Design of UCR and GCR Strategies to Reduce Moiré in Color Printing

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Abstract

Undercolor removal (UCR) and gray component replacement (GCR) techniques are used to generate CMYK signals from CMY or RGB input. Typically, UCR and GCR are designed to achieve an appropriate trade-off between factors such as neutral response, ink area coverage, and gamut volume. In this paper, we consider an additional factor in UCR/GCR design: color moiré in halftone printers. A mathematical formulation is developed for the three-way moiré between cyan, magenta, and black, which is the most objectionable form of moiré. The formulation presents an approximate relationship between the input CMYK signals to the halftoner, and the amplitude of the resulting moiré. This relationship, coupled with the fact that different CMYK combinations can render the same color, can be used to design the UCR/GCR function to reduce CMK moiré. Several algorithms are suggested for moiré optimized UCR/GCR, and preliminary results are presented. The methods suggest an extension of typical UCR/GCR techniques, which are 1-D functions of lightness or density, to being functions of 3-D color space.

Introduction

Print engines commonly use rotated dot halftoning schemes to represent a continuous tone input signals. The color reproduction of rotated dot schemes is more robust with respect to mis-registration errors than color reproduction using other halftoning schemes (e.g.: dot-on-dot or dot-off-dot). In order to achieve a good reproduction, however, the angles between the different color separations have to be precisely controlled, or moiré will occur[1]. In digital systems it is not possible to perfectly align the different angles of the halftone screens. At the high resolutions used in offset printing ($\geq$ 2400x2400dpi), the discrete nature of the screen is not as critical an issue. The problem persists, however, at resolutions commonly found in xerographic printers. Since moiré is a strong function of the relative screen angles, especially of the C, M, K separations, many approaches have been explored for mitigating moiré patterns via halftone screen and screen angle design.[1] This paper describes a method to reduce the remaining moiré by using a moiré dependent undercolor removal and gray component replacement scheme for a given halftone screen.

There are two basic types of moiré that influence print quality. The first type is the two color moiré commonly found between yellow and cyan or yellow and magenta. The second, and normally more disturbing, moiré is caused by the superposition of cyan, magenta, and black. This paper focuses on the three color moiré.

One interesting aspect of the moiré is that it is not only a function of the relative screen angles, but also a rather direct function of the area coverage of the dots. In order to explain this, we will use a simple 1-dimensional example. Assume the superposition of three transmittances, T_c, T_m, T_k. The output is $T = T_c \times T_m \times T_k$. Knowing that each transparency has the form of a halftone dot, i.e. a binary periodic function and neglecting constant terms, we can write:

$$T_i\,(x, \lambda) \propto a_i(\lambda)T_i(x) \propto a_i(\lambda)\;[\; \Sigma_n\, b_{i,n} \cos(2\Pi\, f_i\, n\, x)\;] \quad (1)$$

where $a_i(\lambda)$ is the spectral absorption of the i-th separation, $T_i(x)$ is the periodic screen pattern as a function of spatial location x, f_i is the frequency of the halftone screen of separation i and $b_{i,n}$ are the Fourier coefficients of the halftone screen. Disregarding everything higher than first order, we obtain:

$$T \propto a_c(\lambda)\, a_m(\lambda)\, a_k(\lambda)\, [b_{c,0} + b_{c,1}\cos(2\Pi\phi_\chi x)\,][b_{m,0} + b_{m,1}\cos(2\Pi f_m x)\,]\; [b_{k,0} + b_{k,1}\cos(2\Pi f_k\, x)\,] \quad (2)$$

One well known aspect is obvious from eq.(2): if the individual transmittances would have no unwanted absorption, i.e.: $a_i(\lambda)\bullet a_j(\lambda) = 0$, no moiré would occur. Of all the cross-terms of eq.(2), only the term covering the three periodic components is involved in the moiré. The moiré M can be written as:

$$M \propto b_{c,1}\, b_{m,1}\, b_{k,1} \cos(2\Pi\, f_c\, x) \cos(2\Pi\, f_m\, x) \cos(2\Pi\, f_k\, x). \quad (3)$$

It is eq.(3) that we will use to derive a color correction scheme that reduces the three component moiré.

