Watermark encoding and detection using narrowband illumination

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Abstract

We present a watermark encoding and detection method by which colorant combinations and narrowband light sources are selected to optimally differentiate between colorant combinations that produce the same visual color under wideband illumination. Thus colors that look the same under white light can reveal additional information (e.g. watermarks) under special narrowband illumination. These different colorant combinations produce metameric matches; that is, colors that are spectrally different but that integrate to the same color for a human observer under a particular light source. The metameric colorant combinations and narrowband illumination can be jointly selected to allow sufficient or maximal discrimination under the potential narrowband illuminants. Alternately, for a given colorant combination that achieves sufficiently similar appearance under wideband illumination, narrowband illumination such as LEDs (singly or in combination) can be optimally selected to reveal colorant differences.

1. Introduction

It is common practice to embed watermarks or hidden information into printed documents using special inks that make them invisible in white light and visible under special lights. An example is the ultraviolet (UV) based watermark found in currency and passports. Metameric inks are sometimes used for watermarks in currency printing.[1] Since such special colorants are costly, this type of security feature is feasible only for applications where the document is of very high value (e.g. passports) or printed in very long runs (e.g. currency). These markets are traditionally served by offset printing systems. On the other hand, it would be desirable to offer similar security features with standard digital printing materials and media, thus supporting low-volume and/or personalized imaging applications.

Many reviews are available of digital watermarking techniques.[2] Several researchers have investigated methods for embedding information into a printed image by varying standard colorant signals while holding color appearance information constant. DeQueiroz et al.[3] embed information into a document by modulating the gray-component replacement (GCR) strategy that affects the ratio of black (K) to cyan, magenta, and yellow (CMY) colorants. Decoding is accomplished by detecting specific halftone patterns within a scanned image. UV-based decoding schemes have also been proposed[4,5] whereby colorant patterns are selected that produce a visual match under a standard (e.g. D50) light source, while suppressing substrate fluorescence by different amounts. The watermark is thus detected by viewing the print under UV light. At the other end of the spectrum, infrared (IR) based schemes have also be conceived[6], wherein two colorant patterns appear the same under normal light, but appear different when illuminated with IR light and detected by an IR sensor.

Central to all the aforementioned approaches is the concept of metamerism, whereby two spectrally different colors integrate to the same color for a human observer under a first light source, but integrate to different colors under a second light source.

2. Watermark based on narrowband illumination

The idea presented in this paper complements the aforementioned approaches with a technique for optimally selecting narrowband illumination to reveal information hidden by metameric-based techniques, such as the varying-GCR technique described in Ref 1. Metameric-based embedding techniques result in different spectral reflectance functions for the same desired color. Narrowband light sources are designed or selected to highlight or accentuate the spectral differences. Optimization can be used to design or select illuminants that accentuate a given metameric pair, or the metameric pair and illuminants can be jointly optimized to provide desirable properties in both wideband and narrowband illumination. The experiment described in this paper employs color light-emitting diodes (LEDs) as a type of narrowband illumination. LEDs are inexpensive and commercially available for a large set of peak wavelengths within the visible spectrum.

The embedding method of spatially modulating between two different GCR techniques results in two different spectral reflectance functions (SRFs) for a given color at different locations within a printed image. The colorant combinations of the GCR techniques are determined such their perceived color match for a given light source (often CIE D50 Illuminant for printing). When the light source is different from D50, the match will likely not hold exactly. The effect is usually quite subtle for most white light sources. However, if the light source is carefully selected to have its power in the regions of the spectrum where the two colors have maximum difference, the color difference between them can be accentuated and readily seen. This is the crux of the proposed technique: selecting LEDs with illumination spectral power distributions (SPDs) that produce the greatest color mismatch between two otherwise metameric samples. The metameric pairs can be created using ways other than GCR modulation but was a simple method to achieve metameric pairs for color printing. The present technique is suitable for decoding any method of embedding that relies on the use of metamers to hide information in a printed image.

