Integrating Scanners into Color Systems

Paul G. Roetling
Webster Research Center, Xerox Corporation, Webster, New York

Abstract

In many color systems, all hope of controlled results vanishes at the scanner. It may be surprising to realize that there is still no one, universally accepted, method for designing a practical scanner's spectral sensitivities and related calibration method to provide colorimetrically accurate outputs for a device-independent result. Indeed, even the correct number of separate color channels to use in a practical scanner is an open question. At least 3 channels are needed for full-color, more are usually agreed to be a help. The various approaches are reviewed.

Introduction

In designing any system, the first question is what you want it to do. Therein lies the first problem in scanner design for integration into a color system. While we would probably all agree that we want good color, we will not all agree on how to guarantee a good result. There are many who argue for accurate reproduction. Most of them aim for correct tristimulus values, while some want full spectral data. One argument for spectral data is the desire to enable selection of various viewing illuminants, whereas one cannot accurately predict tristimulus values in one illuminant from a knowledge of tristimulus values under a different illuminant. On the other extreme of system requirements, there are those who say that every image needs to be touched-up, and therefore all the scanner should do is provide 3 well separated color signals; a person will correct the colors. Typically, this approach shows in very practical, how-to articles[1] where the most commonly used methods are described. The truth is that most current scanners are simply not calibrated. Most of the other approaches fall somewhere between these extremes. For example, in many systems, the scanner only sees a limited number of different classes of images. That is, a 35mm transparency scanner will probably only see a couple of brands of slide films and perhaps a couple of types of color negatives. In such a case, one can get colorimetric data or even the full spectrum with a few color channels and a calibration of the scanner. A current topic of research is to determine whether a broad range of inputs still can be handled with a small number of parameters. Another common restriction in systems is that only one or two different printers are in use. In such cases, the systems are commonly calibrated end-to-end, usually in device-dependent terms.

Second, one needs to decide on the precision required. The allowable noise level and the light available usually limit the speed/resolution/area tradeoffs. The amount of light is limited either by inherent brightness of the source or by how much light you can get without burning the paper or transparency. This review is aimed at the color sensing of the scanner for integration into a system, not at the design of optics, etc., so we will only briefly allude to noise problems. One also needs to consider more than the random noise. For example, one of the common problems with flat-platen scanners, or more generally those which illuminate a line or area instead of a spot, is flare and stray reflections. A recently published analysis[2] points out that illuminated backgrounds, even the order of inches away from the spot being measured, can change readings appreciably. A casual test using a commercial flat-platen scanner in our labs showed that one might find 10 to 20% changes in measured reflectance when the surround a quarter inch away is changed from black to white. This is one of the reasons that drum scanners, where only a small area is illuminated, are still used in many high quality applications.

System Integration Methods

Here, we consider several of the approaches to system integration. We start with what may be the least demanding set.

Manual Adjustment Later

If we plan to touch-up the colors later, then the requirements are that the scanner provide good color separation, including good color differentiation, with minimum noise. While lasers or narrow band filters can yield very good separation, unless the inputs are a limited class (like all the same film type or consisting of no more than three colorants), such narrow bands may fail to adequately differentiate colors. That is, different hues may easily be metamers in the narrow bands observed. All that is needed for a metameric match with laser inputs is a spectral match at the 3 laser wavelengths. Nevertheless, although laser input scanners are rare, many high quality scanners are designed and used successfully on limited input sets with relatively narrow band filter/illumination combinations.

By using broader band filters, preferably with sloping response across the spectrum, color differentiation is improved at small loss in separation signal-to-noise ratio and overall light utilization is improved. Generally, for the filters chosen, the red response peaks far into the red and the blue peaks well into the blue to assure good separation. For example, the red (#29) filter often selected has a transmittance which becomes large only above a wavelength of about 630 nm and the blue (#47B) has a peak transmittance at 430 nm. Depending on the sensors used, these measure at considerably more separated wavelengths than one uses to make colorimetric measurements. (Most approximations to colorimetric filters peak at about 450, 540 and 590 nm.)

Closed System Calibration

In practice, many systems do not use more than one or two printers and the calibration can then be done end-to-end for the specific devices. In such cases, it is common to use device-dependent descriptions. One possibility is to use an internally generated digital test target printed on the printer and then scanned back into the scanner to close the loop on system calibration.[3] The internal descriptions used need not match any particular system, so long as they are internally consistent.

