Illuminant Multiplexed Imaging: Special Effects using GCR

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Abstract

A novel spectral imaging technique is presented that allows multiple grayscale images to be combined in a single hardcopy print. The images are individually revealed when the print is illuminated by suitably chosen illuminants. In its basic form, the technique utilizes the complementary relation between cyan, magenta, and yellow colorants and narrow-band red, green, and blue illumination to combine and extract images. Colorant interactions are compensated through a simple calibration process. In addition, we present techniques demonstrating how gray component replacement (GCR) may be defined for illuminant multiplexed imaging and how it may be successfully exploited to allow embedding of additional patterns in the print that are revealed under uncontrolled illumination. The paper is accompanied by a light-booth based demonstration of illuminant multiplexed imaging and the effects described herein.

1. Introduction

The term *color constancy* is used to describe the phenomenon that objects are often recognized as having the same perceived color even under conditions of lighting that exhibit significant variations in their spectral power distributions (SPDs). Typical examples of such SPDs include phases of daylight and a variety of artificial lighting sources. Color constancy however is not perfect and as illustrated by metameric pairs — there are objects whose perceived color varies as the illumination is changed. In common color imaging applications, the variation in color appearance of a hardcopy print as it is viewed under a variety of uncontrolled lighting sources is quite undesirable. In this paper, we present techniques that actively exploit the change in color appearance with change in viewing illumination to produce novel imaging effects.

Under typical changes in lighting, the colors of a hardcopy print may shift but the overall image content remains largely unaltered. Under drastic changes in illumination, however, one can produce significant differences in the perceived image content itself. In the present paper, we describe how the latter type of change can be controlled and exploited for novel imaging applications. In particular, we present techniques that allow us to combine or *multiplex* images with disparate image content such that the individual images are revealed under different light sources. Drawing from the analogy with multiplexing techniques in communication systems, we refer to the technique as *Illuminant Multiplexed Imaging* (IMI).

The basics of IMI and a preliminary demonstration have been presented earlier in [1], where we illustrated how very disparate pictorial images may be multiplexed in a single color print and demultiplexed using suitably chosen narrow-band illumination. In this paper, we illustrate how the concept of *gray component replacement* (GCR) can be extended to IMI and exploited for additional special effects. Using the GCR concept we demonstrate how a visible watermark-like pattern may be embedded using GCR for IMI. The embedded pattern is seen under normal lighting but does not interfere with the individual images seen under the corresponding narrow-band illuminants.

For completeness, we begin with a brief introduction and overview of IMI. We describe how the concept of *gray component replacement* (GCR) can be extended to IMI. In addition we demonstrate both basic IMI and special effects that exploit the freedom offered by GCR in IMI.

2. Illuminant Multiplexed Imaging

Just like conventional color imaging, IMI exploits the interaction between the illuminating light and colorants used for printing and the manner in which the eye adapts to illumination. However, unlike color imaging, IMI uses narrow-band illumination, which combined with the light colorant interaction enable the multiplexing of multiple images.

2.1. Colorant Physics

Color hardcopy printing typically employs cyan, magenta, and yellow colorants that selectively absorb the light energy in the long ($\approx 600 - 700nm$), medium ($\approx 500 - 600nm$) and short ($\approx 400 - 500nm$) wavelength regions, respectively, of the visible spectrum. For an observer, the energy in these long, medium, and short wavelength spectral bands contributes to the sensation of red, green, and blue, respectively, and these are therefore referred to colloquially as the red, green, and blue regions, respectively (of the visible spectrum). Different colors are reproduced in printing by varying the amounts of the colorants to selectively "subtract out" spectral energy from the red, green, and blue regions (the energy being provided by a broad spectrum source of illumination) [2, 3]. In the ideal situation, the colorants absorb light energy only in their absorption bands and have no absorption in other regions of the visible spectrum.

