Tone Curve Stabilization for Color Electrophotography

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Abstract

Color accuracy and consistency is crucial for printing. In order to compensate for fluctuations in consumables and environmental factors associated with electrophotography (EP), calibrations are performed at specific intervals to maintain color quality. During a calibration, color patches are printed on either paper or the transfermedia and EP process parameters are adjusted based on the density measurements of the patches. Since each calibration may require additional time and consumables, it is desirable to increase the interval of calibration as well as to reduce the number of calibration patches. In this paper, an algorithm to improve color consistency while reducing consumable consumption and increasing calibration interval is proposed. The algorithm utilizes statistical model prediction. The proposed algorithm can adapt the EP process to compensate for consumable usage and measurable environmental factors with minimal number of calibration patches. The effectiveness of the proposed algorithm is validated using an off-the-shelf in-line color EP printer under different environmental conditions as well as different consumable usage models.

Introduction

As the technology improves, the demand for color printers is increasing and higher quality printouts are expected at lower cost. Color accuracy and consistency of printouts are two of themajor issues in color print quality (PQ). Over the last twenty years, much effort about color management has been put forth, however many challenges still remain.

A tone reproduction curve (TRC) is commonly used to characterize the ability of a printer to reproduce primary color tones. The primary colors in a four-color laser printer are cyan (C), magenta (M), yellow (Y), and black (K). All output colors are produced by the combinations of these four primary colors. A TRC is obtained by plotting the measured color densities on the output media against the target color densities for a set of predefined density levels. The TRC are often approximated with a small number of density levels. Various units can be used to quantify the color density. For the target density, a unitless integer between 0 and 255 is commonly used to represent an eight-bit tone value, where 0 represents no tone and 255 represents maximum tone value. Either the CIE dE or the CIE L* standards are commonly used as units for the measured density. To achieve color accuracy and consistency, the TRC for each of the primary colors needs to be accurate and stable, respectively.

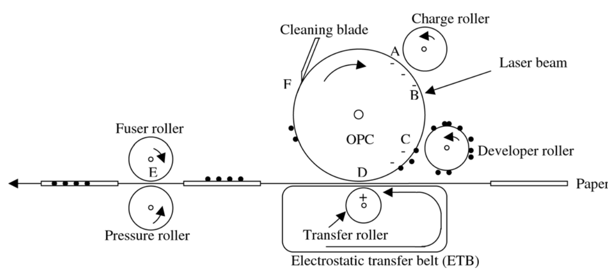

Figure 1. Electrophotographic process: cross-section of a typical laser printer (A) charging, (B) exposure, (C) development, (D) transferring, (E) fusing, and (F) cleaning.

In some electrophotographic (EP) printers, calibrations are performed periodically. During such calibration, a test pattern with specific color density values is printed on a process specific calibration media, such as paper or transfer belts. The densities of the printed patches are measured by density sensors embedded in the printer. The available actuators, such as various bias voltages and fuser temperature, that affect the printed colors are adjusted based on the measurements to stabilize the TRC. For each calibration, significant amounts of time, toner, and cartridge life are consumed. Therefore, it is desirable to minimize the time and the number of calibrations needed and/or the number of patches used.

The objective of this study is to develop an algorithm and the corresponding calibration process that utilizes the available sensor measurements within an EP process and generate proper control set points for a set of adjustable process parameters to stabilize the TRC under various operating conditions, while minimizing the need for calibration and cartridge consumption. The challenging part of the work is that the EP process is highly nonlinear and time-varying and that various uncontrollable factors, such as consumables and environmental conditions, will affect the process output.[1] The consumables are components that need replacement after finite cycles of usage, such as cartridges and transfer kits, and paper. Environment conditions such as temperature and humidity affects the EP process. These factors make the characterization of the system and the design of the algorithm challenging.

This research is closely related to the work of Li and Dianat[2] and Staelin *et al*.[3] Li and Dianat used robust optimal control to stabilize the TRC under uncontrolled operating conditions on a Legacy digital xerographic image output terminal (Legacy printer). Staelin *et al*.[3] focused on reducing the consumable waste and work-flow disruption using model-based prediction for the HP Indigo digital press. This research focused on stabilizing a color printer's TRC by compensating for the effect of measurable process parameters and environmental conditions. To achieve the objective, the TRC stabilization problem is formulated into a quadratic optimization problem. The algorithm for TRC stabilization was developed using a model based prediction for a generic EP process, that was unique from methods proposed in the literatures.[2,3] The proposed algorithm can be used for various printer models with different number of actuators, disturbances, and calibration patches. Scaling and resolution issues were also abstracted in the formulation.

