Multi-spectral imaging of van Gogh's Self-portrait at the National Gallery of Art, Washington, D.C.

Francisco H. Imai, Mitchell R. Rosen and Roy S. Berns
Munsell Color Science Laboratory, Rochester Institute of Technology
Rochester, New York

Abstract

Efforts to apply an end-to-end color reproduction system using multi-channel visible-spectrum imaging to a van Gogh self-portrait at the National Gallery of Art, Washington D.C., have been under way at the Munsell Color Science Laboratory. The goal was to perform preliminary experiments by imaging a target consisting of pigments based on direct spectral measurements of the painting. These experiments are useful in preparing for future imaging that will result in hardcopy that will yield the least metameric matches to the original colors. The approach evaluated consisted of capturing scenes through a trichromatic digital camera combined with multiple filterings and six-color printing. The system was designed to estimate the original scene spectra on a pixel-by-pixel basis. The spectral-based printing used in this research was able to produce the least metameric reproduction to the original. Results show a system accuracy of mean ΔE^*_{94} of 5.0 and spectral reflectance rms error of 3.1%.

Introduction

A general belief among many in the museum community is that deficiencies in image capture are well handled through the use of tone and color balance facilities in tools such as Adobe Photoshop. Once the image is captured, tone and color corrections are adjusted visually. Although these adjustments can produce pleasant results, they are not acceptable in terms of color accuracy nor scientific endeavors.

In order to improve color accuracy, the National Gallery in London, UK has pioneered the development of a colorimetric image archive for their collection.[1] Their initiative was very successful in producing high-quality reproductions that matched the original painting under controlled illumination. However, colorimetric matching decisions are prone to problems associated with metamerism: intransigence to changes in illumination, lack of forgiveness for differences between individuals and the standard observer, and high sensitivity to printer noise and calibration errors. Multi-channel Visible-Spectrum Imaging (MVSI), also known as *spectral imaging*, is far more robust with respect to these limitations at the expense of more system complexity and higher system bandwidth demands[2-7] and has been used in artwork imaging.[4,5]

We have been drawing upon this body of work and extending it to produce an end-to-end scene to hardcopy spectral reproduction system.[6,7] In terms of image acquisition and spectral estimation methods, we have studied two different approaches. The first approach uses wide-band image acquisition combined with either a number of colored filters or a number of differently colored light sources. The captured images are converted to a spectral reflectance image using *a priori* colorant information.[8] The second approach uses narrow-band image capture, that although is more time consuming than the first approach, presents more robustness to any arbitrary spectral curve and does not require specific knowledge of the colorants in the artwork.[9] A description and comparison of these two approaches can be found in reference 10.

In order to print the reflectance image, a six-color inkjet printer is spectrally characterized. The inverse Yule-Nielsen modified Neugebauer equations are used to predict dot areas from spectral reflectance.[11-13] The spectral image is printed producing reproductions that are the least metameric matches to the original objects. This results in high-quality color stability under different illuminations and across observers. The evaluation of the end-to-end system using wide-band acquisition and four-color printing can be found in reference 6. In relation to previous work, we further improved the system from imaging patches generated using in-gamut printer colors and four-color printing to the imaging of actual oil painting patches and six-color printing. Six-color printing would be more effective in matching the spectra of eventual out-of-gamut oil-painting colors.

Preliminary Experiments

To implement our imaging approaches, we were granted exceptional access to an 1889 self-portrait of Vincent van Gogh, at the National Gallery of Art, Washington, D.C.[14,15] Prof. Roy Berns was on sabbatical at the National Gallery of Art as a Senior Fellow in Art Conservation Science and his position enabled us to visit the Gallery while the painting was in the painting laboratory. Preliminary experiments exercised the two different multispectral imaging approaches.

