Color-Accurate Image Archives Using Spectral Imaging

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ABSTRACT

Digital imaging that includes spectral estimation can overcome limitations of typical digital photography, such as limited color accuracy and constraints to a predefined viewing condition or a specific output device. An example includes the use of ICC color management to generate an archive of images rendered for a specific display or for a specific printing technology. A spectral image offers enhanced opportunities for image analysis, art conservation science, lighting design, and an archive that can be used to relate back to an object's physical properties. The Munsell Color Science Laboratory at Rochester Institute of Technology is involved in a joint research program with the National Gallery of Art in Washington, D.C., and the Museum of Modern Art in New York to develop a spectral-imaging system optimized for artwork imaging, archiving, and reproduction. Progress is being documented at the website www.art-si.org. This paper summarizes the scientific approach.

INTRODUCTION

Imaging is an important technique in the scientific examination of art. Its main use has been for visual documentation. Photographs have long been used to document condition before and after transit, microscopic examinations, conservation treatments, and so on. They are used to enable color reproductions in books and from the Internet. Images using materials with spectral sensitivities in such non-visible regions of the electromagnetic spectrum as infrared and X ray are equally important to the visible spectrum. Although images are used to record scientific examinations, they are used infrequently as an analytical tool, that is, the amount of colorant in a photographic material would be used to relate to physical properties of the art. In contrast, astronomy, remote sensing, and medicine have exploited this capability for many years.

The advent of digital imaging offers increased opportunities to exploit images for the scientific examination of art. A research program is underway at Rochester Institute of Technology to develop an image-acquisition system that records reflection information as a function of wavelength. The system initially is limited to the visible region.

This publication will summarize our methodologies and give some performance examples. Full results, documentation, and demonstrations can be downloaded and viewed at www.art-si.org. At the end of this paper are relevant publications written by students, faculty, and staff of the Munsell Color Science Laboratory.

TECHNICAL APPROACH

Complete Sampling—Spectral Measurement

A spectrophotometer records spectral reflectance or transmittance for a specific circular aperture; a single color is measured. By analogy a spectral-imaging system records spectral reflectance or transmittance for a projected scene at a specific spatial resolution; many colors are measured. One can envision a number of techniques to disperse light onto a detector plane. The technique we have taken is to couple a monochrome, area-array chaged-couple device detector with a liquid-crystal tunable filter. Successive images are captured, each image centered at a specific wavelength. Typically we capture 31 bands corresponding to 400-700 nm at 10 nm increments.

As a measurement device, calibration is necessary. For each band, images are taken of a dark field (to remove fixed-pattern noise), several neutral diffuse papers (to compensate for lighting non-uniformity and optical flare), a pressed polytetrafluoroethylene tablet (to determine optimal exposure time), and a color target made from a number of colorants (to compensate for wavelength and geometry bandwidth). These targets are crucial to achieve acceptable performance. In general, spectroradiometry and imaging have greater uncertainty than contact spectrophotometry. Thus, it is necessary to derive transformations that minimize these uncertainties. A typical transformation is shown in Figure 1. The GretagMacbeth ColorChecker DC and a custom target of blue pigments mixed with titanium white were used to develop the transformation. This figure is a visualization of the matrix transformation from spatially corrected 31-band images to spectral reflectance factor images. The matrix contains 961 coefficients

