The Substrate Influence On Color Measurement

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Abstract

The repeatable quality of color image reproduction is a growing challenge for producers of digital printing devices as well as for paper producers. The complex nature of the problem is due to the large number of factors that influence the quality. The properties of the printing substrate such as whiteness, gloss and surface roughness, the colorants and the printing procedure in different combinations together with the properties of the capturing device are all factors that make objective evaluation of print quality very difficult. It is therefore imperative to develop precise methods and routines for color measurement and characterization. In this presentation, the influence of substrate properties on the final printed result will be studied by means of a flatbed digital scanner. The presentation will describe the problems associated with the influence of substrate properties on scanner calibration and will give guidelines for the use of scanners, where large-scale color management control is required. The work reported here is part of an ongoing development of a set of characterization procedures that can be applied to printing situations, consisting of a variety of different printing engines and papers.

Introduction

In a situation where the number of digital color print engines is showing a steady growth, the need for fast and accurate methods to measure color is increasing. A great improvement in the time required for a color characterization of a printing situation could be achieved if the spectrophotometer measurements that are necessary today could be replaced by a fast scanner measurement. In addition, a scanner measurement would provide spatial resolution far better than any spectrophotometer.

This color characterization could be integrated in one of the scanner-based systems for automated objective measurements of other print quality parameters that have become an important and mature tool in digital test printing. Such a system would provide a complete "single-measurement" tool for print quality measurements.

To accomplish this, the scanner must be colorimetrically calibrated to the spectrophotometer it is supposed to replace. A relation must be established between the device-dependent color space of the scanner and a device-independent color space such as CIELab.

The fundamental difference in measurement geometry, illumination and sensors between the two devices makes this calibration complex. There is no standard geometry for flatbed scanners and non-ideal components in the instruments will further complicate the calibration. Black offset current in the CCD elements, illumination geometry, stray light and unsatisfactory gloss trapping, limited dynamic range and inclusion of ultraviolet and infrared light in the detector are all factors that will have an influence on the quality of scanner measurements. Systematic and random errors are also present in the spectrophotometer, variations in the photodiodes, the sample presentation and its geometry. All sources of noise, but in comparison to the uncertainties in the scanner they are relatively small.

Properties of the substrate such as gloss, whiteness, light scattering and the density range of the printed substrate will definitely reveal limitations in the instruments and complicate the calibration. This study will show some of the effects that the printed substrate will have on the color calibration of a scanner. The study is based on printed samples from two different digital printing methods, xerography and inkjet on several substrates ranging from uncoated copy qualities to high gloss specialty inkjet paper.

The color calibration method implemented consists of a non-linear modification to the scanner RGB values followed by a third order three-dimensional polynomial regression function that converts the modified RGB values directly to CIELab space. The output of the routine was a third order transformation polynomial. A calibration test form was printed and measured with both the scanner and the spectrophotometer. The routine was thereafter applied to calculate the transformation polynomial. To evaluate the calibration, an evaluation test form was printed, measured with the scanner and finally the transformation polynomial was used to calculate the Lab values. The evaluation test form was measured with the spectrophotometer and the color difference could be calculated between the spectrophotometer and the scanner Lab values.

Color Calibration of the Scanner

The aim of the color calibration is to find an approximate transformation function g from the scanner RGB color space to the device-independent CIELab color space. (Eq.1)

$$[L, a, b] = g(R, G, B) \tag{1}$$

The method implemented and used in this study was proposed by Hardeberg,[1] it features a non-linear cubic-root transformation of the scanner RGB values followed by a third order three-dimensional polynomial regression function directly to CIELAB space (Eq.2).

$$g = \begin{bmatrix} R \\ G \\ B \end{bmatrix} \underset{modification}{\overset{non-linear}{\Rightarrow}} \begin{bmatrix} R^{1/3} \\ G^{1/3} \\ B^{1/3} \end{bmatrix} \underset{regression}{\overset{3D}{\Rightarrow}} \begin{bmatrix} L \\ a \\ b \end{bmatrix} \quad (2)$$

The RMS error that is minimized in the regression corresponds to ΔE, which is well correlated to visual color differences. The result of the regression is a third order polynomial defining the transformation from the cube root modified RGB values to CIELab values. The regression data was based on the printed calibration test form.

