High-Accuracy Digital Imaging of Cultural Heritage without Visual Editing

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Abstract

At Rochester Institute of Technology, a research program is near completion aimed at benchmarking the quality of direct digital imaging of cultural heritage in American museums, libraries, and similar institutions. The current practice at nearly all institutions surveyed includes visual editing. Digital masters incorporate camera spatial processing, ICC-type color management including encoding in a large-gamut RGB space, and global and local visual editing. Also at RIT, a research program is underway aimed at developing a high-quality digital camera that incorporates spectral imaging. The hypothesis is that when using the new camera system, visual editing is unnecessary, greatly improving workflow efficiency and color accuracy. An experiment was performed to test this hypothesis. The experiment included spectral-based imaging of both color targets and small paintings and rendering the spectral images for a colorimetrically-characterized computer-controlled LCD display. The targets and paintings were viewed adjacent to the display in a laboratory lit by ceiling-mounted daylight-balanced fluorescent lights. A variety of quantitative comparisons were performed including: reflectance spectrophotometry vs. in-situ spectroradiometry, reflectance spectrophotometry vs. spectral-based imaging, forward and inverse model accuracy of the LCD colorimetric characterization, and in-situ spectroradiometric comparison of targets and paintings compared with their LCD renderings. Using the GretagMacbeth ColorChecker as an independent verification target, average color differences varied between 1.0 and 2.9 ΔE_{00}. For two paintings, the average accuracy was 4.2 and 5.1ΔE_{00}. This level of accuracy exceeded that achieved by museums and libraries, even following global and local image editing, confirming our hypothesis that it is possible to create a digital archive of cultural heritage without the need for visual editing.

Introduction

At Rochester Institute of Technology, a research program is near completion aimed at benchmarking the quality of direct digital imaging of cultural heritage in American museums, libraries, and similar institutions.[1,2] The current practice at nearly all institutions surveyed includes visual editing. Digital masters incorporate camera spatial processing, ICC-type color management including encoding in a large-gamut RGB space, and global and local visual editing. Also at RIT, a research program is underway aimed at developing a high-quality digital camera that incorporates spectral imaging.[3,4] The hypothesis is that when using the new camera system, visual editing is unnecessary, greatly improving workflow efficiency and color accuracy. An experiment was performed to test this hypothesis.

Experimental

Targets and Spectrophotometry

The GretagMacbeth ColorChecker, the GretagMacbeth ColorCheckerDC, and two small oil paintings were used as calibration and verification targets. The oil paintings were created from a set of pigments found to represent the spectral properties of many artist materials.[5] The spectral reflectance factor of the targets was measured using a Macbeth XTH integrating sphere spectrophotometer with the specular component excluded. A transparent template was made for each painting to record the position of 11 measurements made at locations corresponding to unmixed paints.

Image Capture and Spectral Estimation

Using diffuse tungsten-halogen illumination (Elinchrom Scanlites with Chimera Softboxes diffusers) at 45° to the surface normal, images were captured using a modified Sinarback 54M color-filter-array digital cameraback and Sinar optics and view camera. Camera modifications included replacing the infrared blocking cover glass with clear glass, and designing[6] two sets of glass filters that were placed sequentially in the optical path. The two sets of RGB images were transformed to a spectral image using the ColorCheckerDC as the calibration target. The estimation method was based on two transformations. The first was a direct linear transformation to reflectance factor, created using a SVD-based pseudo-inverse calculation on several hundred thousand pixels. The second was a nonlinear transformation from the six channels to tristimulus values minimizing average and maximum color differences. The two methods were combined resulting in spectral data with high colorimetric accuracy.[7]

Display Environment and Metrology

In one of the rooms of the Munsell Color Science Laboratory, an environment was created that consisted of an IBM T221 LCD display driven by an Apple G5 and an adjacent custom easel, both placed on a high countertop. Ambient illumination came from ceiling mounted Macbeth D65 fluorescent fixtures, shown in Figure 1. The luminance of the display at peak output exceeded that of a white reference Halon plaque and was reduced to match at about 76 cd/m^2. The display was colorimetrically characterized in the dark using a LMT C1210 illuminance colorimeter.[9] A Photo Research PR704 spectroradiometer was placed at the position of an observer standing and viewing the display and easel; it was used to measure the spectral radiance of the ambient first-surface reflectance from the display and the white reference placed on the easel. Several additional measurements of display colors were measured with the PR704 to transform the LMT measurements to the PR704.[10] Thus, the complete display profile was based on absolute colorimetry in units of cd/m^2. The spectral images were rendered colorimetrically for the ambient illumination and the 1931 standard observer. These XYZ images were transformed to display digital counts.

