Hardcopy Characterization of Banding in Secondary Colors in Color Electrophotographic Processes

Mu-Chih Chen, George T.C. Chiu; School of Mechanical Engineering, Purdue University; West Lafayette, Indiana/USA

Abstract

In this paper, we will report the hardcopy psychophysics study on the human visual perception on banding in the secondary colors of a polychromatic EP process. The goal of the work is to develop appropriate process control metrics for each primary color plane. Our previous softcopy psychophysics experiments have shown that reducing the banding in each primary color layer to under the human visual system (HVS) threshold does not guarantee absence of bandings in secondary colors. It was also shown that the relative phase between the banding patterns on the primary color layers is an important factor for the perceptibility of banding in the secondary colors. The hardcopy experiment results substantiate the same threshold conclusion as that of the softcopy experiments. Due to the other printing artifacts as well as the intrinsic bandings in the hardcopy printout, the phase results are inconclusive for the hardcopy experiments. The embedded process control system used to generate the controlled stimuli on each primary color plane as well as the relative phase between the two primary color layers is also discussed.

Introduction

Electrophotography (EP) is the basic imaging process used in paper copiers and laser printers. For a typical EP process, the image quality strongly depends on the six basic steps, i.e. charging, exposure, developing, transferring, fusing, and cleaning. Any factor affecting these processing steps will also affect the resulting image quality. Wulich and Kopeik [5] pointed out that mechanical vibration would limit the resolution of an EP process. Halftone banding due to scan-line spacing variation is one of the most visible defects, which appears as quasi-periodic contrast or hue variations across a printed page perpendicular to the process direction.

Several passive and active [1]-[3] banding compensation strategies have been proposed in recent literatures for monochrome electrophotographic (EP) processes. In these studies, banding can be effectively reduced. For polychromatic EP processes, in which multiple color layers are superimposed on top of one another, the perceptibility of banding increases. Since process control are mostly done in the primary color planes, it is important to develop reliable banding thresholds for each primary color plane.

Some literature has devoted to the modeling and analysis of banding in EP process. Loce et al [6] modeled vibration-induced halftone banding in laser printers. Although scan-line spacing and reflectance variation are shown to be direct contributor of banding, a model of the human visual system (HVS) is needed to reflect the actual perceived banding. The contrast sensitivity function (CSF) is one of such models that help capturing the modulation transfer function (MTF) of the HVS on perceiving periodic contrast variation. Several researches have contributed to the analysis and synthesis of the CSF function, which has been used by others to quantify perceived image quality [7, 8]. The band-pass-like CSF function reveals the fact that mid-frequency disturbances have greater impact on perceived banding so that a banding cancellation scheme should supply its reduction effort mainly on bandings located in this frequency region.

Goodman [9] has proposed curves similar to the CSF for single primary color layers, but no information about the superimposition of two or more color layers was provided. Most of the studies in this field approach the problem by carefully varying only one axis of the color space and carefully maintain control of the remaining variables. The resulting conclusions can provide insight for many different imaging applications. However, since most of the process control happens at the primary color planes, it is useful to generate perceptually scaled process control metrics a the primary color plane. In our previous study [4], softcopy psychophysics experiments were performed to characterize human visual perception of chromatic banding in secondary colors that are generated by superimposing two primary color layers that have different levels of banding. It was observed that reducing banding in each primary color plane to below its corresponding perceptual threshold does not guarantee absence of banding in secondary colors. Furthermore, the relative phase between the banding patterns in the primary color planes also has significant impact on perceptibility of banding in the resulting secondary color.

In this work, we have conducted corresponding hardcopy experiments to substantiate the findings in the softcopy study [4]. The same 4-color in-line color laser printer modeled used in [4] was used. An embedded closed-loop control system was constructed to effectively reduce perceptible intrinsic banding and inject desired extrinsic banding pattern with precisely controlled relative phasing between color planes. Both hardcopy and corresponding softcopy experiments are conducted.