The printed calibration test forms were scanned and an image processing routine was applied to the acquired images to localize the color patches and calculate the mean intensity values from an area of approximately 4 x 4 mm in the center of each patch resulting in a set of RGB values to be used in the regression. A spectrophotometer was used to measure the printed test forms to obtain the reference CIELab values. Two different spectrophotometer filters were used; a neutral filter and a polarization filter, resulting in two sets of reference Lab values. Hereby, two transformation polynomials were produced for each combination of printer and substrate. The illumination used for all measurements was D50 and the observer angle was 2º.

Evaluating the Calibration

Substrates

Three substrates were used, an uncoated paper without any fluorescence whitening agents and high ink absorption named *OCR*, *Copy* an uncoated, calendered paper containing fluorescence whitening agents with higher whiteness than *OCR*, and finally a coated paper named *Photo* with a high whiteness and a very even and glossy surface that allows more colors to be reproduced resulting in a larger color gamut.

Test Forms

The test forms consisted of square color patches as shown in figure 1. They were produced in PostScript and converted to Adobe PDF 1.2 format without any color adjustments. To ensure consistent measurements, each patch was 9 x 9 mm, in comparison to the spectrophotometer aperture size of 4 mm.

The calibration test form contained 1400 color patches selected to be evenly distributed inside the printable gamut for all printer–substrate combinations involved in this study. It was ensured that the test form contained colors distributed in the printable gamut as well as out-of-gamut colors for all printer-substrate combinations used. The evaluation test form contained 475 test patches and was designed to have colors evenly distributed in all areas of the CIELab color space. The choice resulted in colors inside the gamut as well as colors on the edge of the gamut for the printed substrates.

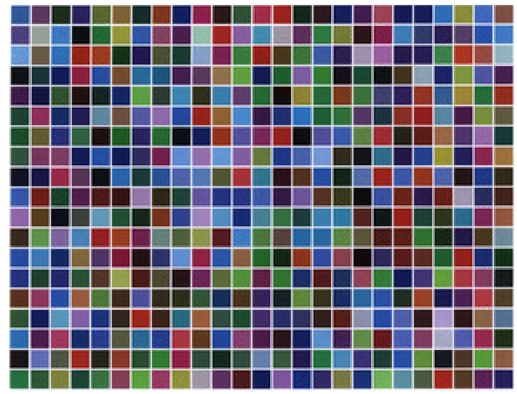

Figure 1. The A4-sized evaluation test form

Printing

Two printers were used; a HP DeskJet 970 Cxi thermal color inkjet printer and a HP 4550 Laser Color xerographic color printer. All printing was performed in a room with controlled temperature and relative humidity (21°C, 40%). No color adjustments were made and all prints were visually inspected to ensure that there were no major artifacts caused by the printers, such as banding and mottling.

Evaluation Method

The printed evaluation test forms were scanned and the RGB values for each patch were extracted and transformed to CIELab coordinates with the proper calibration polynomial. Finally, the approximated Lab values could be compared to the corresponding spectrophotometer Lab values. The CIE 1976 color difference formula was used. (Eq. 3)

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (3)$$

Results and Discussion

Inkjet Printed Substrates

The results for the three substrates printed on an inkjet printer, with mean and maximum ΔE values for the 475 color patches in the evaluation test form are presented in table 1. The calibration was performed on the same substrate as the evaluation.

Not surprisingly, the best result is achieved for the *OCR* substrate with its relatively small and regular color space. The result was satisfying both in terms of mean and maximum errors. The largest errors were observed for dark colors, implicating that the scanner is saturating towards the upper limit of its density range. The result for the *Copy* substrate was in parity with the *OCR* result, with the difference that the errors in dark colors and bright bluish colors were moderately larger. The later effect is most likely caused by the fluorescence whitening agents in the *Copy* substrate. Furthermore, they give the *Copy* substrate such a high whiteness that it gave rise to scanner saturation when the unprinted substrate was measured.

Table 1. Color differences between calculated and reference Lab values for the inkjet printed evaluation test form.

