Modeling of Tone Deviation during Switch-on Transient for Color Electrophotography

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Abstract

Transient tone fluctuations after switch-on have been observed in color electrophotographic (EP) printers. This paper presents preliminary results of using regression analysis to model the behaviors and to identify the key contributing factors. A pilot study using off-the-shelf color EP printers revealed systematic deviation in tone reproduction during the switch-on transient under certain environmental conditions. It can be shown that the tone values reproduced during the switch-on transient are statistically different from the tone values reproduced during continuous printing after the switch-on transient has ended. In the mid-tone areas, the tone values of the first page printed after switch-on and the mean tone values of the pages printed during continuous printing can differ by four ΔE_{76} units under low temperature and humidity conditions. Analyses of experimental data showed that number of pages printed after switch-on and halftone levels are statistically significant factors in modeling tone deviation. The resulting regression model can accurately predict the switch-on transient deviation to within one ΔE_{76} unit based on cross-validation.

Introduction

A color electrophotographic (EP) printing system typically uses four primary colors – cyan, magenta, yellow, and black. Tone reproduction curves (TRC) of the primary colors are characterizations of the EP process and determine the intensities of the primary colors that would be reproduced on output media. A pilot study using off-the-shelf single-pass color EP printers revealed systematical TRC fluctuations for a transient period immediately after printing switch-on. This study seeks to characterize the transient TRC behaviors after switch-on and to identify the key contributing factors through statistical analysis.

The TRC of a primary color relates input halftone levels to output tone values. In typical life tests, primary color images at pre-determined halftone levels are printed on output media. Their measurements, the output tone values, are examined for tone reproduction inconsistency. Typically the measured tone values of the same halftone level for given prints are plotted in sequence of the corresponding page index numbers. Hence the page index numbers of aberrant tone values can be identified and the patterns of tone reproduction inconsistency can be characterized.

The pilot study showed that the tone values reproduced immediately after switch-on are statistically different from the tone values reproduced during continuous printing under certain environmental conditions. The tone values of the first page printed after switch-on and the mean tone values of the pages printed during continuous printing can differ by four ΔE_{76} units. Switch-on is inevitable. It is desired to know how the EP system responds to switch-on and the ability for the tone values to reach a stationary state after switch-on. In this study, the transient tone value behavior of an EP system after switch-on is investigated and is characterized through regression analysis. The resulting model can accurately predict the switch-on transient tone deviation to within one ΔE_{76} unit based on cross-validation.

Pilot Study

Pilot Experiment Design

A pilot study was conducted to investigate the impact of printing switch-on to color reproduction. A pilot experiment is designed to consist of three identical printing suites, each of which includes two hundred pages. The pages in a suite are designedly to be printed continuously. An idle with a length randomly chosen from five to sixty minutes is hold before the printing switch-on for each suite. Measurable pages, each of which contains ten color images at different halftone levels for each primary color, are placed every twenty pages from the first page in the suite. To simulate typical customer usage, the vacancies in the suite are randomly chosen from a variety of test patterns, such as measurable pages, text pages, and some other color figure pages.

The pilot experiment is performed on off-the-shelf in-line color EP printers of the same model that employs single-component development and in-direct transfer technologies. The printing speed of the test EP printer is thirty page-per-minutes (ppm). The experiment is performed under several environmental conditions, covering an extensive temperature and humidity range in typical customer usage. Multiple cartridges sets are utilized in the experiments. Calibration is suppressed during the experiment to prevent adjustments on EP process setups and consequential TRC variation. An ordinary 80 g/m^2 white paper (Hewlett-Packard®) is used as the output media. The measurements of the tone values are made by spectrophotometers (X-rite® DTP70).

In this study, an input halftone level is represented by a unitless 8-bit word length integer, where 0 represents no tone and 255 represents the maximum. A tone value is defined as the Euclidian distance (ΔE) in CIE L*a*b* space between the color point of a primary color printed at a particular halftone level and the substrate appearance color.

