Spectral Reproduction Research for Museums at the Munsell Color Science Laboratory

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Abstract
Museums are undergoing extraordinary changes. The digital revolution continues to redefine every aspect of business from collections management to exhibition presentation. Along with the institutions themselves, museum photography departments have moved swiftly into the digital arena, solving old problems, enabling new possibilities, and encountering many new complications along the way. A group from the Munsell Color Science Laboratory of the Rochester Institute of Technology has been building a growing body of research probing the state of museum imaging and investigating ways to improve the museum reproduction chain. At the same time, the research group has been participating in the development of imaging spectrometry for color reproduction. The overlap between museum reproduction needs and spectral imaging possibilities makes for important synergies that should contribute important new capabilities to the documentation, analysis and reproduction of museum artifacts.

Introduction
Photography departments from more than 50 cultural heritage institutions from across the US recently participated in an extensive survey probing their use of digital imaging.[1,2] The respondents reported a median of 90% of their photography is performed digitally. More than half of the institutions also indicated that their photographers spend a median of 12 minutes per image editing the results. One out of five is investing a half an hour or more to each image for post-capture processing.

The disadvantages of digital photography as applied to image quality often stemmed from frustration with color fidelity. When asked "Do you know enough about Color Management?" only 1% of respondents gave themselves highest marks. More than 50% rated themselves as neutral to "I do not know enough." In witness that the institutions are trying their best, 80% of those using color management said they were building their own color profiles. In spite of these efforts, photographers are still spending much time correcting individual images for color problems.

On-site case studies[3,4] were performed at four institutions chosen from among the best funded facilities with the most aggressive programs for transitioning to digital. Of the many camera parameters measured, μ-factor[5] is the most relevant to intrinsic color quality. μ-factor indicates how closely a set of camera channel spectral sensitivities emulates the color matching functions of a human observer. A μ-factor rating of 1.0 is a perfect score and zero is infinitely bad. A μ-factor value of at least 0.90 is desirable for a digital camera used to photograph cultural heritage.[4]

Even though some of the best available studio cameras were used at the case study institutions, the μ-factor measurements were far from perfect, ranging from 0.65 to 0.81. This means that those cameras are susceptible to instrumental metamerism[6] between themselves and humans. In turn, metamerism condemns the system to imperfect colorimetry, leaving some colors to continue to require human interaction to fix. This concept will be demonstrated in the *Instrumental Metamerism* section below.

Recognizing the need to reduce camera/human instrumental metamerism when color rendition is of primary importance, multichannel camera systems have been developed for the estimation of spectral reflectance or spectral radiance.[7-10] Time spent in post-capture color correcting of photographs should be reduced or eliminated for camera systems that accurately estimate spectral information.

Spectral data in the reproduction chain brings with it new opportunities such as the ability to create hardcopy reproductions true to how original colors shift under different illuminants. The Munsell Lab began research into spectral reproduction over a decade ago.[11] The spectral imaging research program[12] currently covers many important component pieces including spectral capture,[13] processing of spectral signals[14] and spectral hardcopy.[15]

Instrumental Metamerism
This section demonstrates how easy it is for error to be introduced into the imaging stream when a camera does not have perfect color channels. The need for visual editing to mend color inaccuracies increases as metamerism increases.

An area array camera popular with museum photography departments for high-end imaging studios was utilized for this demonstration. It has a μ-factor of 0.67. Camera spectral sensitivities optimally transformed to the human Color Matching Functions (CMFs) is shown in Figure 1. Note how different the curves are from the CMFs. Daylight balanced HMI lights were used to illuminate the targets.

Two targets were separately used for this demonstration. The first was a GretagMacbeth Digital ColorChecker SG. (GM ColorChecker) See Figure 2. The SG is a 140 patch target in the ColorChecker line. An important feature of this target is that within its patches sits a complete standard 24 patch ColorChecker target.

