Printer Characterization for UV Encryption Applications

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Abstract

At the last year's conference, a technique was presented for exploiting substrate fluorescence to embed information into printed documents that was revealed only under pure ultra-violet (UV) light. It required the ability to characterize printed colors under both normal and UV lighting conditions. Printer characterization under normal light has been a very mature technology. This paper will focus on several different approaches for modeling the printer response under UV light. For this security application, it is not necessary to predict all the conventional color appearance attributes, but only the lightness is required. The first and the most straightforward approach was to measure a color target under UV light with a spectroradiometer and to build a printer model for this specific illuminant. While accurate, this approach suffered from the drawback that radiometric measurements were time-consuming and laborious. Two simple alternative approaches were brought forth to model the lightness response under UV light. One was based on a spectrophotometer with and without a UV cutoff filter, and the other was based on a commercial digital camera. Furthermore, visual post-correction method was used together with these two alternative approaches to improve the prediction accuracy of lightness under UV light.

Introduction

At the last year's conference, the idea of exploiting substrate fluorescence for UV encryption applications was introduced [1]. The underlying hypothesis is that the substrate fluoresces and the toners or inks selective suppress the substrate fluorescence. Two patterns consisting of different color combinations were used to form the distracting background and the hiding text of a watermark that was invisible under normal light, but easily detected under UV light. In order to automatically find these two patterns, two printer models were required to predict the color appearance of prints under both normal and UV lighting conditions. In essence, the printer model maps input colorant values to output colorimetric values. Printer characterization for normal light has been well documented and published in the literatures [2-7]. Thus, the subject of this paper was to investigate the methods to predict the color appearance of the prints on the fluorescent substrate under UV light.

Standard printer characterization involves the narrowband reflectance measurements of a printed target with a spectrophotometer. The colorimetric values can be easily calculated from these measured reflectance spectra for a specific illuminant, and then a printer profile can be built for this illuminant. The underlying premise of this method is that the light reflected at a given wavelength depends only on the light incident at that wavelength. The method therefore can not be extended to the case of a fluorescent substrate viewed under UV light, whereby incidence at one wavelength engenders reflection at a different wavelength.

The straightforward approach to model the printer's response under UV light would be to make direct radiometric measurements of a printed target under UV light, and build a printer model from these measurements using the standard techniques (e.g. the Yule-Nielsen modified spectral Neugebauer model). However, spectroradiometric measurements are time-consuming and laborious. It is desired to develop more cost-effective approaches.

For this security application, it is not necessary to predict all the conventional color appearance attributes (lightness, chroma and hue). Rather, only the prediction of lightness under UV light is required. The security watermark is revealed under UV light because the hiding text has the different lightness compared with the distracting background. Hence, only the prediction of relative lightness between one color and another is really important. Two convenient and cost-effective approaches were brought forth to predict relative lightness of color prints under UV light. One was based on a spectrophotometer with and without UV cutoff filter, and the other was based on a commercial digital camera. Visual post-correction method was used together with either approach to improve the prediction accuracy of the lightness. The straightforward approach and two alternative approaches will be described in the following sections.

Spectroradiometric Approach

The Yule-Nielsen modified Spectral Neugebauer model (YNSN) was used to derive a transformation from colorant values to tristimulus values XYZ calculated from the spectral radiometric measurements under UV light, as shown in Eqs. (1.1)-(1.3), where n is the empirical Yule-Nielsen factor and w_i is the Demichel weight [3]. For a CMYK printer, there were sixteen Demichel weights, corresponding to sixteen primaries of 4-colorant printer.

$$\hat{X} = \left(\sum_{i=1}^{16} w_i X_{i,primary}^{1/n} \right)^n \tag{1.1}$$

$$\hat{Y} = \left(\sum_{i=1}^{16} w_i Y_{i,primary}^{1/n} \right)^n \tag{1.2}$$

$$\hat{Z} = \left(\sum_{i=1}^{16} w_i Z_{i,primary}^{1/n} \right)^n \tag{1.3}$$

A target comprising single-color ramps, 16 primaries and 16 independent test colors was measured with the spectroradiometer Photo Research PR705 under UV light in a standard light booth. The tristimulus values XYZ were calculated from the measured spectral radiance and normalized with the luminance value Y of the bare substrate. These tristimulus values for single-color ramps were used to derive the optimal Yule-Nielsen n value and effective dot area coverage functions. It was found that the n value was equal to 1.8. Then the tristimulus values for 16 independent test colors were used to evaluate the model performance. This approach provided the most accurate characterization, and could be used as a reference to assess the performance of the other approaches discussed later.

