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Characterization of Printer MTF

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Abstract. *We develop a comprehensive procedure for characterizing the modulation transfer function (MTF) of a digital printer. Especially designed test pages consisting of a series of patches, each with a different one-dimensional (1D) sinusoidal modulation, enable measurement of the dependence of the MTF on spatial frequency, bias point, modulation amplitude, spatial direction of modulation, and direction of modulation in the color space. Constant tone patches also yield the extreme and center color values for the input modulation. After calibrating the scanner specifically for the direction of modulation in the color space, we spatially project the scanned test patches in the direction orthogonal to the modulation to obtain a 1D signal, and then project these sample points onto a line in the CIE* $L^*a^*b^*$ *color space between the extreme color values to obtain a perceptually relevant measure of the frequency response in a specific color direction. Appropriate normalization of the frequency response followed by compensation for the scanner MTF completes the procedure. For a specific inkjet printer using a dispersed-dot halftoning algorithm, we examine the impact of the above-mentioned parameters on the printer MTF, and obtain results that are consistent with the expected behavior of this combination of print mechanism and halftoning algorithm. © 2006 Society for Imaging Science and Technology.*
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INTRODUCTION

The modulation transfer function (MTF) of an optical system is defined as the modulus of optical transfer function of the system.[1] The MTF of an imaging system, as a function of frequency, shows how much the system attenuates an input modulation signal. Generally, the MTF tends to decrease as the frequency increases, so that the imaging system blurs fine details in the captured image. It is typically associated with the optics of the system. The MTF is an important characteristic of the imaging system that has been used to quantify its detail-resolving capability. It has been also used to compensate for image blur, achieving an appropriate level of sharpness.[2]

There are a few methods to measure the MTF for digital image capture devices. The first method is the sinusoidal method, which uses a set of sinusoidal wave targets at different frequencies to measure the MTF of the system.[3,4] The second method uses a slanted-edge target. This method is standardized in the ISO 12233[5] for still-picture cameras and in the ISO 16067[6] for digital scanners. The MTF is characterized by measuring the one-dimensional uniformly supersampled edge profile from the sequentially scanned two-dimensional slanted edges.[7–9] The third method uses a random noise target.[10,11] The MTF is obtained by measuring the noise power spectra of the input and output signals.

There also have been efforts to characterize and measure the MTF of printing devices. The MTF of a printing system was measured by using three different methods (sinusoidal method, one-pixel line method, and step image method); and the MTF results were compared.[12] Also, the noise power spectra of prints generated from five different halftoning methods were measured to analyze the modulation characteristics of a printing system.[13] In addition, the MTF of paper has been measured by using a sinusoidal test pattern to analyze the contrast transfer function of the print.[14,15]

As we described above, many researchers have studied the measurement of MTF for digital imaging acquisition systems such as cameras and scanners. Also some researchers have studied the characteristics of the signal modulation of printing systems generally by using a black colorant. However, little research has been devoted to the characterization of color modulation of a printer. In this paper, we introduce a methodology to measure the modulation performance of a color inkjet printer.

In order to characterize the color modulation of an inkjet printer, we use a set of color patches, each of which contains a sinusoidal modulation signal generated with fixed values for the following parameters: Frequency, bias point, modulation direction in the color space, spatial direction of modulation, and modulation amplitude. We develop a test target page which contains a set of one-dimensional color modulation patches that are generated with different parameter values. Once we print the test target page, we scan it by using a flatbed scanner at a high resolution to obtain scanner *RGB* values, which are then converted into CIE $L^*a^*b^*$ values. We develop a method that yields a one-dimensional characterization of MTF for arbitrary modulation. The characterization expresses the spatial frequency response in ΔE units for a given set of parameter values.

The rest of this paper is organized as follows. In the next section, we describe how to design a test target page con-

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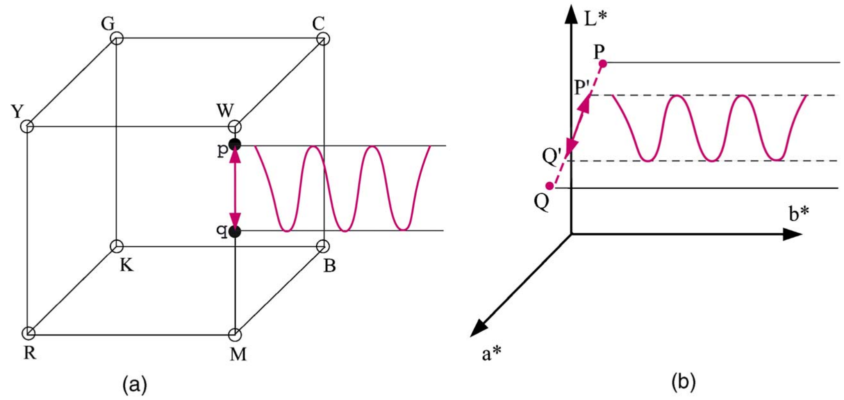

Figure 1. (a) Color modulation in the 3D color cube. A signal is modulated between the color points p and q on the line $\overline{WM}$. (b) The corresponding modulation attenuated by the printing system. It is represented in the L*a*b* color space.

taining a set of color modulation patches. Following that, we discuss how to characterize the scanner, which we use to measure the printer MTF. We then present methods to process the scanned image to obtain the printer MTF. Finally, we show the result of the inkjet color printer MTF measurement for a specific printer. In this paper, we will use the letters C, M, Y, and K to denote the colors of cyan, magenta, yellow, and black, respectively.

COLOR MODULATION GENERATED BY A PRINTER

In this section, we show how to design a test target page which we print, scan, and process to obtain the printer MTF. First we explain the parameters with which we generate a color patch containing a modulation signal. We then describe the arrangement of the major features in the test target page for an efficient measurement procedure.

Color Patch with Sinusoidal Modulation

We characterize the MTF of a color inkjet printer with a set of color modulation patches. A color patch is modulated in a particular direction in a color space described by the RGB digital values that are input to the printer. For example, Fig. 1(a) illustrates color modulation along the line $\overline{WM}$ in the three-dimensional (3D) color cube between the two color points p and q. Figure 1(b) depicts the corresponding color modulation attenuated by a printing system. It is represented in the CIE L*a*b* color space. The attenuated signal is modulated between the color points P' and Q' rather than the color points P and Q, which are the counterparts of the color points p and q in the RGB color cube shown in Fig. 1(a). In our study, we characterize the MTF along the directions $\overline{WC}$, $\overline{WM}$, $\overline{WY}$, and $\overline{WK}$. For a certain modulation direction in the color cube, we generate a color patch $s_i^d[m,n;l]$, $l=C,M,Y$ in the subtractive color mode. Here, i represents the vertex in the 3D color cube, $i=C,M,Y,K$. And l is the color plane of the pattern to be printed. The color signal is modulated between the two vertices i and W according to

$$s_i^d[m,n;l] = \begin{cases} \alpha \sin(2\pi f n) + \beta, & \text{if } (l=i \text{ or } i=K) \text{ and } (d=h), \\ \alpha \sin(2\pi f m) + \beta, & \text{if } (l=i \text{ or } i=K) \text{ and } (d=v), \\ 0, & \text{if } (l \neq i \text{ and } i \neq K). \end{cases} \tag{1}$$