Effect of UCR/GCR on moiré

Undercolor removal (UCR) and gray component replacement (GCR)[2, 3] are techniques for transforming a CMY combination to a CMYK combination via suitable addition of K and possible reduction of CMY. UCR and GCR algorithms are designed to achieve the best trade-off among several factors, the key ones being ink area coverage, response along the neutral axis, the overall color gamut, and the smoothness of sweeps from neutral to highly chromatic colors. This paper takes into account an additional factor, namely the moire magnitude. It is easily seen that Eq.(3) is strongly influenced by the relative amounts of C, M, and K, which are intimately related to the UCR/GCR strategy. Here, one has to remember that the k-component - and consequently $b_{k,n}$ - was generated by the color correction software and that several (C, M, K) triplets would result in the identical color. One trivial way to eliminate the three component moiré would be to eliminate k, thereby setting $b_{k,n}$ to zero. This is equivalent to a standard three color process. However, this would eliminate the other advantages from the use of K, e.g. larger gamut in the dark regions of color space. Examining eq.(3) one can find another option for reducing the moiré: the Fourier coefficients $b_{i,n}$ are a function of the opening ratio of the halftone dot and consequently of the input level to the halftoning step. The Fourier coefficients for n>0 can be written as:

$$b_{i,n} = \frac{4}{P}\int_0^{P/2} T_i(x)\cos\left(\frac{2n\pi\ x}{P}\right)\ dx = \frac{4}{P}\int_0^{IP/2}\cos\left(\frac{2n\pi\ x}{P}\right)\ dx = \frac{2}{n\pi}\sin\left(n\pi\ I_i\right) \tag{4}$$

Here we use a normalized input $0 \le I \le 1$ and an area coverage of the halftone dot of $0 \le IP \le P$. The moiré M is therefore directly dependent on the color triplet (I_c, I_m, I_k) that is derived from the original input color using the GCR/UCR scheme (with no black being used, we have $I_k=0$). From eq.(4) it is clear that in the one-dimensional case $b_{i,1}$ is maximum for $I_i=½$. Eq.(3), therefore is maximum if all three components (I_c, I_m, I_k) equal ½.

From eq.(4), it is clear that the output moiré is a function of the UCR/GCR scheme. Assume an input color triplet (*R*, *G*, *B*). This color can be represented in the output by a quadruplet of the form (I_c, I_m, I_y, $I_k(I_c, I_m, I_y)$) that is underdefined. Only the GCR/UCR scheme defines the one quadruplet to be used. Taking into account only the first order harmonics, that quadruplet will have a moiré amplitude of:

$$M(I_c,\ I_m,\ I_k) = \frac{2}{\pi}\sin\left(\pi\ I_c\right)\cdot\frac{2}{\pi}\sin\left(\pi\ I_m\right)\cdot\frac{2}{\pi}\sin\left(\pi\ I_k(\mathrm{I_c},\mathrm{I_m},\mathrm{I_y})\right) \tag{5}$$

Recall that eq.(5) only describes the one-dimensional case. A simple extension to two dimensions can be made as shown in eq.(6):

$$M(I_c,\ I_m,\ I_k) = \frac{2}{\pi}\sin\left(\pi\ \sqrt{I_c}\right)\cdot\frac{2}{\pi}\sin\left(\pi\ \sqrt{I_m}\right)\cdot\frac{2}{\pi}\sin\left(\pi\ \sqrt{I_k(\mathrm{I_c},\mathrm{I_m},\mathrm{I_y})}\right) \tag{6}$$

We have to keep in mind that this extension is only a first order approximation of the real moiré amplitude, since the two-dimensional Fourier coefficient will have a different form of the generalized one-dimensional coefficient. A contour plot of $M(I_c, I_m, I_k)$ is shown in Fig. 1. as a function of I_c and I_k, with I_m = 0.4. (For this illustration, we are not fixing any UCR/GCR strategy). The function has a maximum value of 0.258 at $I_c = I_m = I_k$ = ¼. and vanishes at the boundaries (i.e. when at least one of I_c, I_m, I_k is 0 or 1). This model suggests that one should stay away from CMK combinations in the vicinity of $I_c = I_m = I_k$ = ¼. Comparison of the moiré amplitude predicted by (6) and observation of actual prints shows that the moiré model is sufficiently accurate for the purpose of this work.

