Algorithm-Independent Color Calibration for Digital Halftoning

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Abstract

A novel method based on measuring 2 × 2 pixel patterns provides halftone-algorithm independent color calibration for digital halftoning. The binary CMY(K) color signals can be mapped into CIE XYZ color space at the printer resolution level. Therefore, any binary CMY(K) color images can be described as continuous-tone images in standard color spaces. The new method has been successfully applied to halftone screen calibration, vector error diffusions, as well as stochastic screens.

Introduction

Typically, all dots printed by halftone printers are not perfect squares and adjacent dots tend to overlap each other. This overlap is a characteristic of each color printer because different printers or the same printer using different types of media produce differently shaped and sized dots. Color calibration is required for each individual printer and for each different medium. In the calibration process, a series of color patches is printed and measured. These color patches are digitally created by a chosen halftone method, either dithering or error diffusion, before they are printed by a particular printer. Currently, almost all color calibration methods are also halftone-algorithm dependent. Calibration conducted for one halftone algorithm can not be applied to another algorithm without losing color accuracy. Even for the same dithering method, different halftone screens require separate color calibrations. In this presentation we will describe a novel concept for directly characterizing dot overlapping, therefore, the resulting color calibration is halftone algorithm independent. Applications of this new concept to overlapping correction in black-and-white halftoning have been presented in a previous IS&T conference.[1] In this paper we will describe the 2 × 2 centering concept applied to color halftone screen calibration and vector error diffusion.

Two-by-Two Centering Concept

An idealized color printer is expected to print all dots in perfect square shape and to have no overlapping between adjacent dots. For example, the dot pattern shown in Figure 1 consists of four different color pixels which are perfect cyan, yellow, green and black squares. Since a CMY halftone printer only has eight possible color outputs, cyan, magenta, yellow, red, green, blue, black and white, the color calibration for an idealized CMY color print is easy. Once eight patches printed with eight different solid colors are measured, any color pixel combinations can be accurately described pixel by pixel in the same color units used in the measurement. However, real dots are not perfect squares and they overlap. A conventional dot model used in black-and-white halftoning[3,4] is shown in Figure 2. This model assumes that all dots have an identical shape and size and each dot is located at the center of the square pixel defined as the idealized output. The average color appearance of each square pixel depends not only on the dot centered at this pixel, but also on the surrounding dots. With this overlapping model, at lest eight immediate neighbors should be counted. For example, in the pattern shown on the left of Figure 2, each cyan dot is surrounded by two black dots, two green dots and four yellow ones. Since each dot has eight possible colors, the total number of all possible combinations of three-by-three dots is given by the power 8^9, or 134, 317,728. This is a huge number for color calibration. Furthermore, even a simple dot pattern, as the one shown in Figure 2, is a combination of four different 3 × 3 overlapping patterns centered by cyan, black, green and yellow dot, respectively. Under this conventional 3 × 3 overlapping model, there is no practical solution to design calibration patches and to calculate each individual 3 × 3 overlapping pattern from the measurement of these patches.

The new concept proposed here redefines the coordinate used in the dot overlapping model. In Figure 3, the same dot pattern shown in Figure 2 is associated with a shifted coordinate, so that each dot is located at one cross point of the grid. Under this new centering concept, the color appearance of each square pixel can be specified by the four dots at four corners of this specific pixel. Therefore, the total number of all overlapping possibilities is reduced from 8^9 for the 3 × 3 model to 8^4, or 4,096, for the new 2 × 2 model. If we can further assume that all dots have shapes symmetric about both the vertical and the horizontal axes, for example, circles or ellipses, many overlapping patterns are mirror images of others. One may notice that the four 2 × 2 overlapping patterns in Figure 3 are mirror images to each other. The average color appearances of the four overlapping patterns are identical and this identical color is also the average color appearance of the entire color patch shown on the left of Figure 3. With this symmetry consideration, it is not difficult to derive that there are only 1072 different overlapping patterns in terms of average color appearance. All these colors can be directly measured from 1072 2 × 2 patches. The picture, Figure 4, is an actual set of the 1072 patches printed by a Xerox 5790 color laser printer in 400 × 400 DPI mode and used for the following experiments discussed in this paper.

The CMYK color printer adds the black option, so the total number of all overlapping possibilities becomes 16^4, or 65,536. However, with desired Under Color Removal (UCR) and/or Gray Component Replacement (GCR) options many of these combinations can be eliminated from practice. Although the actual number of patches needed depends on the choice of UCR and/or GCR, the applications to halftone screen calibration and vector error diffusion have no essential difference from CMY printers. We will concentrate on the CMY case for the following discussion.