2.2. Color Perception Under Narrow-Band Illumination

Under normal viewing illumination, the eye adapts to the *white point*, which usually corresponds to unprinted paper with the highest reflectance and different colors can be seen by the eye for prints made with different colorant combinations. Most models for chromatic adaptation are based on the Von Kries model [4], which hypothesizes that chromatic adaptation is achieved through individual adaptive gain control on each of the three cone responses. It can be shown that the Von Kries model predicts that all objects with tristimulus values in the same proportion as the substrate will appear to have the same CIELAB hue as the substrate. Under monochromatic illumination, it can be further shown that all tristimulus values are in the same relative proportions [5]. Thus prints viewed under monochromatic illumination appear to have a single constant hue identical to the substrate. If the substrate is perceived as achromatic or gray, so are all other regions. This is indeed observed in practice: Images viewed under narrow-band illumination appear to have only varying levels of gray and little or no chroma[1]. We exploit this aspect of "monochromatic perception" in IMI. Since the tristimulus values are in a fixed proportion, under monochromatic lighting only one of these values is independent. For our discussion, we will use the luminance (Y) value. The illumination typically used for IMI is narrow band rather than strictly monochromatic, however, the above description is still largely applicable.

2.3. Illuminant Multiplexing

A general mathematical framework for IMI has been previously described [1] and additional details are covered elsewhere [5], where additional analogies are drawn with conventional color imaging and an IMI gamut is defined. In this section, we present an idealized description that illustrates the principle and also forms the basis for the discussion on GCR for IMI in the next section.

Since cyan, magenta, and yellow colorants absorb red, green, and blue regions of the visible spectrum, respectively, illuminating a color print with red, green, and blue illumination reveals primarily the images printed in the corresponding separations as the variation in luminance. This is true in general, whether the illumination is narrow-band or occupies a wider-band in the corresponding spectral region. Narrow-band illumination, however, has the added advantage that the perceived images do not have any hue variations and appear to be the same hue as the substrate, thus producing the impression of a grayscale image. Thus both the physical interaction of colorants under narrow band illumination and the adaptation in the eye are necessary in order to facilitate IMI.

As an idealized model of imaging, we assume that the subtractive colorants combine additively in (spectral) density and the illuminants are sufficiently narrow band to be approximated as monochromatic. For notational simplicity we further assume that the amount of a colorant is normalized in terms of its optical density under the complementary illuminant.

Consider a region of the image printed with cyan and yellow colorant amount a_C and a_Y, respectively. When the print is illuminated by red light, the normalized "visual" density of the region is

$$d^R(a_C, a_Y) = -\log\left(\frac{Y^R(a_C, a_Y)}{Y^R(0,0)}\right)$$

where $Y^R(a_C, a_Y)$ represents the perceived luminance of the region under red illumination, and $Y^R(0,0)$ is the luminance of the unprinted substrate under the red illumination. Under our idealized model, $d^R(a_C, a_Y)$ is a function of a_C alone and in order to simplify notation and graphs, we further assume that the colorant amounts are normalized so that $d^R(a_C, a_Y) = a_C$. Likewise we assume that the density under blue illumination is identical to the amount of yellow, i.e., $d^B(a_C, a_Y) = a_Y$.

Figure 1 illustrates IMI in this ideal scenario. The abscissa of the plot indicates the spatial dimension and the ordinate represents the density/colorant amount normalized

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[1] One may note here that a particular discrepancy can be seen between the modes of vision [6, pp. 168-172] corresponding to self-luminous objects and surface colors with regard to monochromatic sources of light. Narrow-band self luminous sources such as lasers and LEDs appear colored even when viewed in isolation, indicating that the eye never fully adapts to these. However, objects illuminated by these sources, indeed appear to be gray indicating that the adaptation in the eye in this mode is fairly successful.

between 0 and 100. Different spatial patterns are printed with the cyan and yellow colorants, shown as the plots labeled a_C and a_Y, respectively. Under red illumination the optical density d^R matches the amount of cyan colorant — the perceived image is thus the "negative" of this spatial profile of the cyan colorant amount. Similarly, under blue illumination, the optical density matches the spatial profile of the yellow colorant amount and the corresponding image is revealed. The plot also shows the appearance of the image under broad-band ("white") illumination as the density d^W, which for the purposes of the plot is approximated as $d^W = 0.6a_C + 0.1a_Y$. Note that the "white" density is dominated by the cyan colorant because the visual luminous efficiency function weights the green and red regions of the spectrum significantly higher than the blue region.

