A High Consistency Color Correction System in an Inkjet Printer

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Abstract

A variety of sources of variability cause inconsistent color reproduction in Inkjet Printers. Difference in the size of drops ejected, paper type and environmental conditions, to name a few, can lead to big differences in the printed colors. This paper describes a system based on sensing the color shift with respect to pre-determined color targets and compensating for it. The system relies on a combination of several components that work together to provide the best results while minimizing cost and user intervention. The key components are: a built-in sensor tuned to get estimates of ink density in the particular ink/media system, a sensor characterization process, a user triggered calibration process that senses and corrects the color errors and a set of color profiles built in the printer's driver.

A periodical calibration of the printer/media system ensures consistent and accurate colors in the output. The performance achieved is currently the leading edge in inkjet printers, enabling color accuracy errors below 4 dE_{ab}^* maximum, which is at least 50% more accurate than most Inkjet printers.

Introduction

Background

Some amount of color variation is inherent in all printing processes. Inkjet printing is no exception. There are many sources of color variation that have been characterized, however the two most important sources of variation in thermal inkjet printing are dot size variations (due to drop weight variation or dot gain variations) and variations in the hue of primaries (due to environmental ink-media interactions). Since the goal of any production or commercial printing process should be to achieve consistent color reproduction, there is a need of actively controlling the reproduction of color in inkjet printers via a closed loop measurement and correction process.

Objective

To design a low cost solution to achieve strict color goals in an inkjet printer.

Color Error Metrics

There are two principal types of metrics of color errors in a digital color output device. The first type is color repeatability or color consistency. The second type is color accuracy. The former refers to how well a device can replicate the same output color over time given the same input color specification. The latter refers to how well, on average, the output device can match a target color or set of target colors.

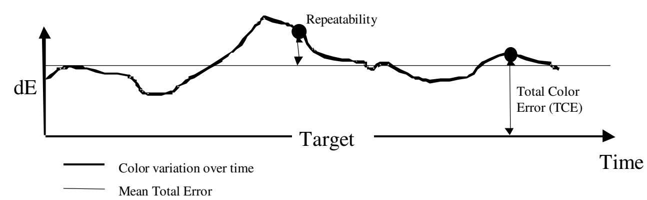

Figure 1. Representation of the Total Color error experienced on a time basis by an inkjet printer

The figure above illustrates these two concepts for the example of a single output color varying over time. The thick line represents the color difference (dE_{ab}^*) relative to the target (x-axis). The thin line represents the average of the color variation over time, and thus the distance from the thin line to the target is the Mean Total Error for this color. The variation of the thick line around the thin one is an illustration of the repeatability or consistency of the color. The superposition of the two types yields the Total Color Error (TCE), which represents the color error that a customer would actually experience at a given instant in time. Although the customer experience of color performance is linked to this Total Color Error, we choose to analyze the components separately from a system design standpoint since they have different root causes and different means of improvement.

Color repeatability issues are known to be very closely linked to the Writing System and its ability to compensate for changes in the system or environment (i.e. change in relative humidity or the drop weight of a new print head). Color accuracy on the other hand is more closely associated with the color profiling (or color mapping) methods used by the printer's RIP or driver. Therefore, to improve color repeatability/consistency, we will focus on system color hardware (i.e. color sensor) improvements, calibration triggering protocol enhancements and algorithm enhancements. In addition to improving color consistency we will focus on developing better methods for color profiling. Improvements in both areas will lead to overall improvements to the TCE of the system, and thus improved customer experience and satisfaction.

Solution Space

One important thing to note is the relative importance of the method used for calibration and the proper timing. Sometimes the protocol (rules for triggering the calibration process) plays a bigger role on the final result than the precision of the sensor used to correct the color errors. On a simulation (Fig.2), we have seen that different methods and protocols have more impact on the final consistency than the capability of the sensors evaluated. Taking that into account, the designer has to do the appropriate selection of a sensor and a method that, while meeting their constraints, when combined they work well together and achieve the desired performance. The graph below shows several combinations of methods and sensors that illustrate this point. The metric shown is 95% dE_{ab}^{*} (95% of the colors inside the printer's gamut have an error equal or less than that value).

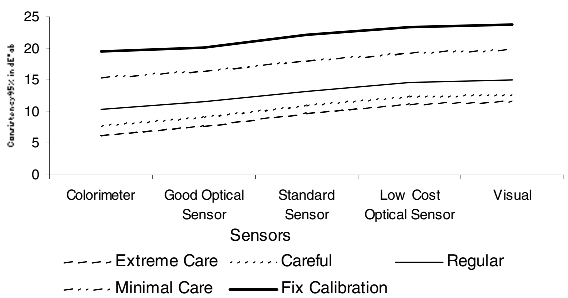

Figure 2. Relative importance of Sensor/Correction Capabilities and Triggering methods

There is another variable that also plays a major role in the solution space; it is the correction method, that is, the type of computation or correction that is being applied along with the amount of information that it is captured from the system in order to feed the correction engine. Here we can find different approaches like the densitometry-like type of measurement of primary colors (involving the measurement of a given number of color tiles, usually ranging from 20 to 40) to perform a uni-dimensional correction, or a calibration made by measuring a huge sample of the printer's color space with a spectrophotometer or colorimeter in order to re-profile the system. The degree of color accuracy achieved will in the end depend on this variable as well.

