Direct Color Consistency Control for Xerographic Printing

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Abstract

The digital color printing process can be described by the color reproduction characteristics (CRC) function that maps the input color to the output color. The CRC map is high dimensional in that there are potentially high number of output colors that a digital color printing process can reproduced. To maintain color consistency, it is desirable to have the CRC to match the desired CRC map at all times. In this paper, we first propose an effective sparse sensing approach known as time-sequential sampling to retrieve the time-varying CRC using small number of color samples at each print cycle. The availability of this information enables formulation of a 2-`STAGE` *process level control system:* `STAGE-I` *is a curve fitting robust control that makes best use of the xerographic actuators and* `STAGE-II` *is a image feedforward compensation scheme. The key contribution of this paper is in proposing direct CRC control(full closed loop) for maintaining color consistency, as opposed to stabilizing the TRC of all the primary color separations (i.e. Cyan, Magenta, Yellow and Black) in previous works. Effective CRC stabilization is demonstrated using the proposed approach while requiring small number of color samples.*

Introduction

An important performance criterion in digital xerographic printing is that any desired colors in the desired customer image(s) are faithfully reproduced at all times. Achieving good color consistency is difficult because the marking process is subject to many disturbances including temperature, humidity, material age and variations, etc. These factors contribute to prints that look different from one print to the next and from the desired customer image. In this paper we propose a direct color control approach to maintain color consistency of xerographic printing process. Notice that, unlike the control objective for most processes which is to control or regulate the output of the process, the color control problem consists of maintaining the *process itself* to be constant and stable. The difference is because every customer image to be printed can contain *many* and *any* possible colors which the xerographic printer must reproduce correctly all at once. Moreover, xerographic printers are often used in an on-demand manner in which consecutive customer images are different.

By ignoring the spatial dimension (such as lines and textures) of print quality for the moment and focusing on the issue of consistent color reproduction only, a color xerographic printer can be represented by the color reproduction characteristics(CRC) function

$$CRC(t) : \mathscr{C} \rightarrow \mathscr{C}, \mathbf{x}_{desired} \mapsto \mathbf{y}_{printed} \tag{1}$$

where $\mathscr{C}$ is any consistent 3-dimensional colorspaces e.g. CIE $L^*a^*b^*$, CMY, etc. An ideal printer is the one in which the CRC matched the desired CRC map. In order to motivate the need for *direct* CRC control for maintaining color consistency, a brief description of the digital xerographic printer is in order. A digital xerographic color printer generates colors by printing and overlaying the Cyan, Magenta, Yellow and blacK (CMYK) separations. The printing of each color separation is characterized by the tone reproduction curve (TRC), $TRC : \mathscr{T} \rightarrow \mathscr{T}$, $\tau_{desired} \mapsto \tau_{printed}$, where the tone, τ of the separation is the solidness of the primary toner color. Hence, the control problem can be formulated for the printing of each color separation. In this case, the control objective is to maintain and stabilize the tone reproduction curve (TRC) for each separation. However in this approach, the output colors are consistent only if the manner in which the primaries are combined is stable and constant i.e. there is no disturbances in the color mixing process. The color mixing is a complex process that is dictated by possibility of mis-registration of the different primary layers and disturbances in the color fusing process(typically through heating). Therefore, variations of colors can occur despite having all the primary TRCs stabilized. Hence, direct CRC control that enable full feedback color control system will likely be more effective.

However, the color control formulation poses significant problems for *sensing* and *control*. The color print *sensing* involves *multi-dimensional* time-varying spatial signal (1 temporal dimension and 3 spatial/color dimensions) using only small number of n color samples. In this paper, this sensing issue is addressed using time-sequential sampling as reported previously in [1]. The color print *control* involves control of potentially high number of reproducible colors using limited actuation authorities. In this paper, a 2-`STAGE` process level control is used to maintain color consistency. `STAGE-I` control makes use of the limited xerographic actuators to stabilize the print process in a least squares sense. Residual variations can then be compensated using `STAGE-II` by continuously updating a software profile in the image processing process.