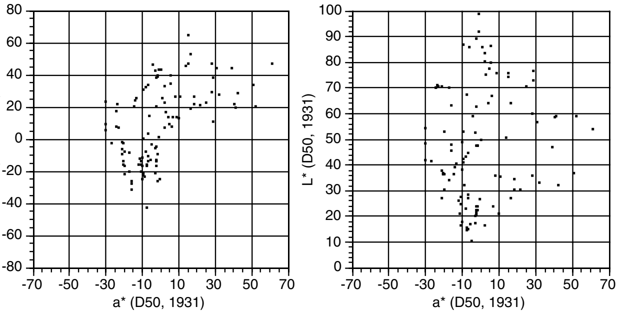
The wide-band capture approach was applied by imaging the painting with a Dicomed scanning back coupled with a Mamiya 4" by 5" conventional camera. It uses tungsten-halogen illumination and polarizing optics to reduce specular reflection capturing images with resolution of up to 6000 by 8000 pixels. Kodak Wratten filters were used in conjunction with the scanning system to deliver 12 bit multi-channel images of the self-portrait painting, the ubiquitous GretagMacbeth ColorChecker, Kodak Gray Scale and some other color targets. The imaging resulted in unexpectedly poor results. Further analysis of the scanning system showed that the since the CCD sensor was designed for flat-bed scanners, it had densitometric spectral sensitivities. The multi-channel technique requires much wider-band sensitivities. This limitation as well as some operational problems of the software associated with bit captures resulted in the poor results.

For the narrow-band acquisition, the van Gogh painting and characterization targets were imaged in 16 bands using a liquid crystal tunable filter attenuating the exposure of pan-chromatic high-speed black-and-white silver-halide negative film. The negative film was developed and 12-bit digitized in a Nikon Super CoolScan LS-2000. Before this, the imaging system was calibrated establishing the exposure time for each band using the GretagMacbeth ColorChecker and a Kodak Gray Scale. Then the painting was imaged with characterization targets. After developing, digitizing the film and linearizing the image data, linear analysis of the characterization targets imaged with the painting allowed us to remove the effects of the film and scanner in order to build a transformation from scanner digital counts to spectral reflectance.

After imaging the painting a GretagMacbeth SpectroEye reflection spectrophotometer was used to perform direct spectrophotometric measurements in different colored areas of the painting, such as the background, greens and blues of the jacket, reds and browns of the beard, yellows and greens of the hair, flesh tones, and the palette colors presented in the painting. From a database of retouching paints created *a priori* at the Gallery, a set of modern pigments were selected that well reproduced the spectral properties of the painting: cobalt blue, prussian blue, yellow ocre, cadmium red, naples yellow light, ivory black, and titanium white. It is important to note that it would be unwise to use identical pigments used by van Gogh, for example arsenic based emerald green. Specific combinations of the pigments were used to match specific image areas and a target with 106 patches was painted using a combination of these pigments. The color distribution of our target in CIELAB a*b* space for D50 illuminant and the 2° observer is shown in Figure 1. We call this target the *van Gogh Target*. The van Gogh Target is designed to allow us to evaluate the performance of our multi-channel visible-spectrum imaging system through evaluating its performance on pigments yielding similar spectral properties to the painting.

Experimental

For this analysis, we used a medium-spatial resolution trichromatic IBM Pro 3000 digital camera system that consists of a monochrome scanning back and a filter wheel (3,072 x 4,096 pixels, R, G, B filter wheel, dark current corrected 12 bits per channel that has a 45°/0° imaging configuration using tungsten-halogen illumination).[16] Multi-channel images were obtained combining the IBM trichromatic images without external filtering and with Kodak Wratten filter number 38 (light blue filter). White spatial correction was performed to the captured image to account for spatial non-uniformity of the illumination. For the printer we used an Epson Photo Style 1200 ink-jet printer, that has 6 ink capability, the CMYK inks with orange and green added. Previous experiments with this printer showed that it can repeat the same colors with sufficient precision.[6] All the spectral measurement was performed using the Gretag Spectrolino 45°/0° spectrophotometer that presents accuracy of 0.12 ΔE^*_{94} units (D50 illuminant and 2° observer).



a) a x b** *b) a* x L**

Figure 1. Colorimetric plots for the van Gogh Target (under D50 illuminant, 2° observer).