Results and Discussion

The results for the ColorChecker, used as a verification target in this experiment, are summarized in Table I. The first analysis compares direct spectroradiometry of each patch with calculated spectral radiance by multiplying each patch's spectral reflectance factor with the ambient spectral radiance. We see that differences in metrology led to an average color difference of $1\Delta E_{00}$. Lack of inter-instrument agreement is typically caused by differences in geometry, photometric scale, wavelength scale, and bandwidth.[11] Given that the digital camera was used as an imaging spectroradiometer, this metrology-based difference will also contribute to the total uncertainty when using cameras to measure the spectra and colors of cultural heritage.

We analyzed the LCD profile accuracy in two ways. First, we calculated the absolute tristimulus values based on spectrophotometric measurements of the ColorChecker and a spectroradiometric measurement of the ambient illumination from the reference white. These were compared with measurements of the display's rendering of the ColorChecker. This resulted in an average performance of $1.9\Delta E_{00}$. When we input in-situ measurements of the ColorChecker using the spectroradiometer, average performance improved to $1.5\Delta E_{00}$. This difference was caused by the differences between spectrophotometry and spectroradiometry as discussed previously. This evaluation is much more stringent than typical display profile evaluation since the input is based on real samples rather than numerical data. The profile accuracy using the customary forward-model approach was $0.8\Delta E_{00}$ on average with a maximum of $2.2\Delta E_{00}$ across the display's RGB color space.

The average camera accuracy was $2.3\Delta E_{00}$; this accuracy was reasonable at the stage of our research when this experiment was performed. Subsequent experiments have reduced the average and maximum accuracy to 0.9 and 2.2 ΔE_{00}, respectively.[12]

Finally, we evaluated end-to-end performance in which the spectroradiometer was used to measure both the in-situ ColorChecker and its rendering on the LCD display. The average performance was $2.9\Delta E_{00}$. This value incorporates all the uncertainties: metrology of spectrophotometer vs. spectroradiometer, LCD profile, and camera profile. If we consider each of these uncertainties as uncorrelated variables, then the average of 2.9 was within the expected total uncertainty ($3.1\Delta E_{00} = \sqrt{1^2 + 1.9^2 + 2.3^2}$, on average).

Two small oil paintings were also imaged followed by the identical processing as applied to the ColorChecker. Eleven positions on each painting and its LCD rendering were measured in-situ using the spectroradiometer. The results are listed in Table II. The average difference increased from the ColorChecker. This increase was a result of differences in surface properties between paintings and matte test targets. The oil paintings have impasto and variable gloss across their surfaces. This accentuates differences in lighting geometry between spectrophotometry (used to characterize the calibration target), the camera-taking illumination, and the ambient conditions. Secondly, the calibration target, the ColorChecker DC, does not have spectral properties that span the spectral variability of the paintings. In particular, cobalt blue was used in each painting. Without a calibration target with blue samples with similar spectra to cobalt blue, errors will always result.

These paintings were used in our research program to benchmark the color and spatial image quality of direct imaging of cultural heritage in American institutions.[2] These paintings were imaged and then visually edited with Photoshop to improve their color accuracy. The editing could be either global or local. The photography and visual editing were performed at several museums by their in-house photographers. These rendered paintings were measured using a spectroradiometer, the results listed in Table III. On average, our approach exceeded each institution.

Conclusions

An experiment was performed to evaluate end-to-end color reproduction accuracy between oil paintings and their rendering on a high-resolution liquid-crystal display. The paintings and display were situated adjacently in a laboratory with overhead fluorescent lighting. The displays's luminance was adjusted to match a reference diffuse white under the room's ambient lighting. Based on in-situ spectroradiometric measurements of the display and contact spectrophotometry of the two paintings, the average accuracy was 4.2 and $5.1\Delta E_{00}$. This level of accuracy exceeded that achieved by museums and libraries, even following global and local image editing, confirming our hypothesis that it is possible to create a digital archive of cultural heritage without the need for visual editing.

Table 1. CIEDE2000 Colorimetric performance of each listed evaluation for the independent verification target, the GretagMacbeth ColorChecker. See text for explanation.