Substrate	Filter	ΔE max	ΔE mean
OCR	Neutral	3.4	1.2
OCR	Polarization	5.6	1.3
Copy	Neutral	4.0	1.6
Copy	Polarization	4.5	1.5
Photo	Neutral	6.8	1.4
Photo	Polarization	6.7	1.8

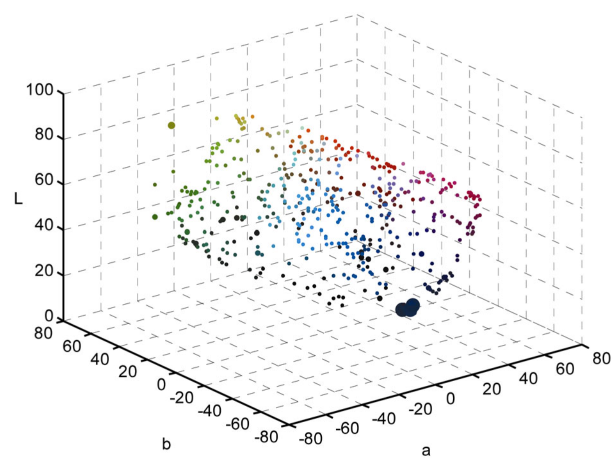

Figure 2. Color difference plot for the inkjet printed Photo substrate. The marker size corresponds to the size of the color difference.

For the *Photo* substrate the problems for dark colors were further accented, especially in dark bluish colors. Errors above the mean level were also observed in highly saturated colors close to the edge of the printable gamut. Although the performance of the calibration was not as successful as for the uncoated substrates the mean color differences was still acceptable.

The results from the calibration of the Photo substrate indicate that the largest errors in the calibration are induced by the limitations in the dynamic range of the scanner rather than the high gloss level. To further investigate this, a grayscale was printed on the Photo substrate and measured with the scanner. It was also measured with the spectrophotometer, which was able to resolve all gray levels. Figure 3 shows how the scanner is saturating for high tone levels in the printed color patches.

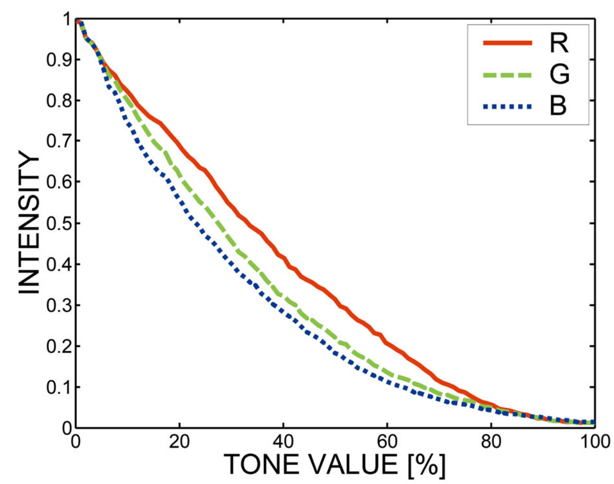

Figure 3. Scanner saturation occurs for grayscale printed with inkjet on the Photo substrate.

Generally, the use of the polarization filter lowers the performance of the calibration routine. This implies that gloss reflections have influence on the calibration, which is further emphasized by the fact that the calibration with the glossy paper showed larger color differences.

Xerographically Printed Substrates

The results for the three substrates printed on a xerographic printer, are presented in table 2. The calibration was performed on the same substrate as the evaluation.

Table 2. Color differences between calculated and reference Lab values for the xerographically printed evaluation test form.

Substrate	Filter	ΔE max	ΔE mean
OCR	Neutral	8.5	2.4
OCR	Polarization	12.0	3.6
Copy	Neutral	8.7	2.7
Copy	Polarization	10.3	3.6

In general, the calibration results for the substrates printed in a xerographic process were unsatisfying both in terms of mean and maximum color differences. Errors above the mean level were distributed all over the color gamut. One conclusion could be made though, the largest differences were observed for vivid colors, in other words; colors for which there were a lot of toner. A likely assumption is that this is due to differential gloss in the xerographic print. A color patch where more toner is used will in most cases have a higher gloss than a patch with less toner. As observed in the inkjet case, a more successful calibration was performed on the *Photo* substrate, which had a high, but relatively even gloss level for all colors.