Pilot Experiment Analysis

The pilot study reveals systematic tone deviations immediately after switch-on for all primary colors under certain environmental conditions. Figure 1 and 2 displays the measured tone values at halftone level 44, 96, and 126 plotted against page indices in each printing suite for cyan color. Figure 1 displays the

results of the experiment performed under 15°C and 10% relative humidity (15°C/10%) condition. It is shown that the tone values of the first page immediately after switch-on are consistently larger than the tone values of the other measurable pages. The mean tone values of the first page after switch-on are significantly different from the mean tone values of the other measurable pages based on statistic t-tests [1] at 99% significance level for all the tracked halftone levels. The differences between these mean tone values are 2.5, 4.0, and 3.1 ΔE_{76} units for halftone level 44, 96, and 126, respectively.

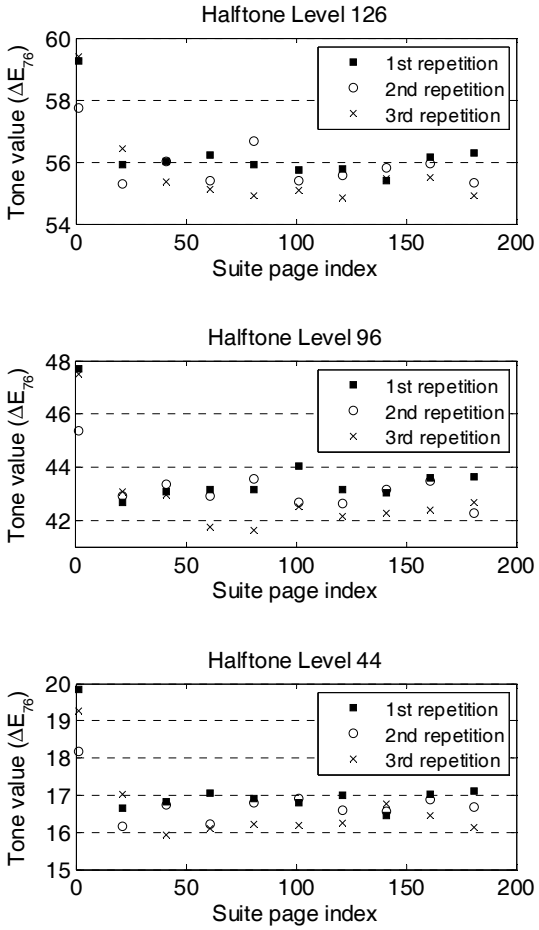

Figure 1. *Measured tone values at halftone level 44, 96, and 126 under 10°C and 15% relative humidity environmental condition for cyan.*

Figure 2 displays the measured tone values at halftone level 44, 96, and 126 plotted against page indices for cyan under 30°C and 80% relative humidity (30°C/80%) condition. It is shown that the tone values of the first page immediately after switch-on are consistently smaller than the tone values of the other measurable pages. The mean tone values of the first page immediately after switch-on are significantly different from the mean tone values of the other measurable pages based on statistic t-tests at 99% significance level for the three halftone levels. The differences between these mean tone values are 2.2, 4.2, and 2.5 ΔE_{76} units for halftone level 44, 96, and 126, respectively. Note that the differences between the mean tone values in the mid-tone range are larger than those in the highlight and shadow ranges under the both environmental conditions.

