https://doi.org/10.2352/issn.2168-3204.2018.1.0.11

Practical UV-VIS-NIR Multispectral Imaging

Roy S. Berns
Rochester Institute of Technology
54 Lomb Memorial Drive, Munsell Color Science Laboratory
Program of Color Science
Studio for Scientific Imaging and Archiving of Cultural Heritage
Rochester, New York, 14623-5604
585-475-2230 (fax) 585-475-4444
berns@cis.rit.edu

Abstract

A seven-channel multi-spectral camera has been developed using commercial products and both commercial and custom software. The camera components are manufactured by Finger Lakes Instrumentation, Rodenstock, and the Andover Corporation. The colored glass filters were optimized for image quality, colorimetric accuracy, and spectral accuracy. The system can be used for color, VIS, UV, UV-excitation-VIS-emission, and NIR imaging. The system was designed for use in a cultural heritage institution's photographic studio.

Introduction

The author has been active in multispectral imaging for over 20 years [1]. The first milestone was developing the Dual-RGB approach where multiple colored filters or lights are combined with an RGB camera having its IR cut-off filter removed [2]. This technology is used in products manufactured by Sinar (CTM system) and Flux Data.

During the early stages of this research, a more traditional approach to multispectral imaging was taken using a monochrome sensor and colored filters. The design goal was to achieve both spectral and colorimetric accuracy. At the time, monochrome sensors had inadequate resolution for studio photography. Today achromatic (monochrome) sensors are available with resolutions of 50MP (TruSense), 60MP (Dalsa), and 100MP (Sony), making this traditional approach viable for cultural heritage applications.

Design Challenges

The first challenge was developing a system for studio photography. In addition to high resolution, the system should use existing studio lighting such as Broncolor and Profoto. This eliminates approaches using colored LEDs (rather than colored filters), for example, the MegaVision EV system.

The second challenge was cost. The goal was to limit cost to $25,000 so that more cultural heritage institutions could afford to perform multispectral imaging. The system would need to use commercially available components.

The third challenge was filter type. In conservation science, interference filters are used. However, these were rejected because of angle dependent transmittance behavior necessitating very small apertures or complex spatial corrections [3], both reducing image quality. The solution was to use colored glass filters, either as single filters, or two or three filters glued together.

A question that is often posed is how many channels are required for multispectral imaging? The Dual-RGB approach has five unique channels—the two green channels are nearly identical and only one is used. Multispectral systems have been built using between five and about thirty channels. Increasing the number of channels increases spectral accuracy, but with diminishing returns because of the wide absorption properties of colored materials in the visible spectrum. Furthermore, for medium and large format cameras, the filters need to be large because of the large sensor sizes. It is the author's opinion that ten channels would be ideal: one in the UV, seven in the VIS, and two in the NIR regions.

The fourth challenge was filter design. There were three criteria: image quality, colorimetric accuracy, and spectral accuracy—listed in descending rank order. The solution was a complex filter selection process using nonlinear optimization with an objective function incorporating all three criteria [4]. The candidate filters were manufactured by Schott or Hoya and sold by the Andover Corporation.

The fifth challenge was lens quality. Ideally, the lens should maintain focus throughout the UV-VIS-NIR wavelength range, that is, have negligible chromatic aberration and a design that maintains sharpness over this extended wavelength range. We considered the MegaVision 120mm f/4.5 multispectral lens, which has outstanding sharpness, shown below. Unfortunately, this lens was too expensive. Alternatively, we selected a traditional large format apochromatic lens with a mechanical shutter and added a computer-controlled helical focus.

Because of different focal lengths changing magnification and filters that may have slightly different thicknesses causing translation, the sixth challenge was registration software. We used automatic feature-based (SURF) registration to derive transformations for user-defined sub-sections of the object.

The seventh challenge was deciding on a wavelength range. CCD sensors have sensitivity from about 300 – 1,100nm. In order to image over this full range, the sensor has to have high quantum efficiency, limiting the choice of sensor.