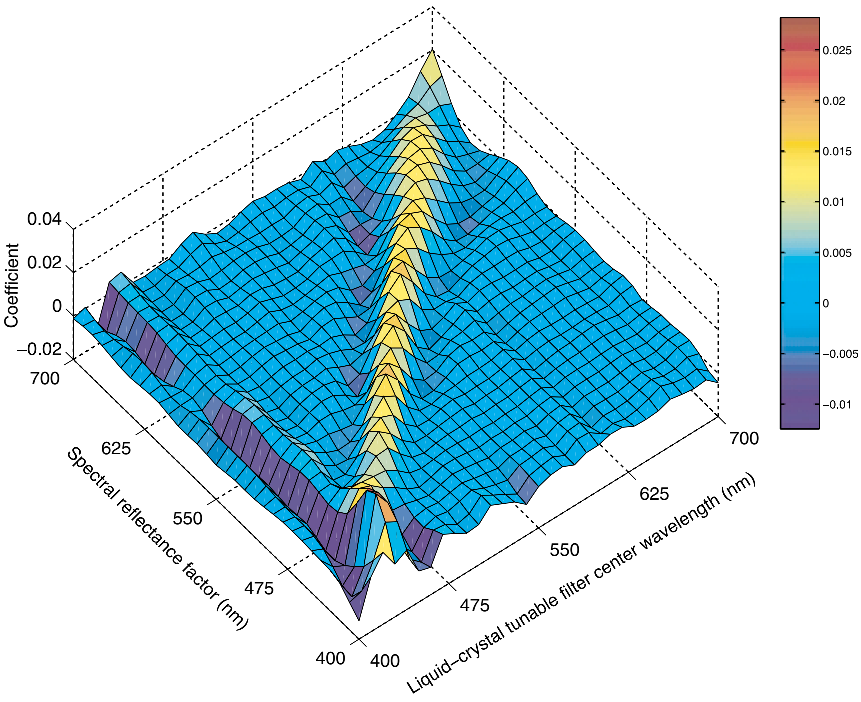

FIGURE 1 Visualization of calibration matrix for 31-band image-acquisition system.

(31 × 31). Ideally the matrix should have dominant diagonal and small off-diagonal coefficients. Figure 2 is an image of the well-known color target, the GretagMacbeth ColorChecker Color Rendition Chart. This independent evaluation target provides a method to benchmark color and spectral accuracy. Typical performance is shown in Figure 3 for these colors. The spectral accuracy was 1.4 percent root-mean-square (RMS) reflectance and an average color accuracy of $1.5\Delta E_{00}$ under daylight (D65) and viewed by the 1931 CIE standard observer.

Subsampling—Spectral Estimation

The system described in the previous section performs spectral measurement; there are the same numbers of image bands as wavelengths. The majority of natural and synthesized colorants have large-bandwidth absorption spectra in the visible region. Furthermore, there are not many sharp transitions from high to low reflectance (and vice versa). From a dimensionality reduction perspective it may not be necessary to collect images every 10 nm, that is, sub-sampling may not result in a loss of accuracy. For example, during the 1970s, many spectrophotom-

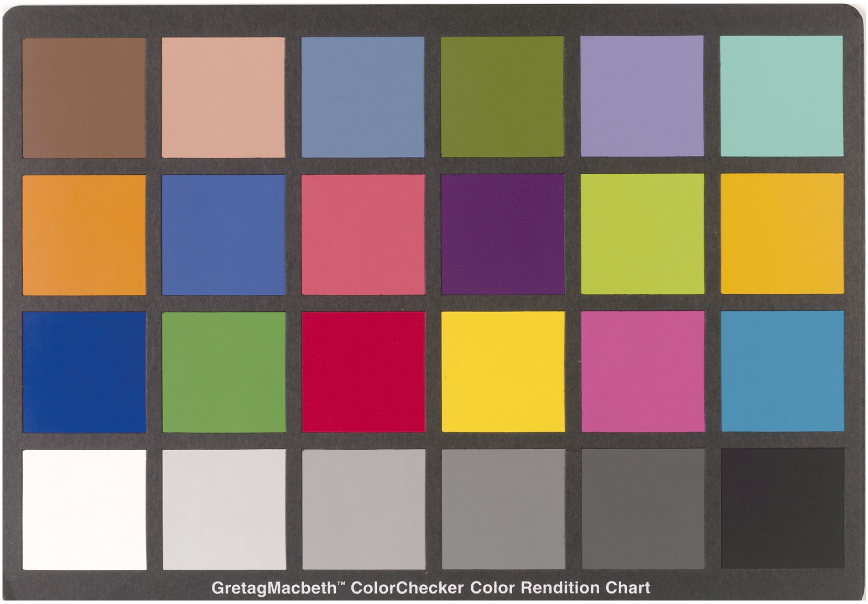

FIGURE 2 GretagMacbeth ColorChecker Color Rendition Chart.