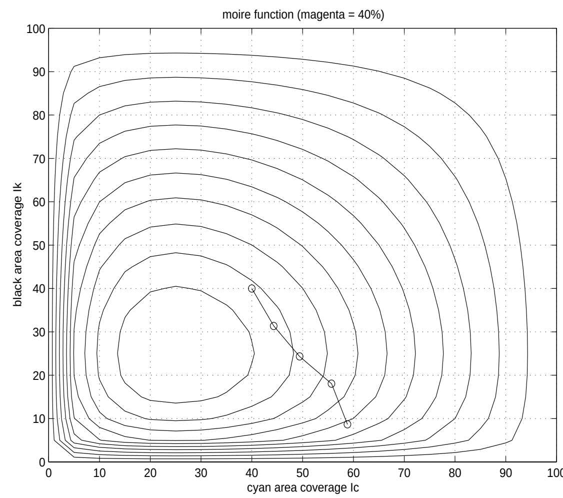

Figure 1. Contour plot of moiré amplitude as function of cyan and black area coverages for I_m = 40% and I_y = 0%. Also shown is a plot of five I_c-I_k combinations that result in the same printed color.

Modification of UCR/GCR to reduce moiré

Typical GCR/UCR strategies are a function of the minimum component of the requested color. Commonly this means that a GCR/UCR is performed for darker colors, but the UCR is set to zero for light colors, and colors with high chroma. This paper proposes to change that strategy and to use a GCR/UCR that is a function of the actual color (and not only the minimum component) of the input pixel. Examining eq.(6) it becomes clear that the UCR/GCR in the red area of color space should be different from the UCR/GCR used in the blue area for the same luminance component. Eq.(6) can be used to restrict the GCR/UCR scheme in the blue area (c and m are present) to those schemes that have a small moiré value. In the red area, the CMK moiré limitation disappears. GCR/UCR schemes that do not take this into account run the risk of introducing a moiré in one area or of using a sub-optimal GCR/UCR in another area of color space. Several types of moiré reduction schemes are described next.

Moiré amplitude minimization

A key observation is that multiple CMYK combinations can result in the same color. In figure 1, a plot is included that shows 5 CMYK combinations resulting in the same CIELAB color within a tolerance of 1 ΔE unit. Superimposed on the contour plot, this shows that it is possible to render the same average color with different moiré amplitudes. This is in agreement with observations of printed samples, and will be exploited in the methods described below.

One approach is to obtain, for a given CMYK value from the UCR/GCR table, the resulting colorimetric (e.g. CIELAB) value of the printed color, and the moiré amplitude M. The CMYK to CIELAB relationship can be obtained through the use of a printer model[4], and the moiré amplitude is calculated using eqn. (6). For a given CIELAB value, the printer model is used to search for those CMYK combinations that yield the given CIELAB color within a specified tolerance. From this candidate set, the CMYK combination that results in the lowest moiré amplitude M is selected. If there are other constraints such as maximum ink area coverage, these should be imposed during the search for candidate CMK values.

Moiré amplitude restriction

The aforementioned approach may result in large deviations in CMYK from the original combinations produced by a given UCR/GCR strategy. An alternative scheme would be to apply an adjustment only to those CMYK values for which the moiré amplitude M exceeds a preset limit. The adjustment can be made very simply: the input component with the largest amplitude is examined and changed (this is done by decreasing area coverage for $I < ¼$ and increasing area coverage for $I \geq ¼$) and the change is monitored. The remaining components may be adjusted to compensate for this change, using the printer model. This approach might take several computations per point in color space, but it is only performed once on a selected number of points during the generation of the color profile. Note that linearization TRC's often follow the GCR/UCR module in the image path. In this case, these TRCs must be incorporated into the moiré model (6).

Input area coverage restriction

Another potential scheme just considers the area coverage of one of the color components - preferably K - and limits its area coverage to reduce moiré. Since the model (6) predicts the highest moiré around ¼ area coverage, the chosen component could be restricted to $I < ¼ - \Delta$ and $I > ¼ + \Delta$ for the "blue" part of color space, where "blue" can be defined by an approximation to hue, derived from the input CMYK. This limit in one of the components could be compensated for by changing the values of the remaining 3 components using the printer model.