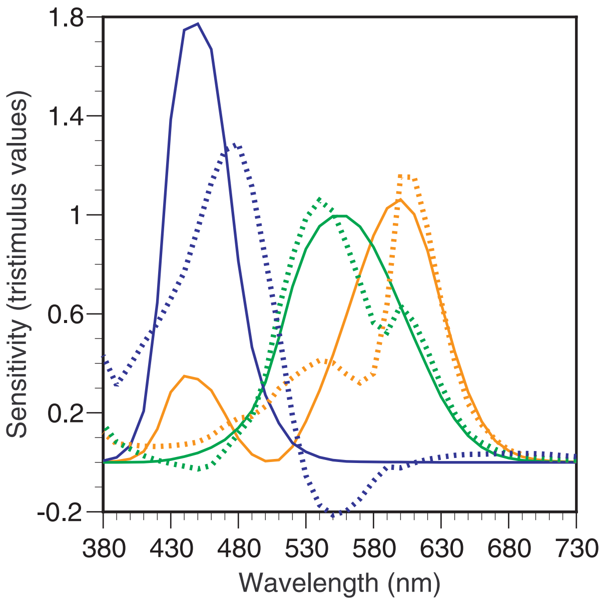

Figure 1. Camera sensitivities (dashed lines) linearly transformed to optimally match color matching functions (solid lines).

Figure 2. GretagMacbeth Digital ColorChecker SG on left. Standard 24 patch ColorChecker is included as noted on right.

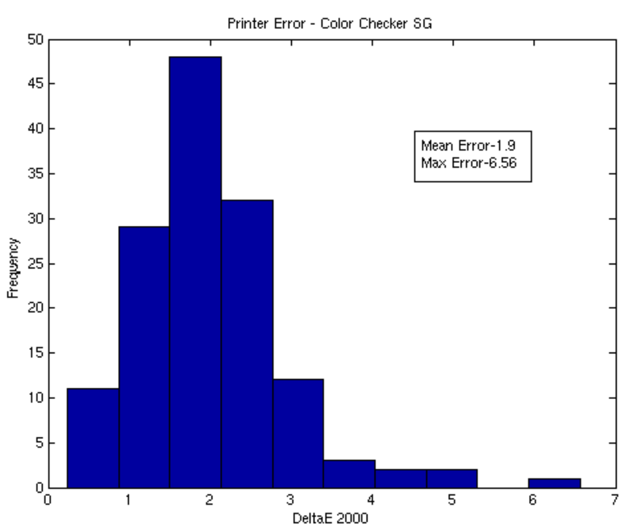

Figure 3. CIEDE2000 between GM and IG ColorChecker targets.

The second target was carefully produced to be a colorimetric copy of the ColorChecker SG under the HMI lights (IJ ColorChecker). It was printed on an ink-jet printer. The reproduction was very accurate. Over the 140 patches, it had a mean CIEDE2000 from the original of 1.9 and a maximum error of less than 7. A histogram of color differences is found in Figure 3. Example spectra from the same associated patches on the two targets are shown in Figures 4 and 5. Like many of the simulated patches, these have less than 1 CIEDE2000 difference from the original patches under the HMI lights.

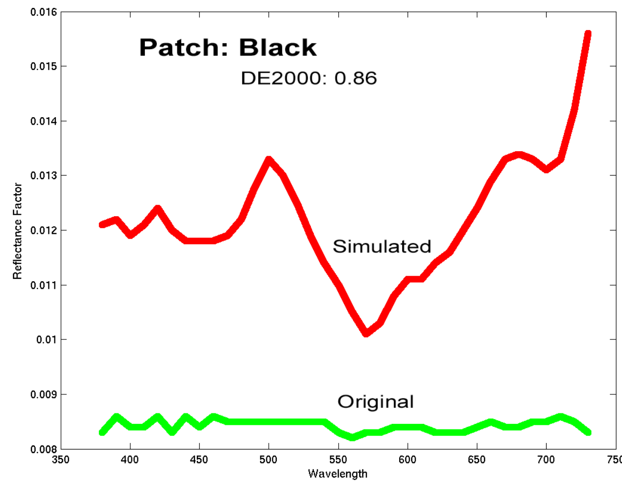

Figure 4. Black patch. Lower curve is reflectance spectra from the GM ColorChecker SG, IJ ColorChecker patch above. CIEDE2000 between the two patches is 0.86.

