Illuminant Multiplexed Imaging: Basics and Demonstration

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Abstract

We present a novel spectral imaging technique that allows multiple gray-scale images to be combined in a single hard-copy print. The images are individually revealed when the print is illuminated by suitably chosen light sources. In its basic form, the technique utilizes the complementary relation between cyan, magenta, and yellow colorants and narrow band red, green, and blue illuminants to combine and extract the images. Instead of the conventional color imaging scenario, where three-dimensional color attributes of a print are controlled under a wide-band illuminant using a set of colorants, in illuminant multiplexed imaging, one dimensional luminance attributes under two or more narrow-band illuminants are simultaneously controlled using the same colorants. We present a brief mathematical framework for illuminant multiplexed imaging and describe useful approximations that significantly simplify implementation. Several applications of the technology are presented.

1. Introduction

The perception of color is the result of interaction between a physical stimulus; receptors in the eye that sense the stimulus; and the neural system and the brain; which are responsible for communicating and interpreting the signal sensed by the eye. One of the fascinating aspects of human vision is that perceived object colors remain largely invariant under lights with significant variations in intensity levels and spectral distributions. Thus objects are often recognized as having approximately the same color in phases of daylight having considerable difference in their spectral power distribution (SPD) and also under a variety of artificial lighting sources. This phenomenon is called *color constancy* [1, 2]. In practice, however, color constancy holds true only approximately and it is not uncommon for a change in perceived color with change in illumination. A particular illustration of this can be seen in *metameric pairs* which match under one illuminant and differ under another.

In common applications of color printing, the printed images are often viewed under a variety of uncontrolled lighting sources and the variation in color appearance with change in viewing illumination is typically undesirable. The colorants and processing algorithms for colorant selection are therefore designed so as to minimize variations in perceived color under commonly used lighting sources. As an alternative, in this paper, we present techniques which exploit the change in color appearance with change in viewing illumination to produce novel imaging effects.

The change in the appearance of a printed image under different common viewing illuminants (office fluorescent lighting, outside daylight, incandescent lamps, etc) is typically a change in the apparent colors of different regions, without a change in the overall image content. Under drastic changes in illumination, however, it is possible to 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 in communications, we refer to the technique as *Illuminant Multiplexed Imaging* (IMI).

2. Illuminant Multiplexed Imaging

IMI exploits the interaction between the illuminating light and the colorants used for printing and also the manner in which the eye adapts to illumination with narrow band spectral power distribution. For illustrating the idea in concrete terms, we base parts of our description on the Cyan, Magenta, Yellow, and Black colorants commonly used in color printing applications and narrow band Red, Green and Blue illumination obtained, for instance, by using the individual channels of a cathode ray tube (CRT) as sources of light. The technique however is general and can apply to arbitrary colorants and illuminants with trade-offs determined by their physical characteristics.

2.1. Colorant Physics

Color hardcopy printing is a subtractive process, wherein color is produced by spectrally selective subtraction of light energy from illumination emanating from a source [3, 4]. Cyan, Magenta, and Yellow colorants are the commonly used primary colors because they offer the largest gamut in a subtractive system. Ideal Cyan, Magenta and Yellow colorants absorb the light energy in the long (roughly, 600-700nm), middle (roughly, 500-600nm) and short (roughly, 400-500nm) wavelength regions, respectively, of the visible spectrum leaving other regions of the visible spectrum unchanged. These long, middle, and short wavelength regions of the visible spectrum will be referred to as the red, green and blue regions. Furthermore, in the ideal situation the absorption bands of the individual colorants are non-overlapping and completely cover the visible region of the spectrum. Actual colorants do not satisfy these *block-dye* assumptions[1], instead, their absorption spectra are smooth and include some unwanted absorptions in their transmission bands. The black colorant absorbs light energy uniformly over the full extent of the visible spectrum. The reflectance spectra for white paper and Cyan, Magenta, Yellow, and Black colorants (100%) on a dye-sublimation printer are shown in Fig. 1.