Time-Varying CRC

The time-varying CRC map given in (1) is potentially infinite dimensional because ideally any specified colors can be reproduced. This map is made up of three main processes : *image processing* (software), *xerographic marking* (hardware) and *human perception* (psychophysics). Hence,

$$CRC(t) := \underbrace{f_{percept}}_{\text{human}} \circ \underbrace{f_{comb} \circ f_{mark}}_{\text{printer}} \circ \underbrace{f_{htone} \circ f_{sep}}_{\text{image processing}} \tag{2}$$

where f_{sep} separates the image into primary color planes[1], f_{htone} performs half-toning on each color separations, f_{mark} prints these

[1]The separation process is typically achieved by using the inverse map of the actual printing process. To improve the print quality, in current printing system this inverse map is periodically updated through the device characterization methods i.e. the ICC profile [2].

half-tones separations, f_{comb} forms a composite image from the printer separations, and $f_{percept}$ models the human color perception.

In both sensing and control for maintaining color consistency, it is convenient to take the input colorspace as the CMY colorspace (i.e. taking f_{sep} as an identity map) and the output colorspace as the CIE L*a*b* colorspace. The CMY colorspace is used as the input colorspace because it is the colorspace where colors are specified in typical digital color printers(corresponding to C,M,Y,K print engines). The CIE L*a*b* colorspace is used as the output colorspace because it is a perceptually uniform device-independent colorspace that enables meaningful formulation of print quality requirements. Henceforth, $CRC(t)$ is defined with input CMY colorspace(denoted by $\mathscr{C}_{\mathrm{CMY}}$) and output CIE L*a*b* colorspace(denoted by $\mathscr{C}_{\mathrm{L^*a^*b^*}}$), unless stated otherwise.

Uniformly discretizing the CMY colorspace domain, typically given by $\mathscr{C}_{\mathrm{CMY}} = [0,1)^3 \subset \Re^3$, by M_1, M_2 and M_3 points in each of the C, M, Y coordinates respectively, the CRC can be adequately approximated by its response at a finite number of $M_t = M_1M_2M_3$ color combinations. Thus, the xerographic color control process at time $t = kT \in \Re^+$ where T is the inter-sampling time can be represented by:

$$\mathbf{CRC}(k) = \left[L_1^*(k),\ldots,L_{M_t}^*(k),a_1^*(k),\ldots,a_{M_t}^*(k),b_1^*(k),\ldots,b_{M_t}^*(k)\right]^T \tag{3}$$

Note that $\mathbf{CRC}(k) \in \Re^{3M_t}$. The nominal CRC is denoted here by $\mathbf{CRC}^* \in \Re^{3M_t}$.

Similar to the case of the TRC [3], in the presence of xerographic control inputs and disturbances, the possibly nonlinear CRC, can be represented by the static, linear time varying, uncertain model as follows:

$$\mathbf{CRC}(k) = \widehat{\phi}(\mathbf{I}+\Delta(k)\mathbf{W}_u)\bar{\mathbf{u}}(k) + \mathbf{CRC}^* + \bar{\mathbf{d}}(k) \tag{4}$$

where $\mathbf{u}(k) \in \Re^{3m}$(corresponding to the C, M, Y print engines with m actuators each) denotes the xerographic actuators of the CMY print engines, $\mathbf{CRC}^* \in \Re^{3M_t}$ is the nominal CRC and $\bar{\mathbf{d}}(k) \in \Re^{3M_t}$ denotes a slowly time varying disturbance. Also, $\bar{\mathbf{u}}(k) := \mathbf{u}(k) - \mathbf{u}_o$, where $\mathbf{u}_o$ is the nominal control input. $\widehat{\phi} \in \Re^{3M_t\times 3m}$ is the nominal sensitivity function, $\Delta(k) \in \Re^{3m\times 3m}$ is the multiplicative uncertainty, $\mathbf{W}_u \in \Re^{3m\times 3m}$ is the matrix of given uncertainty weights.