The evaluation of the color accuracy of our MVSI color reproduction system for the van Gogh Target was divided in two parts: evaluation of the spectral reflectance estimation of the MVSI acquisition system and the evaluation of the entire MVSI system including both spectral estimation and spectral-based printing minimizing metamerism.

The accuracy of the spectral estimation from the multi-channel acquisition can be evaluated starting from the analysis of the eigenvector reconstruction followed by estimation from the camera signals. The evaluation of the spectral reflectance of the MVSI acquisition system is then subdivided in two parts. At first, eigenvector analysis is evaluated theoretically reconstructing the spectral reflectances from the derived eigenvectors and eigenvalues and comparing the estimated reflectances with the measured spectral reflectances. In the following stage the spectral reflectance is estimated from the eigenvectors and actual digital counts. The estimated spectral reflectances are then compared to the original spectral reflectances.

The evaluation of the accuracy of the MVSI system for the van Gogh Target including both spectral estimation from multi-channel images and spectral-based printing system minimizing metamerism was performed comparing the spectral reflectance measurement of the original targets and the spectral reflectance measurements of the printed targets using dot areas derived from the spectral reflectance estimated from the multi-channel image capture.

Results

The spectral reflectances of the van Gogh Target were measured and eigenvector analysis was performed. Table I shows the cumulative contribution for each multiple-of-three eigenvectors and the influence of the number of eigenvectors on the colorimetric accuracy and spectral accuracy of the spectral reconstruction. The colorimetric accuracy is calculated using CIE94 for D50 and the 2° observer.

Table I. Cumulative variance contribution and influence of the number of eigenvectors used in the spectral reconstruction of the van Gogh Target on the colorimetric and spectral error. ΔE^*_{94} calculated for D50 and the 2° observer of the eigenvectors in reflectance space.

Number of eigenvectors	Cumulative variance contribution (%)	Mean ΔE^*_{94} (D50, 2°)	Spectral reflectance rms error factor
3	98.43	4.4	0.021
6	**99.91**	**0.7**	**0.006**
9	99.99	0.2	0.003
12	100.00	0.1	0.001

From Table I it is possible to notice that 6 eigenvectors can reconstruct the original spectrum with 99.91% of accuracy. From colorimetric and spectral evaluation we can conclude that the use of six eigenvectors to reconstruct spectra is a good compromise between accuracy and our aim of reducing the number of channels. Theoretically, using six eigenvectors to reconstruct spectra gives colorimetric error less than one ΔE^*_{94} unit and spectral reflectance rms error less than 1%.

The imaging without filtering and with the light-blue filter give 6 signals that were used with 6 eigenvectors of the spectral reflectance of the target in order to estimate the spectral reflectances from digital counts. Table II shows the colorimetric and spectral accuracy for the van Gogh Target. The ΔE^*_{94} calculation was performed for illuminant D50 and 2° observer. The metameric index was calculated using the Fairman metameric black method, between standard illuminants D50 and A using ΔE^*_{94} in the calculations.[17]

The estimated spectral reflectances were used to predict the printing dot areas using the spectral-based printing algorithm minimizing metamerism. Table III shows the colorimetric and spectral accuracy of the MVSI system comparing the measured spectral reflectance of the original target and the printed targets.

Further analysis of our result show that among the worst matches are some critical pigments for our van Gogh self-portrait. One such pigment is cobalt blue. Figure 2 shows a comparison of spectral reflectance curves of the cobalt blue patch between the measurements of the original, the estimation by multi-channel imaging and the measurement of the printed patch.