No.	Name	Metrology: Spectro-photometer vs. Spectro-radiometer	Inverse LCD: Spectro-photometer vs. Display	Inverse LCD: Spectroradiometer vs. Display	Direct Digital Imaging: Spectrophotometer vs. Camera	End-to-End: Spectro-radiometer vs. Display
1	Dark Skin	0.7	1.1	1.5	1.1	8.1
2	Light Skin	0.3	2.0	1.9	1.7	8.3
3	Blue Sky	1.0	1.8	2.2	2.4	6.7
4	Foliage	1.8	1.8	1.8	1.4	1.5
5	Blue Flower	1.1	1.2	2.3	1.6	1.9
6	Bluish Green	1.0	0.4	1.3	2.2	1.0
7	Orange	1.2	4.0	2.8	1.9	5.3
8	Purplish Blue	1.3	0.6	0.7	1.6	1.7
9	Moderate Red	0.3	1.4	1.7	2.4	2.9
10	Purple	2.2	3.2	1.3	3.4	2.8
11	Yellow Green	0.8	1.3	1.1	2.7	2.0
12	Orange Yellow	1.0	2.9	2.3	9.2	4.0
13	Blue	1.1	0.8	0.4	1.3	2.0
14	Green	0.7	1.8	1.5	2.3	1.6
15	Red	1.1	2.2	0.7	2.8	1.4
16	Yellow	1.0	1.3	1.4	2.4	1.7
17	Magenta	0.7	2.0	1.5	2.6	2.1
18	Cyan	1.1	2.1	1.2	2.3	1.0
19	White	1.8	2.2	1.2	2.3	1.7
20	Neutral 8	1.3	2.4	1.4	2.1	2.3
21	Neutral 6.5	0.9	3.0	2.2	1.7	2.9
22	Neutral 5	0.8	3.7	2.7	1.8	3.6
23	Neutral 3.5	0.4	1.0	0.8	1.2	1.9
24	Black	1.0	1.8	1.3	0.8	1.7
	Average	1.0	1.9	1.5	2.3	2.9
	Median	1.0	1.8	1.5	2.1	2.0
	Minimum	0.3	0.4	0.4	0.8	1.0
	Maximum	2.2	4.0	2.8	9.2	8.3

Table 2. CIEDE2000 colorimetric performance of two paintings comparing contact spectrophotometry of the painting with in-situ spectroradiometry of the display.

Paint	Fish	Flowers
Phthalocyanine blue	2.6	9.4
Cobalt blue	7.3	2.4
Phthalocyanine green	8.6	6.6
Chromium oxide green	2.0	2.8
Cadmium yellow medium	4.5	3.5
Indian yellow	2.2	2.9
Venetian red	3.9	8.2
Cadmium red medium	3.8	4.7
Quinacridone red	4.0	7.0
Titanium white	4.0	2.0
Ivory black	3.7	6.1
Average	4.2	5.1
Median	3.9	4.7
Minimum	2.0	2.0
Maximum	8.6	9.4

Table 3. CIEDE2000 colorimetric performance of two paintings comparing their spectrophotometric-based coordinates with spectroradiometric measurements of images rendered for display following visual editing at three representative institutions (CS2, CS3, CS4). (See submission by Murphy, Taplin, and Berns.[2])

	Fish			Flowers		
Paint	CS2	CS3	CS4	CS2	CS3	CS4
Phthalocyanine blue	4.8	10.6	7.8	5.1	10.3	4.0
Cobalt blue	3.3	11.2	5.8	7.1	8.6	5.4
Phthalocyanine green	7.2	13.5	8.3	6.6	10.5	8.1
Chromium oxide green	6.1	10.1	8.0	3.3	6.8	5.4
Cadmium yellow medium	8.1	9.1	12.3	5.2	8.4	5.3
Indian yellow	3.4	7.6	4.4	5.7	8.5	8.4
Venetian red	7.1	10.7	9.2	6.7	9.9	8.3
Cadmium red medium	4.7	8.4	4.6	5.6	8.6	7.7
Quinacridone red	5.0	10.1	4.7	5.0	10.9	6.9
Titanium white	6.4	11.2	8.5	9.6	9.7	11.8
Ivory black	4.9	11.4	9.1	5.5	9.4	8.0
Average	5.6	10.4	7.5	7.1	8.6	5.4
Median	5.0	10.6	8.0	6.6	10.5	8.1
Minimum	3.3	7.6	4.4	3.3	6.8	5.4
Maximum	8.1	13.5	12.3	5.2	8.4	5.3

Figure 1. Experimental setup of LCD (left) and easel (right).

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Biography

Dr. Roy S. Berns is the Richard S. Hunter Professor in Color Science, Appearance, and Technology at the Munsell Color Science Laboratory and Graduate Coordinator of the Color Science master's degree program within the Center for Imaging Science at Rochester Institute of Technology. He received B.S. and M.S. degrees in textile science from the University of California at Davis and a Ph.D. degree in chemistry with an emphasis in color science from Rensselaer Polytechnic Institute. His research includes spectral-based imaging, archiving, and reproduction of cultural heritage; digital rejuvenation of paintings; spectral modeling of multi-ink printers; quantifying the optical properties of painting varnishes and the impact on appearance; and general color science.