The remaining of the paper is organized as follows. The embedded closed-loop control system used to modulate the imaging drum speeds are described in the next section with specific emphasis on the control of the relative phase between two primary color planes. The third section describes the psychophysical experiments followed by the discussion of the experimental procedure. Experimental results are then presented. A summary of the findings and the comparison with the softcopy experiments conclude the last section.

Embedded Closed-loop Control System

The target EP platform has four imaging drums corresponding to the cyan (C), yellow (Y), magenta (M), and black (K) color planes, see Fig. 1. In the original system, the imaging drums are controlled by a dc controller. In our implementation, one 1200-count optical encoder is mounted to the shaft of each imaging drum, which is driven by a BLDC motor and a series of gear train. A fixed-point microcontroller, TMS320F2812, is programmed to take the encoder input, compare it with a reference, and generate and send an appropriate PWM signal to the motor.

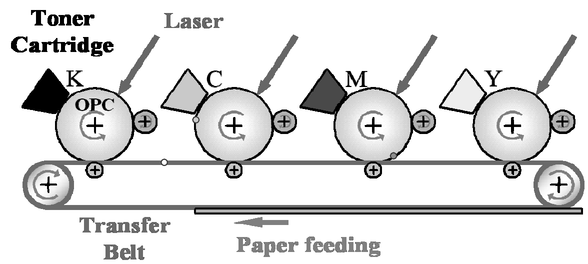

Figure 1. Illustration of the target EP platform

Reduce Intrinsic Banding

The target EP platform has specific intrinsic banding pattern that needs to be effectively removed before carefully controlled extrinsic banding stimuli can be injected. The motor control algorithm that is implemented in the F2812 microcontroller accomplished two objectives. A loop-shaping control algorithm maintains the nominal speed, and a multi-frequency non-integer repetitive control algorithm reduces the major speed fluctuations that cause bandings. Figure 2 shows the speed spectra of an imaging drum when controlled by the original dc controller and by the embedded controller. It can be seen that many of the periodic speed fluctuations that can generate banding are effectively reduced with the new control algorithm. This will enable the injection of extrinsic or desired speed fluctuations to generate controlled banding patterns in the hardcopy images.

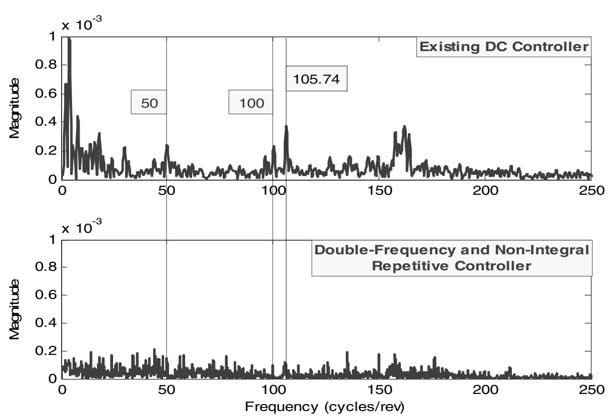

Figure 2. Effectiveness of the embedded closed-loop banding reduction system

Inject Extrinsic Banding

Having effectively reduced the intrinsic bandings, we can inject extrinsic banding of interest by modulating the drum speed to follow the reference signal

$$\omega(k) = \omega_0 \times [1 + p \times \sin(2\pi fk + \phi)], \quad (1)$$

where ω_0 is the nominal angular speed, p is the relative amplitude of the sinusoidal modulation, f is the modulation frequency, ϕ is the phase, and k represents a sample instance.