The resulting color patch $s_i^d[m,n;l]$ shows modulation in either the horizontal ($d=h$) or vertical ($d=v$) direction. In Eq. (1), f is the spatial frequency of the modulation signal, α is the modulation amplitude, and β is the bias level which is the center of the sinusoidal signal. In our study, we use 19 values for β out of 256 tone levels

$$\mathcal{B} = \{\lfloor k \times 255 \rceil | k = 0.05, 0.10, 0.15, \ldots, 0.95\}, \tag{2}$$

$$= \{13, 26, 38, \ldots, 242\}, \tag{3}$$

where $\lfloor x \rceil$ denotes the integer closest to x. For each tone level, we generate color patches of the sinusoidal modulation signal at nine different frequencies. The color patches are generated to show modulations at frequencies

$$\{10, 20, 30, 40, 50, 60, 80, 100, \text{ and } 150 \text{ cycle/in}\}. \tag{4}$$

We assume that RGB is the input color space of the printer; so we convert the color patch $s_i^d[m,n;l]$, $l=C,M,Y$, which is described in the CMY color space, into an RGB image $t_i^d[m,n;l]$, $l=R,G,B$ according to

$$t_i^d[m,n;R] = 255 - s_i^d[m,n;C], \tag{5}$$

$$t_i^d[m,n;G] = 255 - s_i^d[m,n;M], \tag{6}$$

$$t_i^d[m,n;B] = 255 - s_i^d[m,n;Y]. \tag{7}$$

Here, we assume that the pixel values for both the CMY and RGB images are represented in an unsigned 8-bit integer format.

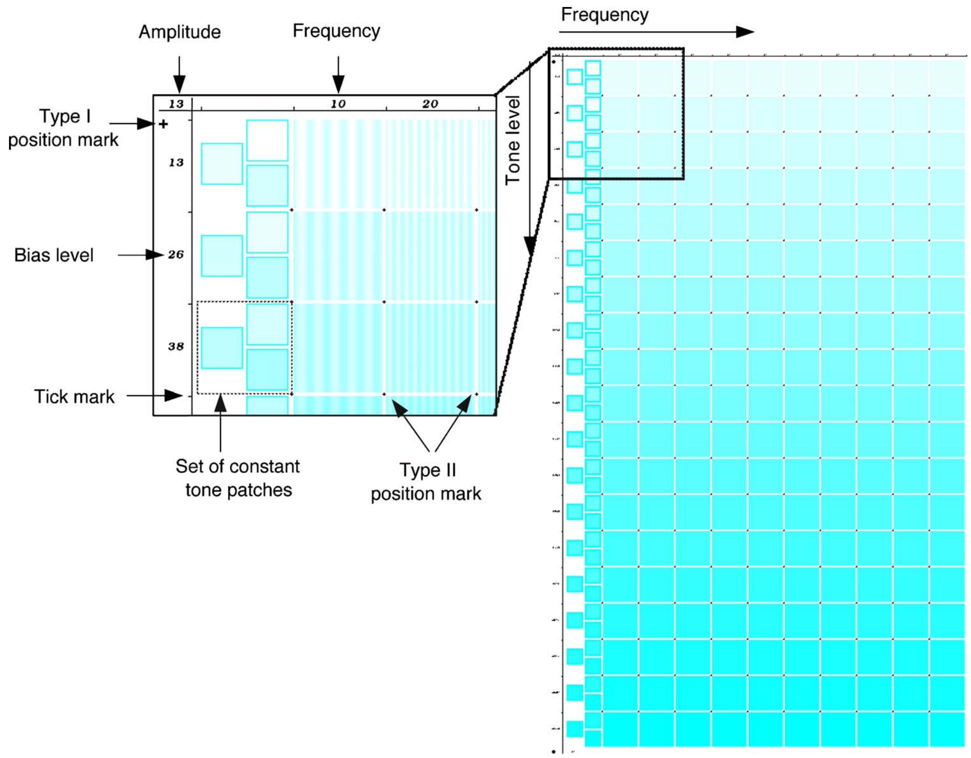

Figure 2. Test target page designed for efficient measurement of printer MTF.

Test Target Page Design

We design a test target page shown in Fig. 2 that includes a set of color modulation patches, segmentation tools, and visual aids. In each test target page, we fix the color modulation direction ($\overline{WC}$, $\overline{WM}$, $\overline{WY}$, or $\overline{WK}$), and the spatial modulation direction that is either the horizontal direction (pen sweep direction) or the vertical direction (paper process direction). For example, the color modulation direction in the test target page shown in Fig. 2 is $\overline{WC}$, and the color signal is modulated in the horizontal direction. In this study we fix the modulation amplitude α to be 13, which is the maximum integer value with which we can modulate the signal at any bias level $\beta \in \mathcal{B}$ without clipping the modulation signal. We arrange the color modulation patches in a matrix, horizontally varying the frequency f and vertically varying the bias level β. The size of each color patch is 0.53 in $\times$ 0.53 in. We print the test target page by using the color inkjet printer that we wish to characterize. We then use a flatbed scanner to scan the printed target at 1200 dpi, and segment each color patch from the scanned image to individually extract the color modulation information for a particular parameter set. To avoid edge effects, the segmented color patch is cropped to 0.50 in $\times$ 0.50 in, which is equivalent to 600 pixels $\times$ 600 pixels at the scanning resolution of 1200 dpi. Since the cropping margin in each direction is only 0.03 in or 36 pixels, an unwanted area might be included in the cropped image unless the position of the patch is accurately located.

In order to precisely determine the position of each color patch, we put a series of position-locating marks on the test target page. There are three different types of position marks as shown in Fig. 2: The Type I position mark, Type II position marks, and tick marks. The Type I position mark has a cross shape, and is used to find the initial position of the scanned target image. The tick marks are placed on the vertical and horizontal lines at the left and top edges, respectively, of the test pattern region. They are used to locate the positions of the color patches in the first column and on the first row. The Type II position marks are used to locate the remaining color patches on the test target page.

In order to search for the Type I position mark in the scanned image, we perform a matched filtering operation using the Type I position mark as the template.[16] We then look for the position showing the greatest value of the matched filter output computed within a region of interest which is selected from the upper-left corner area of the scanned test target page. Once the position of the Type I mark is located, we sequentially search for other position-locating marks within regions of interest based on our knowledge of the location of these marks relative to the Type I mark. We again find these marks by a matched filtering approach.

The position marks are also used to determine how much the page was skewed during the scanning process. We calculate the slope of a straight line fitted to the locations of the vertically arranged tick marks in the scanned image. We consider the scanned data to be valid only if the skewing angle is less than 1.67×10^{-3} rad, which is equivalent to a 1 pixel horizontal displacement for each 600 pixels in the

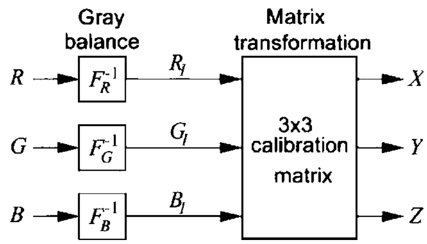

Figure 3. A color scanner calibration model.

vertical direction. This criterion is based on the fact that the side of a segmented color patch is 600 pixels.