Metameric pairs for a set of 300 color samples were printed on a Xerox DocuColor 8000 printer and the SRFs measured. The SRFs for two such pairs are shown in Fig. 1. Each pair was created by finding two CMYK combinations that produce the same CIELAB value for CIE Illuminant D50 and the CIE Standard 2º Observer. The two members of the pair were made with the minimum and maximum allowable K respectively. Interestingly, we observe in Fig. 1 that the most pronounced spectral differences between the two members of a pair occur in similar wavelength bands for both examples. Remarkably, we found this to be the case for the vast majority of the colors in the set. This suggests that LEDs whose SPDs are concentrated within these bands will produce good distinction between metamers for a wide range of metamer pairs. Note that this is expected to hold true only for the given set of printing parameters, which includes the printer, colorant set, substrate, marking technology, halftoning, etc. A variation in any of these parameters may require a new analysis and different choice of LEDs.

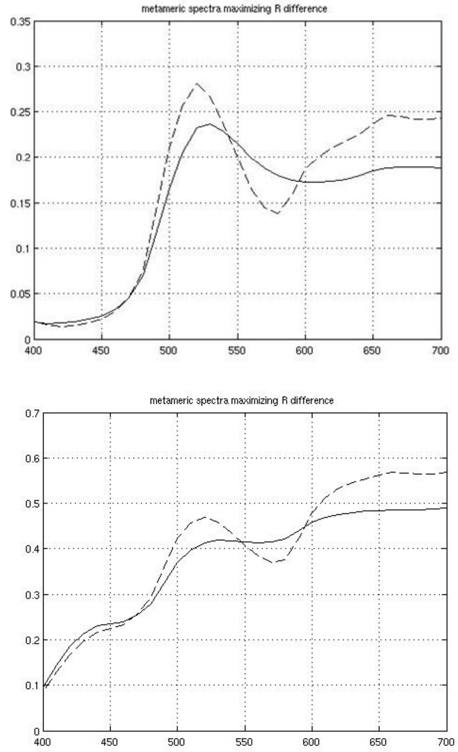

Fig. 1. Spectral reflectance functions of metameric pairs created on a Xerox DocuColor 8000 using maximum and minimum GCR strategies.

To determine the best LEDs for detecting metameric watermarks with the given printer, the following methodology was used. 300 CIELAB colors were chosen that were approximately uniformly distributed within the printer gamut. For each color, a metamer pair was created as described previously, with minimum and maximum allowable K respectively. Note that using GCR strategies that are not as drastically different may make the watermark less susceptible to being seen under regular viewing conditions, but then less visible under the revealing conditions.

The following analysis was performed to determine the optimum LED peak wavelengths for a given set of colorants. Define $D(\lambda) = R_1(\lambda) - R_2(\lambda)$ where R_1 and R_2 are the two members of a metameric reflectance pair, and define

$$F(\lambda) = \int D(\lambda')V(\lambda')L(\lambda - \lambda')\, d\lambda' \quad (1)$$

where $V(\lambda)$ is the photopic luminous efficiency function that describes the sensitivity of the human visual system to luminance at wavelength λ, and $L(\lambda)$ is a function whose shape is that of a typical LED SPD, but shifted to a peak wavelength of 0. The quantity $F(\lambda)$ therefore describes the luminance difference between the metamers R_1 and R_2 when illuminated with an LED with its peak at wavelength λ. Note that F is a signed function taking on positive values when R_1 is brighter than R_2, and negative when R_1 is less bright than R_2. Figure 2 plots $F(\lambda)$ for the first pair of metamers in Fig. 1.