System Description

The basic monochrome EP process is shown in Figure 1. More details can be found in Refs. [4] and [5]. The EP process can be divided into six main steps, namely charging, exposure, development, transferring, fusing, and cleaning. First, the charge roller or corona wire uniformly charges the OPC drum surface to a constant negative voltage. In the exposure step, the laser beam is scanned across the OPC and is turned on to discharge the OPC surface at appropriate locations. These discharged locations then attract the negatively charged toner particles in the development step. After development, the transfer roller applies a positive charge to the paper. This positive charge creates a force pulling the negatively charged toner particles to the paper. Next the paper passes between a heated fuser roller and a pressure roller which melt the toner and fuse it to the paper. Finally, the non-transferred toner particles on the OPC drum are removed/cleaned with the help of a blade or a brush.

Typically, the image to be printed is converted to a page description language (PDL) format, which contains the target densities for specific locations on paper for each of the primary colors (CMYK). They are unique to the target images and independent of the printers being used. For the purpose of this research, it is assumed that no additional image processing is performed by the printer on the PDL CMYK values.

A typical image pipeline is shown in Figure 2. In step 1, the continuous image is sent to a tone-correction look-up table (LUT). The tone-correction LUT modifies the CMYK values at each density level (256 levels for an eight-bit representation). The modification is necessary because the tone reproduction characteristic of the EP process varies depending on the operating conditions and from printer to printer. The outputs of the tone-correction LUT, tone-corrected target densities, varies depending on the scaling, but typically ranges from 0 to 255 or 0 to 1. The objective is that the modified CMYK values are suitable for a particular printer at a particular operating condition to produce the expected colors. In step 2, the halftone algorithm converts the continuous image to the binary image. This process is needed because the EP process is binary, i.e. the signal for the laser beam can only be turned on or off to lay down toner. The binary image is then used by the printer to make a printout. At the time of printing (step 3), disturbances affect the EP process. Some of disturbances may be measurable and the appropriate actuators can be adjusted to compensate for the effects of the disturbances. The desired result is that the toner image on the output media should approximate the continuous tone image with the perceptually correct colors.

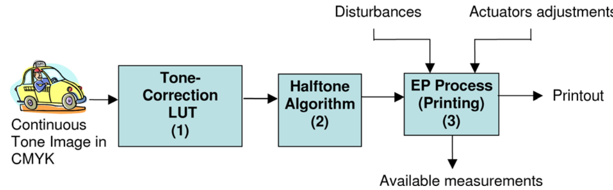

Figure 2. Image Pipeline

Tone Reproduction Curve (TRC) Stabilization

Let $u \in R^{Nu}$ represents the EP parameters that are used to adjust the EP process, which will be referred to as the actuators. *Nu* is the number of actuators. Let $d \in R^{Nd}$ represents the exogenous parameters that will affect the EP process, which will be referred to as the disturbances. *Nd* is the number of these non-controllable disturbances. It should be noted that the tone correction LUT is not included in u and will be considered separately. Let $v \in R$ represents the calibration density measurement within the printer, $w \in R$ represents the TRC density measurement in CIE dE or CIE L* units, and $w_D \in R$ represents the density of the desired TRC. Let $x \in R$ represents the target density, $\bar{x} \in R$ represents the tone-corrected target density, which is the output of the tone-correction LUT. Let U be the set of u inside an appropriate operating range. Let $X_v \in R^{Nv}$ represents the target densities at the calibration media with *Nv* being the number of calibration patches. Let $X_w \in R^{Nw}$ represents the target densities at the output media, where *Nw* is the number of the density levels. Let $\bar{X}$ be $\bar{x}$ corresponding to X_w. Let V represents the calibration measurements correspond to X_v. Let W represents the TRC density measurements correspond to X_w, and W_D represents the desired TRC densities at X_w.

