Scanner Characterization for Color Measurement of EP Printed Output

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Abstract

Typical automated print quality assessment tools use desktop scanners to analyze printed output. Unfortunately, due to the non-colorimetric properties of scanners, results can vary significantly depending upon the scanner used. This paper describes an investigation into using ICC (International Color Consortium) profiling as a tool to characterize the color response of a given scanner. The goal of this work is to create a scanner profile that can accurately measure the color of EP (electophotographic) printed output through the manipulation of targets, post processing refinement techniques, and the minimization of the effects of scanner non-uniformities. Targets with known color characteristics were created and scanned. Using open source software, ICC profiles were created from the scans to characterize a scanner's response to the colors in the targets. Through experimentation, it was determined that the maximum error of the profile can be minimized through post processing refinement. The main contributors to the average error were scanner non-uniformities and target characteristics, including uniformity, type, layout, and gamut. The results show that it is possible to, on average, characterize the output of a single EP printer to within 2 ΔE_{76} and the output of several EP printers to within 3 ΔE_{76}. This is a quality level good enough to suggest that ICC profiling can be a fast, cost-effective solution toward obtaining reasonable color consistency across scanners, as well as a possible low-cost alternative to a spectrophotometer for specific applications.

Introduction

Several existing automated electrophotographic (EP) print quality assessment tools rely on a typical desktop scanner. These tools provide the ability to quantify such print quality artifacts as mottle, jitter and banding [6-8]. Moreover, desktop scanners with improved quality and functionality are becoming increasing popular and less expensive, which lends credence to the idea of using a scanner for high-volume data collection and analysis. However, these tools depend upon colorimetric data so the results are not directly tied to the scanner used to perform the analysis.

Consistent and accurate color measurements are an essential aspect of maintaining, calibrating, and assessing the quality of printed output. Typically, spectrophotometers and colorimeters are used to perform these color measurements due to their high accuracy and precision. Nevertheless, these devices are generally slow, relatively expensive, and offer poor spatial resolution for many applications. Alternatively, color scanners offer significantly higher spatial resolution, are generally easier to operate, more readily available, and less expensive than a colorimetric device. However, a color scanner is almost always non-colorimetric, which implies the scanner's response is not linearly related to that of the human visual system [1]. Scanner characterization provides a method for overcoming the non-colorimetric nature of a scanner.

Standard scanner characterization methods use a photographic target such as the Kodak Q-60/IT8 or the ColorChecker DC target. However, this type of target poorly characterizes the output of an EP printer. This paper offers a method for using ICC (International Color Consortium) profiles to characterize the output of a given scanner and effectively measure the color of EP printed output. The results presented in this paper are very comparable to previous attempts to characterize the output of a scanner which use a 4D look-up table (LUT) with a controlled black level to perform the characterization [1]. In addition to focusing on a different media type, previous attempts generally use significantly fewer points to create a profile and verify the accuracy of a given profile. Lastly, target design, the limitations of a scanner for color measurement, and a profile accuracy refinement technique are investigated.

Experimental Setup

The scanner that was used to create all the profiles in this paper was the Epson 10000XL. This scanner was chosen because of its high optical resolution and competitive specifications. In addition, it offers an automatic document feeder (ADF), which improves the ability to perform high-volume analysis. Lastly, it offers stable and consistent output which is discussed later in the paper when the effects of scanner non-uniformities are analyzed. All colorimetric measurements were made using a D50 illuminant and a 2° observer. The measurements were gathered using a Gretag-MacBeth SpectroLino spectrophotometer mounted on a SpectroScan stage. All error measurements in this paper are ΔE_{76} calculations between the International Commission on Illumination L*a*b* (CIELAB) data that comes from the spectrophotometer and the scanner profile.

$$\Delta E_{76} = \sqrt{(L_{scan} - L_{spectro})^2 + (a_{scan} - a_{spectro})^2 + (b_{scam} - b_{spectro})^2} \qquad (1)$$

Profile Creation Process

The ICC profiles analyzed in this paper were created using Argyll CMS, an open source, ICC-compatible color management system [2]. The scanner ICC profile creation process is well-defined. A target is chosen, measured with a spectrophotometer, and scanned using the scanner that will be profiled. The scanned page is then analyzed within each of the patches on the target. The scan data and measured data from the spectrophotometer are then combined to form the target information file. The target information file consists of both the RGB data from the scan and the device-independent data from the spectrophotometer. This file can then be used by Argyll CMS to create a profile. This process is also outlined in the flowchart seen in Figure 1.