Sensing the Time-Varying CRC

The goal of the sensing system is given as follows

Sensing Goal: *Sense using $n \in \mathscr{Z}^+$ color samples at each print cycle, k such that we:*

- *(i) achieve maximum sampling efficiency, that is to maximize the inter-sampling time, $T \in \Re^+$.*
- *(ii) enable high fidelity recovery of the time-varying CRC at each print cycle, k.*

The easiest way to achieve these objectives is to sample all the M_t(i.e. take $n = M_t$) colors at each print cycle and ensure that it fulfills both the temporal and spatial Nyquist conditions. We called this as the *full-sampling* approach. However, this is not a feasible as it requires extensive sensor's hardware and other sensing resources. To restrict having only n small number of color samples to achieve the aforesaid objectives brings forward questions on which color samples and when these samples should be taken. These issues are resolved by a design approach for time-sequential sampling called the $TS(n)$ sampling[1, 4].

$TS(n)$ sampling of the CRC amounts to printing different n small number of color test patches(specified by different values setting for the C,M,Y input tones) and measuring these samples on paper at different print cycles. The sequence of which and when the n different samples are taken is given by the designed $TS(n)$ sampling sequence, $\alpha(k)$. As the $TS(n)$ sampling design procedure is fairly involved, it is not possible to describe it here. For an example and further details refer to [1, 4]. The time-varying CRC can then be recovered from the time-sequentially sensed signal through a reconstruction process via a periodic Kalman filter[5]. The output of the periodic Kalman filter gives an estimate of the disturbances. At nominal and for known control inputs it is possible to estimate the time-varying CRC by equation (4).

The benefits of the $TS(n)$ sampling are as follows:

1. The sampling strategy even with $n = 1$ has been shown to perform as well as if we have full measurement of the CRC.
2. The sampling strategy with $n = 1$ achieves 40% to 50% savings in the required number of samples without any penalty in reconstruction performance compared to full sampling approach.
3. The design can be extended to any $n > 1$ number of color samples at each sampling instance. Increasing the number of samples, n, increases the inter-sampling time. Hence, we can always fulfill the print cycle duration by proper selection of n.

Stabilization of the CRC

The goal of the xerographic color consistency control system is to ensure that the CRC map is as close to the nominal map as possible at all times i.e.

Control Goal: *Match the desired nominal CRC, CRC^* at each input colors, $\mathbf{x}_i \in \mathscr{C}_{CMY}, i = 1,2,\ldots,M_t$, as $k \to \infty$*

$$\mathbf{CRC}(k)[\mathbf{x}_i] \to \mathbf{CRC}^*[\mathbf{x}_i] \tag{5}$$

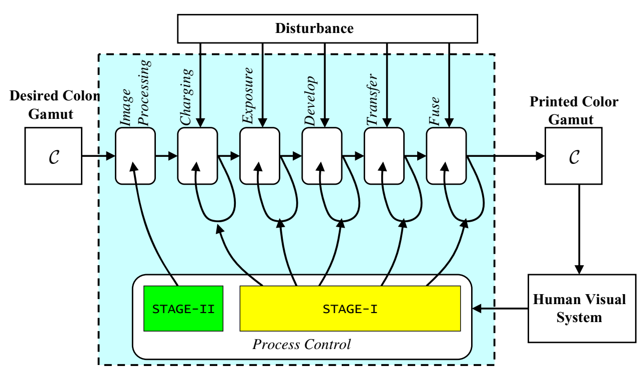

Figure 1. Proposed color consistency control strategy

This control goal is realized with a two-stage control strategy as shown in Figure 1. An inner control loop (`STAGE-I`) utilizes the xerographic actuators, $f_{comb} \circ f_{mark}$ to regulate the nominal print behavior. Since there are fewer xerographic actuators than the number of colors to be controlled, it is typically not possible for (5) to hold for all the colors in the presence of disturbances. In this paper a robust curve-fitting approach is proposed to minimize the 2-norm error of the CRC over the entire color range.

While we expect that STAGE-I control improves the color consistency subject to the presence of disturbances, the small number of xerographic actuators does not completely eliminate the CRC deviations from the desired CRC. By preserving the CRC range with STAGE-I control (in addition to maintaining the CRC to be relatively stable), we can introduce a pre-filter compensation (STAGE-II) that makes use of the image processing process to compensate for the residual CRC variations. In both STAGE-I and STAGE-II control, full feedback information (i.e. the time-varying CRC map) is available through the proposed sensing approach using time-sequential sampling strategy.