The EP process model characterizes the density measurements on the calibration media, v, as a function of the target density, x, actuators, u, and disturbances, d. It is assumed that it can be characterized by the static mapping:

$$\hat{v} = f(x,u,d), \tag{1}$$

where $\hat{v}$ is the estimate of the density measurement, v. The density mapping is the mapping from the calibration density measurements, V, to the output density measurements on the output media, w, given the tone-corrected density, $\bar{x}$, and disturbances, d. It is assumed that it can also be characterized by the static mapping:

$$\hat{w} = g(\bar{x},V,d), \tag{2}$$

where $\hat{w}$ is the estimate of the TRC density measurement, w. Notice that Eq. (2) can also be written as:

$$\hat{\hat{w}} = g(\bar{x},\hat{V},d) = g(\bar{x}, f(X_V,u,d),d) = h(\bar{x},u,d), \tag{3}$$

where $\hat{v}$ is $\hat{v}$ corresponds to X_v. The tone correction operation can be represented as:

$$\bar{x} = T(x,W) = \arg\min_{i\in[1,\cdots,N_w]} \left|W_D(x) - W(i)\right| \tag{4}$$

Let $s \in R$ represents the cost to be minimized and it can be written as:

$$s = \|W - W_D\|_Q^2 + \|u\|_R^2, \tag{5}$$

where Q and R are symmetric positive semi-definite weighting matrices with appropriate dimensions. In this way, the TRC stabilization problem can be viewed as minimizing the cost using the printer actuators in a quadratic optimization framework.

The TRC stabilization for a generic EP process can be now summarized as follows. The available measurements are the calibration density measurements, V, and the condition of the disturbances, d. The actuators, u, and the tone correction LUT are the control inputs. The objective is to find the optimal state of the actuator, u^*, and the corresponding values for the tone correction LUT, $\bar{X}$, such that the cost, s, is minimized for every printouts, i.e.,

$$u^* = \arg\min_{u\in U} s, \tag{6}$$

where $\bar{X} = T(X_w,W) = T(X_w, h(X_w, u^*, d))$.

Given the quadratic optimization problem statement, the optimal input u^* can be analytically found by setting the partial derivative of the cost with respect to u, s', to zero. s' can be written as:

$$s' = 2(W - W_D)^T QW' + 2u^T R \tag{7}$$

The estimate of s' with or without using the calibration measurements, V, can be written as:

$$\begin{aligned}\hat{s}' &= 2(g(X_w,V,d) - W_D)^T Q \\ &\frac{\partial}{\partial V} g(X_w,V,d)\frac{\partial}{\partial u} f(X_w,u,d) + 2u^T R,\end{aligned} \tag{8}$$

or

$$\hat{\hat{s}}' = 2(h(X_w,u,d) - W_D)^T Q \frac{\partial}{\partial u} h(X_w,u,d) + 2u^T R, \tag{9}$$

respectively. The analytical solution for the optimal input is complex or may not be found. More practical way is to use look-up tables. The values for $\hat{s}'$ and $\hat{\hat{s}}'$ inside the operating range can be stored in the table. The optimal inputs can be found in the table where the corresponding $\hat{s}'$ or $\hat{\hat{s}}'$ is zero.

An example of graphical illustration of the proposed calibration and printing algorithms when u is one dimensional is shown in Figure 3. The idea can be easily expanded for the case where u is multi-dimensional. Initially the cost gradient estimate for $u \in U$ at calibration, $\hat{\hat{S}}'_C$, is calculated given the disturbance, d_c. u_o is found by setting $\hat{\hat{S}}'_C$ to zero. The first calibration patch measurement is performed and the initial estimate of the cost function gradient, $\hat{s}'_O$, is calculated and denoted as x_1 in the figure. $\hat{s}'_O$, is then added to $\hat{\hat{S}}'_C$ to update the printer model. u_c is computed by setting $\hat{\hat{S}}'_C$ with the added offset to zero. The second calibration patch measurement is then performed and the updated estimate of s', $\hat{s}'_C$, is calculated and denoted as x_2 in the figure. This step is the end of the proposed calibration algorithm. At the time of printing, cost gradient estimate for $u \in U$ at printing, $\hat{\hat{S}}'_P$, is calculated given the disturbance, d_p. The estimated change in s' at u_c, which is denoted by $\Delta\hat{\hat{s}}'$, is estimated based on the change in disturbances. $\Delta\hat{\hat{s}}'$ is then added to $\hat{s}'_C$, to obtain $\hat{s}'_P$, which is the estimate of s' at the current operating condition. An offset is added so that $\hat{\hat{S}}'_P$ goes through $\hat{s}'_P$ at u_c. u_p can be found by setting $\hat{\hat{S}}'_P$ with the added offset to zero. The tone-correction LUT is then updated and completes the proposed printing algorithm. The block diagram for the combined algorithm is shown in Figure 4. The inputs to the combined system are the measured disturbances d_c and d_p. The outputs of the combined system are the EP parameter for printing, u_p, and the corresponding values for the tone-correction LUT, $\bar{X}$.