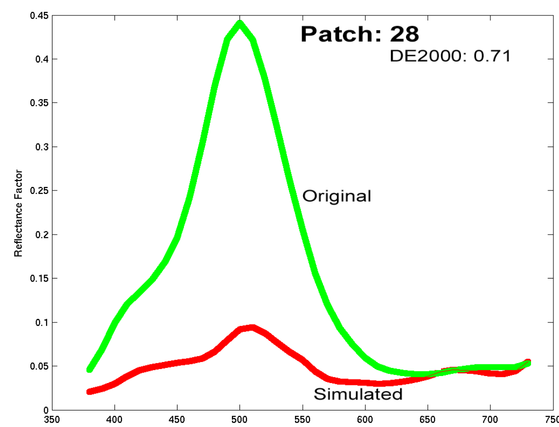

Figure 5. Patch 28. Upper curve is reflectance spectra from the GM ColorChecker SG, IJ ColorChecker patch below. CIEDE2000 between the two patches is 0.71. Note that there is a different scaling of the Y-axis relative to Figure 4.

Two optimized transforms were constructed converting camera RGB to colorimetry. One transform was associated with the GM ColorChecker (original) and the other was associated with the IJ ColorChecker (simulated on ink-jet). 30 patches from a target were used to as a basis for the transform optimization. 24 of the 30 patches came from the standard embedded ColorChecker, plus an additional 6 grayscale patches. Each transform was embedded into an ICC profile.

Profile Performances

From each target, 110 patches not involved in building the transforms were used to evaluate the impact of instrument metamerism on the quality of profile performance. The patches were transformed through the profile and then to CIE absolute colorimetry for comparison with measurements and each other.

Even though the same camera is used, the same lights and the same profile, the camera sees colors differently than a human does, as quantified with the non-unity μ-factor. Thus, two targets that look to a human as containing the same colors can be misrepresented through a camera as different colors. The color differences found in Table I make it clear that good color management cannot overcome camera imperfect spectral sensitivities in a 3-channel camera. The average color error increases from 26% to 57% as the profile and the target used to optimize the transform become spectrally different.

Table 1: Mean CIEDE2000 Performance of Profiles

		Profile from GM target	Profile from IJ target
GM (original) ColorChecker	training patches (30)	3.7	5.0
	test patches (110)	3.2	5.8
IJ (simulated on ink-jet) ColorChecker	training patches (30)	5.6	2.4
	test patches (110)	5.2	3.2

Spectral Capture

The program at the Munsell Lab has evaluated three different approaches for spectral photography. A liquid crystal tunable filter has been used in front of a monochrome sensor to create 31-channel spectrally narrow-band captures[16]; a color filter wheel with six absorption filters has been used in front of a monochromic sensor making for six wide-band spectral channels[16]; and, a trichromatic RGB color-filter array sensor with a pair of absorption filters placed serially in front of it, also creates six spectrally wide-band channels.[13] The great advantage to this latter technique is the ease with which off-the-shelf professional-level camera equipment can be used.

Figure 6 is a Sinarback 54H digital camera back, with a Sinar M shutter, a prototype filter slide, a P3 body and 105mm HR lens. This camera system was used to test spectral capture using a trichromatic camera system with two filters.

Figure 6. Prototype "off-the-shelf" trichromatic camera system using two filters to create 6-channel image for estimating spectra.

It has been shown in much research concerning spectral reconstruction from cameras that minimizing spectral RMS error is often associated with non-minimum colorimetric error (e.g. Refs. 17, 18 and 19). A method for combining optimal colorimetric transformation with optimal spectral transformation based on parametric decomposition[20] has been used to produce excellent performance.[17]

The high quality colorimetric capabilities of such a system can immediately impact the museum photographer's experience by reducing or eliminating the need for visual editing. Alternatively, the fact that the spectral estimation is of such high quality allows for a completely new reproduction chain. Using the spectral signal beyond capture requires the ability to transform that information eventually into output signals as will be discussed in the following two sections.