For each bias level, there are three constant tone patches. One is generated with the color value of the corresponding bias level, and the other two patches are generated with the extreme colors between which the color signal is modulated. Each test target page is also imprinted with the bias level, frequency, spatial angle and modulation amplitude. We designed the test target page using MATLAB (Math Works, Inc. Natick, MA 01760-2098) with a TIFF output file format.

CHARACTERIZING THE MEASUREMENT DEVICE

In this section, we discuss the characterization of the flatbed scanner (HP Scanjet 8290: Hewlett-Packard, Ft. Collins, CO 80528) that we use to measure the modulation within each color patch. In order to use the scanner as a measurement device, we have to address two key aspects of its performance. The first is color calibration, and the other is the scanner MTF. We discuss these topics in the following two subsections.

Color Calibration

The color calibration of the scanner is the process whereby device-dependent scanner *RGB* values are converted into color values of a device-independent color space such as CIE *XYZ*. Kang presented a color calibration technique,[17] which is a two-step procedure consisting of gray balance and a matrix transformation. Wu et al. used this approach for the color calibration of a digital camera.[18] We use the same approach for the color scanner calibration as depicted in Fig. 3.

Scanner nonlinearity and gray balance

Let F_k denote the scanner nonlinearity of the kth channel, where $k=R,G,B$.[19] In order to determine the scanner nonlinearity, we use a set of Munsell gray patches (Neutral value scale, glossy finish: GretagMacbeth, New Windsor, NY 12553). We measured the luminance value Y of each gray patch by using a spectrophotometer (Gretag SPM 50: GretagMacbeth, New Windsor, NY 12553), and scanned the patches to get the device *RGB* values. Figure 4 shows the nonlinearities of our scanner. We use these curves to get the gray balanced *RGB* values from the device *RGB* values. The curves are basically equivalent to the operations F_k^{-1}.

Transformation matrix

After obtaining the gray balanced *RGB* values, we use a transformation matrix to convert the *RGB* values to CIE

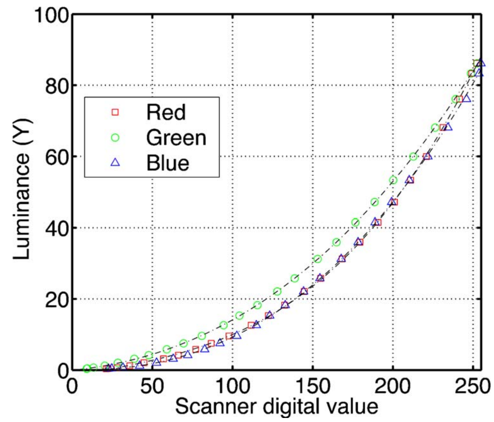

Figure 4. Scanner nonlinearities for the *RGB* channels.

XYZ values. We determine this matrix by applying linear regression to data measured from a set of color patches.[18] Let N be the number of color patches in the training set. Let T be the $N\times 3$ matrix of CIE *XYZ* values of the N color patches measured by the spectrophotometer and let S be the $N\times 3$ matrix of the gray balanced *RGB* values. Let M be the 3×3 matrix to transform from gray balanced *RGB* values to CIE *XYZ* values. Then a linear regression model suggests that

$$T = SM + E, \tag{8}$$

where E is the calibration error matrix. To obtain the transform matrix we solve the least squares problem

$$\hat{M} = \arg\min_{M} \sum_{i=1}^{N} \|[X_iY_iZ_i] - [R_iG_iB_i]M\|^2, \tag{9}$$

resulting in

$$\hat{M} = (S^tS)^{-1}S^tT. \tag{10}$$

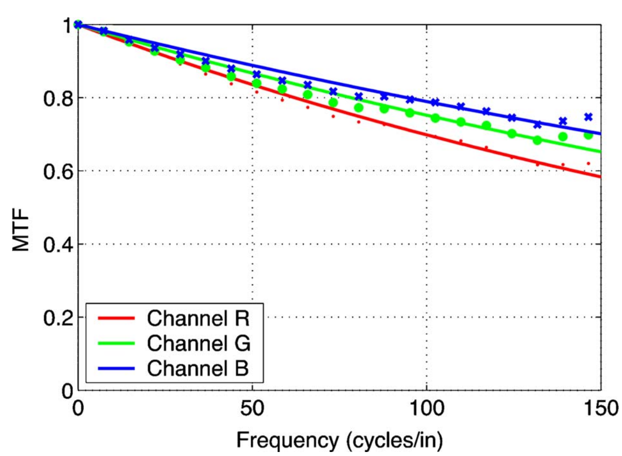

Figure 5. Scanner MTF curves for the *RGB* channels.

Table I. Scanner calibration results.

	$\overline{WC}$	$\overline{WM}$	$\overline{WY}$	$\overline{WK}$
average ΔE	0.341	1.126	1.052	1.865
maximum ΔE	1.280	1.983	2.458	3.044

Calibration results

It is well known[17,18] that the spectral response functions for a typical desktop scanner do not span the human visual subspace. Therefore, the accuracy of the calibration model given by Eq. (8) will be limited. To overcome this problem, we restrict the domain of application of the model as much as possible, and perform the regression given by Eqs. (9) and (10) using only data from within this domain.

In this study, we used four different transformation matrices to convert the scanner *RGB* values to the CIE *XYZ* values for the four different color modulation directions $\overline{WC}$, $\overline{WM}$, $\overline{WY}$, and $\overline{WK}$. We generated 38 color patches in each color direction in the 3D color cube, and printed them in the same way in which we printed the color modulation patches. The digital values of those color patches are uniformly spaced in each color direction. Then we measured their CIE *XYZ* values under the Illuminant D65 again using a spectrophotometer (Gretag SPM 50: GretagMacbeth, New Windsor, NY 12553). We also scanned those patches and extracted the *RGB* color values to obtain the transformation matrix by the linear regression method. Table I summarizes the calibration results for the training sets.

Scanner MTF

The goal of this paper is to use a measurement device, specifically a flatbed scanner, to determine how much an input modulation signal is attenuated by a printing system. Since the scanner can also attenuate the signal thereby affecting the final result of the measurement, we characterize the scanner MTF, and use this information to compensate the modulation amplitude that is estimated from each color modulation patch.

We use the slanted-edge method[6] to measure the scanner MTF. By scanning the slanted-edge target in *RGB* mode and processing the scanned image, we obtain the estimated data points of the scanner MTF for each of the *RGB* color channels. For each channel $j=R,G,B$ we fit to the data in the range $[0,150]$ cycles/in where we wish to measure the printer MTF, a two-sided exponential with frequency constant $\bar{f}_j$ according to

$$H_j(f) = \exp(-|f|/\bar{f}_j). \tag{11}$$

The resulting scanner MTF for each *RGB* channel is shown in Fig. 5, which illustrates both the data from the slanted-edge measurements and the fitted curves. We estimate the scanner MTF in a linear *RGB* space, while we measure the printer MTF in CIE L*a*b* space. Due to the discrepancy between these spaces, we indirectly apply the scanner MTF in the compensation process. We discuss this process in the section *Compensation of the Scanner MTF*.

