A Black Point Compensation Method for Black-to-Gray Problem of CMYK Profiles

Bin Ma and Allan Nengsheng Zhang, Singapore Institute of Manufacturing Technology, Singapore;
Winson Lan, Kikuze Solutions Pte Ltd, Singapore

Abstract

Today, ICC profile is the de-facto standard for color reproduction between different color devices in the digital printing industry. However, there is a problem for pure black color reproduction while using a CMYK profile due to the transformation of black color based on spectral data in the profile. The black color is usually printed in gray instead. This paper addresses this problem, presents a Black Point Compensation (BPC) method and provides experimental results. The method can significantly improve the quality of black reproduction, and has been successfully implemented in a commercial color management software.

Introduction

For the digital color printing industry, to reproduce color correctly and consistently is a key requirement. By nature, digital color printing is based on light-absorbing the cyan (C), magenta (M), yellow (Y) and black (K) inks printed on the paper. Theoretically, pure C, M and Y pigments should be combined to absorb all colors and produce black. Unfortunately, all printing engine are subject to physical influence – heat, humidity, ink characteristics, paper used, etc. The CMY colors actually produce muggy brown if without combining with black color to produce a true black, and the pure black is usually printed as gray. While printing a RGB / L*a*b* or CMYK image to the CMYK printer, the non-linear color transformation between different color spaces causes the black reproduction to be more challenging.[1] This is so-called the "Black-to-Gray" (K2G) problem in digital CMYK printing.

The key to preserve black and map the source black to destination black properly is to combine the C, M, Y and K colors correctly. That means a "suitable" workflow and "good" CMYK profile are required for the particular print engine. Adobe® System implements a three-processing-step method for BPC in some products to solve the K2G problem,[2] which is application-dependent and the effects can not be maintained without its applications.

This paper presents a novel method for compensating the black point in the ICC profile-level based on the color differences between the print engine's actual output color space and its theoretical color space in the reference profile, which are captured intelligently. The paper also discusses its reusability and provides some experimental results.

The Proposed BPC Method

A practical color quality control methodology based on a Negative Color Comparison (NCC) algorithm was proposed recently.[3] This methodology includes a 5-step workflow: Print, Scan & Digitalize, Analyze & Adjust, Verify and Apply. Using the workflow, the initial Target Profile is generated from the Reference Profile for processing. The proposed method in this paper aims to refine the initial target profile by compensating the black points using the method shown in Figure 1:

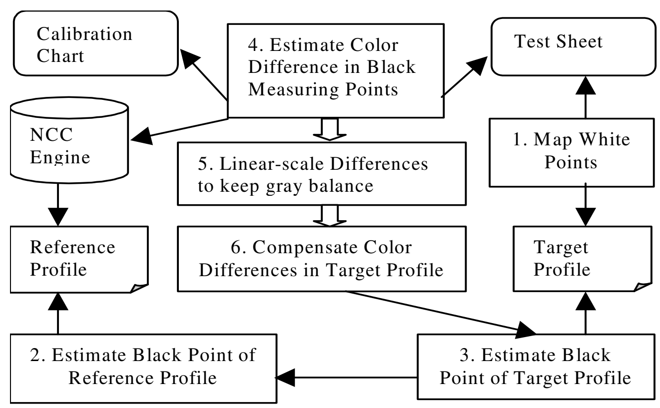

Figure 1. Proposed BPC Method

After mapping white point of the target profile to the paper white of the test sheet, the black point of the reference profile could be estimated based on individual transform according to different intent using the method described in pseudo-code shown in Fig. 2.

```
If intent = PERCEPTUAL
    Create a transform: Lab->[AToB0]->Profile->[BToA0]->Lab;
If intent = RELATIVE_COLORIMETRIC
   Create a transform: Lab->[AToB1]->Profile->[BToA1]->Lab;
If intent = SATURATION
   Create a transform: Lab->[AToB2]->Profile->[BToA2]->Lab;
Convert <L_i, a_i, b_i> to Reference Profile's Black <L*_i, a*_i, b*_i>
using the  above transformations (where <L_i, a_i, b_i> pairs are
valid entries in the CLUT table of the respective output curve in
Reference Profile, and L_i's range in 0 to 50, a_i and b_i is 0);
```

Figure 2. Reference Black Point Estimation

After compensating individual C, M, Y and K with color differences in the output curves of target profile based on NCC analysis and Bi-cubic interpolation, the black point of target profile could be estimated based on the above estimated Reference Black Point using the method described in pseudo-code shown in Fig. 3:

If intent = PERCEPTUAL
 Create a transform: Lab->[AToB0]->Profile->[BToA0]->Lab;
If intent = RELATIVE_COLORIMETRIC
 Create a transform: Lab->[AToB1]->Profile->[BToA1]->Lab;
If intent = SATURATION
 Create a transform: Lab->[AToB2]->Profile->[BToA2]->Lab;
Convert <L^*_i, a^*_i, b^*_i> to Target Profile's Black <L'_i, a'_i, b'_i> using the transformation created;

Figure 3. Target Black Point Estimation

Since the target profile is derived from the reference profile, the particular round-trip curve created in step 3 provides the base inputs for steps 4 and 5.