STAGE-I *Control*

Consider the linear uncertain model given in (4), with $\Delta(k)$ and $\bar{\mathbf{d}}(k)$ being effectively unknown. Let $\bar{\mathbf{U}}(z) = \mathbf{K}(z)\bar{\mathbf{E}}(z)$ be some linear feedback to be specified, where $\bar{\mathbf{e}}(k) = \mathbf{CRC}(k) - \mathbf{CRC}^* \in \Re^{3M_t}$. Defining the error weighings $\bar{\mathbf{W}}_e \in \Re^{3M_t \times 3M_t}$ to specify the relative importance of the CRC error at different colors. The closed-loop system can be expressed as a linear fractional transformation (LFT) given as follows:

$$\begin{pmatrix} \mathbf{w} \\ \bar{\mathbf{W}}_e\bar{\mathbf{e}} \\ \bar{\mathbf{e}} \end{pmatrix} = \underbrace{\begin{pmatrix} \mathbf{0} & \mathbf{0} & \bar{\mathbf{W}}_u \\ \bar{\mathbf{W}}_e\widehat{\phi} & \bar{\mathbf{W}}_e & \bar{\mathbf{W}}_e\widehat{\phi} \\ \widehat{\phi} & \mathbf{I} & \widehat{\phi} \end{pmatrix}}_{\mathbf{P}} \begin{pmatrix} \mathbf{v} \\ \bar{\mathbf{d}} \\ \bar{\mathbf{u}} \end{pmatrix} \tag{6}$$

with feedback connections $\mathbf{v}(k) = \Delta(k)\mathbf{w}(k)$ and $\mathbf{U}(z) = \mathbf{K}(z)\bar{\mathbf{E}}(z)$. Due to the static nature of the xerographic printing process, and the disturbances are generally slowly varying, the performance optimization is restricted to the steady-state case. Hence, since $\bar{\mathbf{W}}_e\bar{\mathbf{e}}^\infty$ is linear with respect to $\bar{\mathbf{d}}_e^\infty$, there exists some matrix, $\mathbf{F}(\mathbf{P},\Delta^\infty,\mathbf{K}^\infty)$ such that $\bar{\mathbf{W}}_e\bar{\mathbf{e}}^\infty = \mathbf{F}(\mathbf{P},\Delta^\infty,\mathbf{K}^\infty)\bar{\mathbf{d}}_e^\infty$. The goal here is therefore to find a controller $\mathbf{K}(z)$ such that for the worst case performance and for as large class of uncertainty $\Delta(\cdot)$ as possible $\|\mathbf{F}(\mathbf{P},\Delta^\infty,\mathbf{K}^\infty)\|_2$ is minimized. The design of this static robust control and its realization is described in [3]. The controller is given by:

$$\bar{\mathbf{u}}(k+1) = \mathbf{A}_\Delta\bar{\mathbf{u}}(k) + \mathbf{B}_\Delta\bar{\mathbf{e}}(k) \tag{7}$$

where $\mathbf{A}_\Delta$ and $\mathbf{B}_\Delta$ are the controller gains that can be determined according to a desired bandwidth through the design process. To implement (7), the periodic Kalman filter estimate of the temporal-spatial signal error based on $TS(n)$ sampling, $\widehat{\mathbf{e}}(k) = \widehat{\mathbf{CRC}}(k) - \mathbf{CRC}(k) \in \Re^{3M_t}$ is used in lieu of the actual error, $\bar{\mathbf{e}}(k)$. In [3], TRC stabilization is assumed. In this paper, this work is extended for the stabilization of the CRC map. The error weighting, $\mathbf{W}_e = \bar{\mathbf{W}}_e^T\bar{\mathbf{W}}_e \in \Re^{3M_t\times 3M_t}$ which specifies the relative importance of the CRC error at different colors is made up of the color and image specific weightings as reported in [6].

STAGE-II *Control*

The objective for STAGE-II pre-filter compensation is to find the inverse print map, $CRC^{-1}(t) : \mathscr{C}_{\mathrm{L^*a^*b^*}} \rightarrow \mathscr{C}_{\mathrm{CMY}}$ and impose it in f_{sep} in (2) such that CRC is an identity map. This will enable the printed colors to correspond to the desired(or requested) colors.