Blending of UCR/GCR schemes

A third scheme begins with a standard GCR/UCR which is optimized with respect to other criteria such as neutral reproduction. Subsequently, patches of constant color in the "blue" region of color space are generated using different UCR/GCR schemes. For each strategy, the resulting moiré is evaluated either by using the proposed moiré model, or via printing and visual examination. A UCR/GCR strategy is chosen that yields acceptable overall moiré amplitude in this region of color space. The final GCR/UCR scheme then uses the original scheme, adapted to the moiré scheme in a limited hue range of color space. Smooth transitions are achieved by conventional blending techniques.

Results

An experiment was conducted on a Xerox 5760 CMYK laser printer with a resolution of 400 dpi. A clustered rotated dot screen was employed to binarize the contone input. The test image was a CMY sweep from a bluish-purplish color to black. This image was processed through a conventional UCR/GCR strategy with a parabolic black addition function, and CMY subtraction function that was designed to compensate for the added K along the neutral axis. The CMYK values at either endpoint were [102, 102, 16, 102] and [255 255 255 255]. Rendition of this sweep (denoted sweep A) resulted in noticable moiré through a significant portion of the sweep. A plot of the moiré amplitude of sweep A, calculated using (6), is shown in Fig. 2 as the solid curve.

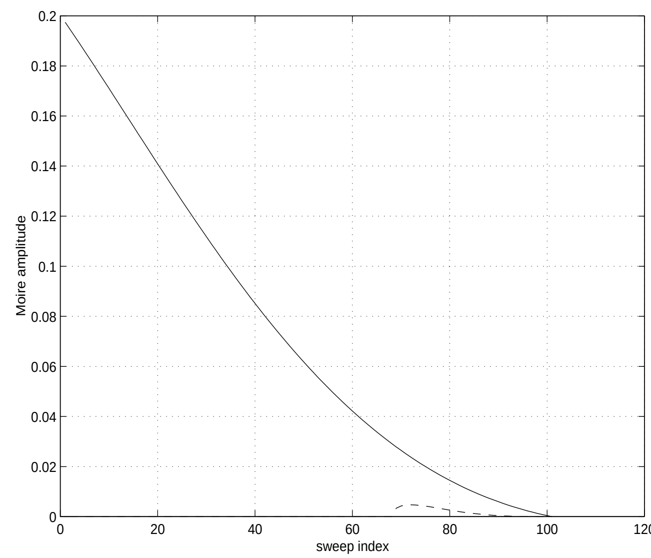

Figure 2 plot of moiré amplitude for sweep A generated from conventional UCR/GCR (solid) and sweep C generated from proposed approach (dashed).

A corresponding CMY sweep, denoted sweep B, was derived that would result in the same color rendition as sweep A. There is no moiré to be seen in this sweep since K=0. A problem, however, is that the darker colors in sweep A cannot be reproduced using only C, M, and Y. Hence K must be introduced in order to achieve the same gamut spanned by sweep A.

The approach of moiré minimization was then used to modify the UCR/GCR of sweep A. A tolerance of $\Delta E = 2.0$ was used to search over a range of CMYK combinations of the same printed color, that would result in a solution with minimum moiré amplitude. This approach resulted in combinations with K = 0 for about 70% of the range of the sweep (i.e. moiré = 0). Beyond this point, the use of K was needed to achieve dark saturated colors and black. However, in this region of the sweep, the area coverages for

C and M are large enough that the introduction of K does not result in significant moiré. The dashed plot in Fig. 2 shows the moiré amplitude from the adjusted GCR scheme. Clearly, the moiré has been either eliminated or significantly reduced. Observation of the printed samples shows the same effect, with no reduction in the reproducible gamut.

Conclusion

An approach has been described for reducing 3 color moiré in halftone printers by controlling the continuous tone input to the halftoner via UCR/GCR adjustment. This approach is based on the observation that

i) moiré amplitude is a strong function of area coverages, which are in turn controlled by the UCR/GCR strategy;
ii) several different CMYK combinations can result in the identical average color with different moiré amplitudes.

A simple and sufficiently accurate model has been derived that relates moiré to input area coverages. The moiré model, in conjunction with a colorimetric printer model, has been used to automatically adjust UCR/GCR to reduce moiré without sacrificing other factors in color correction such as gamut volume and ink area coverage.

Future work includes the implementation and testing of the other techniques described in this paper, namely the moiré amplitude restriction, area coverage restriction, and blending techniques.

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