In step 4, the color difference (ΔCj, ΔMj, ΔYj and ΔKj) in the Black Measuring Point j (BMPj), which is one of ten pure black patches printed in the calibration charts and test sheet with fixed Lab value (<Lj, aj, bj>) in the CMYK space of target profile, will be estimated based on the NCC algorithm.

To keep the gray balance in the target profile, linear scaling is used to distribute the CMYK color difference to the grid points of the target profile according to its L element (illuminant) in step 5.

Finally in step 6, the CMYK color in the grid points of the target profile's output space will be compensated with the color difference by k-Nearest Neighbor algorithm, which could be illustrated as Formula (1) to (4) below.

$$C' = f(C, \Delta C, \Delta M, \Delta Y, \Delta K, k) \tag{1}$$

$$M' = f(M, \Delta C, \Delta M, \Delta Y, \Delta K, k) \tag{2}$$

$$Y' = f(Y, \Delta C, \Delta M, \Delta Y, \Delta K, k) \tag{3}$$

$$K' = f(K, \Delta C, \Delta M, \Delta Y, \Delta K, k) \tag{4}$$

The number of k is subject to the number of grid points in the CLUT table of target profile's output space, and the ΔE*LAB - CIELAB (or CIE1976) between original CMYK color and compensated one's is selected as the distance measurement, which is formulated as Formula (5) below:

$$\Delta E^*_{LAB} = \sqrt{(L'-L)^2 + (A'-A)^2 + (B'-B)^2} \tag{5}$$

Experimental Result

Using Adobe Color Engine (ACE) on Microsoft Windows® 2000 professional platform, we have conducted a number of tests to evaluate the black color improvement for the proposed method on HP® Color LaserJet 9500n printer based on its default CMYK profile HP9500C.icm (reference profile). This profile has identical AToB and identical BToA color space for comparing effects (Notes: its AToB0, AToB1 and AToB2 tags share the same set of data, and BToA0, BToA1 and BToA2 tags share another same set of data as well). The image-capturing device is HP® Scanjet 4670 scanner. sRGB IEC61966-2.1 was used as RGB color space for visual inspection, and U.S. Web Coated (SWOP) v2.0 was used as working CMYK space for image source. The 10 pure K patches represented 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% black respectively in the test sheet shown in Figure 4 are used as the source for testing, which actual CMYK values in working CMYK space and RGB values in working display space are shown in Table 1.

Figure 4. Source Image (Pure K Test Patches)

Table 1: Color Values in Black Measuring Points

RGB Color (sRGB)					Actual Color (SWOP)							
R	G	B	X	Y	Z	L	A	B	C	M	Y	K
230	231	232	0.7782	0.8070	0.6765	92	0	-1	0	0	0	10
209	211	212	0.6177	0.6407	0.5377	84	0	-1	0	0	0	20
187	189	192	0.4969	0.5153	0.4331	77	0	-1	0	0	0	30
167	169	172	0.3794	0.3934	0.3380	69	0	-2	0	0	0	40
147	149	151	0.2931	0.3040	0.2621	62	0	-2	0	0	0	50
128	130	132	0.2119	0.2197	0.1904	54	0	-2	0	0	0	60
109	111	113	0.1545	0.1602	0.1396	47	0	-2	0	0	0	70
88	89	91	0.0973	0.1009	0.0859	38	0	-1	0	0	0	80
65	64	66	0.0491	0.0509	0.0437	27	0	-1	0	0	0	90
34	30	31	0.0142	0.0141	0.0116	12	2	0	0	0	0	100

HP9500C_iccs.icc in the test cases is the CMYK profile refined by Folcotone® ICCS 2.1 based on the proposed method after its 3 cycles refinement.