Full Spectral Determination

Although it requires considerable data storage for a color image, almost everyone would agree that measurement of the full spectral reflectance assures that one has acquired the data needed for later use. Measurement with a spectroradiometer is used in most published papers as their basis of "truth". Measurements are typically made at 10 nm intervals, from 400 to 700 nm, yielding 31 measurements/point. Many commercial colorimeters now measure the reflectance (or transmittance) spectrum and then calculate tristimulus values, rather than trying to measure tristimulus values directly.

Several difficulties are obvious if one were to use this approach for image scanners. First, spectroradiometer measurements usually run at the order of seconds, rather than microseconds, per point, typically limited by light levels. One could conceive of ways to improve the design for image scanners, mainly by making parallel measurements, but that is not the only problem. If we were to assume a page scanner, operating at 400 pixels/inch, we would obtain about 500 million ($400\times400\times31\times100\text{in}^2$) measurements per page. This clearly creates both memory and bandwidth problems in most systems. Moreover, most would agree that there is considerable redundancy in these data and it is probably better to remove most of the redundancy early in the system. We return to this point later in the paper.

Colorimetric response

Assuming one knows the desired viewing illuminant throughout the color system, the now "classic" solution is to work in colorimetric, or tristimulus, units. This is commonly called "device-independence", although device-independence could encompass many other representations.

Human color vision is trichromatic, that is, we act like we have 3 different kinds of color sensors[4] (physiological evidence tends to agree, but that is irrelevant here). Thus, in any system where the desired result is that inputs and outputs can be made to appear to match, tristimulus values are sufficient to describe colors. If the description is in terms of reflectance units, then, as already noted, a standard illumination needs to have been chosen.

A scanner can theoretically be made to measure tristimulus values directly by simply making the scanner spectral sensitivities match those of the eye. In fact, that is more restrictive than necessary. If we are willing to include a simple matrix correction, all that is needed is for each of the scanner responses to be a linear combination of the visual responses. (Surprisingly, this fact does not seem to be well known and proofs are still being published to inform people[5].) In practice, we normally use the CIE color-mixture functions (xbar, ybar, zbar) or linear combinations of them. For convenience, Yule[6] specifies an ortho-normal set of color-mixture functions, as well as a procedure for testing how closely any scanner sensitivity function approximates a color-mixture function. This measure, called colorimetric Q-factor,[7] ranges from 0 (no resemblance to color-mixture) to 1 (precisely a color-mixture function). Table 1[8] shows Q-factors for one desktop color scanner and for a 3 laser scanner (lasers at 450, 540 & 590 nm). The low Q-factor for the red in the desktop scanner is largely accounted for by its peak response being further into the red than is appropriate for colorimetric scanning. Note that this is consistent with attempting to improve color separation, as already discussed.

	Desktop Scanner	Laser Scanner
Red	0.66	0.16
Green	0.73	0.18
Blue	0.86	0.24

Table 1. Colorimetric Q Factors

There are difficulties in building colorimetric scanners. First, the filters are not easy to build. Some sets require negative parts, usually those with narrow filters. With broader filters, one can get all positive responses, but the filters tend to become more similar to each other. Theoretically, any 3 different colorimetric filters could be used, but clearly the more similar they are, the more sensitive the transformation to any given set of color primaries becomes, and the worse the errors become as small amounts of noise affect the individual responses. Unfortunately, the colorimetric Q-factor analysis does not directly describe how large color errors might become when filters do not quite match the color-mixture functions.

In practice, current commercially available desktop scanners do not provide colorimetric response. Therefore a 3×3 matrix correction of their RGB outputs typically yields color errors large enough to be readily visible and often objectionable. On the other hand, a lookup table (LUT) approach to correction, or a higher order matrix correction, can bring the errors within tolerable levels for most applications. Unfortunately, a full LUT is impractical and interpolation must be used. Note that if one considers a typical 8 bit/color scanner, a 24 bit/full color LUT would be 16M entries or 48Mbytes if 24 bits were desired as output. Thus, the current approach is to represent the values more sparsely in a smaller LUT and interpolate to get output colors. Research on the best ways to load LUTs and to interpolate for outputs is currently in progress (see papers at this conference).