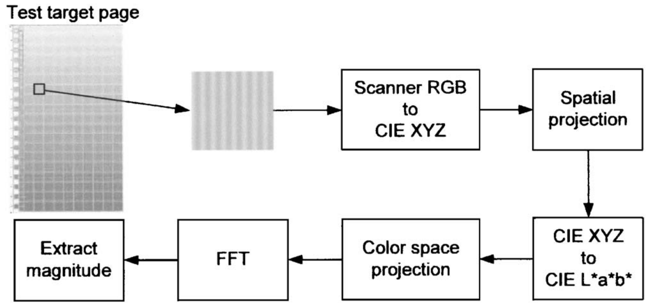

Figure 6. Printer MTF measurement procedure.

MEASUREMENT PROCEDURE FOR THE PRINTER MTF

Once we segment each color patch from a scanned test target page, we process it following the procedure in Fig. 6 to obtain the magnitude of the color modulation at a given frequency in CIE L*a*b* color space. The first step is the color conversion from the scanner *RGB* value to the CIE *XYZ* value. Then, for each of *XYZ* channels, we spatially project the color calibrated patch in the vertical or horizontal direction, which is perpendicular to the modulation direction. From the projected profile, we perform the color space conversion from the CIE *XYZ* space to the CIE L*a*b* space. By projecting the color points onto a line in the CIE L*a*b* space, we obtain a modulation signal from which we extract the modulation magnitude in CIE ΔE units at the given frequency. We process an entire row of color patches from the test target page in this manner to obtain the printer MTF for a specific bias level, and spatial and color modulation direction. In this section, we discuss each step in detail.

Color Calibration

Earlier in this paper, we discussed the color calibration model that we use to convert the *RGB* values captured by a scanner into CIE *XYZ* values. As we described in a previous section, we used four different transformation matrices to separately calibrate the scanner for each direction of the color space modulation $\overline{WC}$, $\overline{WM}$, $\overline{WY}$, and $\overline{WK}$.

Spatial Projection

In this study, we characterize the printer MTF in one direction which is either horizontal or vertical. We obtain the projection profile for each *XYZ* channel from a color calibrated patch $g^h[m,n;l]$ or $g^v[m,n;l]$ according to

$$g^h[n;l] = \frac{1}{M}\sum_{m=1}^{M} g^h[m,n;l], l = X,Y,Z, \tag{12}$$

for a horizontal modulation patch, and

$$g^v[m;l] = \frac{1}{N}\sum_{n=1}^{N} g^v[m,n;l], l = X,Y,Z, \tag{13}$$

for a vertical modulation patch.

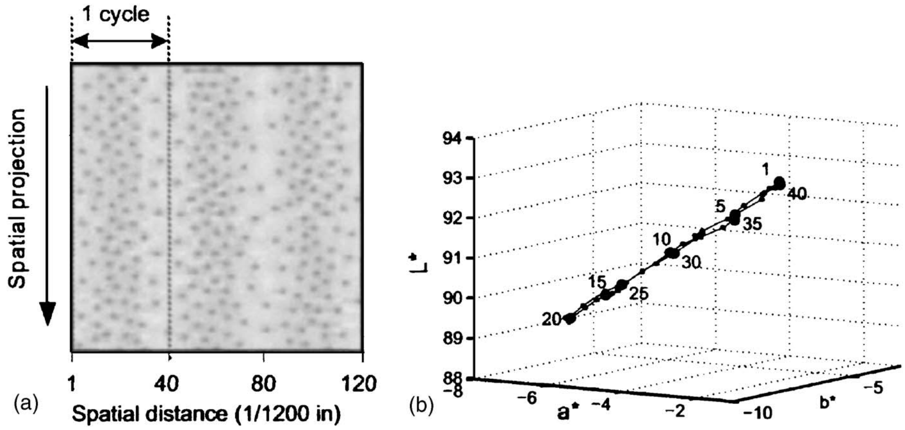

Figure 7. (a) A sample color patch $\overline{WC}$ (α=13, β=26, f=30 cpi) (b) one cycle of 40 sample color points in L*a*b* color space.

In Eqs. (12) and (13), M and N are the height and width, respectively, of the segmented color patch. We call this operation *spatial projection*.

Color Space Conversion from CIE XYZ to CIE L*a*b*

We convert from the color space CIE XYZ where we perform the spatial projection to the color space CIE L*a*b* where we evaluate the modulation of each color patch. This conversion is done with the white point (X_n, Y_n, Z_n) by

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16, \tag{14}$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right], \tag{15}$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right], \tag{16}$$

with the constraint that $X/X_n, Y/Y_n, Z/Z_n > 0.008856$,[20] which was always satisfied in our experiment. The white point that we use is D65.

Figure 7(a) illustrates a magnified part of the color patch $\overline{WC}$ ($\alpha=13$, $\beta=26$, $f=30$ *cpi*). Since we scanned the test target page at ***1200 dpi*** and the modulation frequency of this color patch is ***30*** cpi, 40 sample points correspond to one cycle. Figure 7(b) depicts one cycle of color points in CIE L*a*b* color space. As we notice, the color points are dispersed in a particular direction. However, they are not placed exactly on one line. We measure the modulation magnitude of the color patch by projecting the color points onto an appropriate line and calculating the distance between each projected color point and a reference point. In the next subsection, we describe how we project the color points onto a line in CIE L*a*b* color space.

Color Space Projection

For a given bias level β, there are two extreme color points $\boldsymbol{A}$ and $\boldsymbol{B}$, between which we assume the other color points are dispersed as shown in Fig. 7(b). We project these scattered color points onto the line which connects the two points $\boldsymbol{A}$ and $\boldsymbol{B}$ which are obtained from the constant tone patches for the given bias level. Figure 8 shows how a point $\boldsymbol{Q}$ is projected onto the line which connects the points $\boldsymbol{A}$ and $\boldsymbol{B}$. In this figure, let $\boldsymbol{a}=OA$, $\boldsymbol{b}=\boldsymbol{O}B$, $\boldsymbol{p}=OP$, and $\boldsymbol{q}=OQ$. We define the unit vector

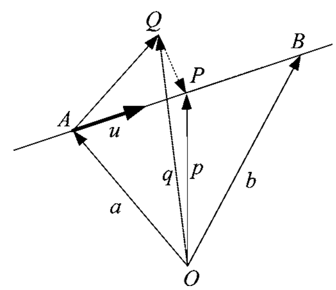

Figure 8. Projection of a point onto a line.

$$\boldsymbol{u} = \frac{\boldsymbol{b}-\boldsymbol{a}}{\|\boldsymbol{b}-\boldsymbol{a}\|}. \tag{17}$$

Then the point $\boldsymbol{P}$ which is projected from a point $\boldsymbol{Q}$ onto the line connecting the points $\boldsymbol{A}$ and $\boldsymbol{B}$ is calculated as

$$\boldsymbol{p} = \{\boldsymbol{u}\cdot(\boldsymbol{q}-\boldsymbol{a})\}\boldsymbol{u} + \boldsymbol{a}. \tag{18}$$

Also the distance $\|\overline{AP}\|$ between points $\boldsymbol{A}$ and $\boldsymbol{P}$ is obtained by

$$\|\overline{AP}\| = \boldsymbol{u}\cdot(\boldsymbol{q}-\boldsymbol{a}). \tag{19}$$