Spectrophotometric Approach

Spectrophotometric measurement of reflective prints is much quicker and more convenient than spectroradiometric measurement. The challenging problem is how to predict the lightness of a print under UV light from a reflective measurement made by a device that has an unknown built-in illumination. It is known that the illuminant inside most spectrophotometers contains a UV component, and that most devices also come with the option of using a UV cutoff filter in front of the illuminant to block the UV part. Intuitively, if one can make spectral measurements of a sample with and without a UV cutoff filter, the difference between these two measurements should provide an approximation of the spectral radiance emanating from the sample under pure UV illumination.

The radiance, $\hat{\mathbf{I}}_{UV}$, can be simply predicted by:

$$\hat{\mathbf{I}}_{UV} = \mathbf{I}_{VIS}\left(\mathbf{R}_U - \mathbf{R}_{UV}\right) \quad (2)$$

where $\mathbf{R}_U$ is the spectral reflectance measured without a UV cutoff filter, $\mathbf{R}_{UV}$ is the spectral reflectance measured with a UV cutoff filter, and $\mathbf{I}_{VIS}$ is the spectral power distribution of the illuminant within the spectrophotometer. The instrument illuminant might not be known to a high degree of accuracy, and even when known, it might not have the same UV property as the light source used in the final security application. Even with these shortcomings, this approach could achieve sufficient accuracy for this application. The spectrophotometer used in this experiment was the X-Rite DTP70 high speed, full-sheet autoscan spectrophotometer with the light source specified in the manual as gas pressure @ 2850°K. Thus the illuminant used in Eq. (2) was the CIE standard illuminant A, chosen to be a close approximation.

After that, the tristimulus values could be easily calculated from the predicted radiance [Eq. (2)], and the Y value was used to predict the lightness under UV illumination. However, the Y value exhibited very little dynamic range, and was highly susceptible to noise that raised from the differencing operation in Eq. (2). To illustrate this, the Y and Z values of a black ramp calculated from two spectrophotometric measurements with and without UV cutoff filter were compared with the corresponding values obtained from the direct spectroradiometric measurements, as shown in Fig. 1. The dynamic range of the Z values for both approaches was almost ten times larger than that of the Y values. The Z values derived from both approaches were linearly correlated to each other, while this was not true for the Y values. It was concluded that the Y values based on the spectroradiometric approach was susceptible to noise.

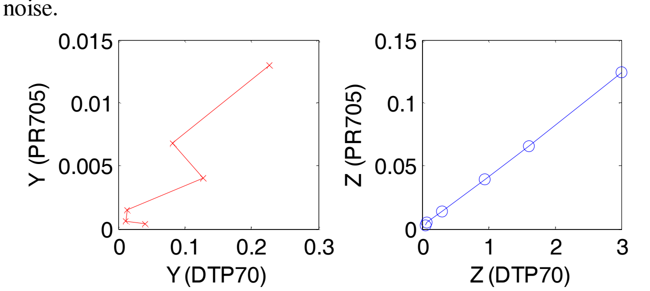

***Fig. 1** Y and Z values calculated from direct spectroradiometric measurements (PR705) compared with those calculated based on the spectrophotometric approach for a black ramp with six levels.*

To further understand this, the reflectance differences between two spectrophotometric measurements with and without UV cutoff filter were plotted in Fig. 2 for three black samples (0%, 60% and 100%). The standard CIE 1931 color matching functions (CMFs) were also superimposed. Within the region of support of the y-bar CMF, the reflectance differences were negligible, and thus the resulting Y values had very low dynamic range. Even small spectral errors caused by the differencing operation [Eq. (2)] could result in a significant error in the Y value.