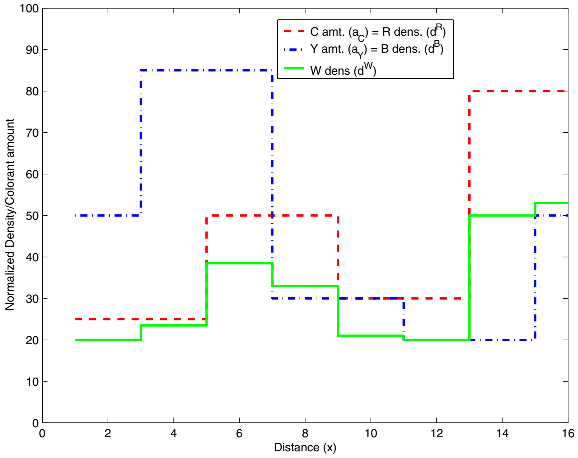

Figure 1: *IMI with ideal cyan and yellow colorants.*

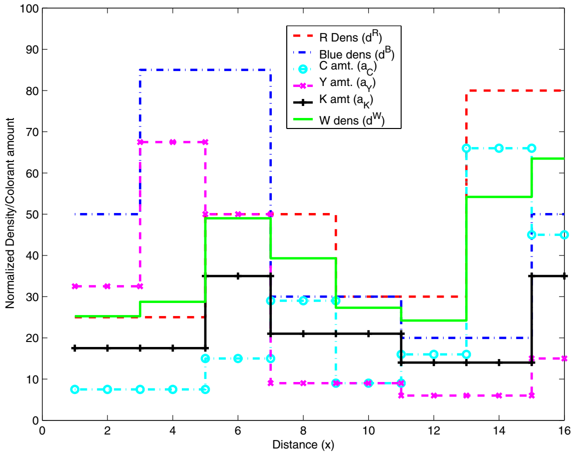

Figure 2: *GCR at 70% for IMI with ideal colorants.*

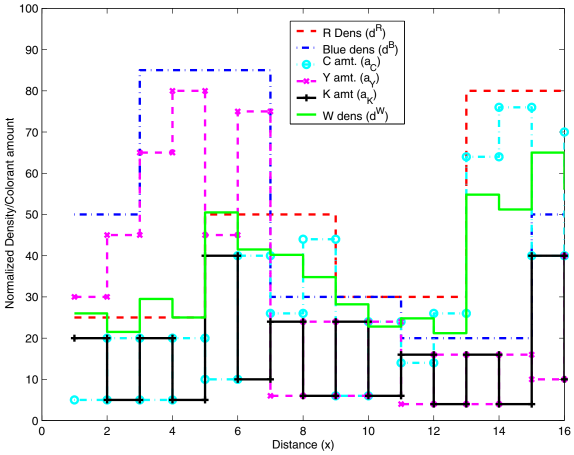

Figure 3: *GCR at 70% for IMI with ideal colorants.*

3. Black Colorant and Gray Component Replacement in IMI

A black colorant is commonly used in conventional color imaging. The black colorant absorbs light energy uniformly over the full extent of the visible spectrum and is used as a replacement for combined CMY for reasons of economy and improved rendition of dark regions (larger gamut in darker regions). In several regions of the color space, the black colorant offers a degeneracy in conventional color imaging, i.e., several desired colors can be produced by using varying amounts of the black colorant, within a range from a minimum to a maximum. The selection of the amount of the black colorant is typically done through process that replaces the gray component of colors with the black colorant, typically referred to as *gray component replacement* (GCR).