Since the color signal is modulated between the white point $\boldsymbol{W}$ and another vertex in the 3D color cube, the lightness of one extreme color generally shows a higher value than that of the other extreme color. Here we assume that the color point $\boldsymbol{A}$ represents the darker extreme color. We then calculate the Euclidean distance between each projected color point and this point. Since the projection is done in

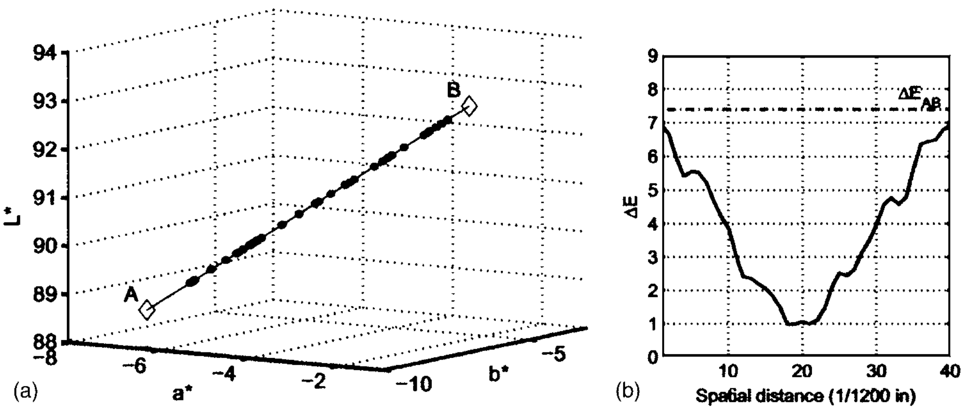

Figure 9. (a) Color space projection of one cycle of 40 sample color points in L*a*b* color space of the color patch $\overline{WC}$ (α=13, β=26, f=30 cpi), and (b) the corresponding modulation signal obtained by measuring the Euclidean distance between each projected color point and the reference point A, which is one of the extreme color points. In this case, the color difference between the two extreme colors is ΔE_{AB}=7.32.

the CIE L*a*b* color space, the distance represents a color difference ΔE.[20] Figure 9 shows one cycle of the projected color points and the resulting modulation signal obtained by calculating the distance of each color point from the reference.

Discrete Fourier Transform (DFT) Spectrum

Figure 10 shows a set of scanned sample patches, their distributions of color points in the CIE L*a*b* space, the modulation signals in ΔE units, and their corresponding DFT spectra.[21] Each row in this figure shows one of the sets for three frequency levels f=20, 50, and 80 cpi, under the condition of $\overline{WC}$ (α=13, β=26). The second column in this figure reveals that the color points are dispersed more narrowly as the frequency increases. This fact is reflected in the modulation signals which have a smaller range for the higher frequency samples. Consequently, the DFT spectra for the higher frequency samples show smaller magnitudes at the corresponding frequencies, as indicated in the fourth column in Fig. 10. The magnitude of each DFT spectrum is multiplied by an appropriate factor so that it shows the peak-to-peak value of the modulation signal.

Printer MTF

As described above, we obtain a spectrum which has a peak at the given frequency of each color patch. For a fixed direction of color modulation, bias level, and spatial direction, we obtain the data points of the frequency response $\mathcal{F}_{AB}(f)$ by extracting the DFT magnitude at the frequency corresponding to the modulation for each color patch in the row of the test target page for the given bias level. Figure 11(a) shows the frequency response acquired from the color patches for $\overline{WC}$ (α=13, β=26).

Let the color difference between the two extreme color points A and B be $\mathcal{E}_{AB}$. We define the MTF $\mathcal{M}_{AB}(f)$ in CIE L*a*b* space as the ratio of the frequency response $\mathcal{F}_{AB}(f)$ to the color difference $\mathcal{E}_{AB}$

$$\mathcal{M}_{AB}(f) = \frac{\mathcal{F}_{AB}(f)}{\mathcal{E}_{AB}}. \tag{20}$$

Then the MTF $\mathcal{M}_{AB}(f)$ is a normalized frequency response that reveals the modulation performance of the printer.

Compensation of the Scanner MTF

The MTF $\mathcal{M}_{AB}(f)$ resulting from the steps described thus far is, however, affected by the measurement system that in our study is a scanner. In order to achieve an MTF which is not affected by the scanner characteristics, we compensate the signal attenuation caused by the scanner. We assume that the MTF $\mathcal{M}_{AB}(f)$ can be factored as

$$\mathcal{M}_{AB}(f) = \mathcal{M}_{AB}^{pr}(f)\mathcal{M}_{AB}^{sc}(f), \tag{21}$$

where $\mathcal{M}_{AB}^{pr}(f)$ and $\mathcal{M}_{AB}^{sc}(f)$ are the printer MTF and scanner MTF, respectively. Let

$$\mathcal{C}_{AB}(f) = \frac{1}{\mathcal{M}_{AB}^{sc}(f)}. \tag{22}$$

Then, from Eq. (21), we obtain

$$\mathcal{M}_{AB}^{pr}(f) = \mathcal{M}_{AB}(f)\mathcal{C}_{AB}(f). \tag{23}$$

We can consider $\mathcal{C}_{AB}(f)$ to be a factor that compensates the impact of the scanner MTF on the modulation signal between the two color points A and B in the CIE L*a*b* color space. But we measure the scanner MTF in a linear RGB color space. Due to the discrepancy between these two color spaces, we cannot directly use the measured scanner MTF in this compensation process.

Instead, we use a two-step method by which we indirectly remove the influence of the scanner MTF. First, we estimate the color points in the RGB color space. Then we calculate the compensation factor in CIE L*a*b* space.

