University in 1995. From 1995 to 1996 she was a postdoc at Argonne National Laboratory working on automated target recognition and multispectral image processing. Since then she held positions in a few industrial companies and her work has been focused on automated target recognition, image processing and device color characterization. She is currently with Conexant Systems, Inc.