The black colorant offers similar advantages of economy and improved gamut in IMI and the notion of GCR can also be readily extended to IMI. The central idea behind GCR for IMI is that a fraction of the common density required under red and blue illumination may be replaced by using a black colorant instead. The amount of black colorant that may be utilized can be selected according to various criteria similar to those used for determining GCR in conventional imaging. Figure 2 illustrates GCR in IMI for the ideal model developed in the last section. For the purposes of this figure we assume that 70% of the common density between the red and yellow colorants is replaced by the black colorant. Furthermore, for simplicity we assume that the amount of black colorant a_K is normalized to be identical to its density which is the same under "white", red and blue illumination. The plot in Fig. 2 is intended to relate to Fig. 1. Note that the plots representing the perceived density under red illumination d^R are identical in the two figures, despite the difference in colorant combinations. Likewise, the plots for perceived density under blue illumination d^B are identical in the two figures. Thus the perceived images under red and blue illumination are the same for either of these colorant combinations. In Fig. 2, however, the black (K) colorant is used to replace some of the common amount of cyan and yellow colorants. In particular, for this plot the amount of black (K) colorants is determined as $a_K = 0.7 \min(d^R, d^B)$ corresponding to a "70% GCR" as indicated earlier. Under our simplified model, the density under red is the sum of the amount of cyan and black colorants $d^R = a_C + a_K$ and the density under blue is the sum of the amount of yellow and black colorants $d^B = a_Y + a_K$. From the desired red and blue densities (the desired images to be multiplexed), the amounts of cyan and yellow may therefore be readily determined as $a_C = d^R - a_K$ and $a_Y = d^B - a_K$. Figure 2 also includes a plot of the "white" density, which for the purposes of this illustration is approximated as $d^W = 0.6a_C + 0.1a_Y + a_K$. Note that in comparison to Fig. 1 the amount of cyan and yellow colorants consumed are lower.

By comparing the plots labeled d^W in Fig. 2 and Fig. 1 we can see that in addition to the saving on more expensive colorants, GCR has an unintended side effect that the "white" density or equivalently, the perceived image under broad-band illumination changes. This suggests additional opportunities for exploiting GCR.

By varying the GCR spatially, additional special effects may be obtained in IMI. In particular the spatial variation in GCR can controlled (or modulated) using a lower resolution image or pattern. The pattern of the GCR is then visible under uncontrolled broad-band illumination. This is illustrated in Fig. 3 where the GCR varies between 20% and 80% in alternate regions. Note that the modulation in GCR is seen as alternate light and dark stripes in the image under broad-band illumination (the plot d^W), while the images seen under red illumination (d^R) and under blue illumination d^B are unchanged. In actual practice, a 2-D pattern may be embedded. The technique can used, for instance, to embed a binary logo pattern which is visible in uncontrolled broad-band illumination by setting the GCR to a high value over the logo and to a low value over the remainder of the image. Spatial modulation of the GCR may also be used for alternative purposes. By varying the GCR randomly over small blocks of the image one can create a noisy appearance for the image under "white" illumination that makes the individual multiplexed images less apparent under normal (uncontrolled) broad-band illumination.

4. Practical IMI Implementation

Actual colorants used in color imaging show considerable deviation from the ideal behavior described in the previous sections. The primary non-ideal characteristic is that the colorants absorb spectral energy outside their primary absorption bands. This is illustrated in Fig. 4, which shows the reflectance spectra for white paper and cyan, magenta, yellow, and black colorants (100%) on a dye-sublimation printer. From Fig. 4, it is clear that in addition to absorbing in its primary red absorption band, the cyan colorant also absorbs in the green and blue regions of the visible spectrum. Likewise, the magenta colorant has significant absorption in the blue region in addition to its primary green absorption band. The yellow colorant shown in Fig. 4 has negligible absorption in the red region of the spectrum and also a relatively minor absorption in the green region with most of its absorption restricted to the blue region. The situation shown in Fig. 4 is fairly typical of most colorants used in practice. The unwanted absorptions of the colorants limit the achievable color gamut in color printing applications and are therefore undesirable. In practice, however, colorants with no unwanted absorptions remain commercially unrealizable and color printers work as best they can with the available colorants.

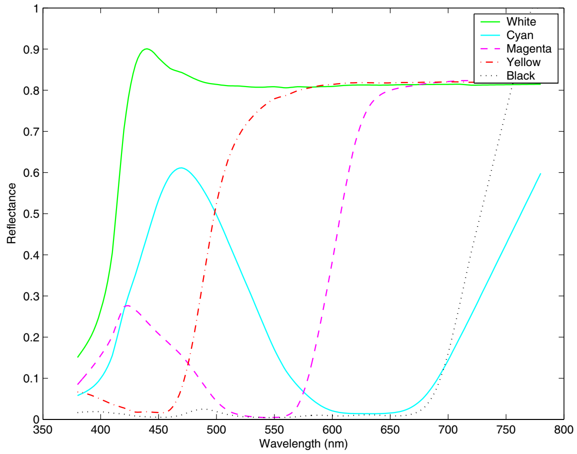

Figure 4: Reflectance spectra for white, cyan, magenta, yellow, and black (100%) for a dye sublimation printer.