Table II. Spectral reconstruction of the van Gogh Target using 6 eigenvectors and 6 digital counts from IBM PRO\3000 digital camera system. The measured digital counts were obtained combining the trichromatic camera without a filter and with the light-blue filter

Number of eigenvectors	Mean ΔE^*_{94} (D50, 2°)	Spectral reflectance rms error factor	Metameric Index (ΔE^*_{94}) (D50, A)
Average	1.7	0.020	0.3
Standard deviation	1.0	0.015	0.2
Maximum	4.2	0.088	1.3
Minimum	0.2	0.004	0.01

Table III. Comparison of the spectral reflectances measured from the original van Gogh Target and the printed targets estimated from the multi-channel acquisition.

Number of eigenvectors	Mean ΔE^*_{94} (D50, 2°)	Spectral reflectance rms error factor	Metameric Index (ΔE^*_{94}) (D50, A)
Average	5.0	0.031	0.6
Standard deviation	3.7	0.023	0.6
Maximum	20.3	0.147	4.6
Minimum	0.5	0.005	0.04

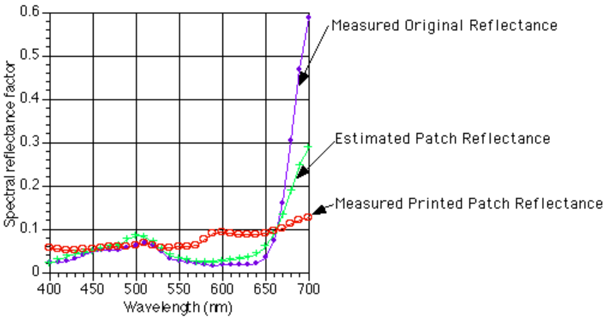


Figure 2. Comparison of the spectral reflectances for the cobalt blue patch.

From the figure it is possible to see that the estimated spectral reflectance and the measured printed patch reflectance diverge progressively from the measured original reflectance particularly in the large reflectance tail in the long-wavelength end of the visible spectrum. This infra-red tail is also responsible for the purplish color rather than dark blue color when conventional photography is used to capture this particular painting. A careful choice of filters in the imaging capturing process and an ink optimization procedure18 in the printing will be necessary to achieve a better spectral match.

Conclusion

Our MVSI system was able to produce the least metameric reproduction to the original van Gogh Target. Results show a system accuracy of mean ΔE^*_{94} of 5.0 and spectral reflectance rms error of 3.1%. The van Gogh Target made using the pigment set estimated from the van Gogh painting helped us to evaluate the performance of our MVSI system deriving information for future improvements. The use of an alternative target is important when dealing with paintings with very limited access. This work is part of an international effort to study all van Gogh paintings, many of which are sadly fading significantly in color. Particularly problematic is a red-lake pigment that van Gogh used extensively which has extremely poor lightfastness. We believe that an accurate spectral description of van Gogh's painting is an important concern for the conservation study of his paintings. An added advantage to pursuing an MVSI approach to the painting is that it enables reproduction with minimal metamerism. Also, having an accurate description of the spectral reflectance properties associated with each pixel of the painting allows the possibility to accurately "add back" faded colors to various parts of the painting using models such as Kubelka-Munk theory.

A new state-of-art multi-channel visible-spectrum imaging system using a Quantix camera is in preparation for future imaging. This imaging system will use a CRI liquid crystal tunable filter that allows both wide-band low contrast and narrow-band high contrast captures. Experiences from the experiments described in this paper will help guide efforts associated with the new spectral-acquisition device.

Acknowledgements

The authors would like to express their gratitude to DuPont for their support of this research. We would also like to acknowledge the work of many members of the Munsell Color Science Laboratory who are working on building our end-to-end spectral-based system, particularly Lawrence Taplin who has been working in the six-color printing system. Finally we are particularly grateful to the staff of the National Gallery of Art, Washington, D.C. Without their help it would not have been possible to perform these experiments.

