Use of Color Science in Image Processing

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Abstract

With the advances in computing and communication technology, there has been a proliferation of color imaging applications. For example, electronic prepress, textile manufacturing, color scanners and printers, HDTV, and multimedia workstations. With these applications comes a need to produce high quality color images both in soft and hardcopy. In this paper, we discuss the impact color science and image processing have on one another.

Introduction

Color affects many aspects of our lives, from the clothes we wear to the workstations in our offices. The sensation of color is caused by electromagnetic radiation of various frequencies being received by the cones in the retina. The retina contains three types of cones which filter the incoming electromagnetic radiation forming the basis for the three color primary systems used in television, printing and photography. That is, any color can be reproduced by combining different amounts of red, green and blue primaries. Given this model, it is natural for an image processor to represent color as a three-band extension of a monochrome image. Unfortunately, combining color and image processing is not so easy.

Color perception in humans involves the entire psychovisual system, both physiological and psychological components. The physiological component involves the sensing of the light by the photoreceptors (rods and cones). The output of the photoreceptors is transmitted to the brain where the psychological component of color perception takes place. Color perception occurs because of the color sensitive receptors in the three types of cones in the human eye.

An image processing (vector space) approach to color[1] can be formulated if we assume the visual portion of the electromagnetic spectrum, approximately between 400-700 nm, can be sampled finely enough to allow the accurate use of numerical approximation of integration. The spectral response of the photoreceptors can also be sampled, yielding three lin- ear independent N-vectors which define the visual subspace. We represent the spectral sensitivity of the eye by a matrix $\mathbf{S} = [\mathbf{s}_1, \mathbf{s}_2, \mathbf{s}_3]$, where the N-vectors, $\mathbf{s}_i$, represent the response of the ith type of cone. A visible spectrum is represented by an N-vector $\mathbf{f}$ and the response of the photoreceptors to the input spectrum is a 3-vector, $\mathbf{c}$,

$$\mathbf{c} = \mathbf{S}^T\mathbf{f} \tag{1}$$

If two visible spectral distributions appear to have the same color to a human observer, they are called metamers. Using the notation given in Eq. (1), N-vectors $\mathbf{f}$ and $\mathbf{g}$ representing two different spectral distributions are metamers if

$$\mathbf{S}^T\mathbf{f} = \mathbf{S}^T\mathbf{g} \tag{2}$$

Consider an N × 3 $\mathbf{P} = [\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3]$ matrix containing three linearly independent, N-dimensional primaries, $\mathbf{p}_1$, $\mathbf{p}_2$, and $\mathbf{p}_3$. Let the monochromatic colors be denoted by $\mathbf{e}_i$, i = 1,...,N, where $\mathbf{e}_i$ has a one in the ith component and zeros in all other components. The stimulus $\mathbf{e}_i$ is matched by $[m_1(i)\ m_2(i)\ m_3(i)]$ units of primaries $[\mathbf{p}_1\ \mathbf{p}_2\ \mathbf{p}_3]$, respectively if

$$\mathbf{S}^T\mathbf{e}_i = \mathbf{S}^T\,(m_1(i)\mathbf{p}_1 + m_2(i)\mathbf{p}_2 + m_3\,(i)\mathbf{p}_3) = \mathbf{S}^T\mathbf{P}\mathbf{m}_i \tag{3}$$

where $\mathbf{m}_i = [m_1(i)\ m_2(i)\ m_3(i)]^T$ is the three-dimensional vector of the gains of the primaries. If we match all the spectral colors

$$\mathbf{S}^T\mathbf{I} = \mathbf{S}^T\mathbf{P}\mathbf{M}^T \tag{4}$$

where $\mathbf{I}$ is an N × N identity matrix. The N × 3 matrix $\mathbf{M}$ is referred to as the color matching matrix. The columns of $\mathbf{S}$ and $\mathbf{P}$ are independent and both matrices are rank three. Thus, we can rewrite Eq. (4) as