The non-ideal behavior of colorants also impacts IMI. If three (different) individual images are printed using practical non-ideal colorants and viewed under narrow-band red, green and blue illumination, the unwanted absorptions cause interference among the images in the different planes. To avoid the problem of interactions between the colorants under the different illuminants, a characterization of the printing process and the illuminants is required so that the interaction effects can be compensated. With proper compensation we can produce suitable prints such that under each illuminant only the corresponding desired image is seen, with minimal interference from images intended to be seen under other illuminants. The special conditions for IMI do allow for some simplification of the characterization process. Details of this process may be found in [1, 5].

5. Experimental Results

A contone dye sublimation printer and a xerographic color printer were individually calibrated for use in IMI. The calibrations were based on measurements of spectral power distributions of selected narrow-band red, green, and blue illuminants and spectral reflectance measurements of printed samples on the individual devices, from which the luminance responses under the individual illuminants were determined.

Several IMI examples were generated by using the IMI techniques discussed and printed on the respective printers. These include prints with:

1. two images multiplexed using cyan, yellow, and black colorants for viewing under red and blue narrow-band illumination.
2. two images multiplexed using magenta and cyan for viewing under green and red narrow-band illumination.
3. one image multiplexed with a flat field using cyan and black such that the image spatial variation is seen under narrow-band red illumination but disappears under blue illumination.
4. two images multiplexed using cyan, yellow, and black colorants for viewing under red and blue narrow-band illumination, where the amount of black is selected according to an X shaped pattern that is visible under uncontrolled illumination and only the individual images (without the X) are seen under the corresponding narrow-band illuminants.
5. two images multiplexed with cyan, yellow, and black colorants for viewing under red and blue narrow-band illumination, where the amount of black is randomly varied over square blocks to produce added noise under uncontrolled broad-band illumination.

The demonstration accompanying this paper shows these images in a light booth where alternating between the corresponding narrow-band illuminants reveals the two different images.

The color insert accompanying this paper illustrates the use of GCR in IMI. Color Plate A illustrates a print where two images have been multiplexed using cyan, yellow, and black colorants, such that one is revealed under narrow-band red illumination and the other is revealed under narrow-band blue illumination. Color Plate B illustrates the same two images with an additional pattern in the shape of an X that is visible under broad-band illumination but does not impact the visual appearance of either of the images. narrow-band illumination for viewing these samples can be obtained, for instance, by using the individual red and blue channels of a cathode ray tube (CRT) as sources of light in an otherwise darkened room[2].

6. Conclusion

We introduce an alternate “color/spectral” imaging framework that we refer to as *illuminant multiplexed imaging* (IMI). The technique allows multiple gray-scale images to be combined in a single hardcopy print such that the individual images are revealed under suitably chosen narrow-band illumination. We describe the basic theory of illuminant multiplexing which exploits the control offered by the colorants in a printing system to simultaneously control the 1-D luminance attributes of the print under multiple narrow-band illuminants. This is in contrast with the conventional color imaging scenario, where the 3-D color attributes under a single broad-band illuminant are controlled using the colorants.

Several simplifications of this general framework were also presented ranging from practically useful to those intended to illustrate the concepts in an idealized setting. The theory of IMI was extended to cases employing a black colorant in a manner similar to the extension of conventional imaging with the incorporation of a black colorant and *gray component replacement* (GCR) methods were discussed for IMI. Particular demonstrations of special effects using the flexibility offered by GCR were also discussed.

The prints included with the hardcopy version of this paper demonstrate IMI and the use of GCR in IMI in a suitably controlled lighting environment.

References

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[2] Care should be exercised to minimize “stray” light from both the display offset and from outside. In particular, even a small amount of light in other spectral regions produces a significant interference with the image under blue illumination.

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