Relative Phase Control

To study the effect of relative phase angle between two primary color plane banding patterns on banding perception, we need to have precise measurement of the timing of the primary color planes. This is difficult without access to the firmware of the existing dc controller. A workaround was accomplished by implementing a circuit to detect the start-of-scan (SOS) of the laser video signal. The SOS detector monitors the laser data bit. Once it detects a laser data bit, it sets to high and triggers the drum speed fluctuation through the general purpose I/O channel of the F2812 microcontroller. Figure 3 illustrate the conceptual block diagram of the SOS detector. With this method, the origins on all color planes can be synchronized at the same scan line, as long as they all have pixels printed at the specific sca-line, which is achieved by design of the test targets.

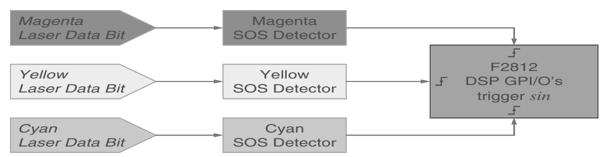

Figure 3. Block diagram of triggering speed fluctuation with laser data bit

If the banding patterns in two primary colors are

$$\omega_A(k) = \omega_{A0} \times [1 + p_A \times \sin(2\pi fk + \phi_A)]$$
$$\text{and} \quad (2)$$
$$\omega_B(k) = \omega_{B0} \times [1 + p_B \times \sin(2\pi fk + \phi_B)],$$

then the relative phase is

$$\Delta\phi_{AB} = \phi_B - \phi_A \quad (3)$$

Hardcopy Psychophysics Experiment I: Detection Thresholds in Primary Colors

Following the softcopy experiments reported in [4], the detection thresholds of banding in primary colors need to be determined first.

Preparation of Stimuli

The stimuli are cut to 2 inch by 2 inch squares. Each stimulus is cut from a 50% postscript density uniform field of one single primary color printed by the target EP platform, while the corresponding imaging drum is modulated using the embedded closed-loop control system. The stimulus strength is defined by the value p in Eq. (1). For each primary color, there are seven levels of test stimuli labeled from S1 to S7. Two stimuli without extrinsic banding serve as the catch trial and the reference stimulus and are labeled as S0 and SR, respectively.

Experiment Procedure

For the experiment, the method of constant stimuli is used. Each time the subject is presented with SR and any of the test stimuli from S0 to S7. Each pair including the one with S0 is presented 10 times, 5 times with SR on the left and 5 times on the right. The orders of the trials are random.

When seeing a pair of a test stimulus and the reference, the subject is asked to respond if he or she can distinguish that one has more banding at the target frequency than the other does. The subject does not have to indicate which one has more banding. This way, the subject always has to compare the test stimuli with the reference, thus reducing possible bias.

Process of Results

The subject responses are applied with probit analysis in SAS and form a psychometric function. The detection threshold for each primary color is determined by the level of extrinsic banding at the 50th percentile.

Hardcopy Psychophysics Experiment II: Perceptibility in Secondary Colors

For each subject who participates in the first experiment, we use his or her detection thresholds in primary colors to generate his or her own set of stimuli for the second experiment.

Preparation of Stimuli

In this experiment, the stimuli are again in size of 2 inch by 2 inch squares. Each stimulus is cut from a 50% postscript density uniform field of a secondary color printed by the target EP platform, while the imaging drums corresponding to the two primary colors that produce the secondary color are modulated using the embedded closed-loop control system. The stimulus strength is defined by the variable r, which is defined as

$$r = \frac{p_A}{p_{AL,A}} = \frac{p_B}{p_{AL,B}}, \quad (4)$$

where $p_{AL,A}$ and $p_{AL,B}$ are the detection thresholds in the primary colors A and B, respectively. Values p_A and p_B are the modulation strengths of the imaging drums corresponding to the primary colors A and B, respectively. The stimuli are generated as shown by Eqs. (2), (3) and (4). The corresponding control variables are r and $\Delta\phi_{AB}$. For each secondary color, there are three levels of r and three different values of the relative phase angle $\Delta\phi_{AB}$. The test stimuli are labeled from S1 to S9. Two stimuli without extrinsic banding serve as the catch trial and the reference stimulus and are labeled as S0 and SR, respectively.