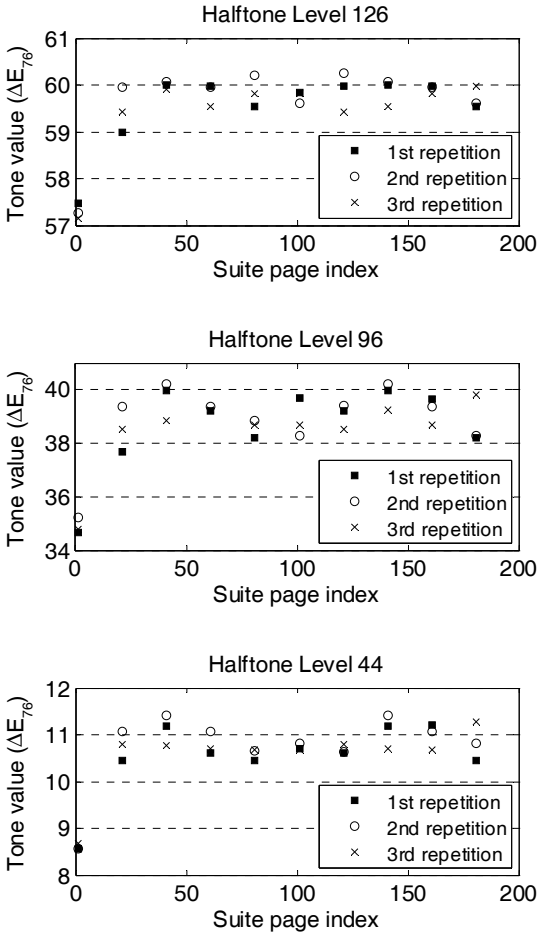

Figure 2. *Measured tone values at halftone level 44, 96, and 126 under 30°C and 80% relative humidity environmental condition for cyan.*

System Identification Study

System Identification Experiment Design

A system identification (ID) experiment is designed to investigate and to characterize the systematic tone value fluctuations immediately after switch-on under the 15°C/10% condition. The same procedure can be applied to other environmental conditions. The system ID experiment consists of three identical printing suites, each of which includes one hundred and one pages. The pages in the suite are designedly to be printed continuously. An idle period randomly chosen from a length of one, two, or three minutes is held before the printing switch-on for each suite.

The measurable pages, each of which contains forty-six color images at different halftone levels for each primary color, are placed every other page from the 1st page to the 21st page, and then are placed every twenty pages after the 21st page in the suite. The

measurable test pages are put into three groups. Each group contains five measurable test pages. The group I includes the 1st, the 3rd, the 5th, the 7th, and the 9th pages in the suite. The group II includes the 11th, the 13th, the 15th, the 17th, and the 19th pages in the suite. The group III includes the 21st, the 41st, the 61st, the 81st, and the 101st pages in the suite. The mean tone values of the group II and the group III will be used to determine the significance of tone value difference through statistical tests.

The system ID experiment is performed under the 15°C/10% condition with six different cartridge sets. The cartridges carry various of cartridge life remaining (CLR). The CLR ranges from 0 to 100%, where 0% represents an empty cartridge and 100% represents a new one. Other setups in the system ID experiment are identical to those in the pilot experiment. Totally eighteen observations (three repetitions on each of the six cartridge sets) are obtained in the system ID experiment.

Analysis of Tone Value Fluctuation

Statistical tests are conducted to analyze the system ID experimental data. Note that these tests are applied to tone values at same halftone levels. Figure 3 displays the measured tone values of the first twenty-one pages at halftone level 96 for black color. A statistical paired t-test is performed to determine the significance of tone value difference. The tone values of the first and the third pages in each observation are compared to the mean tone values of the group II in the same observation. Note that the paired t-test is chosen because cartridges are observed to reproduce inconsistent un-calibrated TRC's due to their various consumable conditions (CLR). The test result shows the mean tone values of both the first and the third pages are significantly larger than the mean tone value of the group II at 99% confidence level. On average, the tone value of the first page and the third page are 3.7 ΔE_{76} units and 2.0 ΔE_{76} units, respectively, larger than the mean tone value of the group II.

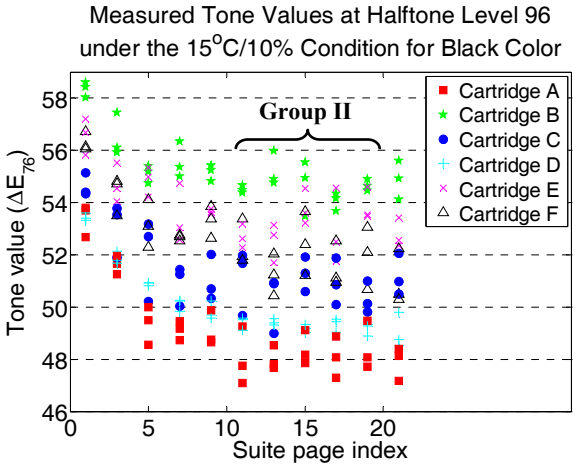

Figure 3. *Measured tone values of the first twenty-one pages at halftone level 96 under the 15°C/10% condition for black color.*