All profiles were created using a LUT based approach with a profile connection space of CIELAB. This method of profile creation generally gives the best results, especially when it is possible to supply a large number of color points [2]. Alternative curve-fitting and matrix based profile creation types poorly characterize a scanner's non-colorimetric output. The quality of the profile was set to the highest feasible level. Also, the profiles were created such that the white point of the characterization target was mapped to its absolute value, not to pure white. This prevents clipping from occurring within the profile and essentially causes the profile to use an absolute colorimetric intent [2].

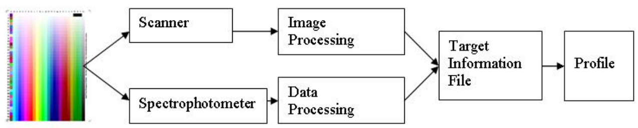

***Figure 1**. Generic profile creation process.*

Target Design

There are several characteristics of a characterization target that can affect the accuracy of the resulting profile. These characteristics include the target media type, uniformity, layout and gamut. Typically, scanner ICC profiles are created using a target such as the Kodak Q-60 Color Input Target. However, since the focus of this paper is on EP printed output, all targets were printed on media typical of common laser printing business applications. The main reason for using this media type was to match the white point of the target(s) used to create the profile to the white point of the pages that were used to check the accuracy of the profile.

The uniformity of the target can affect the profile accuracy in multiple ways. If the uniformity within a color patch is poor, then it is possible the area measured by the spectrophotometer and the region measured after scanning the page may represent a different range of colors. Additionally, if there is low-frequency variation across the page, then the color values of entire regions of the page may be biased based upon the layout of the color patches. Due to these considerations and results supporting this idea [4], it was decided the patches on the target should be randomized (e.g., right target in Figure 2), rather than ordered by intensity, hue, or some other property (e.g., left target in Figure 2). The gamuts of the test targets were determined by the gamut of the printer. Additionally, pure CMYK colors were emphasized, as these primary colors are used most commonly for algorithmic print quality analysis [6-8].

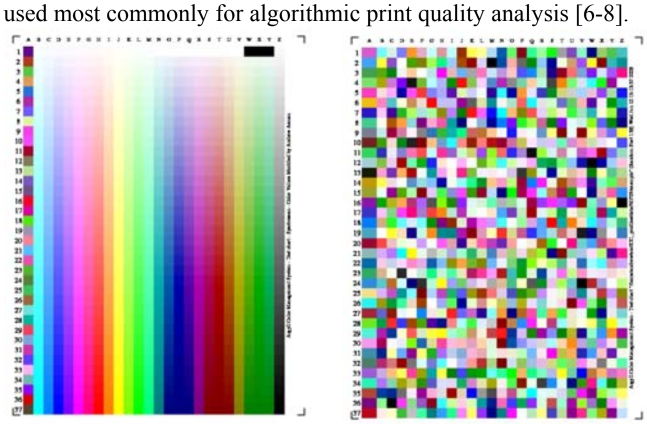

***Figure 2**. Sample characterization target used for profile creation. The right target represents the randomized version of the target on the left.*

Accounting for Scanner Non-Uniformities

Scanner Spatial Non-Uniformities

When analyzing the accuracy of a given profile, large errors often occur when the scanner output is non-monotonic with respect to the data given by the spectrophotometer. To illustrate this, consider a gray ramp that is being measured with both a scanner and a spectrophotometer. If the spectrophotometer designates a particular shade as being darker than some reference shade, but the scanner sees it as being lighter, then large errors will occur as a result of this discrepancy. One reason why these discrepancies occur is because of the difference between the way that the spectrophotometer and the scanner measure the light that is reflected from the page. However, occasionally they are a result of the spatial non-uniformities of the scanner.