Experimental Procedures

Similar to the first experiment, the method of constant stimuli is used. Each time the subject is presented with SR and any of the test stimuli from S0 to S9. Each pair including the one with S0 is presented 10 times, 5 times with SR on the left and 5 times on the right. The orders of the trials are random.

When seeing a pair of a test stimulus and the reference, the subject is asked to respond if he or she can distinguish that one has more banding at the target frequency than the other does. The subject does not need to point out which one has more banding. This way, the subject always has to compare the test stimuli with the reference, thus reducing a source of possible bias.

Results

The average of all the subject data are plotted in a 3-dimensional space shown in Figures 4 to 6. In the figures, the x-axis is the value r, the y-axis is $\Delta\phi$, and the z-axis is the probability that the subjects can distinguish stimuli with banding from the one without.

Note when $r = 1$, the perceptibility of banding in secondary colors is close to 100%. This implies that reducing banding in each primary color to below its corresponding threshold does not guarantee the absence of perceptible banding in the secondary colors. The perceptibility of banding in secondary colors reduces as the banding strength in each primary color reduces. For cyan plus magenta, the 50th percentile perceptibility occurs at $r = 0.55$; For magenta plus yellow it occurs at $r = 0.6$; For yellow plus cyan, it occurs at $r = 0.4$. If a conservative threshold estimate is needed, the banding in each primary color has to be reduced to at least below 40% of its corresponding detection threshold, to avoid generating perceivable banding in the secondary colors. These results match well with that from the softcopy experiments reported in [4].

We notice a reduced effect of the relative phase $\Delta\phi$. The perceptibility reduces while the relative phase increases from 0° to 180°, except for the combination of magenta plus yellow, i.e. red at the modulation level of $r = 0.7$. This is different compared with the softcopy experiment results, where cyan plus magenta and magenta plus yellow showed a deep reduction of perceptibility associated with a relative phase of 180°. One possible hypothesis for the discrepancy is the existing of other printing artifacts in the hardcopy experiments may mask the impact of relative phase difference between the two primary color patterns. Validation of this hypothesis can be performed by adding measurable noise from the hardcopy stimuli into softcopy stimuli and redo the softcopy experiments. Another possible factor is the order in which the color planes are applied. More investigations and studies are needed.