Imaging System

The system consisted of a Finger Lakes Instrumentation (FLI) Microline camera with an 50MP achromatic TruSense KAF-50100 microlens CCD sensor, FLI CFW10-7 seven position filter-wheel holding 65mm square filters with a maximum filter thickness of 5mm, FLI Atlas Focuser, and Rodenstock Digaron-S 100mm f/4 apochromatic lens with Copal shutter and helical focus. The camera is shown in Figure 1. The sensor's published quantum efficiency (QE) is compared with the Teledyne Dalsa 60 MP sensor's published QE, shown in Figure 2. The TruSense sensor has excellent QE across the UV, VIS, and NIR spectral regions.

(This sensor is also used in the MegaVison system.) The Dalsa sensor would be limited to the VIS-NIR regions.

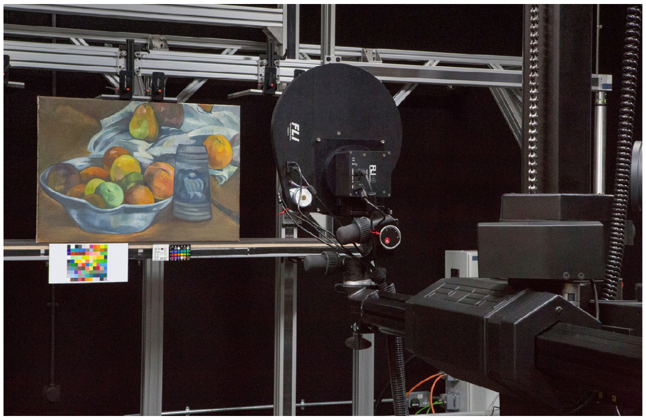

***Figure 1**. Multispectral imaging system being demonstrated in a workshop at the National Gallery, London.*

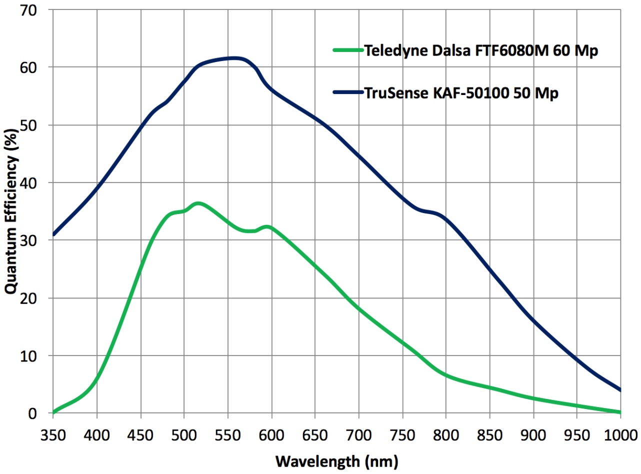

***Figure 2**. Quantum efficiency of each listed sensor.*

Filter Design

The filter wheel is limited to seven filters. The current configuration has been designed for UV-VIS imaging. The specific filters are listed in Table I and the system spectral sensitivities (camera quantum efficiency multiplied by the filter transmittances) are plotted in Figure 3. Because of the three criteria described above, the spectrum is not evenly sampled. The longest wavelength filter can be changed for different applications such as NIR imaging. In essence, the central five filters are fixed and the outer two filters can be changed for different applications.

These differences in sensitivity across wavelength lead to a wide range of exposure times depending on the light source. However, the sensor is cooled to -20° C; these differences have a negligible effect on image quality.

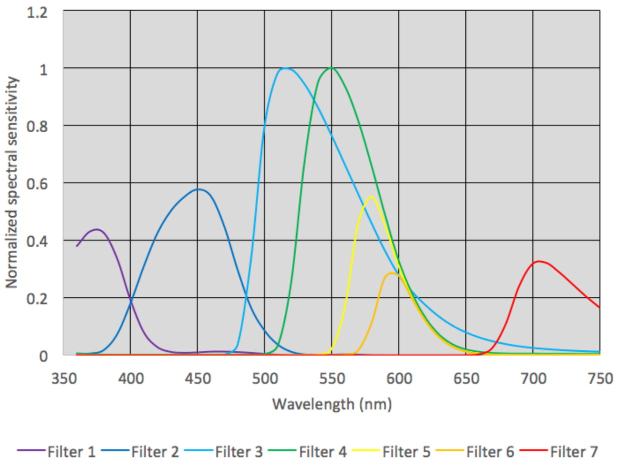

***Figure 3**. Normalized (peak of filter 4) spectral sensitivities of the imaging system (detector and filters).*

Table I. Filter construction. The peak wavelength includes the sensor spectral sensitivity. Unless noted, all filters are 2.5 mm.