Therefore, it becomes a critical question what the kind of errors and what the origin are in order to tackle the problem at the source. The following chapter attempts to go deeper into the physics of the system to explore what is the viable solution.

Physics

The principle of the color correction presented here points towards the deviations in color with respect to a standard. It can be described by the equation[1] (1).

$$\Delta E_{ab}^{*} = \sqrt{\left(L_i^{*} - L_{std}^{*}\right)^2 + \left(a_i^{*} - a_{std}^{*}\right)^2 + \left(b_i^{*} - b_{std}^{*}\right)}^{2} \qquad (1)$$

Being *i,std* the reference of actual color and target color respectively. In a CMYK printing system, similarly to what happens in a press device, the color deviation, also known as color error, can be interpreted as deficiencies in the quantities of each individual color ink. Therefore, the lack or excess of cyan ink, coupled with the lack/excess of magenta or yellow ink, will result in deviation in L*, a*, b* for a particular color. This is only a single way of color error origin on a printing space. There are other ways not treated in this paper like the change in spectral properties of the inks on a particular media.

In real life, the majority of color error experiences on an inkjet printer are due to changes in density of the primary color inks, for a particular media. The approach taken in this paper points to that particular effect.

Typically the deviations on an inkjet printer can normally be threefold: print head drop weight (DW) differences, environmental changes and media changes. For instance, a DW difference of 1.25ng on a 100% density area fill translates into up to 5L* of error on media.

It is important to note that the biggest difference is on the darkest points (high density). In other words, the control on the so-called dark point (100% ink density) is crucial in minimizing color errors. The difference in a* and b* for a change in DW on a primary color ink is not as big as in L*, except for the yellow ink in which the biggest difference is on b*.

With all this in mind, a good approach in controlling the color performance of an inkjet printer would be to specifically control the performance in L* for cyan, magenta and black inks and b* for yellow ink. That is exactly the approach suggested by this paper.

Thus, the key is to be able to accurately detect and correct for the changes in L* and b*. Since they depend on ink density, it looks like a good densitometer could do the job. For us, a densitometry-like sensor consists in one or a group of narrow-band light sources (i.e. Light Emitting Diodes, LED's) as illuminants and a photodiode (sensor) to capture the reflected light of the illuminants on the inked media surface in a scanning operation.

A densitometry-like device will measure a signal resulting from combining the spectra of the ink/media, the illuminant and the sensor (photodiode).

The measurement of the L* of dark point presents a difficulty due to the non-linear response of L* and sensor signal (because of the non-linearity of L*-Y/Yn[2] function, where Y and Yn are the Y tristimulus values for the actual color and the reference white respectively).

The consequence is that the sensor has potentially less resolution in the dark areas when measuring L*. This is also true for the L* of cyan, magenta and yellow, although in some colors the curvature effect is bigger than in others. Therefore a specific calibration of the sensor and a higher resolution in this area are critical.

Besides the ability to estimate density, there are several aspects of the LED/sensor performance that have to be taken into account in the final design. They are listed below:

LED Spectral Shifts

One of the problems with LED's is in the variability of their emission spectrum (Fig. 3). The problem is twofold:

1. Different relationship between sensor signal and L*
2. Variation of signal range

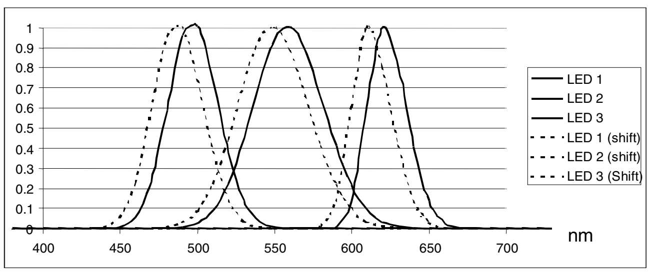

Figure 3. Spectral shifts for different LED's

There is also a spectral shift created by a forward current variation (Fig. 4).