Input/Illuminant Spectral Models

The above indication that practical cases, although still only borderline of being "good enough", are not as bad as one might anticipate, has led investigators recently to seek better approaches and to question once again what is really needed to describe color in a system.[9, 10] There are at least two areas of interest. First, the range of spectral reflectances of input images is unlikely to consist of the 31 completely independent values, as tacitly assumed by typical spectrometer measurements. There is undoubtedly correlation between values, so that reflectances can be described by less than 31 values. For example, Farrell[2] states that 6 basis functions can account for more than 99% of the variance in spectral reflectance functions for over 400 samples from various sources. Second, investigators question whether a single standard illuminant for viewing is realistic for desktop systems. If not, we may need more than tristimulus values to describe color through the system.

The approach taken in a number of recent works is generally to examine typical collections of input images, illuminants, or both, in terms of their spectra. The spectra are analyzed either by determining their principal components or by determining sets of filters which minimize either tristimulus or perceptual errors for the collection of inputs or illuminants. In this way, one can both determine optimum filters for scanning and estimate errors which will remain, assuming that the system will handle given statistical collections of inputs or given sets of viewing illuminants. It is found that for broad ranges of reflecting objects, the input spectra may be well described by 4 to 6 basis spectral curves, where well described means that differences from the exact spectra cause essentially no visual difference.

Using Vhrel's[10] work for example, he finds that errors are significantly reduced by using 4 measurements rather than 3, and that the gain in going to 5 measurements is much less. His analysis also allows evaluation of sensitivity to filter shape and noise. Thus, his work indicates that one could significantly reduce tristimulus errors and also make the system less dependent on the illuminant used for viewing by using a 4 parameter color description instead of the 3 tristimulus values. Even if the system used tristimulus values beyond the scanner, the 4th filter, and filter design by these criteria, significantly improves the ability to determine the tristimulus values over a range of input materials.

Conclusions

Many practical systems continue to use uncalibrated scanners and manual color adjustment of the scanned images. Many others, in which one or two printers are used, utilize end-to-end device-dependent color calibration and corresponding device-dependent (or unspecified internal) color descriptions. One may even wish to question whether device-independent descriptions will be totally acceptable.

The current approach to device-independent systems using tristimulus values to describe color is handled by making scanners which are somewhat like, but not precisely, colorimetric. Empirical calibration, using LUTs or high order matrices, yields barely adequate corrections for color critical applications. Very recent works are beginning to show an alternative approach in which scanners may well use more than 3 sensing channels. This approach may simply reduce errors in determining tristimulus values in scanners or it may change the way color is described throughout device-independent systems.

References

1. F. J. Romano (with side-bar by D. Pfeiffer), "Tools for Desktop Color Separation", *Color Publishing*, Vol. **3**, no. 4, p. 31 (July/August 1993).
2. J. Farrell & B. A. Wandell, "Scanner Linearity", *Journal of Electronic Imaging*, Vol. **2** no. 3, p. 225 (July 1993).
3. See, for example, *Ofoto Version 2 User Manual*, Light Source Computer Images, Inc. (1993).
4. R. M. Boynton, *Human Color Vision*, OSA ISBN 1-55752-266-9 (1992).
5. J. J. Gordon & R. A. Holub, "On the Use of Linear Transformations for Scanner Calibrations", *Color Research and Applications*, Vol. **18**, no. 3, p. 218 (June 1993).
6. J. A. C. Yule, *Principles of Color Reproduction*, App. C, John Wiley & Sons, New York, 1967.
7. H. Neugebauer, "Quality Factor for Filters whose Spectral Transmittances are Different from Color Mixture Curves and its Application to Color Photography", *J. Opt. Soc. Am.,* Vol. **46**, p. 821 (1956).
8. P. G. Roetling, J. E. Stinehour and M. S. Maltz, "Color Characterization of a Scanner", *Proceedings of IS&T Advances in Non-Impact Printing Technologies*, Vol. **1**, Oct. 6-11, 1991.
9. D. H. Marimont and B. A. Wandell, "Linear Models of Surface and Illuminant Spectra", *JOSA*, Vol. **9**, no. 11, p. 1905, Nov. 1992.
10. M. J. Vrhel and H. J. Trussell, "Filter Considerations in Color Correction", to be published in *IEEE Transactions on Image Processing*, March 1994.