Spatial non-uniformities on the flatbed of a scanner can be seen either as low frequency variation across the bed, or as a 'hot-spot' in a particular area of the bed [3]. To quantify the effects of these spatial non-uniformities, several pages were scanned in multiple orientations, and then the RGB values within each color patch were averaged across the orientations. A profile was then created for each orientation and the averaged values. The results of this experiment can be seen in Table 1. As evidenced by the results, the profile that was constructed using the averaged values (across all orientations) performed better in all statistical categories. This improvement occurred because the number of non-monotonic discrepancies between the scanner and the spectrophotometer decreased. This experiment was performed using 4 different scan orientations. In theory, however, additional scan orientations would decrease the effect of the scanner spatial non-uniformities even further.

Table 1. Example indicating the differences in profile accuracy when scanned in different orientations as well as when averaged across all four orientations. All error measurements are ΔE_{76} calculations.

	Average	95^{th} %	Max
Orientation 1	1.55	3.15	11.35
Orientation 2	1.67	3.33	8.05
Orientation 3	1.67	3.28	16.68
Orientation 4	1.68	3.31	9.15
Averaged	1.43	2.96	7.88

Scanner Temporal Non-Uniformities

To quantify the effects of temporal non-uniformities on a scanner, a single page was scanned 20 times consecutively on 3 different scanners of differing quality levels beginning from a cold start. This was investigated due to previous experience with certain scanners exhibiting the need for a "warm-up" scan in order to get the scanned output into a steady state [3]. The results for this experiment can be seen in Figure 3. The x-axis on this graph represents consecutive scans, which explains why there are only 19 data points for the 20 scans. The value at each data point represents the difference between the consecutive scans. This difference (ΔRGB) between consecutive scans was calculated by taking the absolute value of the difference between the average values for each RGB plane within each patch. This can be seen in Equation (2) for a given number (N) of patches.

$$\Delta RGB = \frac{1}{N}\sum_{i=1}^{N}\left(\left|\overline{R}_{1i} - \overline{R}_{2i}\right| + \left|\overline{G}_{1i} - \overline{G}_{2i}\right| + \left|\overline{B}_{1i} - \overline{B}_{2i}\right|\right) \quad (2)$$

The results show that for certain scanners, a "warm-up" scan is necessary when beginning from a cold start, while for other scanners this is not quite as critical. Based upon this information, it was confirmed the Epson 10000XL (seen as "Scanner 1" in Figure 3) would be suitable to create the profiles because it did not exhibit the need for a "warm-up" scan and consistently generated a ΔRGB value of under one.

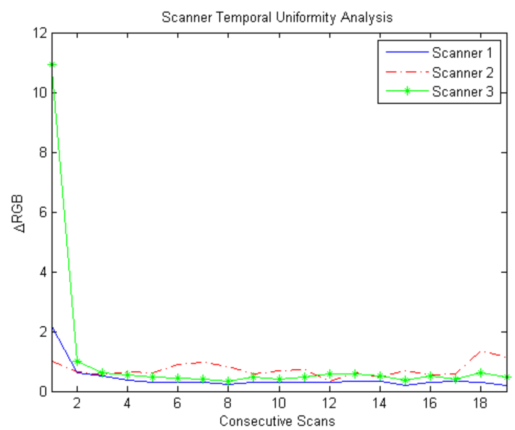

***Figure 3**. An individual scanner's consistency between scans over time.*

Post-Processing Refinement to Minimize Maximum Error

When applying a given LUT based profile to data that was not directly used to create the profile, large errors will often occur. This is due to the fact that none of the color points used to create the profile are in the close vicinity of certain color points in the subsequent set of data. These large errors can be minimized through the post-processing refinement technique that is described in Figure 4. It is important to note that the refinement process only helps decrease the error values associated with points that do not have a nearby neighbor in the LUT. Error values due to deficiencies inherent to the printing or scanning device will not be minimized by the refinement process.

The refinement technique is an iterative process that involves editing the target information file that Argyll CMS uses to create the profile. These files are simple text files in which each line represents a single color patch. Since they are simple text files, they can be easily combined and filtered. The refinement process works by creating a filtered target information file that contains only the points converted poorly by the profile. Through visual inspection or statistical analysis it is possible to determine a ΔE_{76} threshold such that all color points that generated an error larger than the ΔE_{76} threshold can be considered outliers in the data set. The filtered target information file can then be combined with the target information file that was used to create the profile, and a new profile can be created from the combined file. This process can be repeated multiple times.