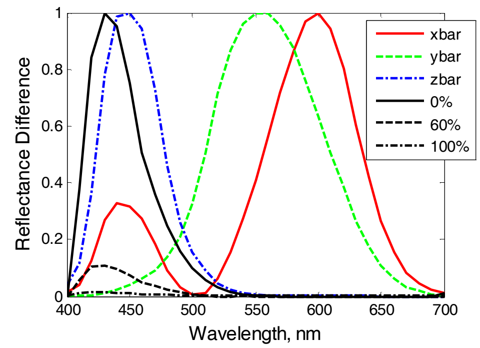

***Fig. 2** Reflectance differences between two spectrophotometric measurements with and without UV cutoff filter for three black samples (0%, 60% and 100%), along with the standard CIE 1931 color matching functions.*

On the other hand, most of the spectral variation occurred in the short-wavelength region or within the region of support of the z-bar CMF. Thus, the Z values exhibited much higher dynamic range. Is it possible to use the Z value as a lightness predictor with the advantage of higher dynamic range and lower susceptibility to noise corruption? The assumption is not valid obviously for normal lighting condition, where the Y value is the lightness predictor. However under UV lighting condition, three-dimensional perceptual color space roughly reduced to one lightness-darkness dimension. So it was tempting to entertain the possibility that the Z value might be a good predictor of the lightness-darkness dimension under this specific lighting.

To test this hypothesis, the Y and Z values calculated from direct spectroradiometric measurements for cyan, magenta, yellow, and black ramps were shown in Fig. 3, and the Z vs. Y was plotted in Fig. 4. For the black ramp, there was excellent correlation between Y and Z. For the other color ramps, there was generally a linear correlation, but the slope of the linear predictor varied with the colorant. Therefore, the Z value was a good lightness predictor for single color ramp, but might produce erroneous prediction across different colorants and their mixtures. For example, the Y value of solid yellow was much larger than that of solid black (which agreed with visual impression), but the Z values of the two colors were nearly the same.

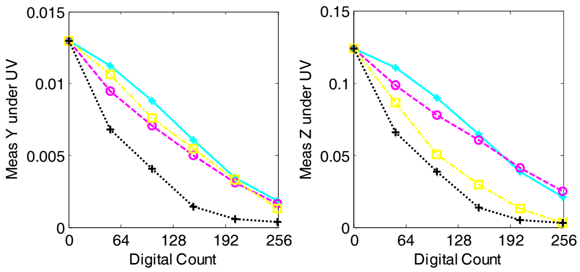

Fig. 3 *The Y (left figure) and Z (right figure) values calculated from direct spectroradiometric measurements for cyan, magenta, yellow and black ramps.*

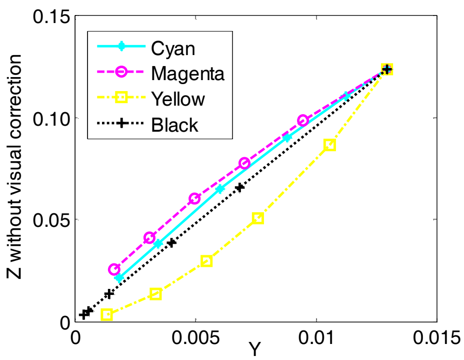

Fig.4 *Plot of Z vs. Y calculated from direct spectroradiometric measurements for cyan, magenta, yellow and black ramps.*

The trends in Fig. 4 suggested a simple method for correcting the Z value to be a reliable predictor of lightness. First, a correction factor from Z to Y was determined for each solid overprint. Then the Z value for intermediate area coverages was corrected through a simple form of interpolation. This method required the knowledge of the Y value for the solid overprints. In order to bypass the process of making spectroradiometric measurements, a simple visual luminance-matching experiment was conducted.

For the black ramp, excellent linear correlation existed between Y and Z values under UV light (Fig. 4). Furthermore, the Z values calculated from two spectrophotometric measurements were linearly correlated to those values calculated from direct spectroradiometric measurements [Fig. 1 (right)]. It was concluded that the Z values calculated from the spectrophotometric approach were an accurate lightness predictor for the black ramp. A tone reproduction curve (TRC) that mapped digital black amount to the luminance values was built. Then the relative luminance values of the overprints were found through a simple visual luminance-matching experiment. It was assumed that the two-color overprints with black colorant (e.g., cyan and black) and three-color overprints had the same luminance as solid black, so only the relative luminance values for six overprints (cyan, magenta, yellow, red, green and blue) needed to be determined.

The test target for the visual matching task was designed comprising a series of numerals made up of increasing black levels, overlaid on a given background of solid color overprints, as shown in Fig. 5. The black levels on this target increased from 53.125% to 100% with 3.125% intervals. The task of an observer was to pick a numeral which was the most difficult to read against the background under UV light in a standard light booth. So the selected black level visually matched the luminance to a given solid overprint. The relative luminance values of the color overprints were determined through the TRC curve of the black ramp.