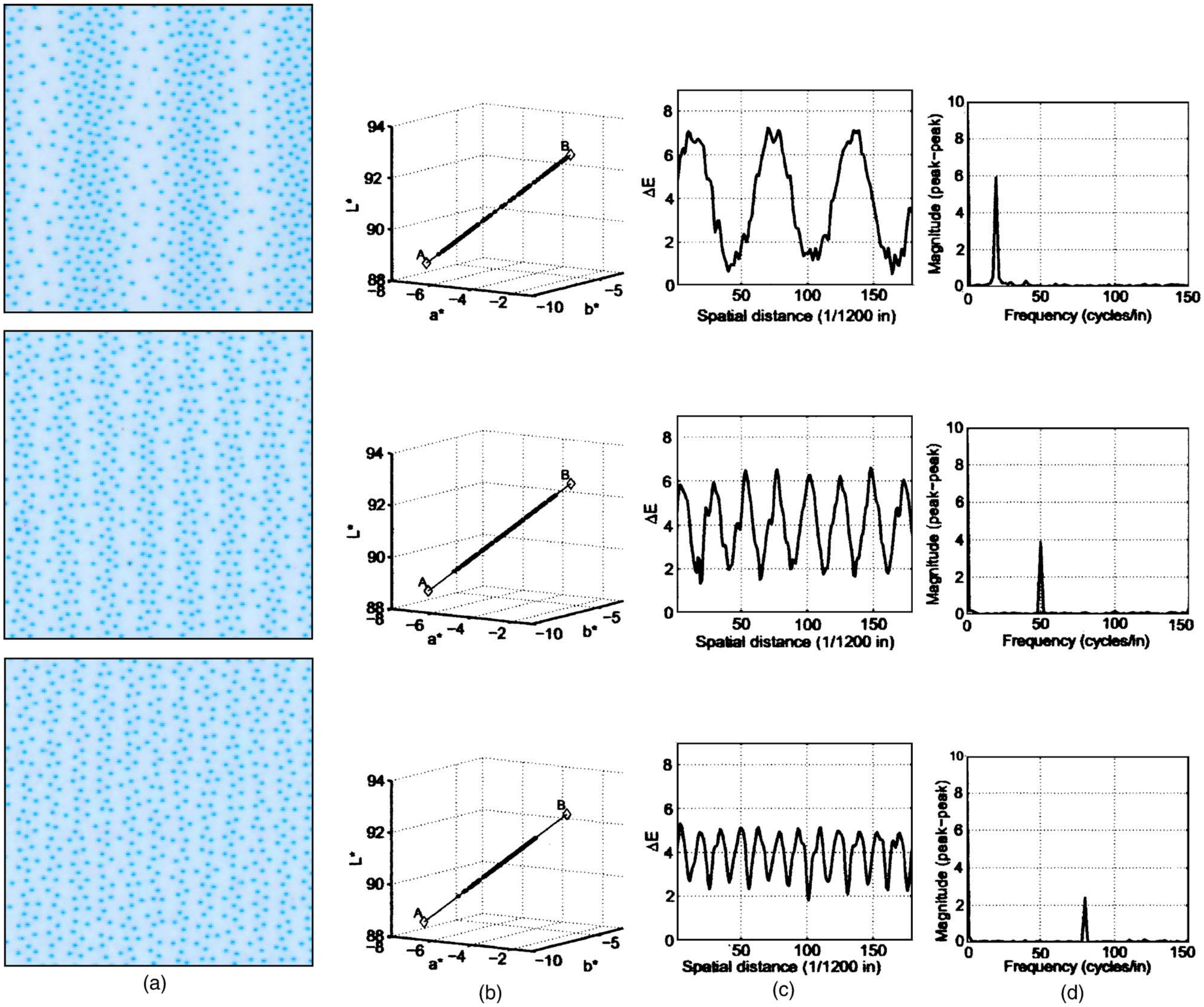

Figure 10. (a) Scanned samples, (b) color points in L*a*b* space, (c) modulation signals, and (d) DFT spectra for the color patches $\overline{WC}$ ($\alpha=13$, $\beta=26$) at three different frequency levels $f=20$, 50, and 80 cpi.

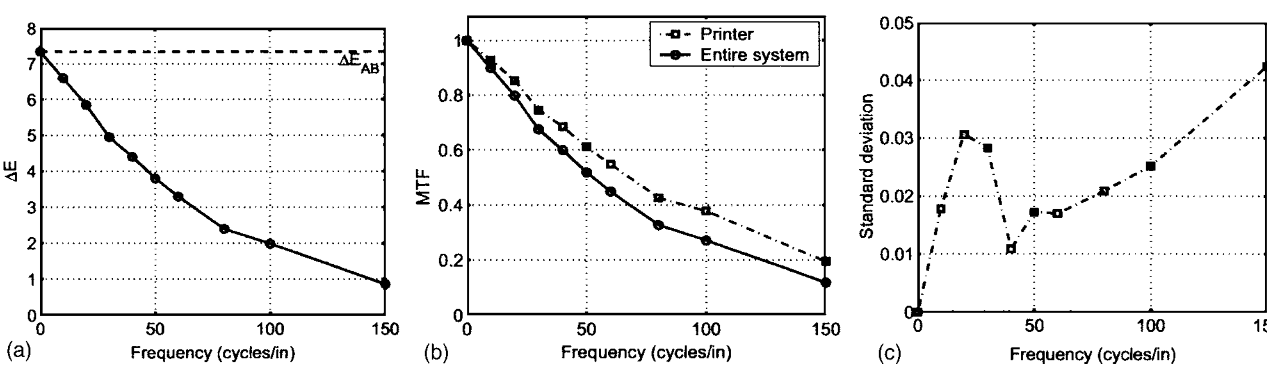

Figure 11. (a) The frequency response, and (b) the MTF of $\overline{WC}$ ($\alpha=13$, $\beta=26$). Here the normalizing factor of the color difference ΔE_{AB} used in calculating the MTF is 7.32. (c) The standard deviation plot of the printer MTF curve $\overline{WC}$ ($\alpha=13$, $\beta=26$). Each standard deviation at the corresponding frequency was calculated from the MTF measurements of 10 test target pages.

Estimation of color points in the RGB color space

Let $\mathbf{a}=[a_R,a_G,a_B]^t$ and $\mathbf{b}=[b_R,b_G,b_B]^t$ be the two color points between which a sinusoidal signal $\mathcal{S}$ is modulated at frequency f in the *RGB* color space. Let us assume that this signal $\mathcal{S}$ is captured by the scanner; and the scanner generates an attenuated signal $\mathcal{S}'$ modulating between the two color points $\mathbf{a}'(f)=[a'_R(f),a'_G(f),a'_B(f)]^t$ and $\mathbf{b}'(f)=[b'_R(f),b'_G(f),b'_B(f)]^t$. Let $\mathbf{c}$ be the center which we assume to be common to the two modulation signals $\mathcal{S}$ and $\mathcal{S}'$; so

$$\mathbf{c}=\frac{\mathbf{a}+\mathbf{b}}{2}=\frac{\mathbf{a}'(f)+\mathbf{b}'(f)}{2}. \quad (24)$$

If we assume that there is no interaction between any two channels of the scanner, the scanner MTF $\mathcal{M}_i^{sc}(f)$, $i=R,G,B$, can be expressed as

$$\mathcal{M}_i^{sc}(f)=\frac{a'_i(f)-b'_i(f)}{a_i-b_i}, \quad i=R,G,B. \quad (25)$$

By using the center point $\mathbf{c}$, Eq. (25) can be rewritten as

$$\mathcal{M}_i^{sc}(f)=\frac{(a'_i(f)-c_i)-(c_i-b'_i(f))}{(a_i-c_i)-(c_i-b_i)}, \quad i=R,G,B. \quad (26)$$

Since $a'_i(f)-c_i=c_i-b'_i(f)$ and $a_i-c_i=c_i-b_i$, Eq. (26) can be rewritten as

$$\mathcal{M}_i^{sc}(f)=\frac{a'_i(f)-c_i}{a_i-c_i}, \quad i=R,G,B. \quad (27)$$

Thus,

$$a'_i(f)=c_i+\mathcal{M}_i^{sc}(f)(a_i-c_i), \quad i=R,G,B. \quad (28)$$

With the assumption that there is no interaction between the color channels of the scanner, we can define a matrix $\mathbf{M}^{sc}(f)$ as

$$\mathbf{M}^{sc}(f)=\begin{bmatrix}\mathcal{M}_R^{sc}(f) & 0 & 0\\ 0 & \mathcal{M}_G^{sc}(f) & 0\\ 0 & 0 & \mathcal{M}_B^{sc}(f)\end{bmatrix}. \quad (29)$$

Then, Eq. (28) becomes

$$\mathbf{a}'(f)=\mathbf{c}+\mathbf{M}_i^{sc}(f)(\mathbf{a}-\mathbf{c}). \quad (30)$$

Similarly,

$$\mathbf{b}'(f)=\mathbf{c}+\mathbf{M}_i^{sc}(f)(\mathbf{b}-\mathbf{c}). \quad (31)$$

*Calculation of the compensation factor in CIE L*a*b* space*

In this section, we describe how to calculate the compensation factor $\mathcal{C}_{AB}(f)$ for the scanner MTF in CIE L*a*b* color space. We use the notations $\mathbf{a}_{RGB}$ and $\mathbf{a}_{L^*a^*b^*}$ to represent the color point $\mathbf{a}$ in *RGB* space and the corresponding color point in CIE L*a*b* space, respectively. Let $\mathbf{a}_{RGB}$ and $\mathbf{b}_{RGB}$ be the two color points between which the sinusoidal signal $\mathcal{S}$ is modulated at frequency f in the *RGB* color space. Let $\mathbf{a}'_{RGB}(f)$ and $\mathbf{b}'_{RGB}(f)$ be the color points between which the attenuated signal captured by the scanner is modulated, which are estimated by using Eqs. (30) and (31).