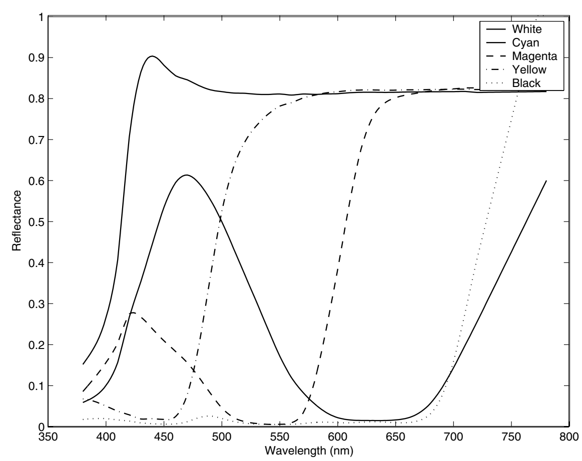

Figure 1: *Re ectance spectra for White, Cyan, Magenta, Yellow, and Black (100%) for a dye sublimation printer.*

2.2. 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. However, under relatively narrow band illumination, such as that obtained from a single gun of a CRT monitor, the eye is unable to distinguish color. Images viewed under narrow band illumination therefore appear to have only varying levels of gray and little or no chroma. Since the absorption characteristics of the colorants differ in different spectral bands, their reflectance (or density) under different narrow band illuminants is also different. For the remainder of this paper, the viewing illuminants are assumed to correspond to narrow band illumination in the long, middle and short wavelength regions of the visible spectrum, which is referred to using colloquial language as red, green, and blue light. An example of red, green and blue narrow band illumination is shown in Fig. 2, where the spectral power distributions obtained using typical Red, Green, and Blue CRT primaries are shown.

[1]For a more detailed background, refer to [4, 5].

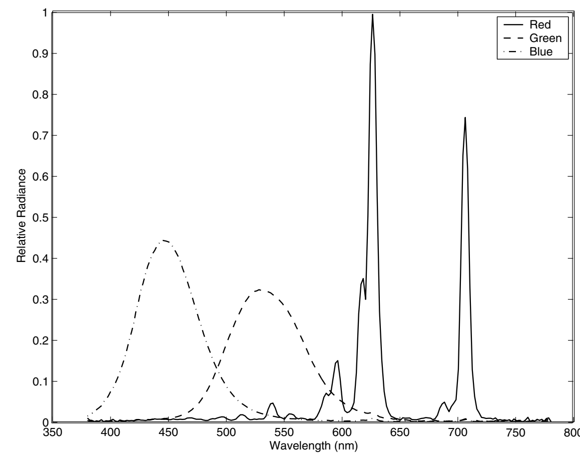

Figure 2: *Relative Radiance Spectra for the red, green, blue primaries for a typical CRT.*

2.3. Illuminant Multiplexing

Since cyan absorbs red, cyan printed regions appear darkest under red light and lightest under blue light with an intermediate darkness under green light. Likewise magenta appears darkest under green light, and typically lightest under red light with intermediate darkness under blue light. Yellow appears darkest under blue light and lightest under red light with intermediate darkness under green light. If the colorants are ideal, they appear dark under the light they absorb and white under lights outside their absorption bands. Thus using ideal CMY colorants and non-overlapping RGB illuminants, three individual images could be printed using each of the C, M, Y colorants and these will be revealed under R, G, and B lights, respectively. However, the colorants found in practice have unwanted absorptions outside their primary absorption bands and practical illuminants may have partially overlapping spectra. From Fig. 1, 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. 1 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. 1 is fairly typical of most colorants used in practice. The near ideal characteristics of the Yellow colorant are commonly expressed as the statement: "yellow is the purest colorant and cyan and magenta colorants are impure." 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. If three (different) individual images are printed using practical non-ideal colorants, the images interfere with each other and are therefore not perceived as separate images under the different lights.

3. Mathematical Framework for IMI

A general theory of IMI may be presented in a mathematical framework that is similar to conventional color imaging [6]. Consider a color hardcopy output device with M colorants. Prints from this device are to be viewed under N different illuminants, $\{L_i\}_{i=1}^{N}$. The luminance characterization of the printer under the N viewing lamps is given by the relation between the control values $\{A_j\}_{j=1}^{M}$ used for each of the M colorants at a given pixel location and the luminance produced at the given pixel location under each of the N illuminants. This can be denoted as the set of N functions,

$f_i(A_1, A_2, ...A_M) =$ luminance under ith illumination L_i of a region with colorant control values $A_1, A_2, ...A_M$

where $i = 1, 2, \dots N$.