Peak	Filter 1	Filter 2	Filter 3
377 nm	S8612	UG5	
443 nm	S8612 (1mm)	BG25 (1.5mm)	GG420 (2.5mm)
515 nm	BG23	GG495	
547 nm	S8612	OG530	
577 nm	BG40	OG570	
594 nm	BG38	OG590	
705 nm	KG3	RG695	

Software

The camera is controlled using SkyX Professional (bisque.com). The system can be automated to change filter-wheel position, focal length, exposure time, and subtract dark field images.

multiSpectralTools was used to process the seven-channel images of a flat field, calibration target, and object. Our most recent software is written in Python, an open-source language. We have modules for colorimetric calibration, image registration, and rendering. An earlier version has been written in Matlab, having more modules, but inferior registration. (We are migrating to Python.)

Experimental

Two systems were used as benchmarks. The first was the Sinar CTM system (S-CTM) using the Dual-RGB approach, previously found to have high quality [5]. It has a 48MP Dalsa RGB sensor, micro-positioning for full-frame RGB images, Repro body, and Rodenstock Digaron-S 100mm f/4 apochromatic lens with e-shutter. Both cameras were mounted on a Foba stand and the lighting was a single Broncolor HMI continuous source placed at 45° from the optical axis. Four targets were imaged: ISA Golden Thread, X-Rite Digital ColorChecker SG, Avian Rochester Next Generation Camera Target, and an ISA Artist Paint Target (APT).. The cameras were set to an aperture of f/8. Both cameras were focused using the central slanted-edge/wedge portion of the Golden Thread, shown in Figure 4. For the Sinar, its focus tool was used to maximize sharpness while adjusting focus manually. For the Finger Lakes, the autofocus feature of SkyX (focus@3) was used where the Atlas focus was moved until sharpness was maximized; each channel was focused separately and the values stored. For both systems, *multiSpectralTools* was used for colorimetric and spectral profiling using images of a white flatfield and the ColorChecker SG.

The second system was the MegaVision EV multi-spectral system (MV) using the same sensor as the FLI system, MegaVision's unique 120mm f4.5 hyperspectral lens, and 16 narrow-band LED illumination. This system was used to benchmark sharpness. Focusing was performed visually using overhead fluorescent lighting and the aperture was f/11.

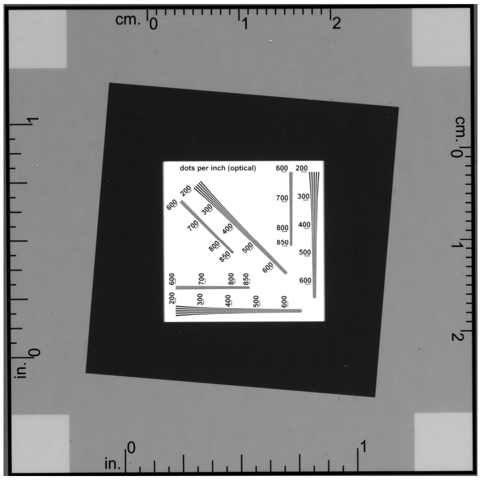

***Figure 4**. Central portion of Golden Thread resolution target imaged using the MegaVision EV system.*

Results and Discussion

Spatial Image Quality – Sharpness

The spatial frequency response of the left vertical slanted edge was calculated for each image using the Matlab software *sfrmat3* written by Peter D. Burns. Data were interpolated to even increments using a cubic spline function between 0 and 0.5 cycles per pixel.