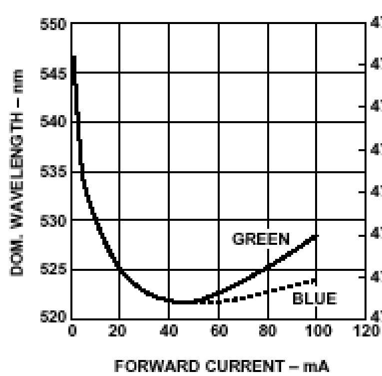

Figure 4. Spectral shifts due to current variation

LED Degradation Along Life

LED's experience a certain degree of luminosity reduction along life. The problem is worse at higher operating currents. This causes a reduction in the precision of the sensor. That is a strong reason to calibrate the gain and offset parameters in the HW so that we can use as much digital range as possible.

Optical Operation

The field of view is the effective area scanned by the color sensor under some specific criteria. In our design this can be around 3mm. The final design of the color tile that is being scanned has to take into account this parameter, especially in the design of the size of the color patches.

Variation of Sensor to Paper Distance

Mechanical tolerances would vary the Sensor to Paper distance if the sensor scans over the color tiles. It is important to know how sensitive is the sensor to these variations in height since they would induce noise in the sensor signal. A good layout of the patches in the color target can reduce the impact of this noise in the primary color measurements.

Color Sensor HW Calibrations

The sensor outputs an analogical signal that has to be digitalized. There are several options depending on the number of bits of the A/D Converter resulting in different number of counts available. For instance, on an 8-bit A/D Converter the sensor range in digital counts is 0 to 255.

The number of bits of the A/D Converter (number of counts) is a decision that impacts the total cost of the solution. Fig.5 is a representation of the sensitivity of L* readings versus A/D resolution (expressed in total number of counts). The graph helps determining the number of counts needed as a function of the precision required in the estimation of L*.

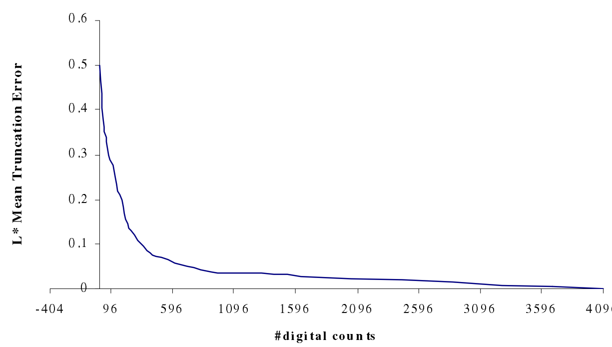

Figure 5. Truncation error sensitivity to L as a function of the number of counts used (A/D converter)*

However, the variability of the sensor signal reduces the number of available counts, resulting in a decrease in the precision. Therefore, it is critical to ensure the maximum digital range of the signal. The HW has be tuned to optimize the signal for all LED's/Colors scanned. A special algorithm sets the Gain and Offset values to properly scan each color with the maximum signal.

Sensor Characterization

The different spectrum of inks, media and LED's would produce different sensor signals. Therefore we need to characterize the sensor measurements for each media type in order to get accurate L* estimations. In addition, manufacturing variability of the LED's causes spectral shift from a nominal LED. This will in turn create differences in sensor signal.

Thus, it is necessary to characterize the densitometry response of the inks on every media and every sensor, since, in the end, what it is needed is a good estimation of L* of all inks in all relevant media.

Architecture

Once we've seen the limitations of the sensor, now let's take a look at all the other aspects of the system in the form of a description of the solution provided.

Description of the System

The Color Correction System (CCS) ensures consistent, repeatable color from one print to the next and from one printer to another, independent of system variables like ink level, ambient conditions, and print head life, but relative to a single printer configuration: media type, ink type, resolution, print mode, and half toning method. It does not ensure accurate color, which must be obtained via printer profiling and color management, nor does it ensure color matching from one configuration to another but it plays an important role in achieving those goals. As such, it is comparable to traditional densitometry-based methods of process control used for commercial printing presses, although the solution presented here is much more automated.

Solution

The solution is composed by the following elements:

1. Sensor = 3 LED + photodiode
2. One-dimensional 12-bit LUT (Look Up Table) linearization with cut-off points, previous to the half toning stage
3. One-dimensional 8-bit LUT to describe sensor AD counts to L*/b*
4. Restricted environmental operating range
5. Recommended user triggering calibration (protocol)
6. Specialized color profiles

System Overview

The basis of the CCS is the principal of measuring the reflected energy from primary color tiles which are illuminated with a narrow-band light source (i.e. a Light Emitting Diode, LED) and detected by a photodiode, much the same way a classical densitometer works. The reflected energy is correlated to L* or b* via lookup tables. The estimated L* and b* values are used to correct the system back to a known linear tonal response (analogous to a gamma correction on a CRT). Secondary colors are corrected by virtue of the primary colors which make them being corrected.

Once a color calibration has been launched, the basic calibration process proceeds as follows:

Printing: A color target consisting of primary color ramps of different ink quantities is half toned and printed the usual way, using all default settings and system configurations that will be used for printing the actual job.

