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Color Imaging: Current Trends and Beyond

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Abstract

This paper reviews areas of active research in color image processing. Several open problems are mentioned and future directions for research are suggested.

1 Introduction

Monochrome signal processing has been an active area of research for well over 25 years. With a few exceptions, early digital color image processing was often approached as an extension of monochrome image processing, where each of the color bands was treated as an independent monochrome image. With the proliferation of color output and recording devices, there has been an increased demand for accurate and consistent color. This demand has led to a significant amount of research into the problems of color image processing. There have been several books [3, 5], conferences, and review articles [6, 7, 1, 8] on this topic. This paper reviews the areas of current research and suggests directions for future research.

Since color is a psycho-physical process, the first section will deal with color appearance. With an appearance model in place, the primary problems in color image processing can be classified into three broad areas upon which this paper will be organized. These areas are: color image recording, color image communication, and color image reproduction. Each of these areas will make up a section of the paper, with a final section dealing with future research directions. It will be assumed that the reader is familiar with the CIE system and the basics of color science. If not, then [9] provides detailed information and [4] provides a lighter overview. For references and discussions on many of the topics discussed here, the reader is referred to [6, 7] and to www.mvrhel.com/icip2000.html which contains a list of publications that correspond to the sections in this paper.

2 Color Perception

How an image appears to an observer is greatly affected by the viewing conditions. For a long time, researchers have been trying to model the change in image appearance given a change in the viewing condition. Problems investigated include appearance changes due to changing illumination, changing surround color, and radiant versus reflective display. As new appearance models are developed, they can be incorporated into many of the image processing problems that are discussed in the next sections.

Note that if a comparison between two color images is made under the same viewing conditions, then the CIE system works well for quantifying color differences for the standard human observer. In practice, it is necessary to account for the nonlinearity of the human visual system through the use of a uniform color space (e.g. CIELAB) in any cost function minimization. In the uniform color space, the difference between colors is quantified by the Euclidean distance between the color values. Note that for comparing pictorial scenes, a pixel to pixel difference of the image CIELAB values may not relate exactly to the apparent differences, due to the complex interactions in the scene. Essentially, researchers who are interested in digital color image processing need to be aware of the meaning and limitations of the CIE system and the problems of color matching across different viewing conditions. An overview of current developments on color appearance modeling can be found in [2].

3 Color Image Recording

Color image processing starts with acquiring the image data. In situations, where the data is already available, it is important for the researcher to know the source of the data. There are several types of devices that digitally record color images, including digital cameras, desktop scanners, and drum scanners. In this section, some of the issues that arise in the colorimetric design of these instruments and in the initial processing of the recorded data are discussed.

3.1 Characterization

The digital values (device dependent values) from a recording device are related to how that device sees the image. These values may be significantly different than the device independent values that describe how the standard human observer sees the image under a particular illuminant. Characterizing or profiling a recording device is the determination of the mapping from the device dependent values of the recording device to device independent values.

Parametric and non-parametric methods have been used to characterize recording devices. The parametric methods require knowledge of the optical spectral sensitivities of the recording device, which may need to be estimated from recorded data. The non-parametric methods include both look-up-tables (LUTs) with interpolation and neural methods. In many cases, the neural solution is implemented with a LUT and interpolation for computational efficiency.

3.2 Illumination Estimation

It is well known that the illumination under which an image is recorded affects the recorded data. In many cases, it is desired to render an image as if it had been recorded under a different illumination. An example occurs in the case of recording an image with a digital color camera under fluorescent lights. The resulting image will have a green cast, and require an illumination correction.

Having knowledge of the illumination under which the image was recorded would obviously be helpful in performing the correction. In many situations, this information is unavailable and must be estimated from the recorded image. One approach to this problem is to estimate the chromaticity of the illumination from specular components in the image.

Estimation of the entire illumination spectrum from the chromaticity value of the illumination requires significant prior knowledge of the illuminant type. For example, if the image was known to be recorded under daylight, then it is possible to use the known one-to-one relationship between chromaticity and the spectrum of the illumination.