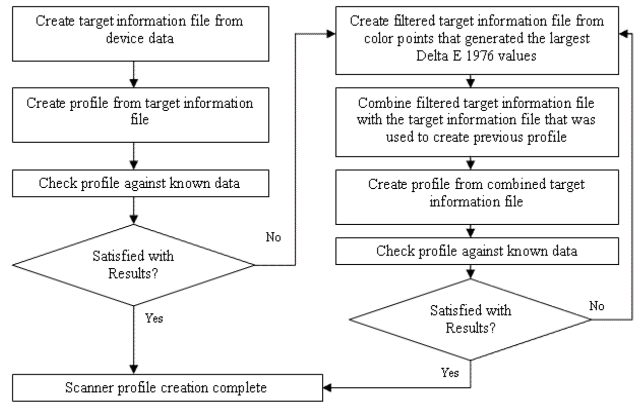

***Figure 4**. Post processing profile refinement process.*

Figure 5 shows the benefits of the refinement process. The histograms reveal the accuracy of a given profile before (top) and after (bottom) refinement. The iterative refinement process was repeated 15 times for these results. The vertical line indicates the ΔE_{76} threshold. In this case, the threshold was approximately 10.0 ΔE_{76}. As the results indicate, the maximum error of the original profile was decreased from approximately 22.0 ΔE_{76} down to 10.0 ΔE_{76}, which is very close to the desired threshold. Additionally, it is important to note that the average error remained relatively unchanged after 15 iterations of refinement. This is a major benefit of the refinement technique because it makes it possible to minimize the maximum error without adversely affecting the average error. In some cases, the average error will be decreased by the refinement technique. This situation generally occurs when the data that the profile is being checked against is drastically different than the data that was used to create the profile.

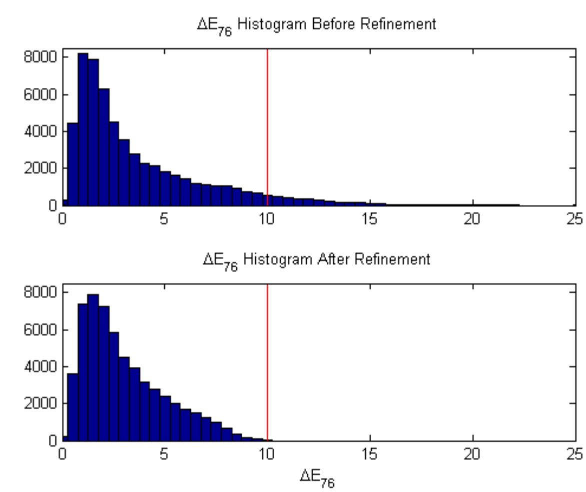

***Figure 5.** Comparison of profile accuracy before (top) and after (bottom) post-processing refinement. The refinement process was performed for 15 iterations.*

Characterization Results

A collection of 12 EP printers were used in this experiment. The printers were chosen to adequately represent a variety of available EP printers on the market today. The printers ranged in price, quality and manufacturer. Five pages of color patches were printed on each printer that was analyzed. Each page consisted of 962 color patches, totaling 4810 color patches per printer. The first page contained ramps of the primary and secondary additive and subtractive colors with varying levels of black toner. The right (randomized) image in Figure 2 shows an example of this target. Recall that the random ordering of the patches helps minimize the effect of scanner and printer spatial non-uniformities. The subsequent four pages focused on the individual color planes (CMYK) of the printer colorspace. For each page, the main color plane was combined with varying levels of the remaining color planes. The page that focused on black consisted of both pure and process (CMY) black. The ability to characterize both the output of a single EP printer and the output of a collection of EP printers was investigated, as described in the following sections.

Characterizing the Output from a Single EP Printer

Characterizing the output of a single EP printer can be useful for several reasons. If the development of a printer needs to be monitored, or if a printer needs to be regularly calibrated, characterizing its color output so that a scanner can accurately measure its output can be useful. The results in Table 2 show the accuracy of 12 profiles created using 12 different printers. Each profile was checked against 4810 color points, each from the printer that was used to create the profile. The results were fairly consistent from printer to printer. The average ΔE_{76} for each profile was under 2.0, and the 95th percentile ΔE_{76} value was under 4.0 for all printers used in this experiment.