Modeling of Tone Deviation

Switch-on Transient

The statistical analyses in the previous section show that the tone values of the first few pages after switch-on fluctuates and then settle down thereafter while the printing is continuously performed. It is reasonable to assume that the sudden changes in EP control setups at switch-on introduces a step input to the EP system, resulting in the tone reproduction changes from an initial idle steady-state to a continuous printing steady-state. The idle steady-state is defined as tone reproduction equilibrium while printing is not performed, and the continuous printing steady-state is defined as tone reproduction equilibrium while printing is continuously performed. The switches between the two steady-states results in transient tone fluctuations. This transient state from the idle steady-state to the continuous printing steady-state is defined as switch-on transient. Note that experimental data suggest that the tone reproduction reaches the idle steady-state with an idle period as short as one minute under the 10°C/15% condition.

Model Formulation

The following model formulation is developed for a primary color. Same process can be applied to all four primary colors since each primary color is reproduced independently for a single-pass color EP process. A model is proposed to characterize tone deviation during the switch-on transient. The tone deviation, $d(x, k) \in \Re$, of the k^{th} page printed during the switch-on transient is defined as the difference between the tone value of the k^{th} page, and the asymptotic tone value reproduced during the continuous printing steady-state at halftone level $x \in \boldsymbol{N}$. Figure 4 illustrates the tone deviation during the switch-on transient at halftone level x. For examples, the deviation of the first page during the switch-on transient at halftone level x, $d(x, 1)$, is the difference between the tone value of the first page, $v(x, 1)$, and the asymptotic tone value, $v(x)^*$, i.e., $d(x, 1) = v(x, 1) - v(x)^*$.

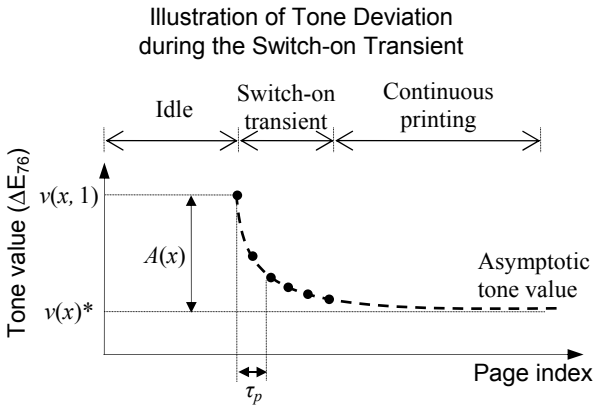

Figure 4. *Tone deviation during the switch-on transient at a halftone level.*

A first-order principal dynamic model [2] is proposed to characterize the tone deviation as a transient response to the printing switch-on, i.e.,

$$d(x,k) = A(x) \cdot e^{-\tau_p (k-1)T}, \quad (1)$$

where $A(x) \in \Re$ is amplitude of deviation at halftone level x, $\tau_p \in \Re$ is time constant of the transient system response, $k \in N$ is page index number, and $T \in \Re$ is period required to print each page. The amplitude of deviation, A, and the time constant, τ_p, are parameters to be determined in the subsequent regression.

The amplitude of deviation, A, is non-uniform across halftone levels due to dot-gain and dot-overlap effects, and is expected to be large in the mid-tone range and small in the high-light and the shadow ranges. A polynomial function is proposed to approximate the amplitude of deviation, A, across halftone levels, i.e.,

$$A(x) = \sum_{j=1}^{n} a_j x^j, \quad (2)$$

where $n \in N$ is order of the polynomial function, and $a_j \in \Re$ are polynomial function coefficients to be determined in the subsequent regression. Figure 5 displays the tone deviation of the first page printed immediately after switch-on for black color.