3.3 Color Filter Design

It is obvious that the optical components through which the the image is formed will affect the resulting recorded values. The separation of the radiant or reflected energy into spectral bands is achieved through various methods, including glass filters, dichroic filters, and multiple illuminants.

To obtain colorimetric information of the image under a particular viewing illuminant, it is necessary to design the recording device optics, filters, and illumination such that the entire optical system satisfies the Luther-Ives (LI) condition. With this condition satisfied, the spectral sensitivity of the recording device is within a linear transformation of the standard human observer's spectral sensitivity under the selected viewing illuminant.

Due to physical constraints, it is often not possible to design the optical components such that the optical system satisfies the LI condition. In this case, it is useful to have a measure that quantifies the "goodness" of a particular optical design. One early measure was the Neugebauer quality factor. A problem with this measure was that it only compared one filter to another filter.

The Vora measure, provides a measure of the quality for the entire set of filters by comparing the intersection of the filter subspace with the human visual illuminant subspace. Researchers have extended this measure to account for system noise as well as a weighting to account for the data that is being measured and the nonlinearity of the CIELab color space.

In certain situations, it may be desirable to obtain colorimetric information about an image for a variety of viewing illuminants. Several researchers have looked at using more than three bands in the recording process to collect this information.

3.4 De-mosaiking

In digital cameras, a Bayer color filter array (CFA) is often used with a CCD array. With this CFA, the spatial sampling of the green channel is twice that of the red and blue channel, to account for the color spatial frequency sensitivity of the human visual system. The de-mosaiking problem is to reconstruct the image from these samples by interpolating the missing color pixels. There are imaging sensors under development that avoid this problem by placing the sensors for each channel on top of one another. In this case, the sampling rate of each channel is the same and there is no de-mosaiking required.

4 Color Image Communication

Once the image data is recorded, it will need to be stored and possibly communicated, which introduces a need for coding. In most cases, compression is performed on data that is in a luminance chrominance space. In this case, the luminance information is in a different channel than the chrominance information and more bits are allocated to the luminance component. MPEG and JPEG are both standards which make use of this idea. Reference [6] contains some discussion on color image coding.

A significant problem in color image communication affects researchers who wish to accurately display color in archival journals. Unfortunately, sending a color print to the publisher does not guarantee a close match. One approach to quantify the transformations that occur on the image, is to include color samples of known CIE values with each image. The change on these colors would provide an indication of the types of change that occurred on the published image. The optimal selection of these color samples is an interesting problem. Ideally, the samples should be within the gamut of most output devices and include neutral and very saturated colors.

5 Color Image Reproduction

Once the data has been communicated, it will usually be displayed with some output device. Accurate soft-copy color reproduction has been well studied and due to the additive nature of these devices, the problem is easily formulated. Accurate hard-copy color image reproduction is a difficult problem due to the large variety of devices that are used and due to the inherent nonlinearity of the process.

5.1 Quantization

There has been a significant increase in the number of 16 bit and 24 bit color devices. Devices that represent color with only 8 bits are becoming less common. For this reason, the significance of palettization as a research problem is decreasing. Past research on this topic is covered in [6].

5.2 Characterization

Output device characterization or profiling entails the determination of the relationship between the output device control values (e.g. RGB or CMYK) and the resulting CIE output value. The methods of characterization can be divided into parametric and non-parametric approaches. The parametric approaches depend upon a model for the reproduction process while the non-parametric approaches rely upon a large sampling of the gamut of the output device.

5.2.1 Soft-copy

The characterization of soft copy devices such as CRTs and LCDs typically rely upon models. One difficulty in characterizing soft-copy displays is due to the observed variation as the observer moves relative to the display. For a CRT, there is a relatively small change in radiant energy to the viewer as the viewer moves from the optimal (front center) viewing location. For many of the solid state displays, there is a large change in the observed energy as the viewer moves slightly. This sensitivity causes a problem for many radiant measuring colorimetric instruments. The problem is that these instruments collect the radiant energy over a range of angles that is different than the typical human observer. Recent advances in LCD technology have reduced this problem.