The results for the three systems are plotted in Figure 5. The S-CTM system had its best sharpness for the wide blue channel and its worst for the wide red, having response to about 720 nm. For the FLI system the 443 nm had the best sharpness and 705 nm had the worst. Except for 443 nm, sharpness decreased with increasing wavelength. This result was somewhat unexpected since each channel was refocused and the lens is considered apochromatic by the manufacturer. Although both the S-CTM and FLI systems used the same lens, the FLI system had slightly better performance, a result of individual focusing. The low frequency response for 705nm does not image quality for colorimetric renderings because this channel is not used to estimate tristimulus values. For rendered images, the two cameras have very similar frequency response.

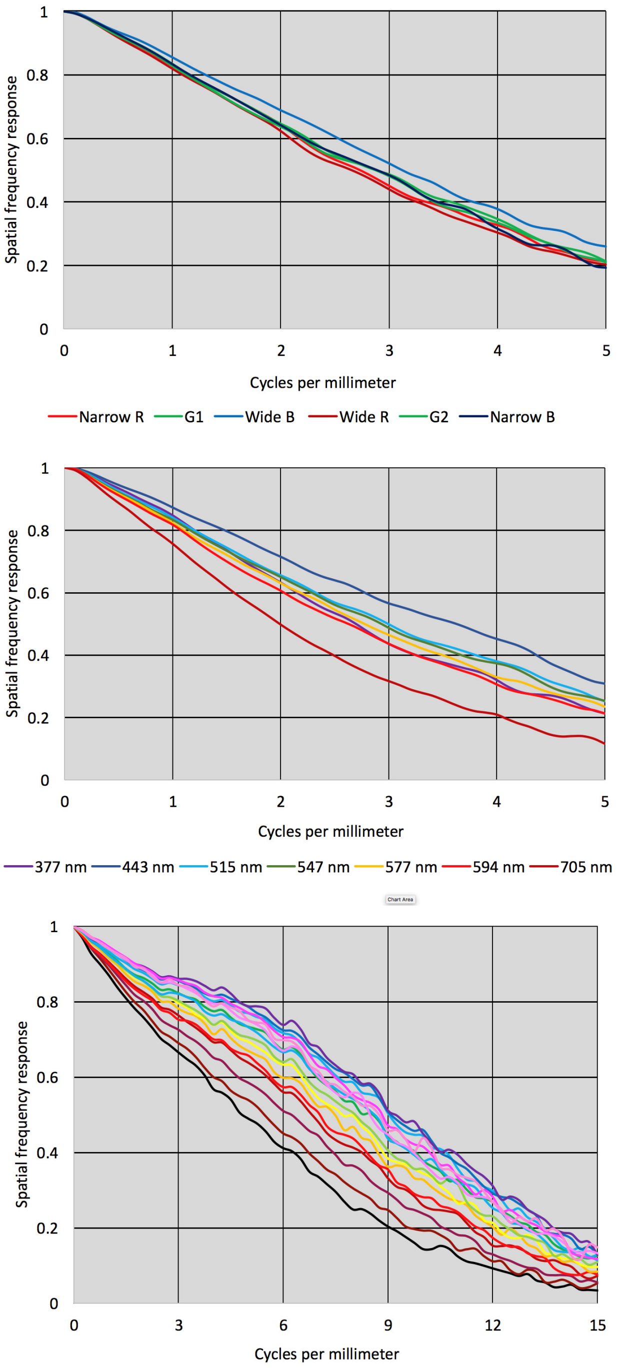

***Figure 5**. Spatial frequency response of each channel of the Sinar CTM (top), Finger Lakes Instrumentation (middle), and MegaVision (bottom) systems plotted from 0 to 0.5 cycles per pixel. The resolution of the three systems was 253 (CTM), 264 (FLI), and 788 (MV) pixels per inch.*

The MV system resolved more detail than the other systems. At 0.5 cycles per pixel, it had about three times the sampling resolution. Similar to the Rodenstock lens, the MegaVision lens also exhibited a loss of response with increasing wavelength.

The MV imaging was done at a different laboratory where the aperture and magnification were fixed. The S-CTM system was set to f/11 and the target was moved closer to achieve a similar magnification to the MV system, 798 and 788 pixels per inch, respectively. (The FLI system cannot focus at such a short distance.) The Dalsa sensor's green response peaks at 530nm and the corresponding data for the MV system at 530nm were compared, the results plotted in Figure 6. The MV system has a superior response across all frequencies and the image is much sharper visually. The reduction in response with increasing wavelength was not visible.