We convert the color points $\mathbf{a}'_{RGB}(f)$ and $\mathbf{b}'_{RGB}(f)$ into $\mathbf{a}'_{L^*a^*b^*}(f)$ and $\mathbf{b}'_{L^*a^*b^*}(f)$ by color calibration and color space conversion. Then we project these two color points onto the line which connects the two color points $\mathbf{a}_{L^*a^*b^*}$ and $\mathbf{b}_{L^*a^*b^*}$, to obtain the projected color points $\underline{\mathbf{a}}'_{L^*a^*b^*}(f)$ and $\underline{\mathbf{b}}'_{L^*a^*b^*}(f)$. Let $\mathcal{E}_{A'B'}(f)$ be the color difference between these two color points $\underline{\mathbf{a}}'_{L^*a^*b^*}(f)$ and $\underline{\mathbf{b}}'_{L^*a^*b^*}(f)$.

We can describe the scanner MTF $\mathcal{M}_{AB}^{sc}(f)$ for the color signal modulated between the two color points A and B in CIE L*a*b* color space as

$$\mathcal{M}_{AB}^{sc}(f)=\frac{\|\underline{\mathbf{a}}'_{L*a*b*}(f)-\underline{\mathbf{b}}'_{L*a*b*}(f)\|}{\|\mathbf{a}_{L*a*b*}-\mathbf{b}_{L*a*b*}\|}=\frac{\mathcal{E}_{A'B'}(f)}{\mathcal{E}_{AB}}. \quad (32)$$

Thus, from Eq. (22), the compensation factor for the scanner MTF is

$$\mathcal{C}_{AB}(f)=\frac{\mathcal{E}_{AB}}{\mathcal{E}_{A'B'}(f)}. \quad (33)$$

Finally, we obtain the printer MTF from Eqs. (23) and (33) as

$$\mathcal{M}_{AB}^{pr}(f)=\frac{\mathcal{F}_{AB}(f)}{\mathcal{E}_{A'B'}(f)}. \quad (34)$$

Figure 11(b) shows the MTF curve of the entire system and the printer MTF which results after compensating for the scanner MTF. These curves were obtained from the set of color patches for $\overline{WC}$ ($\alpha=13$, $\beta=26$). We measured the printer MTF by averaging the measurements for each data point from 10 test target pages. The standard deviation for each data point is shown in Fig. 11(c). We note that it is less than 0.05 across the entire range of frequencies.

MEASUREMENT RESULTS AND DISCUSSION

For the color directions $\overline{WC}$, $\overline{WM}$, $\overline{WY}$, and $\overline{WK}$, we generated test target pages in a *24-bit RGB* image format. We then printed 10 test target pages for each color direction on glossy paper from an inkjet printer. The halftone process is done by the printer driver. In our study we consider the internal system of the printer including the printer driver as an unknown system, so that we characterize the modulation performance of the printer by applying the input modulation signal to the printing system, and then measuring the corresponding output signal from the system.

We scanned the printed test pages at *1200 dpi* and extracted the modulation signal from each color patch to obtain the printer MTF through the procedure described in the previous sections. For a given color direction, we calculated the average value of the MTF for each set of measurement parameters, which are frequency f and tone level β.

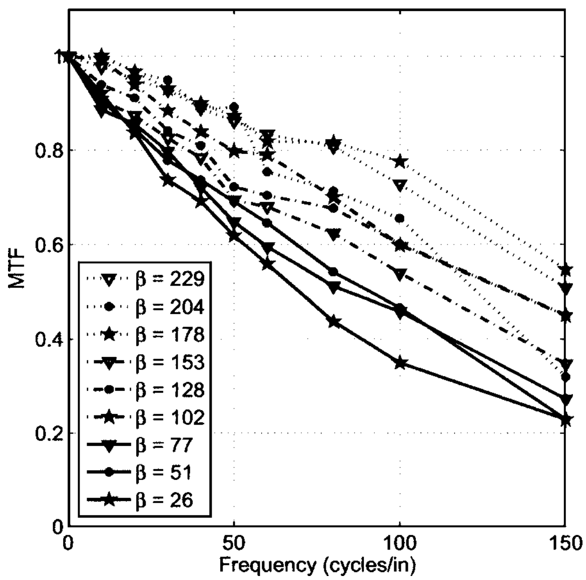

Figure 12. Printer MTF of the horizontal modulation for the color direction $\overline{WC}$ for nine different bias levels β as a function of frequency. The modulation amplitude α is 13.

In Figs. 12–15, we explore several different aspects of the MTF for this particular printer. First, Fig. 12 illustrates the dependence of the MTF on the bias level β for a given color modulation direction ($\overline{WC}$) and horizontal spatial modulation. For each fixed bias level β, we see that the MTF decreases monotonically with increasing spatial frequency f, as is typical for other types of imaging systems.

For each fixed frequency f, we also observe that the MTF generally increases, although not monotonically, with increasing bias level which corresponds to increasing dot density, as we go from the highlights into the midtones. As we move from the midtone into shadows, the MTF generally decreases again. The effect is more pronounced as the spatial frequency increases.

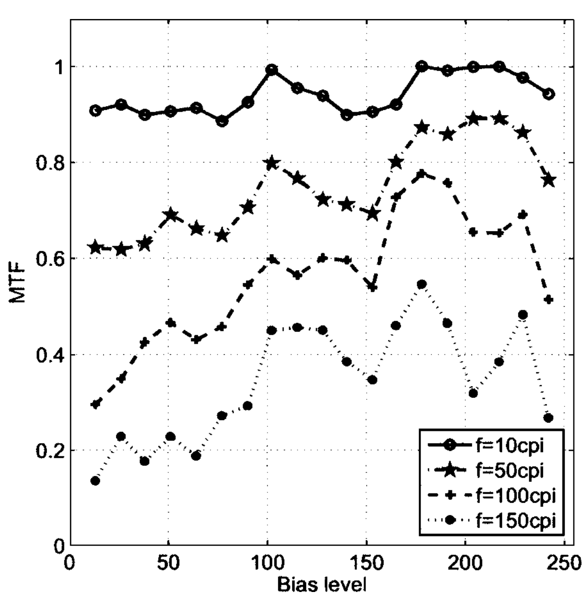

Figure 13. Printer MTF of the horizontal modulation for the color direction $\overline{WC}$ as a function of bias level β for four different frequencies f.