We assume that one or more source images to be recovered are described by the spatial luminance distributions desired under each of the illuminants. Thus, there are N images specified, with $Y_i(x, y)$ being the desired luminance values that we wish to produce under the i^{th} illuminant L_i, where x, y denote the two spatial coordinates. For the purposes of simplifying the notation in the following discussion, the spatial dependence is dropped with the understanding that the discussion applies to each pixel location independently.

With the notation and terminology defined earlier, IMI reduces to the following mathematical problem:

Given N luminance values $\{Y_i\}_{i=1}^{N}$ corresponding to the desired luminance values under the N different illuminants, determine a set of control values for the M colorants $\{B_j\}_{j=1}^{M}$ to be used in printing, such that for all $i = 1, 2, \dots N$

$$\begin{aligned} f_i(B_1, B_2, ...B_M) &= \text{Pixel luminance under } L_i \\ &= Y_i \end{aligned} \qquad (1)$$

Typically, for $N > M$ (number of image specifications greater than number of colorants) the system is over determined and has a solution only under severe constraints on the luminance values $\{Y_i\}_{i=1}^{K}$ limiting its utility in IMI. Even if $N \leq M$ (number of image specifications $\leq$ number of colorants), the system of N equations presented in (1) above has a solution (corresponding to realizable device control values $\{B_j\}_{j=1}^{M}$) only in a limited region of luminance values, which we refer to as the gamut for the spectrally multiplexed imaging problem:

$$\begin{aligned} \mathcal{G} &= \text{gamut achievable for IMI} \\ &= \{Y \in \mathbb{R}_+^K \mid \text{Eqn. (1) has a realizable solution}\} \end{aligned} \qquad (2)$$

where $Y = [Y_1, Y_2, \; .... \; Y_N]$, , denotes the vector of luminance values under the N illuminants, and $\mathbb{R}_+$ is the set of nonnegative real numbers. For specified N-tuples of luminance values within the gamut $\mathcal{G}$, there is a set of realizable control values such that a pixel printed with the control values produces the required luminance values under the given illuminants. Vice versa, N-tuples of luminance values outside the gamut $\mathcal{G}$ cannot be created using any realizable control values. The situation is analogous to the limited color gamut encountered in color reproduction. It is necessary to include a gamut mapping step in the spectral multiplexing described herein to ensure that the source images are limited to the gamut of the system before attempting to reproduce them. The gamut mapping may be image independent or image dependent, where the term image is used to imply the set of desired source images recoverable under the different illuminants.

Once source images to be multiplexed have been mapped to the achievable gamut $\mathcal{G}$, the problem of reproduction reduces to the determination of the control values for each of the M colorants for each pixel. This corresponds to an inversion of the system of equations in (1) and in a manner similar to color calibration, the inverse could be pre-computed and stored in N-dimensional look-up tables (LUTs), with one LUT one per colorant (or alternately, a single N-dimensional LUT with M outputs).

In practice, the function $f_i(A_1, A_2, ...A_M)$ in (1) needs to be determined through measurements of the device response. This is achieved by printing a number of patches with different M-tuples of control values and measuring them suitably to obtain the luminance under the different illuminants. The full spectrum of the patches may be measured, for instance, on a spectrophotometer from which the luminances may be computed using the spectral power distribution of the different illuminants and the visual luminance sensitivity function. The visual luminance sensitivity function might incorporate adjustments for the appropriate light level that account for visual phenomena such as the Purkinje effect [7, pp. 406-409]. In this sense, the term luminance in this paper is understood as being the linear in intensity correlate of perceived light energy rather than the strict CIE definition.