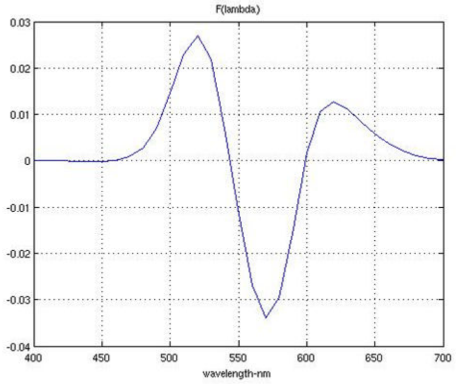

Fig. 2. F(λ) is the spectral luminance difference between the pair of metamers shown in Fig. 1a.

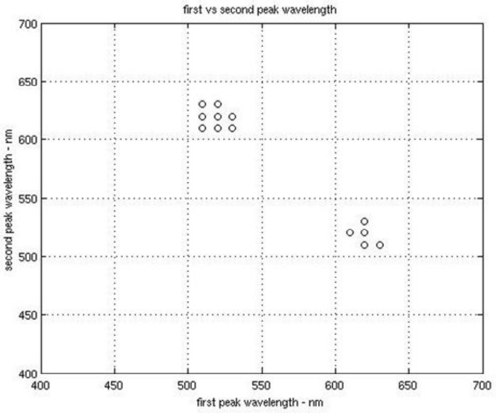

Fig. 3. Peak wavelengths of the spectral luminance difference for 300 pairs of metamers and the given set of printing conditions.

For this pair, we see that F has maxima at 520 nm and 620 nm, and a minimum at 570 nm. A similar analysis was performed for all metamer pairs in our test set, and the wavelengths of the first two maximum peaks were collectively plotted, as shown in Fig. 3.

Figure 3 reveals that the two peaks are closely clustered with means calculated as 518 nm for the shorter wavelength, and 621 nm for the longer wavelength. Note the two clusters are symmetric about the $y = x$ axis. This was taken into account when computing the cluster means. We can infer that LEDs centered around these two wavelengths will produce the best visibility of a watermark signal made up of metameric CMYK pairs for this printer. Since the sign of the luminance difference at both wavelengths is of the same polarity (namely the minimum-K combination appears brighter than the maximum-K combination), Grassmann's law of additive light mixing tells us that a mixture of the two LEDs at the respective peaks will produce even better luminance distinction. A corresponding analysis can be done to find minima of F and obtain wavelengths wherein the minimum-K combination appears darker than the maximum-K combination. For visual watermark detection, it is preferable to look for peak wavelengths that produce differences of the same polarity. On the other hand, if the watermark is to be detected by a device such as a LED scanner, opposing polarities could be detected, and sum and difference operations could be used to maximize the strength of the decoded watermark signal.

Figure 4 shows SPDs of two realizable LEDs that exhibit peak wavelengths that are very close to the optimum cluster means computed above. The LED green and red peaks are at 525nm and 620 nm respectively.

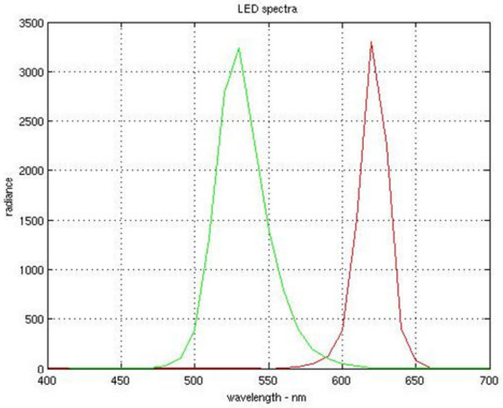

Fig. 4. LED spectral power distributions corresponding to the optimal wavelength peak shown in Fig. 3.