5.2.2 Printer Models

Physical models are sometimes used to characterize the color printing process. Typically, model or parametric based characterization would entail the determination of the model parameters by measuring a relatively small number of output colors from the device. Most models that are used today, are extensions, variants, or hybrids of the Kubelka-Munk, Neugebauer, and Clapper-Yule models. Halftone modeling has received attention with extensions of the Neugebauer model to the spectral domain. For a review on color halftoning, the reader is referred to [5, 6]. Continuous tone printer modeling have also received some attention and the reader is referred to [6] for additional discussion and references on this topic.

5.2.3 Non-parametric Based Characterization

In practice, many of the above models do a poor job of characterizing the printing process. For this reason, research on non-parametric characterization methods has received significant attention. Non-parametric characterization is typically achieved by displaying a large number of colors for a set of control values. The set of control values that are printed are usually a uniform grid in the printer control value space. The forward mapping, which describes the mapping from control values to device independent values, is then defined by a multi-dimensional LUT and an interpolation scheme. Various interpolation schemes including trilinear, tetrahedral, and pyramid have been used for this problem. Comparison of these methods is usually made by considering a trade-off between accuracy and computational complexity.

The inverse of the forward mapping is of more interest however (the mapping from device independent values to device dependent values), and there have been many schemes for inverting the forward mapping. One problem with the inverse mapping is that the actual gamut of the output device may occupy only a small portion of the sampled space. This is certainly true for most printer gamuts in a uniformly sampled CIELAB color space. To overcome this problem, researchers have looked at non-uniform sampling in CIELAB and even developed an iterative approach for determining where samples should be placed to obtain the best results.

Another solution to this problem is to not transfer the data to a device independent color space but instead communicate the color in a standard RGB space. Several of these spaces have been proposed and sRGB is probably the most well known. The advantage of using such a space is that fewer bits are wasted on out-of-gamut colors. A clear disadvantage is that a perceptually based gamut mapping algorithm is more difficult to implement.

5.2.4 UCR and Hi-Fi printing

Many printers include a black colorant in the color printing process. There are also printers that include an orange and green colorant to expand the gamut of the printer. The use of more than three colorants makes the device characterization problem more difficult since different control values can generate the same device independent color value. The difficulty arises in determining which control value to use in creating a specific color. To date, this problem has not been adequately addressed.

5.3 Gamut Mapping

An output device is limited in the colors that it can reproduce. Colors that are outside the device's gamut of reproducible colors must be mapped to colors that are inside the gamut Most approaches have concentrated on methods that preserve the hue of the color at the sacrifice of saturation and often lightness. It is doubtful that there is a universally optimal solution to this problem due to the large variety of devices and the varied perceptual effects that are often desired. For example, a different mapping may be desired when printing business graphics versus pictorial images.

5.4 Control

A significant problem in the creation of accurate color hard copy is the sensitivity of many devices to environmental factors. Changes in temperature, humidity, etc, can cause significant changes in the color that is printed for a particular control value. A change in paper stock or colorant can also be a source of significant change in the color output. For these reasons, the variability of output from these devices is much larger than the variability of most input devices [5]. The development of fast and simple methods for correcting for these changes has not yet received significant research attention.

6 Future Directions

There remain several interesting open problems in color imaging research. For example, the use of six colorants in a printing process introduces a significant multi-dimensional characterization problem. The use of fluorescent colorants and paper further complicates the problem. As new reproduction and recording technologies are developed, unique problems (e.g. the demosaic problem), will occur.

Many of the classical problems in monochrome image processing are only now beginning to be properly extended to color images. The performance of a color image restoration algorithm and coding method will usually be judged by the human visual system. Until recently, there have been few researchers who have incorporated color errors into such problems. Often the approach has been to simply process the RGB images with little concern as to the source of the data or the meaning of the RGB values.

With the growth of image data bases, the use of color in the image data base retrieval problem has received significant attention. Here, it is important to consider the human visual system in the problem, and in particular how that image appeared at one time to the user. In addition, rendering and visualization is an area for which color is of importance. A realistic rendering requires accurate models for characterizing the interaction between surfaces and illuminants.

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