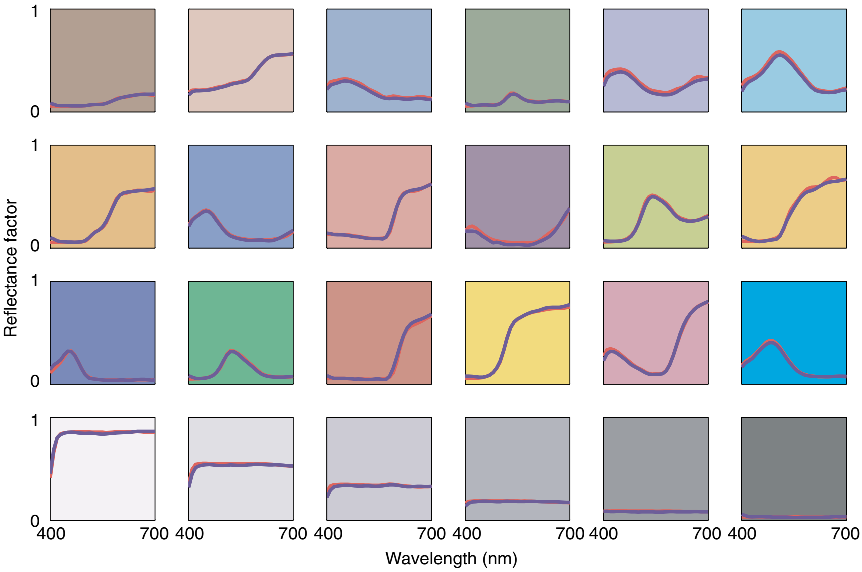

FIGURE 3 Typical spectral-measurement accuracy for the ColorChecker using a 31-band image-acquisition system (blue lines) compared with a small-aperture contact spectrophotometer (red lines).

eters used in color technology sampled the visible spectrum in 20-nm-wavelength increments and bandwidth. As the number of direct measurements reduces we are performing spectral estimation rather than spectral measurement.

Suppose a painting was created from a single chromatic colorant and white (or paper in the case of a watercolor). Because the concentration of one colorant is being varied, one can measure the light reflection at a single wavelength, usually the wavelength of maximum absorption (minimum reflectance ignoring the white). A single image is captured; differences in gray level relate to differences in colorant concentration. At this wavelength, changes in concentration will result in the greatest change in reflectance (i.e., the greatest image contrast). If we measure the spectral absorption properties of the colorant using a spectrophotometer and determine the relationship between camera signals and concentration and between concentration and spectral reflectance (e.g., Kubelka-Munk theory, Beer's law), the single image can be used to estimate a 31-band spectral image. This estimation process has also enabled significant data reduction. We need to archive only the single-band image. The spectral reflectances of the colorant and white, the transformation from camera signals to concentration, and between concentration and spectral reflectance are stored in the image tag. This is analogous to an ICC input profile except in this case, the profile performs spectral color management.

This idea is extended to paintings created with many colorants. Principal component analysis (PCA) is used to define a set of statistical colorants. Because of the spectral properties of colorants in the visible region, the number of statistical colorants (eigenvectors) can vary between 5 and 16. The specific number depends on spectral accuracy requirements and the samples analyzed statistically. In general the imaging system captures the same number of images as the number of statistical colorants. A relationship is determined between the camera signals and statistical colorant amounts (principal components). Concatenating these various steps results in a transformation that relates camera signals to spectral reflectance.

Principal component analysis can be interpreted as constraining the spectral outcome of the mathematical transformation, a type of spectral interpolation. With a large enough number of samples, we can eliminate the use of PCA. In its place we derive a direct transformation from camera signals to spectral reflectance. This method uses a singular-value-decomposition-based pseudo-inverse calculation in which several hundred thousand samples are used to estimate several-hundred-transformation coefficients. These many samples are acquired by considering each pixel of an image an individual data point. We have found that these two methods yield similar spectral accuracy.