Halftone Screen Calibration

Any halftone images printed by CMY color printers, from a simple dot cluster to a complicated color image, can be considered as a linear combination of the 1072 different 2×2 overlapping patterns. Once the 1072 overlapping patterns are measured, we can accurately describe the images at the pixel level in the same color units used to measure the 1072 patches. Let us consider the color calibration of halftone dithering screens. For each of all input levels a given halftone screen will generate a certain dot pattern simulating the desired input. CMY color printers use three dithering screens for cyan, magenta and yellow inputs, respec-tively. Each combination of the CMY dot patterns represents the halftone output simulating the corresponding CMY input values. Using the 2×2 centering concept we can calculate the expected color appearances for all possible CMY input values. The calculation provides screen calibration without measurement of actual halftone patterns and suitable to any dithering screens, whether clustered, stochastic distributed, or their combinations.

To demonstrate the 2×2 centering concept applied to halftone screen calibration, we chose three clustered halftone screens for cyan, magenta and yellow, respectively. The yellow screen has 7×8 elements while the cyan and magenta screens are 34×2 element screens with 14° and 76° rotation, respectively. The CMY inputs are sampled at 0, 85, 170 and 255, respectively. Sixty-four different CMY inputs are chosen and corresponding halftone patches are printed by the 5790 color printer in the 400×400 mode. The actual 64 color patches are shown in Figure 5 and their color appearances are measured in CIE L*a*b* values using a GRETAG colorimeter. Separately, all 1072 2×2 patches are measured in CIE XYZ using the same colorimeter and stored as a look-up table indexed by the corresponding CMY binary codes of the 2×2 dots. For each of the 64 halftone patterns, stored as 238 by 136 element CMY images, there are 238×136 overlapping patterns defined by every 2×2 dot combination. 238×136 XYZ values chosen from the 1072 2×2 look-up table are summed and the average XYZ values are converted into L*a*b*. The differences between the calculation and the measured L*a*b* are calculated in ΔE, defined as the square root of $\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}$. The average ΔE of all 64 halftone patches is 4.9 and the worstΔE among them is 12.0. A similar experiment is also conducted with a HP650C inkjet printer in 300×300 DPI mode. The CMY inputs are sampled at 0, 64, 128, 192 and 255, respectively, so there are 125 different halftone patterns generated. The average ΔE between the measurement and the prediction by the 2×2 concept is less than 5.0 and the maximum ΔE among 125 samples is less than 11.0.

Vector Error Diffusion

The 2×2 centering concept can be adapted to error diffusion halftoning for black-and-white halftoning,[1] as well as to the color vector error diffusion. Since the 2×2 calibration provides the mapping between the CMY(K) binary signals and the XYZ color space, we can directly apply the XYZ images into vector error diffusion without XYZ to CMY(K) color conversion.

Due to the length limitation of this paper, we will not discuss the details of the various algorithms of error diffusion. Interested readers can refer an updated paper collection for recent progress in this topic.[2] Here, we only describe the modification by the 2×2 centering concept for vector error diffusions. The error diffusion is a sequential processing. In Figure 6, we illustrate an intermediate stage of this process. Dots, represented by color circles in the picture, are aligned in a coordinate system defined by the centering concept. Each square of the grid represents a pixel of the output and is surrounded by four dots. While each dot is fully specified by three binary signals, CMY, each square pixel is specified by four groups of CMY signals and is corresponding to one of the 1072 2×2 overlapping patterns. Since the 2×2 patterns are measured in standard color units XYZ, each pixel is also associated with a set of XYZ values. Let us consider the current step of the vector error diffusion processing. The square drawn in heavy black lines represents the pixel currently being processed. Three dots, at the upper-left, upper-right and lower-left corners of the current pixel, have been determined by the previous processing steps. The fourth dot, at the lower-right corner of the current pixel and drawn in dash lines, is determined by the following comparison. Eight options for the fourth dot, combining the three previously determined three dots, provide eight 2×2 choices: GCYW, GCYC, GCYM, GCYY, GCYR, GCYG, GCYB and GCYK. XYZ values of the eight 2×2 patterns are searched from the 1072 element look-up table and compared with the desired XYZ values specified by the input image at the specific pixel. For each of the eight 2×2 patterns we calculate the distance between the desired XYZ and the XYZ values from the look-up table. The one closest to the desired input determines the color of the fourth dot, i.e., the binary CMY output. The corresponding ΔX, ΔY and ΔZ, as the XYZ components of the distance, are diffused to the neighbors. There are various diffusion matrixes to choose for error diffusion,[2] for the experiments described in this paper we use the standard Floyd-Steinberg method.[5]

In the previous experiment for the halftone screen calibration, we calculated XYZ values for 64 dithered halftone patches and compared with the actual output shown in Figure 5. Now, we use the calculated XYZ again as the desired input for vector error diffusion. Sixty-four halftone patches, shown in Figure 7, are calculated by the error diffusion algorithm described above and printed by the calibrated printer. The CIE L*a*b* values of the outputs are measured and compared with the desired L*a*b* values.

The average ΔE of all 64 patches is 4.5 and the maximum ΔE is 12.6. A pictorial halftone image, shown in Figure 8, is also created by the vector error diffusion using the 2×2 centering concept with the 1072 element look-up table and printed by the same printer.

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