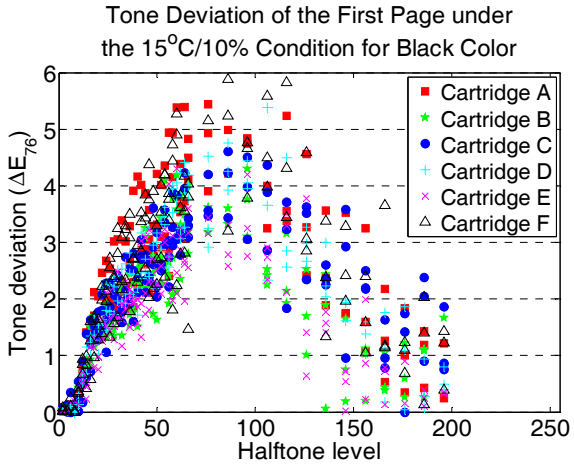

Figure 5. *Tone deviation of the first page printed immediately after switch-on under the 10°C/15% condition for black color.*

Regression Model Development

A regression analysis is performed to identify the coefficients. Based on the tone deviation observed in Fig. 5, a third-order polynomial function is chosen to approximate the amplitude of deviation, A. The printing period, T, is two seconds, calculated from the 30-ppm printing speed of the EP printers. The regression is performed with more than two thousand data points from the system ID experiment for each primary color. The computation is performed using Matlab®.

Figure 6 shows the model-predicted tone deviation of the first twenty pages printed during the switch-on transient at halftone level 96 for the four primary colors. In general, the tone deviations in the mid-tone range of the first three pages are larger than one ΔE_{76} unit, which exceeds the perceptibility threshold for human visual system. The time constants, τ_p, from the regression analysis are 6.5, 5.4, 5.1, and 6.2 seconds for black, cyan, magenta, and yellow color, respectively.

Cross-Validation

A 5-fold cross-validation (CV) without replacement is performed to evaluate the performance of the proposed model. Overall the mean CV root-mean-squared error of the pages printed during the switch-on transient are 0.6, 0.5, 0.6, and 0.6 ΔE_{76} unit for black, cyan, magenta, and yellow color, respectively. The models are reasonably accurate, considering that multiple spectrophotometers are used to measure tone values. The maximum inter-instrument agreement error of the spectrophotometers is 0.5 ΔE_{94} unit.

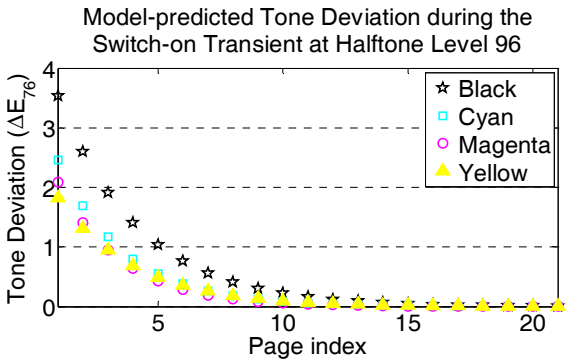

Figure 6. *Model-predicted tone deviation during the switch-on transient at halftone level 96 under the 15°C/10% condition.*

Conclusion

Systematic tone deviations during the switch-on transient are observed in color EP printers under the 10°C/15% and the 30°C/80% condition. Analyses show that the deviation of the first page after switch-on can be as large as four ΔE_{76} units, and the deviation appears with an idle period before switch-on as short as one minute. A first-order principal dynamic model is proposed to characterize the tone deviation under the 10°C/15% condition through regression analysis. The accuracy of the proposed tone deviation model is verified with experimental data. The overall room-mean-squared error of the proposed models during the switch-on transient is smaller than one ΔE_{76} unit for all primary colors based on cross-validation.

Acknowledgements

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References

[1] R. A. Fisher, Statistical Methods for Research Workers (11th ed.), London: Oliver and Boyd (1950).

[2] D. E. Seborg, T. F. Edgar, and D. A. Mellichamp, Process dynamics and control, New York: Wiley (1989).

Author Biography

Yan-Fu Kuo is currently a Ph.D. student at School of Mechanical Engineering, Purdue University. He worked as an intern engineer at Hewlett-Packard Company in 2007 and 2008, developing calibration tools to improve color consistency for electrophotography printers.