Both techniques are constrained in two ways. The first has to do with the camera. Performance depends on the spectral sensitivities of each camera channel. Optimal filter design has been studied for many years; unfortunately these filters, designed by simulation, cannot be fabricated. The practical solution is to select the best filters from those produced commercially. We have taken this approach. We have also used commercial cameras with color filter area-array sensors. With additional filtration using colored absorption filters, sets of color images are recorded. Three, six, or nine image planes (each triplet is the usual red, green, blue image) are related to three, six, or nine statistical colorants or directly to spectral reflectance. The second constraint is the dependence on a color target. The target is used to derive the mathematical transformation. Ideally, the target should have a number of colored patches sampling thoroughly the color gamut of materials to be imaged. The patches should be made from colorants with unique spectral properties. The gloss properties should be consistent. In essence there is an assumption that the color target has spectral properties that encompass those of the art to be imaged. Most commercial targets do not have these ideal properties.

Despite these constraints, the method has proven to be nearly equivalent to 31-band spectral imaging. Using a color-filter-array camera and two absorption filters, the average performance for the ColorChecker was 1.6 percent RMS and 1.2 ΔE_{00}, plotted in Figure 4. The transformation matrix is plotted in Figure 5, derived using the ColorChecker DC. This transformation relates six camera sig-

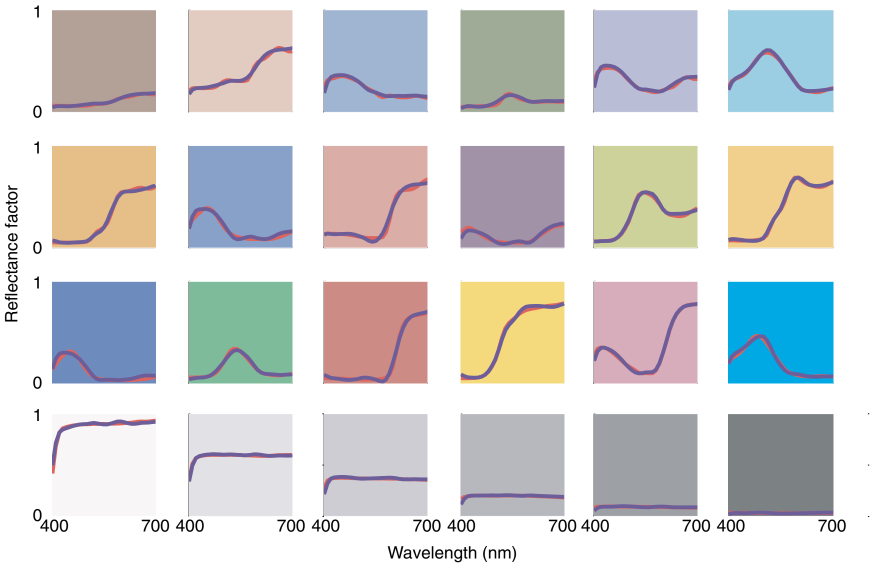

FIGURE 4 Typical spectral-measurement accuracy for the ColorChecker using a two-filter color-filter-array image-acquisition system (blue lines) compared with a small-aperture contact spectrophotometer (red lines).