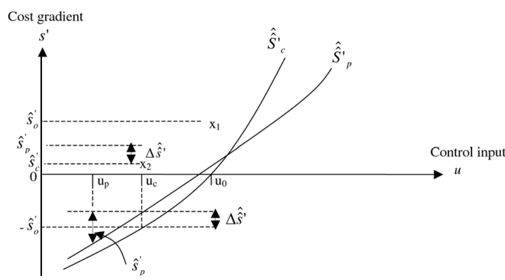

Figure 3. Graphical illustration of the two algorithms.

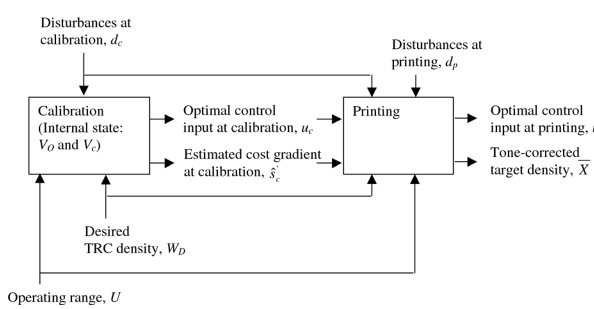

Figure 4. Block diagram for the combined algorithms.

Table 1: Validation Results for the Process Modeling and the Density Mapping

	Black	Cyan	Magenta	Yellow
RMS Density error process modeling	3.59	4.79	4.08	4.67
RMS ΔE error density mapping (using 8 patches)	1.98	1.76	2.07	2.42
RMS ΔE error density mapping (using 2 patches)	2.04	1.86	2.19	2.51

Experimental Result

To test the proposed algorithms, an off-the-shelf in-line color laser printer was used as a testbed. Three types of measurable disturbances were considered, the humidity ratio (HR), temperature (T), and cartridge percent left (CPL). The densities of the calibration patches on the electrostatic transfer belt (ETB) are hereafter referred to as EP Density. The densities of the patches on paper were measured by a spectrophotometer (Gretag SpectroEye). The measurements were taken in CIE L*a*b* unit and were converted to CIE dE from paper white. They will be referred to as SPMdE. The developer bias voltage (DBV) and the tone correction (TC) table were the available actuators. The DBV is applied across the developer roller to regulate the amount of toner developed on the OPC. The TC table was used as the tone-correction LUT. The TC table has eight-bit resolution from 0 to 255.

A system identification experiment was performed to obtain data that is used to construct the printer model. Six environment conditions, five DBV levels were tested in random order. At each DBV, a density calibration was triggered to obtain the EP Density measurements and a test page was printed with patches at ten target density levels for each of the primary colors. The TC table was set as the identity table, i.e. the tone-corrected target density equals to the target density. The entire procedure was repeated three times to generate enough degrees of freedom for the regression analysis. During the experiment, two sets of print cartridges were used to cover a wide range of CPL. A total of 780 useful data sets were collected for each color.

The process modeling and the density mapping can be written as:

$$EPDensity = f(x, DBV, T, HR, CPL) \tag{10}$$

and

$$SPMdE = g(\bar{x}, V, T, HR, CPL), \tag{11}$$

Table 2: Environment Conditions for the Environmental Disturbance Rejection Experiment

Condition #	Temperature (°F)	Humidity Ratio
1	90	0.022
2	90	0.004
3	50	0.004

Regression analysis was used to determine a polynomial model for Eqs. (10) and (11). The statistical software, SAS, was used for the regression analysis and terms with significance of 95% confidence level or higher were included in the model. Based on the regression analysis, it was found that the 3rd order regression and the 4th order regression were adequate for the process modeling and the density mapping, respectively. The details of the multiple regression and the significance analysis can be found in the reference by Hicks and Turner.[6] The density mapping was also obtained using only two patches. The 1st and the 6th densest patches were used because they were the two patches which minimized the root-mean-square (RMS) dE error. The accuracy of the models is tested and is summarized in Table 1.

The proposed algorithm was applied to the test printer. The sum of squared error is used as the cost function for the optimization, i.e.,

$$\min_{u \in U} \| W - W_D \|_I^2 . \tag{12}$$

Experiments were performed to test the effectiveness of the proposed algorithm in reject environmental disturbances without performing calibrations. Three types of calibrations were used. The first was the default method in which the printer's default calibration was performed to determine the DBV and the tone-correction LUT values. The 2nd and 3rd methods used the proposed algorithm for calibration and printing. The 2nd method used all eight patches on the ETB and the 3rd method used only the two patches chosen previously. Four different cartridge sets from the ones used in the system identification experiments were used. The environmental conditions used in the experiments are listed in Table 2. A test page which contained patches at 18 different density levels was used.