Figure 13 shows a subset of the same data as in Fig. 12 but as a function of β for fixed values of f. It illustrates this behavior more clearly, which is due to the inherent limitations of a dispersed dot halftoning algorithm. Rendering any fixed spatial frequency f requires that the dot density be increased and decreased over a spatial interval of length $1/f$. However, as we move from the midtones into the highlights, the number of dots available per unit area decreases making this modulation process increasingly difficult. The same limitations apply as we move from the midtones into the shadows, but with dots replaced by holes. In addition, the specific characteristics of the ink drop size and shape would also be expected to impact the dependence of the printer MTF on tone level. From Fig. 12, we can summarize the characteristics of the MTF for this particular 600 dpi printer and modulation directions in the color and spatial domains by observing that at the Nyquist frequency of 150 dpi, the MTF ranges from a high of approximately 0.55 to a low of approximately 0.22 for all bias levels between 10% and 90%. Although we have only shown here the dependence of the printer MTF on bias level for one color direction $\overline{WC}$ and horizontal spatial modulation, we observed the same general behavior for the other color directions, $\overline{WM}$, $\overline{WY}$, and $\overline{WK}$, and also vertical modulation.

Figure 14 considers a second aspect of the printer MTF—namely its dependence on the direction of modulation in the color space for a fixed bias level. In the highlights, we see very little dependence on the direction of color modulation. As the bias level increases, we see an increasing degree of dependence of the MTF on the color direction, at the higher spatial frequencies.

Finally, in Fig. 15, we examine the dependence of the printer MTF on the spatial direction of the modulation. Although the dependence is weak, we do see that at the higher frequencies vertical modulation provides consistently higher gain than horizontal modulation across the range of bias levels. This is consistent with an earlier investigation of an inkjet printer[22] that revealed much larger variability in dot placement accuracy in the (horizontal) scan direction than in the process (vertical) direction. Such variability, which is due to both the dynamics of the print head movement and the use of print masking,[23] would be expected to decrease the modulation efficiency in the horizontal direction.

CONCLUSION

In this paper, we introduced a methodology to characterize the modulation transfer function (MTF) of a printer in the CIE L*a*b* color space. In the MTF characterization process, we used specially designed test target pages consisting of a set of color modulation patches and scanned the printed pages to analyze the modulation information. A key step in this process is the projection of the measured data points onto a line in L*a*b* space defined by the extreme modulation colors. In order to remove the signal-attenuating effect of the measurement device, we also measured and compen-

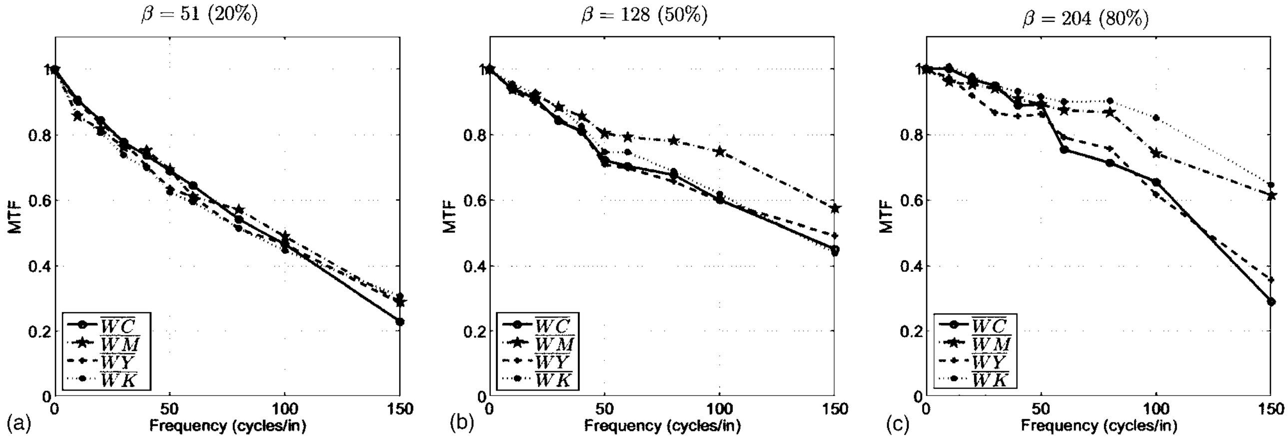

Figure 14. Printer MTF with horizontal modulation for the four color directions $\overline{WC}$, $\overline{WM}$, $\overline{WY}$, and $\overline{WK}$ at bias levels (a) β=51 (20%), (b) β=128 (50%), and (c) β=204 (80%). The modulation amplitude α is 13.

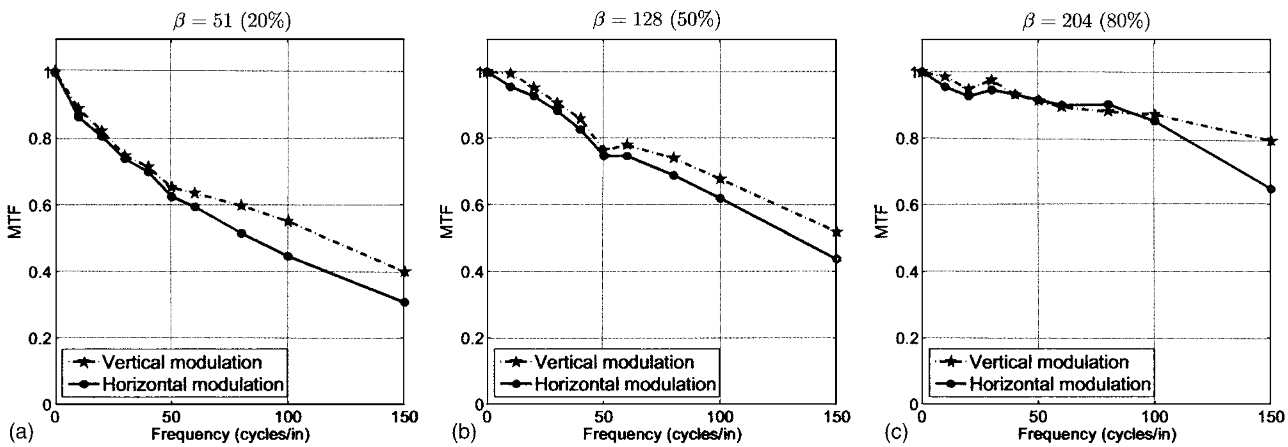

Figure 15. Printer MTF for modulation in the vertical and horizontal directions at bias levels (a) β=51 (20%), (b) β=128 (50%), and (c) β=204 (80%). The color direction is $\overline{WK}$, and the modulation amplitude α is 13.

sated the scanner MTF in the printer MTF measurement procedure. For a specific inkjet printer, we found that the MTF depends not only on the frequency but also on the bias point and modulation directions in both the color space and spatial domain. In particular, we observed that for a fixed frequency, the MTF is largest in the midtones and decreases as we move into the shadows or highlights and also that the MTF is larger for vertical modulation than it is for horizontal modulation. These observations are consistent with the characteristics, respectively, of a dispersed dot halftone process and the print mechanism of an inkjet printer.

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