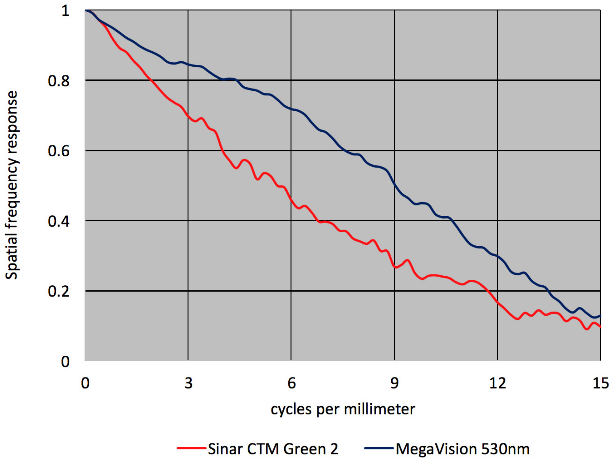

***Figure 6**. Spatial frequency response of the S-CTM system's green channel and the MV system's 530nm channel plotted between 0 and 0.5 cycles per pixel.*

Colorimetric Accuracy

Most profiles are built using the ColorChecker SG, and accordingly, this target was used to build profiles between the flat-fielded camera signals and XYZ where the average $\Delta E_{00(SL=1)}$ was minimized for CIE illuminant D50 and the CIE 1931 standard observer. Images were encoded using ProPhotoRGB in 16 bits.

The colorimetric accuracy of the profiling target is a measure of the similarity between the aggregate spectral sensitivities of a camera and color matching functions including differences between the camera-taking illumination and CIE D50. The results are listed in Table II. Both systems were excellent, a result of using five channels in estimating XYZ. The FLI system's improved statistics were expected because of its filter design. Tuning spectral sensitivities is limited in the Dual-RGB approach where only two filters are optimized.

The APT target, shown in Figure 7, was used as independent verification, the results shown in Table III. This target is composed of artist materials with spectral properties not represented in the ColorChecker SG. The FLI system had twice the colorimetric accuracy. As the object's spectral properties diverge from the profiling target, the improved design of the FLI system becomes more evident.

Table II. $\Delta E_{00(SL=1)}$ statistics for each listed camera for profiling using the ColorChecker SG.

Statistic	FLI	S-CTM
Mean	0.7	1.1
Maximum	3.6	4.1
Minimum	0.0	0.0
90% Percentile	1.3	1.8

Table III. $\Delta E_{00(SL=1)}$ statistics for each listed camera for independent verification using the APT.

Statistic	FLI	S-CTM
Mean	0.9	1.9
Maximum	2.5	4.1
Minimum	0.2	0.6
90th Percentile	1.4	3.3

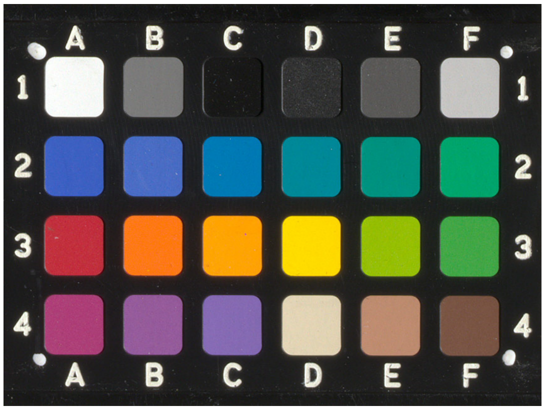

***Figure 7**. APT target, made using artist paints.*

Spectral Accuracy

The main impetus for taking a traditional approach of using a monochrome sensor and filter wheel was to improve spectral estimation accuracy. Previous research revealed that the Dual-RGB approach had insufficient accuracy for pigment mapping [6]. A pseudo-inverse was used to calculate the transformation from camera signals to spectral reflectance factor for the S-CTM and FLI systems, the transformations plotted in Figures 8 and 9. Ideally, there should be large positive and small negative responses. The S-CTM system has reasonable sampling until 600nm. The large negative signal for the narrow-red channel at 730 nm indicates that long wavelengths will be poorly estimated. Not having a signal at short wavelengths will limit short wavelength estimation accuracy. The improved sampling of the visible spectrum by the FLI system is evident with peaks throughout the visible spectrum. Because channels 5 and 6 have peaks in a similar wavelength region, 577 and 594nm, respectively, both channels have large negative signals.