Table 2: List of Test Cases

No.	CMYK Profile	Intent	With Adobe BPC
T1	HP9500C.icm	Perceptual	No
T2	HP9500C_iccs.icc	Perceptual	No
T3	HP9500C.icm	Perceptual	Yes
T4	HP9500C_iccs.icc	Perceptual	Yes
T5	HP9500C.icm	Relative Colorimetric	No
T6	HP9500C_iccs.icc	Relative Colorimetric	No
T7	HP9500C.icm	Relative Colorimetric	Yes
T8	HP9500C_iccs.icc	Relative Colorimetric	Yes
T9	HP9500C.icm	Saturation	No
T10	HP9500C_iccs.icc	Saturation	No
T11	HP9500C.icm	Saturation	Yes
T12	HP9500C_iccs.icc	Saturation	Yes

The Euclidean Distance of CMYK colorants from actual color to proof result (ΔEcmyk) is selected as the numerical measurement criteria besides visual inspection, which is formulated as Formula (6) below:

$$\Delta E_{cmyk} = \sqrt{(C'-C)^2 + (M'-M)^2 + (Y'-Y)^2 + (K'-K)^2} \tag{6}$$

Adobe Photoshop® 7.0 was used as the soft-proof tools to collect the test results for above 12 test cases (T1 to T12), which are listed in the following Table 3 to 8 respectively.

Table 3: Test Results (T1 vs. T2), T2 achieves about 7.89% improvement (49.6808 vs. 53.9366).

T1: Avg ΔE cmyk: 53.9366					T2: Avg ΔE cmyk: 49.6808				
C'	M'	Y'	K'	ΔEcmyk	C'	M'	Y'	K'	ΔEcmyk
10	7	7	0	17.2627	8	6	5	0	15.0000
19	14	12	1	32.5883	15	12	11	1	29.1719
25	19	17	5	43.5890	21	18	17	7	39.7869
30	22	20	13	50.1298	24	21	22	18	44.5533
33	25	23	23	54.5161	27	23	26	30	48.3115
36	28	25	32	59.0678	29	24	29	37	52.7920
39	31	28	43	63.2060	31	27	33	42	59.6909
42	35	31	56	67.2756	33	30	36	54	62.9365
46	39	35	71	72.2703	36	35	39	61	69.8785
44	48	45	93	79.4607	34	41	46	75	74.6860

Table 4: Test Results (T3 vs. T4), T4 achieves about 7.22% improvement (49.8856 vs. 53.7673).

T3: Avg ΔE cmyk: 53.7673					T4: Avg ΔE cmyk: 49.8856				
C'	M'	Y'	K'	ΔEcmyk	C'	M'	Y'	K'	ΔEcmyk
10	7	7	0	17.2627	8	6	5	0	15.0000
18	14	12	1	32.0156	15	12	10	1	28.8097
25	19	17	5	43.5890	21	18	17	7	39.7869
29	22	20	13	49.5379	24	21	22	17	45.0555
33	25	23	22	55.0182	27	23	26	29	48.7340
36	28	25	31	59.5483	29	24	29	37	52.7920
38	31	28	41	63.4823	31	26	33	42	59.2453
42	34	30	54	67.0522	33	30	36	54	62.9365
45	38	34	68	71.4773	36	35	39	60	70.2994
46	46	42	86	78.6893	35	41	46	72	76.1971

Table 5: Test Results (T5 vs. T6), T6 achieves about 7.16% improvement (49.5895 vs. 53.4146).

T5: Avg ΔE cmyk: 53.4146					T6: Avg ΔE cmyk: 49.5895				
C'	M'	Y'	K'	ΔEcmyk	C'	M'	Y'	K'	ΔEcmyk
10	7	7	0	17.2627	8	6	5	0	15.0000
18	13	12	1	31.5911	15	12	10	1	28.8097
25	19	17	4	44.1701	21	18	17	6	40.3733
29	22	20	12	50.0899	24	21	21	16	45.0999
32	25	23	21	54.9454	26	22	25	28	47.6340
35	27	25	30	58.9830	28	24	29	36	52.6972
38	30	27	39	63.5138	30	26	32	41	58.6600
41	33	30	51	67.1640	32	29	35	49	63.6475
43	37	33	64	70.5904	34	33	38	59	68.1909
45	42	39	79	75.8353	35	38	43	65	75.7826

From the test data we can see, the proposed method could improve color matching without/with Adobe®'s BPC under all three different intents.

Table 6: Test Results (T7 vs. T8), T8 achieves about 7.74% improvement (49.3958 vs. 53.5389).