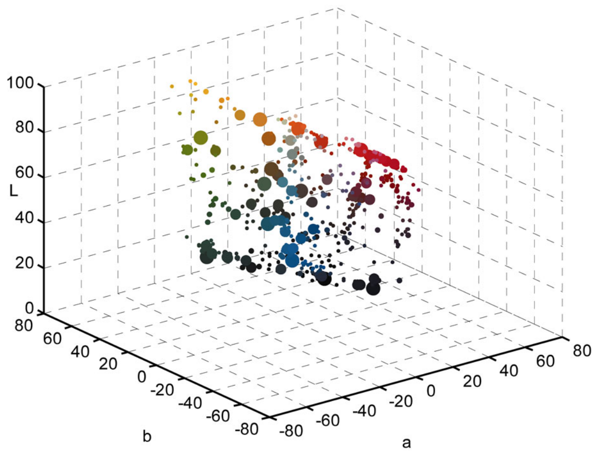

Figure 4. Color difference plot for the xerographically printed OCR substrate. The marker size corresponds to the size of the color difference.

Using One Calibration Routine For Several Substrates

Is it possible to obtain a calibration routine that works for all substrates used in one printer? -It is easily shown that the color gamut for a photo quality glossy substrate will totally surround the gamut of an uncoated substrate with the exception for the area close to the white point of the substrate. This makes it tempting to assume that the transformation polynomial for a substrate with a larger color gamut could be applied to a substrate with a smaller gamut, as long as it is essentially surrounded by the larger gamut. This was examined for the inkjet printer. The measurements were performed using the neutral filter, 2º standard observer and D50 illumination. The *Photo* substrate has a larger color gamut than the other substrates. The *Copy* substrate has a larger gamut than the *OCR* substrate. The results are presented in table 3.

Table 3. Color differences between calculated and reference Lab values using different calibration polynomials.

Calibration Substrate	Evaluation Substrate	ΔE max	ΔE mean
Copy	OCR	6.3	2.2
Photo	OCR	4.5	2.0
Photo	Copy	6.2	3.0

The measurements show increased mean color differences compared to when the calibration and measurement were performed on the same substrate. This is perhaps an indication that differences between the substrates induce a systematic error in the calibration. The results are almost at acceptable levels, at least for the mean error, but better calibration results are obtained when the evaluation is performed on the same type of substrate as the calibration was made.

Scanner Measurements

The printed samples were scanned with 150 ppi and a pixel depth of 12-bits per channel on an Agfa DuoScan T1200 flatbed scanner. All samples were scanned with the same scanner settings. The tonal range was fixed with the minimum set to 0.0D and the maximum set to 2.3D, this span corresponds to the density range of digital printers. No tone curve adjustment or sharpening was used. The time required to measure a test form with 475 color patches is approximately one minute.

Scanner Noise and Warm Up Time

A study was carried out to determine the time required for the scanner lamp to warm up and stabilize. An Agfa IT8.7/2 chart containing 308 color patches printed on photographic material with very even color reproduction was scanned 25 times in a row starting with a cold scanner. The measurements showed that after five minutes, the variations in the intensity values had decreased to a magnitude in parity with the assumed noise. To analyze the noise level for the warmed up scanner it was powered and repeatedly used for two hours and then the IT8 chart was scanned every five minutes for another 25 measurements. An image processing routine was used to extract the mean intensity from a central area of each color patch. Finally, the standard deviation of the mean intensity over 25 scans was calculated for each color patch. The results are presented in table 4.

Table 4. Noise in intensity values for the 308 color patches on the IT8 chart.

Standard deviation in mean intensity [%]			
	R	G	B
Mean	0.10	0.07	0.07
Max	0.31	0.25	0.23

Scanner Point Spread

To certify that the surrounding unprinted area would not distort the mean intensity calculations for the color patches in the printed samples, they were calculated from an area of 4 x 4 mm in the center of each patch. This area was at a safe distance from the edge allowing the printed samples to be somewhat misaligned when they were placed in the scanner. As an extra insurance, a guide frame was constructed to aid the placing of the sample in the scanner.