3.1. Simpli ed IMI Implementation

The IMI framework presented above, while fairly general, requires a full characterization of the device luminance response under each illuminant. The process can be significantly simplified by using a model for colorant behavior and inter-colorant interaction. For contone printers with non-scattering inks, the Beer-Bouguer law [8, Chap. 7] provides a reasonably accurate model. Under narrow-band illumination the model further reduces to an additive one in log-luminance (*visual density*) space[2]. Mathematically,

$$\begin{aligned} d_i(A_1, A_2, ...A_M) &\equiv -\log\left(\frac{f_i(A_1, A_2, ...A_M)}{f_i(0,0,...0)}\right) \\ &= -\sum_{j=1}^{M} \log\left(\frac{f_i(0,0,...,A_j,...0)}{f_i(0,0,...0)}\right) \\ &= -\sum_{j=1}^{M} d_i^j(A_j) \end{aligned} \quad (3)$$

where

$$d_i^j(A_j) \equiv -\log\left(\frac{f_i(0,0,...,A_j,...0)}{f_i(0,0,...0)}\right)$$

Note that in the convention adopted here the control values $\{0,0,\ldots,0\}$ represent an blank paper substrate and therefore $f_i(0,0,...0)$ represents the luminance of the paper substrate under the i^{th} illuminant, and the logarithmic terms represent paper normalized visual densities. In particular,

$$d_i^j(A_j) \equiv \log\left(\frac{f_i(0,0,...,A_j,...0)}{f_i(0,0,...0)}\right)$$

represents the paper normalized visual density under the i^{th} illuminant of a patch printed with the j^{th} colorant alone and no other colorants, with the control value for the j colorant set as A_j.
The additive density model proposed above allows the determination of the visual density of any patch based on the visual density of control patches of individual colorants. This significantly reduces the number of measurements required. Measurements of "step-wedges" of the individual colorants (for which other colorants are not printed) allow one to determine the functions $d_i^j(A_j)$ for $i = 1,2,\ldots N$, $j = 1,2,\ldots M$, from which the complete device characterization function can be determined using (3).
Using the above model, the system of equations in (1) reduces to:

$$\sum_{j=1}^{M} d_i^j(B_j) = \log(Y_i/Y_i^0) \quad (4)$$

where $Y_i^0 = f_i(0,0,...0)$.
The equations in (4) represent a system of N nonlinear equations in M variables $(B_1, B_2, ...B_M)$. The functions $d_i^j(A_j)$ are available from the measurements of the "step-wedges". For luminance values under the multiple illuminants that are within the gamut $\mathcal{G}$, the above equations can be solved for the corresponding colorant control values B_j. Further simplification of these equations is possible by assuming that the densities in different spectral bands are linearly related, i.e.,

$$d_i^j(\tau) = \alpha_i^j d^j(\tau) \quad (5)$$

where $\alpha_i^j = d_i^j(\tau)/d^j(\tau)$ is the proportionality factor relating the visual density for the j^{th} colorant under the i^{th} illuminant to a common (across illuminants) colorant dependent function $d^j(\cdot)$. Note that we assume that the proportionality constant α_i^j is independent of the colorant value τ. Equation (5) is also motivated by the Beer-Bouguer law for transparent colorant materials and the assumption of relatively narrow band illuminants. (For a more detailed background, refer to [9]). Even though a number of colorants and marking processes do not follow the Beer-Bouguer law exactly, in practice, Eqn. (5) often provides a reasonably accurate empirical model for measured data and may be used in practical implementation. With the simplification of (5) the system of equations in (4) reduces to a linear system of equations:

$$\sum_{j=1}^{M} \alpha_i^j \, d^j(B_j) = \log(Y_i/Y_i^0) \quad (6)$$

which can be written in matrix-vector notation as

$$\mathbf{\Lambda d_B} = \mathbf{d_Y} \quad (7)$$

where $\mathbf{\Lambda}$ is the $N \times M$ matrix whose i,j^{th} element is α_i^j, $\mathbf{d_B}$ is the $M \times 1$ vector whose j^{th} component is $d^j(B_j)$ and $\mathbf{d_Y}$ is the $N \times 1$ vector whose i^{th} component is $\log(Y_i/Y_i^0)$. For points within the IMI gamut, the system of equations in (7) can be readily solved through a two step process. First, $\mathbf{d_B}$ is determined to satisfy appropriate constraints for realizability and spatial regularity. With the simplied model presented above, the realizability constraints correspond to simple per element upper and lower bounds on

[2] Additional details may be found in [9]

the elements of $\mathbf{d_B}$. Next, the individual components of $\mathbf{d_B}$, i.e., the $d_j(B_j)$ values can be used with the normalizing density response $d_j(\cdot)$ for the j^{th} colorant to determine the control value corresponding to the j^{th} colorant, i.e., B_j. This process is analogous to inverting a 1-D tone response curve. Repeating the process for each colorant provides the complete set of colorant control values $\{B_j\}_{j=1}^{M}$ that produce the desired set of luminance values under the different illuminants. If no solution exists (because the target luminances under the multiple illuminants are outside the gamut), Eqn. (7) may be "solved" in a least-squares sense subject to feasibility constraints to provide a form of gamut-mapping.