For these LED SPDs the watermark strength for a given metamer pair (R_1, R_2) can be calculated as:

$$\text{Watermark strength} = | Y_1 - Y_2 |, \text{ where}$$
$$Y_1 = \int R_1(\lambda) \times S(\lambda) \times V(\lambda)\, d\lambda \qquad (2)$$
$$Y_2 = \int R_2(\lambda) \times S(\lambda) \times V(\lambda)\, d\lambda$$

where R_1 and R_2 are the spectral reflectances of the metameric pair, S is the spectral power distribution of the one or more LED light sources of interest, and $V(\lambda)$ is again the spectral luminous efficiency function. This figure of watermark strength can be used to find pairs of colors that are particular good for watermarking.

3. Experimental Results

A set of metameric pairs of patches was created on the Xerox DocuColor 8000 printer with GCR strategies employing the minimum and maximum K amounts respectively. The pairs were sorted from strongest to weakest watermark strength (as defined in Eqn 2).

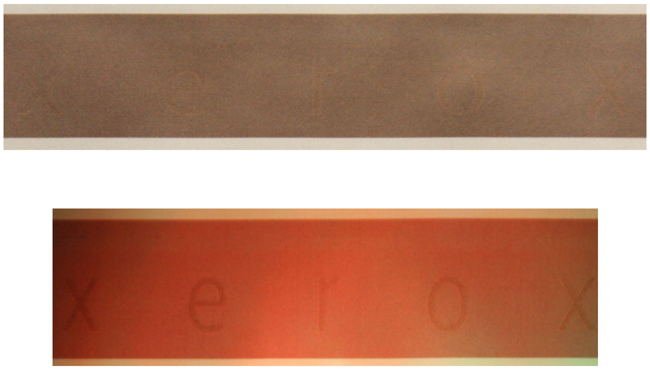

Fig. 5. Watermark example for the strongest watermark signal. Top shows image photographed under daylight illumination. Bottom shows the same image photographed under the LED illumination shown in Fig. 4.

Fig. 5 shows an example of a pair with one of the strongest watermark signals. The samples were photographed with a digital camera under daylight illumination (upper image) and LED illumination comprising the combination of both the red and green LEDs of Fig. 4 (lower image). Note that the visibility under broadband illumination can be further reduced via the use of distraction textures or other means.

Fig. 6 shows an example of a natural image with an embedded watermark photographed under normal light and under LED illumination. The lower image has been magnified in order to make the watermark clearly visible.

4. Summary

There are many techniques in the literature for watermarking documents or hiding information within them. The methods often depend on the availability of special colorants that are visible under IR or UV but not under visible light. We have presented a technique that uses readily available colorants and media in standard digital printers to embed and later reveal information in printed images using illumination that is readily and cheaply available, namely narrowband LEDs. The watermarks are fragile and do not hold up to copying; the metamers in the copy are reproduced by nearly identical colorant combinations and thus the watermark is destroyed.

There are several engineering issues that should be addressed to make this technique more robust. First, the color matches that are obtained by the metameric pairs are sensitive to printer characterization and drift, illumination changes, and possibly observer differences. Thus in the encoding process, a masking texture might be used, or GCR strategies that are not so extremely different. Also the metamers in the experiment were obtained by using a fixed halftoning scheme and searching for pairs in continuous-tone CMYK space. A generalization of this would be to directly derive binary dot patterns that exhibit the metameric property, but that do not necessarily arise from a single halftoning scheme.

The technique described in this paper does not require LEDs as the detection illumination. While carefully selected narrowband illumination are best in bringing out the spectral differences between metamers, certain fluorescent light sources, which are white but have sharp peaks, might also be used in this application, as could lasers, scanners, or color sensors with narrowband illumination.

The metamaric pairs were selected as the extrema in GCR schemes. There may conceivably be alternative ways to select metamer pairs that minimize color difference under broadband light, while maximizing the detected signal under narrowband illumination.[4] Finally a study to determine the robustness (or sensitivity) of the watermarking technique across different printers and print conditions would be a valuable next step.

Fig. 6. Watermark example showing image photographed under daylight illumination (top) and same image photographed under the LED illumination from in Fig. 4 (bottom).

5. References

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