As shown in Eq. (3), correction factor F_i for each of these six solid overprints was the ratio between the $Z_{i,vis}$ value of luminance-matched black level and the Z_i calculated from the spectrophotometric approach [Eq. (2)]. The correction factors for all the other primaries were set to 1. Then the correction factor for intermediate area coverages was weighted correction factors of the sixteen primaries and these weights were still Demichel weights [Eq. (4)]. Finally the correction factor was multiplied with the Z value calculated from the spectrophotometric approach [Eq. (2)] to predict the lightness under UV light, as shown in Eq. (5).

$$F_i = \begin{cases} Z_{i,vis}/Z_i & C,M,Y,R,G,B \\ 1 & otherwise \end{cases} \quad (3)$$

$$F = \sum_{i=1}^{16} w_i F_i \quad (4)$$

$$Z_{corr} = Z_{orig} F \quad (5)$$

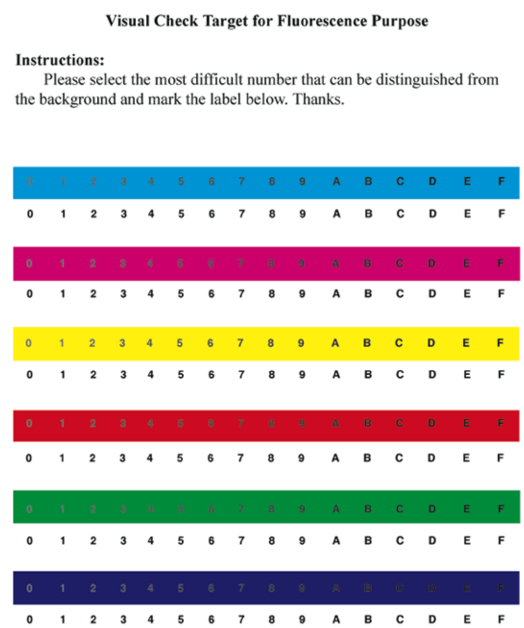

Fig. 5 *Visual luminance-matching experimental target. The task of an observer was to pick the numeral that was the most difficult to read against the background.*

In order to determine the correction factors for six colors, six observers did the luminance-matching experiment under UV light in a light booth. The results of the visual luminance-matching experiment were summarized in Table I. Each table entry was the numeral selected by an observer for a given color. The inter-observer difference was pretty small. The corresponding black levels for these six colors were 59.375%, 62.5%, 65.625%, 96.875%, 93.75% and 96.875, respectively. The luminance values for these primaries could be calculated from the TRC of the black ramp.

Table I. Results of visual luminance-matching experiment

Observer	Cyan	Magenta	Yellow	Red	Green	Blue
1	2	3	3	14	14	15
2	2	3	5	14	12	14
3	3	3	3	13	12	13
4	2	3	4	14	13	14
5	2	3	4	15	13	15
6	2	3	3	14	12	15
Avg.	2	3	4	14	13	14

The visual post-correction method could be used to correct the Z value to match luminance value for all three approaches, including the direct spectroradiometric approach and two alternative approaches. Fig. 6 was a repetition of the plot in Fig. 4, except for this time with the Z value being visually corrected. It was shown that the Z value after visual post-correction could be an excellent luminance predictor with low susceptibility to measurement error.

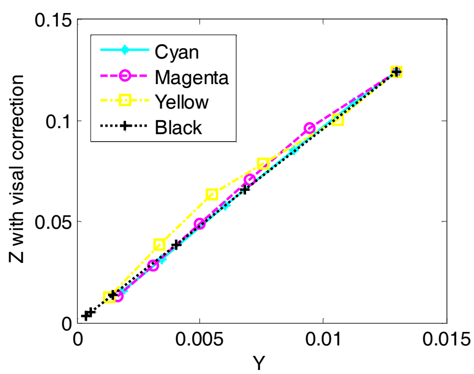

Fig. 6 *Plot of Z vs. Y calculated from direct spectroradiometric measurements for cyan, magenta, yellow and black ramps after the Z value were corrected using visual post-correction method.*

Camera-based Approach

Another approach for predicting the luminance of color prints under UV light was to use a digital camera as a color measurement device. A test target comprising patches of known colorant amounts was captured with the camera under UV light. The luminance value of each patch could be estimated from the camera RGB signals. To do this accurately, the camera should be characterized colorimetrically for the specific illumination. This in turn required spectroradiometric measurements of a target under UV light. The alternative approach proposed here bypassed the requirement of spectroradiometric measurements.