Spectral Color Processing

Traditional image processing techniques used for 3-dimensional processing are not suited to the many-dimensions of a spectral space.[18,21,14] A sparse multi-dimensional lookup table with inter-node interpolation is a typical transform used within a color management implementation. Such an approach for spectral processing becomes problematic because the size of lookup tables is exponentially related to the number of input dimensions. While connecting in XYZ or CIELAB requires a 3-dimensional lookup table, connecting in a 31-dimensional spectral space requires a 31-dimensional lookup table. A 31-dimensional lookup table would be absurdly large.

A low-dimensional Interim Connection Space (ICS)[22] is a critical aspect of this spectral reproduction workflow. The ICS provides a logical way-station during the transition between a full-dimensional spectral space and device-dependent units. Desirable characteristics of an ICS include a reasonably small number of dimensions and a computationally inexpensive calculation from spectra.

LabPQR[14] has been defined to serve as an ICS and to maintain additional important characteristics. The first three dimensions the dimensions of the space are CIELAB under a given illuminant.[23] A simple, invertible transform goes from the CIELAB values to some full 31-dimensional pre-corrected curve. The rest of the LabPQR dimensions are used as correction values that produce a high quality spectral reconstruction from the curve.

LabPQR is useful not only as a convenient low-dimensional spectral description space. It also has been shown to be highly useful for developing spectral gamut mapping methodologies and for spectral gamut visualization.[14]

Spectral Printing

Three categories of approaches have been undertaken to characterize printers for spectral output. They range from purely physical[24] to a combination of a physical model and empiricism[25] to brute force empirical.[26] Recently, the Cellular-Yule-Nielsen-Spectral-Neugebauer (CYNSN) model[27] has shown good results.[15] By "cellular" it is meant that the parameters to the Yule-Nielsen Spectral Neugebauer model are fit within small regions of colorant space, ensuring high accuracy.[28]

The approach required three optimizations. First, the Yule-Nielsen n-value was derived for each of the individual colorant ramps. Based on the calculated n-value, one-dimensional lookup tables were built to transform from digital values to area coverages. The next optimization located for each colorant four coverage levels to serve as cellular primaries. 0% and full area coverage were two fixed choices, leaving only two degrees of freedom per colorant. Finally, the majority of cellular primary combinations were actually unprintable due to physical ink-blotting that occurred on the printer when one attempted to print too much ink-coverage. This required the third optimization where spectral properties of the non-printable ink combinations were synthesized.

The fully parameterized model was able to estimate the spectral properties of 600 random printed ink combinations to within 0.5% RMS spectral reflectance factor error and within 1.0 CIEDE2000.

Conclusions

A research program at the Munsell Color Science Laboratory is looking at many spectral reproduction techniques that may prove useful to cultural heritage institutions. One of the most compelling needs of the community is to improve camera capture so that extensive color editing is no longer necessary. Instrumental metamerism ensures that even the best cameras currently on the market will require some amount visual interaction for many colors. Spectral capture techniques will improve the situation.

Once spectral data is available, processing it for output is an obvious choice. Among the advantages of creating a spectral reproduction of an original is that the reproduction will match the original for all devices, be they cameras or humans. Another feature of a spectral copy is that as illumination changes, the match between an original and the reproduction remains.

New approaches to processing spectral data are being developed. The use of LabPQR as an Interim Connection Space is showing promise. The colorimetric aspects of the space, make it a very useful hybrid ensuring that both colorimetry and spectrophotometry can be taken into consideration when spectral gamut mapping takes place.

Characterizing a printer for spectral reproduction is an important step in preparing for spectral output. The Cellular-Yule-Nielsen-Spectral-Neugebauer approach has been shown to provide good results.

Another place where spectral data will be of value to cultural institutions is in the conservation laboratory as spectral capture can be analyzed to determine chemical content of pixel locations. Also, for documentation purposes, an archived image with spectral data at each pixel can be far more easily be interpreted at some future point than an RGB pixel associated with some long-forgotten camera or some profiled color space where the profile may or may not itself be interpretable.

As museums continue to move into digital photography, multichannel cameras with the ability to estimate spectra are going to grow in importance. The Munsell Lab continues to research many important pieces necessary to spectral reproduction including capture, processing and output. These still represent component pieces. The lab's goal is to bring these abilities together into successful spectral imaging workflows.

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