References

1. J. Cupitt, K. Martinez, and D. Saunders, A methodology for art reproduction in colour: the Marc project, *Computers and the History of Art*, *6 (2),* 1-19. (1996).
2. B. Hill, Aspects of total multispectral image reproduction systems, *Second International Symposium on Multispectral Imaging and High Accurate Color Reproduction,* Chiba University, Japan, pp. 67-78.. (2000).
3. R. S. Berns, F. H. Imai, P. D. Burns and D. Tzeng, Multispectral-based color reproduction research at the Munsell Color Science Laboratory, *Proc. SPIE Europto Series 3409*, Zürich, pp. 14-25. (1998).
4. Miyake, Y. Yokoyama, N. Tsumura, H. Haneishi, K. Miyata and J. Hayashi, Development of multiband color imaging systems for recording of art paintings, in *IS&T/SPIE Conference on Color Imaging: Device-Independent Color, Color Hardcopy, and Graphic Arts IV*, G. B. Beretta, and R. Eschbach, Editors, Proc, of SPIE **3648**, Bellingham, WA, pp. 218-225. (1999).
5. F. Schmitt, H. Brettel, J. Y. Hardeberg, Multispectral Imaging Development at ENST, *Proc. of First International Symposium on Multispectral Imaging and High Accurate Color Reproduction*, Chiba University, Japan, pp. 58-64. (1999).
6. F. H. Imai, M. R. Rosen, D. R. Wyble, R. S. Berns and D. Tzeng, Spectral Reproduction from Scene to Hardcopy I: Input and Output. Submitted to Electronic Imaging 2001.
7. M. Rosen, F.H. Imai, X. Jiang and N. Ohta, Spectral Reproduction from Scene to Hardcopy II: Image Processing, Submitted to Electronic Imaging 2001.
8. F. H. Imai, R. S. Berns and D. Tzeng, A comparative analysis of spectral reflectance estimated in various spaces using a trichromatic camera system, *J. Imaging Sci. Tech.* **44** 280-287 (2000).
9. M. Rosen, X. Jiang, Lippmann2000: A spectral image database under construction, *Proc. of the International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives*, pp. 117-122. (1999).
10. F. H. Imai, M. R. Rosen and R. S. Berns, Comparison of spectrally narrow-band capture versus wide-band with a priori sample analysis for spectral reflectance estimation, *Proc. of in IS&T/SID Eighth Color Imaging Conference*, 2000, pp. 234-241. (2000).
11. D. Tzeng, R. S. Berns, Spectral-based Six-color Separation minimizing Metamerism*, Proc. of Eighth IS&T/SID Color Imaging Conference*, 2000, pp. 342-347.
12. K Iino and R. Berns, Building Color Management Modules Using Linear Optimization I. Desktop color system, *J. Imaging Sci. Tech*, **42**, 79-94 (1998).
13. K Iino and R. Berns, Building Color Management Modules Using Linear Optimization II. Prepress System for Offset Printing, *J. Imaging Sci. Tech* **42**, 99-144 (1998).
14. http://www.nga.gov/cgi-bin/pinfo?Object=106740+0+none
15. The Chroma Zone, Munsell Color Science Laboratory's Newsletter, Spring/Summer 2000.
16. http://www.research.ibm.com/image_apps/capture.html

17. H. S. Fairman, Metameric correction using parametric decomposition, *Color Res. Appl. 12*, pp. 261-265, 1997.
18. D. Tzeng, R. S. Berns, Spectral-based ink selection for multiple-ink printing II. Optimal Ink Selection, *Proc. of Seventh IS&T/SID Color Imaging Conference*, pp. 182-187, 1999.

Biography

Dr. Francisco Hideki has a Ph.D. in Imaging Science from Chiba University in Japan. Since September 1997 he has been working at Munsell Color Science Laboratory at Rochester Institute of Technology. His research has been focused on high-spatial resolution multi-spectral image capture and spectral reconstruction. He was named as the recipient of the 1998 Itek Award for the best student paper in 1997 by The Society for Imaging Science and Technology.