Initially, cartridge set #1 was inserted to the printer, and the environment was brought to condition #1. Then the default calibration and the proposed calibration for the two new methods were performed. Six printouts were made at this condition; two pages with the setting determined by the default calibration and two pages each using the proposed printing algorithm for the two new methods. Then the environment was changed to condition #2 then to condition #3. At each environment condition, six printouts were made in the same way as those at condition #1. No calibration was performed between the printing and different environment conditions. The printer was idled for about an hour for each environment condition. The same experiment was performed with cartridge set #2. For cartridge set #3 and #4, the experiment was repeated except that the environment was changed from #3, #2, and then to #1 instead of from #1, #2, and to #3. A total of 72 test pages were printed.

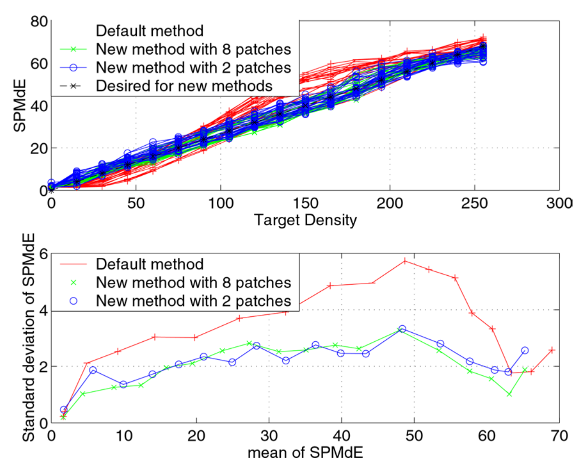

Figure 5. Resulting tone curve and standard deviation of error for black.

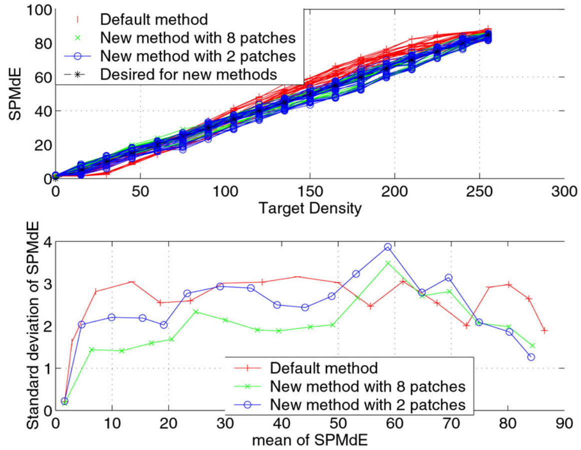

Figure 6. Resulting tone curve and standard deviation of error for magenta.

The results of the experiment are shown in Figure 5 and 6, where the TRC for each method and the desired TRC for the new methods are shown as well as the standard deviation plotted against the mean of SPMdE. The behaviors of cyan and yellow color planes were similar to black and magenta color plane, respectively. Both black and cyan showed significant improvement compared with the existing method. For magenta, the new methods performed about the same as the default method. The level of the overall performance for the two newmethodswas similar, since both method generated similar density mappings. In general, the new methods performed better than the default method. However, as any model-based approach, the of the model is the key factor.

Conclusions

The TRC stabilization problem for the EP process was formulated in the quadratic optimization framework. The problemformulation and the resulting algorithm are generic in that they can be used for similar types of printing systems. The proposed algorithm was applied to an off-the-shelf in-line color laser printer to verify the effectiveness of the algorithm under different environmental disturbances. Based on the collected data, the algorithm demonstrated the desired effect for the experimental printer and a large set of cartridges. The data also suggests that the effectiveness of the algorithm depends heavily on the accuracy of the model. The proposed algorithm using two patches performed as well as the algorithm using eight patches.

It is observed that the proposed algorithm is not effective if the model is not accurate. Several approaches can be suggested to improve the model prediction. One approach is to obtain more experimental data for the system identification experiment. The second approach is to include more parameters in the model. Possible variables to include in the model are the frequency of cartridge use, time of the most recent cartridge use, output media types, drum life remaining, cartridge age, and so on.

In this study, only one print engine was used. More data could be harvested from multiple units so that the model would work with a wider range of printers. The proposed algorithm can also be tested with other types of printer types.

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