Towards cross-media color reproduction

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1. Introduction

Suppose that we wish to compare the color appearance of an image displayed on monitor and a reproduction of the image on a printed page. We could place the monitor and printed image side-by-side and let an observer judge the colors of each. The difficulty with this arrangement is that the ambient illumination interferes with the color appearance of the monitor image. To see the monitor image clearly, the observer would like to turn down the room lighting. But in this case, the observer will be unable to see the printed image. As the room lights are turned up, the printed image becomes visible but the monitor image becomes washed out.

The conflict between the appropriate ambient lighting conditions for viewing monitor and printed images illustrates one of the primary challenges of cross-media color reproduction. We believe that this conflict is best understood by recognizing that the visual system interprets images as illuminated surfaces and adjusts to the ambient illumination to keep the color appearance of surfaces constant. Thus, for a wide range of ambient illuminations, the color appearance of a printed image does not change much.[1,2,3] Although the light reflected to the eye from a printed page varies with changes in illumination, the visual system adjusts to these lighting changes so that the color appearance of surfaces remains approximately constant. For a monitor image, on the other hand, the effect of the visual system's adjustment is quite different. The light coming from the monitor is (except for the glare reflected from the monitor's screen) independent of the illumination. When the room lights are turned down, the visual system interprets the monitor image as a set of illuminated surfaces. As the room lights are turned up, this interpretation is contaminated and the appearance of the monitor image changes.

The above example illustrates that when we reproduce a monitor image with a printed image, our goal should not be to have the printed image appear identical when the two are viewed side-by-side. Rather, we want the visual system's interpretation of the surfaces implicit in both the printed and monitor images to be the same when each is seen under its preferred illumination. The purpose of this paper is to outline a procedure for trying to arrange this sort of *surface color match.*

Our procedure for achieving surface color matches consists of two parts. The first is to analyze a monitor image to determine what surfaces the visual system is likely to find implicit in it. The second is to approximate any given surface reflectance function on a piece of paper using a color printer. We describe each of these separately in the next two sections. To reproduce a monitor image, we first determine the implicit surfaces from the monitor image and then reproduce these surfaces on the printed page.

2. *Monitor image analysis*

How do we determine the implicit surfaces of a monitor image? There are two separate cases. The first is when the first case the monitor image is a simulation of the appearance of a scene where the surface reflectance functions and illuminant spectral power distributions are known. This is the case in for images rendered using the Stanford *Color Analysis Package (CAP)* software system,[4,5] where the hardware-dependent display values for monitor images are actually constructed from internal location-by-location representations of surface and illuminant properties. If the underlying surface representation is available, then we assume that the observer's visual system correctly interprets the surface whose appearance was simulated and use the surface representation directly.

It has not escaped our attention that some color processing systems do not use the surface and light representation provided by *CAP*. The second case is when the monitor image is specified in CIE XYZ tri-stimulus coordinates.[*] This is currently the more common case, and it is necessary to convert the hardware-independent representation to a reasonable estimate of the implicit surfaces. Here we describe a method that is based on the use of linear models to represent the implicit surface reflectance functions and illuminant spectral power distributions. Elsewhere, we and a number of our colleagues have described the advantages of using linear models to represent surface reflectance functions and illuminant spectral power distributions.[5,6,7,8,9,10,11] We assume that a known set of tri-stimulus coordinates, typically those corresponding to the monitor white point, are interpreted by the visual system as white paper under the implicit illuminant. Denote these tri-stimulus coordinates by X_w, Y_w, Z_w. Denote the surface reflectance function of white paper by $W(\lambda)$. Furthermore, we assume that the ambient illumination is one of the daylight spectral power distributions defined by the CIE 1971 daylight illuminant linear model. The basis functions of this model, denoted here as $E_i(\lambda)$, are listed in table V(3.3.4) of Wyszecki and Stiles' book.[12] Thus the spectral power distribution of the implicit light in the monitor image is determined by three parameters, ε_i, as $E(\lambda) = \sum_{i=1}^{3} \varepsilon_i E_i(\lambda)$. From the equation

$$X_w = \sum_{i=1}^{3} \varepsilon_i \left[\sum_{\lambda} \bar{x}(\lambda) W(\lambda) E_i(\lambda) \right] \tag{1}$$

and two parallel linear equations for Y_w and Z_w, we can solve for the three unknown implicit light parameters.