A Pentax K110D SLR digital camera was used in the experiment. The combination of aperture size and shutter speed was selected so that signals for all three channels were maximized but not overexposed. The raw image was read out, and any smart operation was turned off. The blue channel exhibited a higher dynamic range than the other two channels, and was thus the most robust to noise. The blue channel had almost the same characteristic as the Z value calculated from the spectrophotometric approach discussed in the previous section. Namely it predicted the luminance ordering for single colorant ramps, but made errors across colorant mixtures. So the visual post-correction method was also used to correct the blue channel. The camera approach provided another fast and effective method to predict the luminance ordering of color prints under UV light.

A point to note was that in general, the solid overprints were more stable than intermediate halftone mixtures; thus the visual correction task could be performed relatively infrequently and applied to either the spectrophotometric or camera-based approach, which might have to be performed more frequently.

Results and Discussions

Three different approaches were used to predict the luminance ordering under UV illumination, and they were direct spectroradiometric approach, spectrophotometric approach and camera approach. A target consisting of 48 color patches was measured with a spectroradiometer, and the luminance values calculated from the direct radiometric measurements were used as a reference to evaluate all three approaches. The colorants values of these patches were processed through each approach to produce luminance estimates. For each approach, a new target was created with the same patches sorted in order of decreasing luminance predicted. These targets were placed in the UV light booth, and visually inspected to see whether a monotonic lightness relationship was upheld. It was found that the first approach produced an excellent sorting of luminance values. Both the spectrophotometric and camera-based approaches, when combined with visual post-correction method, produced very good sorting, although a few visible deviations could be observed.

To complement the visual evaluation, an objective error metric was defined to measure the ability of a given approach to preserve the same luminance ordering as the direct radiometric measurements. The error metric was the absolute ordering error in indices between two sorting results, as shown in Eq. (6), where I_0 and I_1 are the indices from the reference and testing ordering results, respectively. The ordering result sorted by the Y value calculated from direct spectroradiometric measurements was defined as the reference ordering, as shown in Fig. 7(a). For example, the indices of solid yellow were 18 and 11 based on the sorting by Y and Z values, respectively, so the ordering error was 7 for this patch. Visual inspection also revealed that the solid yellow was not as dark as solid red, as shown in Fig. 7(b), and the ordering sorted by Y was more monotonic.

$$E = |I_1 - I_0| \quad (6)$$

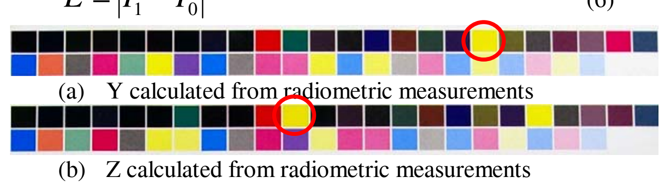

Fig. 7 *The 48 patches sorted by Y and Z values, respectively, calculated from direct radiometric measurements.*

The statistical results of luminance ordering error of three approaches were summarized in Table II. The mean ordering error for the first approach or the YNSN model was less than 1, and so it was the most accurate method. The ordering errors for the other two approaches significantly decreased after applying visual post-correction method. This improvement was also highly noticeable through the visual inspection. The camera approach with visual post-correction was the second most accurate method after the YNN model, with the spectrophotometric approach with visual post-correction being next.

Table II Statistical results of luminance ordering error of three approaches.

	Mean	Std. Dev.	95% Percentile	Max
YNN Model Y	0.83	0.93	3	3
Spectrophotometer Z	2.88	2.35	8.1	9
Spectrophotometer Z with visual correction	2.04	1.71	5.1	8
Camera Blue	2.46	2.04	6.1	10
Camera Blue with visual correction	1.21	1.29	3.1	6

Conclusions

Several approaches for predicting luminance ordering of printed color samples under UV light had been investigated. The YNSN printer model based on direct spectroradiometric measurements yielded the most accurate prediction of luminance under UV light. However, the required spectroradiometric measurements were time-consuming and laborious. Two alternative approaches were brought forth that were very convenient and cost-effective. They used a spectrophotometer and a digital camera, respectively, as color measurement devices. The experimental results showed that both approaches yielded satisfactory predictions of luminance ordering when combined with the visual post-correction method. The two approaches had been used successfully to design security UV watermarks that were invisible under normal light, but revealed under UV light.

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