Table 2. Profile accuracy when checking against the same printer that was used to create the profile (4810 color patches total). All error measurements are ΔE_{76}.

Printer	Average	95th %	Max
1	1.54	3.30	8.54
2	1.29	2.75	5.19
3	1.26	2.70	5.85
4	1.24	2.68	6.77
5	1.56	3.10	8.97
6	1.77	3.61	9.85
7	1.33	2.58	6.85
8	1.33	2.65	6.10
9	1.27	2.72	8.31
10	1.27	2.80	10.26
11	1.49	3.08	7.26
12	1.43	2.93	7.22

Characterizing the Output from Several EP Printers

Creating a single profile that can characterize the output of several EP printers provides a more general profile that can be used for several purposes, including competitive analysis. The results in Table 3 show the accuracy of creating a profile from a single printer and checking it against 12 printers of various price levels, quality levels, and manufacturers. Each profile was checked against 57,720 color points. Additionally, the results before and after refinement are presented in Table 3. The results exhibit the benefit of the post-processing refinement technique, as it decreased the maximum error by an average of approximately 8.0 ΔE_{76}. Additionally, the results show that it is possible to characterize the output of several EP printers to an average ΔE_{76} of approximately 2.5, with a 95th percentile ΔE_{76} of approximately 6.0.

Table 3. Profile accuracy when creating a profile from a single printer and checking the accuracy against several different printers. Each profile was checked against the output of all 12 printers (57,720 color patches total). All error measurements are ΔE_{76} calculations.

	Before Refinement			After Refinement		
Printer	Avg.	95th%	Max	Avg.	95th%	Max
1	3.64	10.49	22.01	2.99	6.99	10.22
2	4.46	11.65	24.91	3.56	8.84	12.85
3	2.81	6.86	17.63	2.81	6.34	11.36
4	2.88	8.00	15.45	2.86	7.14	10.78
5	2.64	6.85	18.37	2.55	6.22	10.84
6	2.63	6.36	13.54	2.62	6.07	10.92
7	2.67	7.46	20.10	2.57	6.47	10.54
8	2.54	7.04	19.20	2.54	6.37	11.19
9	2.83	7.91	21.33	2.65	6.50	10.79
10	2.67	7.63	19.35	2.56	6.54	10.90
11	2.56	6.67	16.53	2.55	6.20	10.90
12	2.46	6.33	19.31	2.53	6.26	10.73

Conclusions

There are several factors that affect the accuracy of a scanner profile. The accuracy of a profile can be significantly increased by controlling the type of media that is used to create each profile. This improvement is seen because the white point of the profile is mapped to the white of the paper, which is nearly constant among the pages that are measured. Analyzing scanner temporal uniformity can provide valuable information about the necessity of a ‘warm up’ scan and the level of accuracy expected between consecutive scans. The effect of scanner spatial non-uniformities can be minimized by averaging the RGB values from multiple scan orientations. Additionally, the post-processing refinement process described in this paper can significantly reduce the maximum error of the profile, especially in cases where the maximum error is a result of color values that were largely different from the colors that were used to create the profile.

Characterizing the output of a single EP printer can be accomplished with a high degree of accuracy. For instances where the output from a single EP printer needs to be monitored over time, scanner characterization offers a fast, inexpensive alternative to using a colorimetric device. Characterizing the output of several EP printers requires a slight trade-off between accuracy and generality. However, depending upon the amount of accuracy needed, a scanner ICC profile can provide high resolution colorimetric data which is essential to many automated print quality assessment or diagnostic frameworks.

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Andrew Asman is pursuing BS degrees from the University of Kentucky in both Electrical and Computer Engineering. He is currently employed at Lexmark International, Inc., where his work focuses on software development, print quality analysis, and scanner characterization. Additionally, Andrew has worked in the Computer and Electrical Engineering Department at the University of Kentucky, where his work focused on audio rendering and sound source location algorithms. His research interests include image processing, audio signal processing, and software optimization.