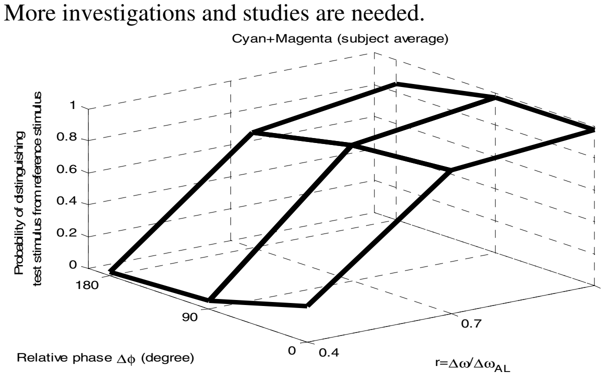

Figure 4. Cyan+Magenta

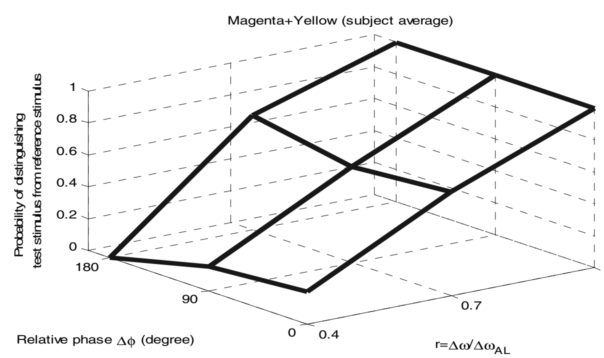

Figure 5. Magenta+Yellow

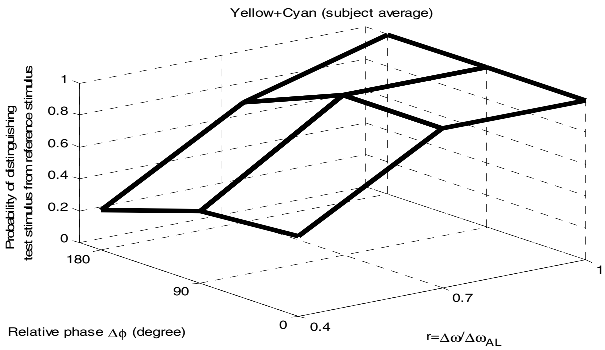

Figure 6. Yellow+Cyan

Conclusion

The results of the hardcopy experiments confirmed one of the findings reported from the softcopy experiments in that reducing banding in primary colors to below its corresponding threshold does not ensure the absence of banding in secondary colors. To avoid perceivable banding in secondary colors, the banding in the primary colors need to be within 40% of its corresponding threshold. The effect of the relative phase on the perceptibility of banding in the secondary colors is different between the softcopy and hardcopy experiments, which warrant further investigation and study.

References

[1] G. Y. Lin, J. M. Grice, J. P. Allebach, G. T. C. Chiu, W. Bradburn, and J. Weaver, "Banding Artifact Reduction in Electrophotographic Printers by Using Pulse Width Modulation," *Journal of Imaging Science and Technology*, vol. 46, pp. 326-337, July/August 2002.

[2] M. T. S. Ewe, J. M. Grice, G. T. C. Chiu, and J. P. Allebach, C. S. Chan, W. Foote, "Banding Artifact Reduction in Electrophotographic Processes Using a Piezoelectric Actuated Laser Beam Deflection Device," *Journal of Imaging Science and Technology*, vol. 46, pp. 433-442, September/October 2002.

[3] C.-L. Chen, G. T. C. Chiu, and J. P. Allebach, "Banding Reduction in Electrophotographic Process Using Human Contrast Sensitivity Function Shaped Photoreceptor Velocity Control," *Journal of Imaging Science and Technology*, vol. 47, pp. 209-223, May/June 2003.

[4] M.-C. Chen, G. T. C. Chiu, and J. P. Allebach, "Characterization of Chromatic Banding Artifact for Secondary Colors in a Polychrome Electrophotographic Process," in *Proceedings of IS&T's NIP20*, pp. 464-469, 2004.

[5] D. Wulich and N. S. Kopeika, "Image resolution limits resulting from mechanical vibrations," *Optical Engineering*, vol. 26, no. 6, pp. 529-533, 1987.

[6] R. P. Loce, W. L. Lama, and M. S. Maltz, "Modeling vibration-induced halftone banding in a xerographic laser printer," *Journal of Electronic Imaging*, vol. 4, no. 1, pp. 48-61, January 1995.

[7] J. L. Mannos and D. J. Sakrison, "The effects of a visual fidelity criterion on the encoding of images," *IEEE Trans on Information Theory*, vol. 20, no. 4, pp, July 1974.

[8] P. Barten, "Evaluation of subjective image quality with the square-root integral method," *Journal of the Optical Society of America A*, vol. 7, no. 10, pp. 2024-2031, October 1990.

[9] N. Goodman, "Perception of Spatial Color Variation Caused by Mass Variations about Single Separations," in *Proceedings of IS&T NIP 14*, pp. 556-559, 1998

Author Biography

Mu-Chih Chen received his B.S. degree in mechanical engineering from National Taiwan University, Taiwan in 1996. He received his M.S. degree in mechanical engineering from Purdue University, Indiana in 2001. He is currently a Ph.D. candidate in mechanical engineering at Purdue University and expects to graduate soon. His fields of interest are digital control of electromechanical systems, embedded system design, and image quality improvement. He has been an IS&T member since 2001.