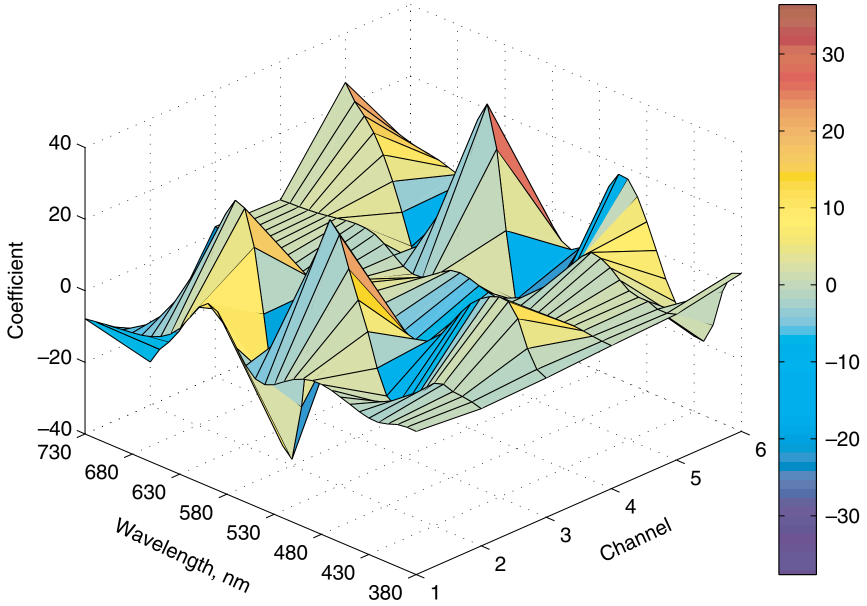

FIGURE 5 Visualization of calibration matrix for six-band image-acquisition system, achieved using two absorption colored glass filters and a color-filter area-array image-acquisition system.

nals to 36 wavelengths, totaling 216 matrix coefficients. At each wavelength, there should be at least one peak or valley.

Spectral Advantage

A spectral image archive has a number of advantages over many current image archives. Sometimes, an archive is created by digitizing photographs. In other cases direct digitization is used with scanbacks, using repurposed flatbed scanning sensors. Film and scanbacks have spectral sensitivities quite different from the human visual system. As a result these archives require significant visual editing as part of the workflow. Thus, the archive is connected to a particular display, viewing condition, and observer. Color accuracy is limited. Color management principles can be used to reduce the reliance on visual editing. Even so, color accuracy can still be limited. The spectral archive is not subject to these constraints; the result is excellent color accuracy, eliminating the need for visual editing.

A non-spectral archive stores three image planes per object, such as RGB

TIFF (tagged image file format). For color-managed images tags are used to relate the digital signals to standardized viewing and illuminating conditions (source profiles). Using ICC color management, this includes CIE illuminant D50 and the CIE 1931 standard observer. Thus, the archive is limited to a single observer and illuminant. The spectral archive can be used to relate the digital signals to any observer, viewing, and illuminating condition. This provides tremendous opportunities by enabling an object to be rendered under multiple conditions without re-imaging. Using vision models that account for chromatic adaptation, one can compare an object's appearance with changes in lighting, providing lighting designers with a unique and powerful tool.

Many colorants have unique spectral properties within the visible spectrum. Thus, the spectral archive can be used to analyze the colorants used in a work of art. The spectral information can aid conservators in selecting colorants for inpainting (retouching) that result in minimal metamerism. We expect that a combination of spectral imaging and direct small-aperture spectrophotometry can be used to create colorant maps.

Printed reproductions are quite useful for scholarly endeavors and during conservation treatments. Color-managed prints are designed to match under CIE illuminant D50 and to be viewed by the 1931 standard observer. By definition the prints are metameric and will only match for this single condition. However, prints are viewed under a variety of conditions. Spectral data can be used to produce prints that better match original objects for these many conditions.

Finally, a visible-spectrum archive can be combined with other wavelength regions such as infrared and X ray, aiding in a more complete record on a work of art's physical properties.

CONCLUSIONS

A spectral image archive results in high color accuracy and facilitates the scientific examination of art in the visible region of the electromagnetic spectrum. Two methods of image acquisition have been described: (1) complete spectral sampling and (2) spectral sub-sampling combined with estimation. Each method has advantages and disadvantages. Issues include spectral accuracy, colorimetric accuracy, hardware complexity and cost, software complexity, image capture time, data storage, ease of use, maintenance, and system duplication complexity. One of the research goals is to describe these trade-offs in order to provide museums, archives, and libraries with information to assist them in making practical decisions regarding the incorporation of spectral imaging into their imaging practices.

ACKNOWLEDGEMENTS

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