$$\mathbf{M} = \mathbf{S}(\mathbf{S}^T\mathbf{P})^{-1}$$

Thus, the color matching matrix $\mathbf{M}$ is determined solely by the sensitivity of the eye and the primaries. The tristimulus values, $\mathbf{t}_p$, can now be calculated using the color matching matrix $\mathbf{M}$:

$$\mathbf{t}_p = \mathbf{M}^T\mathbf{f}$$

where the subscript $_p$ in $\mathbf{t}_P$ denotes the use of the primaries. The N-dimensional spectrum $\mathbf{f}$ is projected onto a three-dimensional subspace that defines a particular color.

Combining Image Processing and Color Science

There are many applications which can benefit from combined use image processing and color science. Use of properties of the human visual system can increase the performance of image coding systems, resulting in very high quality reconstructed images. For example, we have designed a color subband-vector quantization system with a bit allocation algorithm which incorporates perceptual weights.[2] The weights are derived from data provided by experimental measurements[3] of the mean detection threshold of the human visual system for color transitions along the luminance, red-green, and blue-yellow directions. Minimization of an objective function constrained by the desired bit rate gives a perceptually optimal bit allocation, thus allow us to achieve better quality images at higher compression ratios. Murching and Woods[4] have developed an adaptive method for subsampling the chrominance components of an image based on the local high frequency energy content. This approach results in an improved quality vs. sample-rate tradeoff, especially in applications such as compositing color graphic images. Tremblay and Zaccarins[5] propose two new approaches for compressing color quantized images so that requantization of the decoded image is unnecessary. The algorithms restrict the pixels of the decoded image to take values only in the original color palette.

Given the increased activity focused on solving problems associated with the transmission and display of high quality color image/video signals, there is a need for calibrating color output devices, both hardcopy and softcopy. To do this, a relationship needs to be defined between a set of measured (tristimulus) values and a set of control values for the outppt device.[6] Impacting the solution to this problem are: the model of the output device and its limitations, the type and location of the measurement data, the variability in the data, the interpolation and extrapolation methods used, the variability in the output device under normal operating conditions, and the perceptibility of the errors. One way to characterize a color output device is with a three-dimensional look-up table which maps the tristimulus values, $\mathbf{t}$, to the control values, $\mathbf{c}$, of the output device. The functional form of the output device can be written using the vector notation as $\mathbf{t} = \mathbf{F}(\mathbf{c})$. The purpose of the calibration is to define a mapping from the tristimulus values to the control values. Since the function $F(\bullet)$ has no closed form, it can be defined by interpolation from a table of values. Alternatively, Chang, et al.[7] have developed a sequential linear interpolation for interpolating multi-dimensional nonlinear functions. In this technique the grid points can be nonuniformly placed. Using asymptotic analysis, optimal conditions for placing the interpolation grid points are determined to minimize the interpolating error, thus allowing for more efficient use of the grid points.

Color scanners are becoming a popular input device for desktop publishers and image processors. For many applications, it is important to have calibrated color at the output. To properly calibrate a scanner for a variety of illuminants, the spectral sensitivity of the scanner must be estimated. Sharma and Trussell[7] compare the performance of two estimation methods, principal eigenvector (PE) and projection onto convex sets (POCS). They demonstrate that when greater a priori information is available, the POCS method outperforms the PE method, yielding significantly better estimates of the scanner sensitivities.

In applications such as textiles or electronic prepress, high quality of appearance is essential. For example, unintentional variations of color between and within fabrics pose serious problems in textile manufacturing. Most of the quality control requires visual inspection of the fabric. McGregor, et al.[9] have developed models of color defects using standard psychophysical methods which could provide the basis for the design of new sensor systems for automated fabric inspection.

Summary

The problems in color image processing and color science are challenging. While there is a long history of work in both areas, only recently have image processing and color science approaches been combined. The result has been an expansion of the number and type of problems that can be effectively addressed.

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