Similarly, if we assume the surface reflectance at each image location is one of the functions from Parkkinen et al.'s basis set,[10] then the implicit surface reflectance function is determined by three parameters, σ_i, as $S(\lambda) = \sum_{i=1}^{3} \sigma_i S_i(\lambda)$. From tri-stimulus values at each image location, X, Y, and Z, and from the equation

$$X = \sum_{i=1}^{3} \sigma_i \left[\sum_{\lambda} \bar{x}(\lambda) E(\lambda) S_i(\lambda) \right] \tag{2}$$

and two parallel linear equations for Y and Z, we can solve for the three unknown implicit surface parameters.

3. Surface reflectance analysis

When we place ink on the printed page, we control the surface reflectance functions of the printed image. To reproduce the surfaces implicit in the monitor image, we generate the hardware control signals to print a surface that approximates the desired reflectance. In this section, we describe a procedure to do this for a particular modern commercial printer, the Hewlett-Packard PaintJet. The PaintJet generates colors using an error-diffusion dithering algorithm that places four different types of inks adjacent to one another on the printed page.

Our procedure uses a linear model to describe the gamut of surfaces that can be produced with the PaintJet. To create this linear model, we began with measurements of a large number of surface reflectance functions produced by the printer.** We expressed each measured surface reflectance as the sum of two terms

$$S(\lambda) = W(\lambda) - A(\lambda), \tag{3}$$

where $W(\lambda)$ is the reflectance function of the white paper and $A(\lambda)$ is the change in surface reflectance caused by the inks. We then computed a linear model to describe the set of measured changes. To do this, we wrote removed the mean change from the data set. If we call the mean change $A_0(\lambda)$, then the linear model describes the observed changes through the equation

$$A(\lambda) \approx A_0(\lambda) + \sum_{i=1}^{i=N} \alpha_i A_i(\lambda). \tag{4}$$

The $A_i(\lambda)$ are the fixed basis functions of the linear model. These were determined from the data using the singular value decomposition. The α_i are parameters that characterize a particular change $A(\lambda)$. The relation between the linear model and the actual surface reflectance function is given by

$$S(\lambda) \approx W(\lambda) - A_0(\lambda) - \sum_{i=1}^{N} \alpha_i A_i(\lambda). \tag{5}$$

As we use more basis functions (i.e. as N increases), we can approximate the data with arbitrary precision. We have found that for the 193 samples from the H-P PaintJet, which were selected to span the printer's range, the surface reflectance functions could be closely approximated using $N = 4$ basis functions. With four basis functions the typical root mean squared error of linear model fit to the true surface reflectance functions was less than two percent. This deviation is about equal to the size of the measurement error.

As we shall show at the talk, for the H-P PaintJet, the weights α_j can be related to the relative proportions of the four inks that are placed on the page and thus to the hardware control signals sent to the printer. To obtain a desired surface reflectance function on the page, we first solve for its best least-squares representation α_i within the linear model (equation (3)). We then convert the linear model representation to the hardware control signal that will produce the closest match that can be generated by the printer.

4. Summary

When matching the color of a monitor image and a printed image, the two images are normally viewed under asymmetric conditions. Under such asymmetric matching conditions, location-by-location tri-stimulus matches do not generate appearance matches.[13] We suggest analyzing the monitor image in terms of implicit surfaces and illuminants. We use the printer to reproduce the implicit surface reflectance functions of the monitor image.

Our remarks also have implications for the format of digitally stored colored images. The methods we have described are best implemented using image processing software that permits representation of images in terms of surfaces and illuminants. The use of linear models to represent these functions offers an efficient method for coding surface reflectance and illuminant data.

Footnotes

ACKNOWLEDGMENT: Supported by NASA (ARC) grant NC2-307, and NEI grant EY03164, both to Stanford University. We thank R. Motta and J. Farrell for their help and support.

* For simplicity of exposition we will assume that the monitor image is specified in terms of CIE XYZ tri-stimulus coordinates. It is straightforward to convert a specification in any reasonable color coordinate system to this standard coordinate system.

** Our colleague at Hewlett-Packard, Ricardo Motta, kindly provided us with measurements of the spectral reflectance functions of 193 different colors produced on a piece of white bond paper.

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