Scanning: After allowing the ink to dry (using the default dry time algorithm), it is scanned using the embedded optical sensor.

Signal Processing: First there is some data filtering and averaging and then the raw sensor readings get converted into media white-relative L* (rL*) for CMKcm and media white relative b* (rb*) for Y, using algorithms which are described later.

Correction Engine: The rL* and rb* measurements are passed to the color correction engine (part of the Printer's Firmware). The correction engine uses these measurements to calculate new linearization transfer functions to be applied to each channel.

Sensor/Hardware

The basic HW of the measurement device has been detailed in previous paragraphs. It is composed by 3 LED's, a single receptor (sensor) and a Signal Processing Module (Fig. 6).

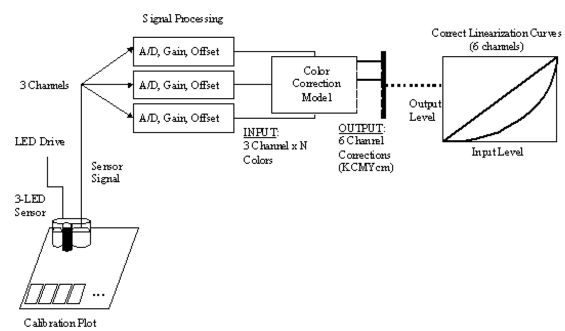

Figure 6. Measurement and correction model process diagram

The decision on how many different light sources are needed depends on the ink/media system. Rarely a single LED can be well tuned to be able to accurately create a reflected light signal. The different ink/media spectra require different LED (narrow-band) to have appropriate Signal to Noise Ratios (SNR).

Correction Algorithm

The correction algorithm is the final stage in which the L* estimations from the sensor are used to adjust all primary colors by means of:

1. Adjusting the darkest point (minimum L*) in the tonal response to a pre-set L* value for that particular primary color and media.
2. Re-scaling the ink levels to get a linear tonal response from media white point to pre-set L* for that particular primary color and media.

3. Computing the new transfer function that will be used at the printer's half toning process (image processing).

Protocol

In order to obtain the optimum level of color performance, the user has to adhere to a given set of guidelines. Temperature variations within the range of 15-35C can be corrected via a new color calibration at those conditions, however relative humidity should be limited to 60% in order to prevent uncorrectable hue shifts on some media.

Moreover, a relatively high frequency in the calibrations triggered would minimize the color variations over time (referred in the chapter *Color Error Metrics*). The recommendation is to perform the calibration on a by-weekly basis for a color critical user.

Performance

The system performs similarly to other higher budgeted proofing systems out in the market (with different technologies) and better than equivalent low cost Inkjet Proofers. Table 1 is a representation of the performance of these different systems in terms of maximum color error (the metric shown is the SWOP error in dE_{ab}^* 95 percentile, that is, the 95% of the colors contained in the SWOP gamut volume have an error equal or less than this value).

Table 1. Performance of different Proofing Systems[3]

Proofing system	95% dE_{ab}^*
High-End Proofer 1	6.75
High-End Proofer 2	7.75
High-End Proofer 3	9.80
HP DesignJet 10ps	8.00
Other Inkjet Proofers	16.75
Other InkJet Printers	23.00

The first three products are three different high budgeted proofers (above 10.000$). The fourth is HP DesignJet 10ps (below 2.000$), the fifth is another Inkjet proofer with a similar cost, and the sixth is another Inkjet printer without a specific proofing system.

Conclusion

The understanding of the actual problem and the constraints in the solution space have lead us to combine a capable, well-characterized sensor with improved calibration algorithms and precisely defined calibration triggering protocol.

A stretched highly efficient low cost solution can deliver similar results to other higher budgeted approaches, allowing a TIJ-based system to enter the proofing market at an extremely competitive price.

Acknowledgements

We would like to thank many of the R&D engineers of HP site in Barcelona and Palo Alto, especially Jim McCullough, Johan Lammens, Nathan Moroney, Salva Sanchez, Jose Luis Valero, Michel Encrenaz, Ramon Vega, Karra Herrero, Marc Serra and Joan Uroz.

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2. Dr. R. W. G. Hunt, "The Reproduction of Colour", fifth edition 1995, page 157 (L* as a function of normalized Y tristimulus value of the reference white Y/Yn)
3. GATF report, "A Comparison of the Hewlett-Packard 10/20ps Inkjet Printer to SWOP/TR001 and Other Competitive Proofing Systems", January 17, 2002

Biography

Ferran Vilanova received his M.S in Mechanical Engineering from *Escola Tècnica Superior d'Enginyers Industrials de Barcelona* (UPC) in 1996. He joined HP in 1997, working in the area of Writing System and Image Quality of different HP DesignJet series. He has published several patents on this field.

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