T7: Avg ΔE cmyk: 53.5389					T8: Avg ΔE cmyk: 49.3958				
C'	M'	Y'	K'	ΔEcmyk	C'	M'	Y'	K'	ΔEcmyk
10	7	7	0	17.2627	8	6	5	0	15.0000
18	13	12	1	31.5911	15	12	10	1	28.8097
25	19	17	5	43.5890	21	17	17	5	40.5463
29	22	20	13	49.5379	24	20	21	16	44.6430
33	25	23	22	55.0182	26	22	25	27	48.1041
35	28	25	31	58.9491	28	24	28	35	52.6213
38	31	28	41	63.4823	30	25	31	40	58.1893
41	34	30	53	66.8281	32	28	35	46	64.7225
44	38	34	67	71.1688	33	31	37	59	66.1816
46	45	41	84	77.9615	35	36	41	62	75.1399

Table 7: Test Results (T9 vs. T10), T10 achieves about 7.89% improvement (49.6808 vs. 53.9366).

T9: Avg ΔE cmyk: 53.9366					T10: Avg ΔE cmyk: 49.6808				
C'	M'	Y'	K'	ΔEcmyk	C'	M'	Y'	K'	ΔEcmyk
10	7	7	0	17.2627	8	6	5	0	15.0000
19	14	12	1	32.5883	15	12	11	1	29.1719
25	19	17	5	43.5890	21	18	17	7	39.7869
30	22	20	13	50.1298	24	21	22	18	44.5533
33	25	23	23	54.5161	27	23	26	30	48.3115
36	28	25	32	59.0678	29	24	29	37	52.7920
39	31	28	43	63.2060	31	27	33	42	59.6909
42	35	31	56	67.2756	33	30	36	54	62.9365
46	39	35	71	72.2703	36	35	39	61	69.8785
44	48	45	93	79.4607	34	41	46	75	74.6860

Table 8: Test Results (T11 vs. T12), T12 achieves about 7.22% improvement (49.8856 vs. 53.7673).

T11: Avg ΔE cmyk: 53.7673					T12: Avg ΔE cmyk: 49.8856				
C'	M'	Y'	K'	ΔEcmyk	C'	M'	Y'	K'	ΔEcmyk
10	7	7	0	17.2627	8	6	5	0	15.0000
18	14	12	1	32.0156	15	12	10	1	28.8097
25	19	17	5	43.5890	21	18	17	7	39.7869
29	22	20	13	49.5379	24	21	22	17	45.0555
33	25	23	22	55.0182	27	23	26	29	48.7340
36	28	25	31	59.5483	29	24	29	37	52.7920
38	31	28	41	63.4823	31	26	33	42	59.2453
42	34	30	54	67.0522	33	30	36	54	62.9365
45	38	34	68	71.4773	36	35	39	60	70.2994
46	46	42	86	78.6893	35	41	46	72	76.1971

Discussion and Conclusion

This paper presents a method to compensate the black color difference in the CMYK profile level, so that the refined color profile could fit with the actual output color space of the CMYK print engine in its dynamic working environment. A significant advantage of this method over others is that the improvement is implemented in the refined CMYK profile, which could be directly reused by different applications, CMMs on different platforms. By integrating into the refined intelligent color quality control workflow with the patented NCC algorithm, it provides a faster, lower cost and higher quality solution for normal operators in the digital color printing industry.

According to the defined Delta E (ΔEcmyk) and test results, the proposed method achieves more closed–to-actual 'black' color in physical printout with smaller color difference and closer visual effect. Overall improvement is about 7 to 8% reduced the color differences for all the 10 test patches on different intents with/without using Adobe®'s BPC.

A further advantage of the method is that this method can be implemented in an iterative and increment workflow with all the benefits discussed by Allan.[3] The results with balanced refinement could be verified visually (proofed on the screen), numerically (the improvement on the screen can be observed) and physically/ visually (printed on the target print engine). End users could control the refinement cycles by human justification.

To physically calibrate the print engine by its embedded functions is a pre-requirement to make sure it is at a stable and reliable working status. The analysis of color difference, BPC process and value adjustment are relied on the test environment including the reference profile used (generic CMYK profile e.g. U.S. Web Coated (SWOP) v2.0 or device-dependent profile provided by the vendor e.g. HP9500C.icm), the "TO_BE" target (calibration chart), and the printer's "AS-IS" status (the printed test sheet, ink tuner & paper used etc.).

Based on the proposed method, a refined calibration system, Focoltone® Intelligent Calibration System version 2, has been developed and launched at DRUPA 2004 successfully. It can improve color consistency by compensating colors in ICC profiles, and works well for most of CMYK profiles.

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Author Biography

Bin Ma obtained his Bachelor of Engineering from National University of Defense Technology, China (1989), and Master of Technology in Knowledge Engineering from National University of Singapore (2004). He joined Singapore Institute of Manufacturing Technology since 2001, and was seconded to a leading color management solution company as R & D Manager for transferring his R & D expertise to the industry. His current research focuses on Intelligent Color Imaging Processing and Color Management.