Scanner Specifications

Agfa DuoScanT1200 Flatbed Scanner
CCD: Tri-linear Coated, 5000 elements
A/D Conversion: 12 bits per Channel
Output pixel depth: 12 bits per channel
Optical Resolution: 1200 ppi x 600 ppi
Density Range: 0.1 to 1.9 D
Scanner Lamp Type: Cold Cathode
Warm-up Time: 180s

Spectrophotometer Measurements

The reference color measurements were performed on a GretagMacbeth Spectrolino spectrophotometer with an x/y table. D50 and D65 illuminations can be simulated from the tungsten light source. Two standard observers are available, 2° and 10°. Additionally, there are three different mountable physical filters:

1. Neutral filter; measuring colors without any alterations.
2. Polarization filter; reduces the amount of directly reflected light, thus decreasing the effect of gloss in the measured sample. It also has a reducing effect for light with shorter wavelengths than 380 nm.
3. D65 filter; lowers the transmission within the visible range, which modifies the emitted light to approximate daylight.

The time required to measure one color patch is about 2.5s with the polarization filter and 1.5s for the other filters. For a printed test form with 475 color patches this translates to 20 and 35 minutes respectively. The warm up time is negligible. Differences in the reflectance levels were observed when the substrates were compared. For most colors and intensities the spectral reflectance was lower for the glossy paper, as a consequence of the lower diffuse reflection. The difference was smaller when the polarization filter was used.

Spectrophotometer Specifications
GretagMacbeth Spectrolino Spectrophotometer
Spectral Analysis: By holographic diffraction grating
Spectral Range: 380 to 730 nm
Physical Resolution: 10 nm
Measurement geometry: 45°/ 0° ring optic, DIN 5033
Measurement aperture: 4mm
Light Source: gas-filled tungsten, type A illumination
Density Range. 0.0 to 2.5D, DIN 16536
Physical Filters: D65, Polarization and Neutral
Short term repeatability: 0.03 ΔE (D50, 2°)

Future Considerations

The influence of gloss on the scanner measurements must be examined more thoroughly since it most likely plays a major role in the calibration procedure. The scanner illumination should be a subject for further investigations; it is suspected that the illumination of a color patch has a spatial variation over the scanner bed. Light scattering effects in the substrate are also believed to further amplify this. Substrates with gloss properties other than the ones already examined should also be included in the continued work. Only two printers were used in this study in order to narrow the span of variations and to focus on the paper properties. Additional printers should also be investigated; different inks and toners will most likely influence the calibration. Finally, the calibration method can most surely be further developed.

Conclusion

The color calibration is most successful when the calibration is made on the same type of substrate as it is intended to be used with. Moreover, the calibration procedure gives good results for inkjet prints, especially when printed on uncoated paper substrates. It does not produce particularly good results for xerographic printing. With a high but even gloss level the calibration is acceptable, but in the presence of differential gloss in the printed substrate the results are less satisfactory. The results give indications that gloss reflections influence the scanner measurements; therefore the calibration is more successful if the reference spectrophotometer measurements are performed without the polarization filter. An error source that lowers the performance of the calibration is that the dynamic range of the scanner used in this study does not entirely cover the dynamic range of the printed substrates.

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References

1. Hardeberg J.Y, Acquisition and reproduction of colour images: colorimetric and multispectral approaches, Ecole National Supérieure des Télecommunications, Département TSI, France, (1999)
2. Hägglund Å, Colour gamut and colour sensitivity of a desktop scanner, Department of Science and Technology, Sweden (2003)
3. Wyzecki G, Stiles W.S, Color Science, Wiley (2000)
4. Hunt R.W.G, Measuring Color, 3rd Edition, Fountain Press (1998)
5. Pauler N, Paper Optics, Lorentzen & Wettre, Sweden
6. Wang J, Differential Gloss in Electrophotography, Proc. NIP15, pg. 406. (1999).
7. Holst G.C, CCD Arrays, Cameras and Displays 2nd Edition, SPIE Optical Engineering Press (1998)
8. Janesick J.R, Scientific Charge-Coupled Devices, SPIE Press (2001)

Biography

Mattias Andersson received his MSc degree in Applied Physics and Electrical Engineering from Linköping University, Sweden in 1998. Since 1998, he has been working as a research engineer at the paper physics division of MoRe Research in Örnsköldsvik, Sweden. He is currently working with his PhD project at the Digital Printing Center, Mid Sweden University in Örnsköldsvik, Sweden. His work is primarily focused on print quality measurements for digital printing.