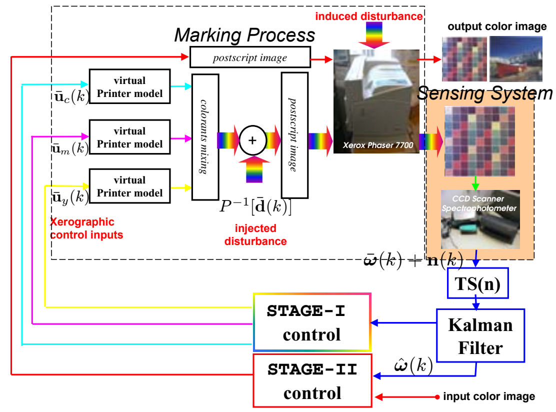

Figure 2. *Sensing and control for CRC stabilization*

There are two important considerations for this strategy to work. Firstly, the effectiveness of this strategy is limited to only colors that $CRC(t)$ (i.e. the printer) can reproduced. Let the color gamut of these reproducible colors be denoted here by $\widehat{\mathscr{C}}_{\mathrm{L^*a^*b^*}} \subset \Re^3$. To realize effective color consistency control, the gamut range of $\widehat{\mathscr{C}}_{\mathrm{L^*a^*b^*}}$ needs to be maximized. This can only be achieved by using the STAGE-I control that directly affects the physical print process. Hence STAGE-I requirement is modified here, so that in addition to maintaining the $CRC(t)$ map to be relatively stable, the goal of preserving and maximizing $\widehat{\mathscr{C}}_{\mathrm{L^*a^*b^*}}$ range will also be emphasized. This emphasis can be achieved by appropriate putting higher weights in weighting matrix, $\bar{\mathbf{W}}_e$.

Secondly, to find the inverse print map, $CRC^{-1}(t)$ at each time, $t = kT, k \in \mathscr{Z}^+$ consider a set of N_T desired colors i.e.

$$\mathscr{D} = \left\{ (\mathbf{x}_i, \mathbf{y}_i) | \mathbf{x}_i \in \mathscr{C}_{\mathrm{CMY}}, \mathbf{y}_i \in \widehat{\mathscr{C}}_{\mathrm{L^*a^*b^*}} \text{ for } i = 1, \ldots, N_T \right\} \tag{8}$$

$\mathbf{x}_i$ for $i = 1, \ldots, N_T$ is assumed to uniformly covers the CMY colorspace. Here we seek to approximate $CRC^{-1}(t)$ such that

$$CRC^{-1}(t) = \arg \min_{CRC^{-1}(t)} \frac{1}{N_T} \sum_{i=1}^{N_T} \left\| \mathbf{x}_i - CRC^{-1}(t)[\mathbf{y}_i] \right\|^2 \tag{9}$$

The most common and easiest way to address this problem is to first evaluate the interpolation functions at a regular lattice of points, in the input space (i.e. CMY colorspace) and then build a multidimensional look-up table (LUT) [2]. A fast interpolation technique such as trilinear or tetrahedral interpolation is then used to transform the image data using this LUT. Here, the data set $\mathscr{D}$ in (8) needed for this construction is obtained from the reconstructed CRC using the time-sequential sampling approach. The use of this reconstructed information avoids the need to print large number of samples to define the inverse CRC. Additionally, the use of the time-sequential sampling approach enables the right instance to update the inverse print map to ensure that the color reproduction consistency is maintained.

Experimental Study

The proposed CRC stabilization system using both STAGE-I and STAGE-II control was experimentally tested on a Xerox Phaser 7700 xerographic printer. A X-rite DTP70 scanning spectrophotometer is used to measured the printed color patches. Figure 2 shows the schematic of the experimental setup. Unfortunately, we do not have direct access to the xerographic actuators.

Therefore, to evaluate the proposed CRC stabilization control system, virtual printer models are first used to generate the tonal responses of the CMY primaries. The disturbances were artificially introduced by injecting a simulated disturbance source as shown in Figure 2 given by $P^{-1}[\bar{\mathbf{d}}(k)]$ where $P : \mathscr{C}_{\mathrm{CMY}} \to \mathscr{C}_{\mathrm{L^*a^*b^*}}$ is the nominal print model of the Xerox Phaser. Here, $\bar{\mathbf{d}}(k)$ is given by a two-band frequency model which is representative of an actual printer(see [4] for details), where the temporal-spatial frequency content is assumed to be contained in an ellipsoidal spectral support $\Theta(W, \mathbf{U}) = \left\{ (f, \mathbf{u}) \middle| f^2/W^2 + \sum_{i=1}^{N} u_i^2/U_i^2 = 1 \right\}$ where $W = 0.01$[Hz] and $\mathbf{U} = [2, 2, 2]$[cycles/tone]. These form our physical color printing setup.