Note that if $N = M$, the above set of equations has a unique solution provided $\mathbf{\Lambda}$ is non-singular, which is normally the case for typical colorants and illuminants. The solution in this case is obtained simply by inverting the matrix $\mathbf{\Lambda}$. Furthermore, if the colorants and illuminants can be ordered in correspondence, i.e., colorant i absorbs illuminant i most, and the other illuminants to a lesser extent, then we can choose $d^j(\cdot) = d^j_j(\cdot)$, which ensures $\alpha^j_i \leq \alpha^j_j = 1$, for all $i = 1, 2 \ldots N$, i.e., the matrix $\mathbf{\Lambda}$ is square with the elements along the diagonal as the largest along each row, which is often desirable from a numerical stability standpoint. If $M > N$ the system of equations will have multiple mathematical solutions, and the choice of a particular solution may be governed by additional criteria. One example of a criterion for choosing among the multiple mathematical solutions is feasibility, a feasible solution being a set of density values that can be realized with the range of colorant control values exercisable. The model inherent in Eqn. (7) can also be used to determine suitable approximations to the achievable gamut $\mathcal{G}$ and can be of assistance in performing gamut mapping.

By taking specific colorant properties into account, it is possible to further simplify the IMI problem to provide both ease of solution and added functionality or maximal gamut. The reader is referred to [9] for details.

4. 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 or 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 included 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.

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. Since the viewing of the images requires carefully calibrated printing of the multiplexed images and control over viewing illumination in order to illustrate the effects, hardcopy prints have not been included with this paper.

5. Extensions and Applications

The IMI work presented here can be extended in several ways. In situations, where other attributes of the print such as differential gloss between the colorants impact visual quality, the addition of some noise can provide visual masking. The idea works on the same principles as dithered quantization, where the goal is to mask contours. The presence of a black colorant in most printing systems offers an added degree of freedom which can be exploited in IMI. The gray component replacement (GCR) strategy can be designed not only to simplify the implementation, as we have described above, but one can also introduce masking or incorporate additional data by varying the GCR on a spatial basis. Variation of the GCR in a spatial pattern, makes the pattern visible under uncontrolled illumination. Thus a logo may be chosen to control the GCR and the resulting print will show a clearly visible logo pattern overlaid on the multiplexed images under uncontrolled broad band lighting, whereas the individual images are seen under the appropriate narrow band lighting. Several of the extensions that are described here have already been developed and details of these can be found in [9].

IMI has potential uses in the advertising and promotion industry. The sudden change in the perceived image with a change in illumination has a significant visual impact that is useful for drawing the observers attention and providing amusement. The use of IMI does require control over the illumination under which the prints are viewed. Environments which are naturally dark and have controlled artificial lighting therefore offer natural venues for the use of IMI. Particular examples include movie theaters, and dance clubs where multiplexed images may be used on T-shirts, soda/popcorn containers etc as a means to promote these items. Alternate ways in which the method could be used include prints in the form of booklets that could be viewed under suitable narrow band illumination. Narrow band LED illuminators are rather inexpensive and these could be included for use as sources. Alternately, in an otherwise darkened room, the use of individual channels of a display can provide a source of lighting. This is particularly attractive because display primaries are fairly narrow band and for CRT displays there is also good agreement in the spectral characteristics across displays. In addition to above outlined uses, IMI provides an excellent technique for teaching the principles of color science and color perception.

6. Conclusion

In this paper, we presented the basic concepts and a demonstration of *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 described 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 color imaging scenario, where the 3-D color attributes under a single wide-band illuminant are controlled using the colorants. The demonstration accompanying the paper shows IMI prints in a suitably controlled lighting environment.

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