To identify the matrix of nominal sensitivity function $\widehat{\phi} \in \Re^{3M_t \times 3m}$ as given by (4), factorial experiments were performed on our experimental setup. Here, each primary's actuator is set at one of 2 settings within its range. With $m = 3$ actuators for each primary color, a total of $2^3 = 8$ different settings are tested. With 3 primaries, we have a total of $8^3 = 512$ different set of actuator settings for the CMY primaries virtual models. From these data, the nominal sensitivity function were obtained using the least square method. Hence we can proceed with the design of the color consistency controller as given in this paper.

The purpose of the `STAGE-I` control is to maintain the range of the CRC, i.e. the printed output color gamut, $\widehat{\mathscr{C}}_{\mathrm{L^*a^*b^*}}$. Residual variations can then be compensated in the image processing actuators with the availability of the reconstructed CRC. The effectiveness of `STAGE-II` control depends on the accuracy of the reconstructed CRC at all M_t tones. In `STAGE-II` control, the inverse print map is achieved with interpolation using the multi-dimensional look-up table approach [2]. In this experiment, the desired color gamut, $\overline{\mathscr{C}}_{\mathrm{L^*a^*b^*}}$ for `STAGE-II` compensation is selected such that $\overline{\mathscr{C}}_{\mathrm{L^*a^*b^*}} \subset \widehat{\mathscr{C}}_{\mathrm{L^*a^*b^*}}$ at all times to avoid infeasible interpolation at the boundary. This assumption greatly simplifies the inversion process and suffices for the demonstration of the proposed color consistency strategy.

Figure 3 shows the CRC stabilization performance in term of the mean of ΔE^*_{94} at each print cycle, k using the proposed color control system. The designed optimal $TS(1)$ sampling is used here. Compared to the case without any stabilization control, the `STAGE-I` control effectively reduces the error between the printed output colors and the desired colors. However more effective stabilization can be achieved using `STAGE-II` control.

Conclusion

In this paper a 2-`STAGE` CRC stabilization controller for maintaining color consistency is proposed. The `STAGE-I` control makes use of the xerographic actuators to ensure that the range of the CRC is preserved. Then, a `STAGE-II` compensation adjust the image processing step such that the CRC is as close as possible to the desired CRC. `STAGE-I` and `STAGE-II` control are made possible by the availability of the time-varying CRC estimates using the designed optimal $TS(1)$ sampling approach. Experimental results show the effectiveness of the proposed approach for CRC stabilization. To maintain color consistency, direct CRC control as opposed to controlling the C, M and Y primary TRCs, has the potential benefit of compensating the disturbances in the mixing process. We will better justify this gain in future publication.

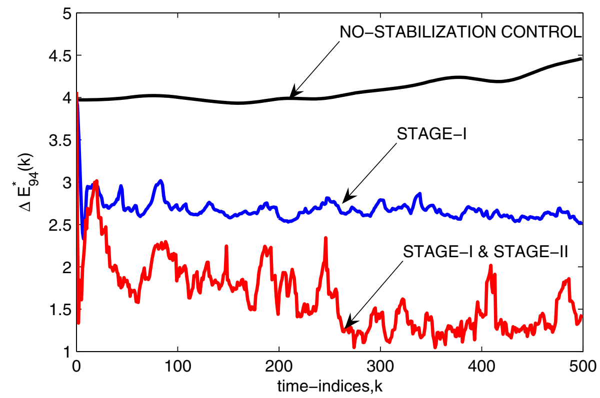

Figure 3. *Comparing CRC stabilization performance using robust static control, for* `STAGE-I` *and* `STAGE-II` *compensation(the designed optimal $TS(1)$ sampling is used here) with the case of no stabilization control*

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