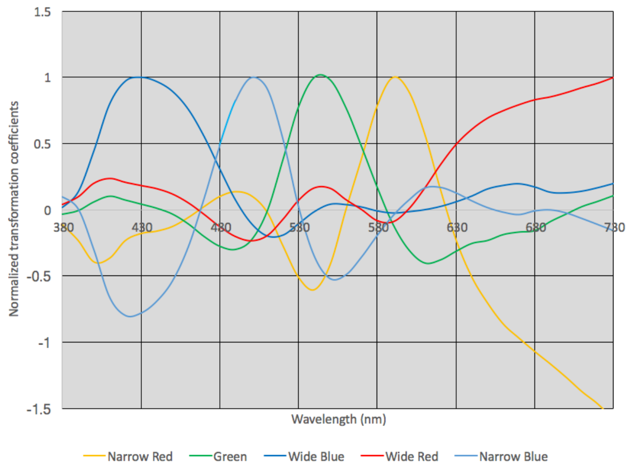

Figure 8. *Sinar CTM system transformation coefficients between camera signals and spectral reflectance factor, normalized to peak height.*

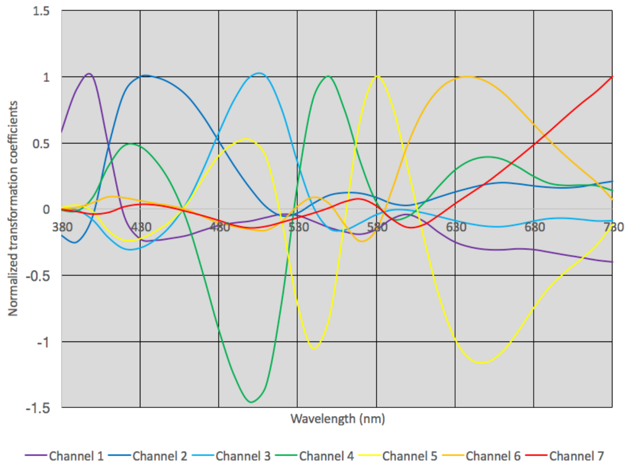

Figure 9. *Finger Lakes Instrumentation system transformation coefficients between camera signals and spectral reflectance factor, normalized to peak height based on the ColorChecker SG.*

Neither transformation was ideal and a contributing factor is the spectral properties of the target. (The other factor is the number of channels) The ColorChecker SG was designed based on colorimetric, not spectral criteria. The APT's design was primarily spectral. The transformation that results from using the APT for calibration is plotted in Figure 10. There is a small improvement at long wavelengths. It is important to note that spectral accuracy was the third criterion in filter design. More even sampling of the spectrum might improve spectral estimation accuracy, but at the expense of colorimetric accuracy.

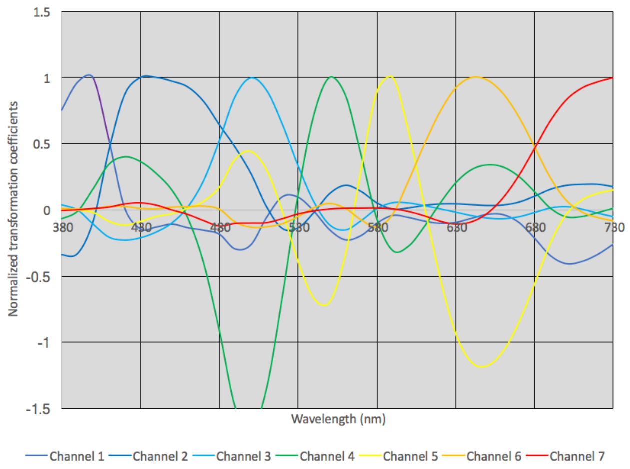

Figure 10. *Finger Lakes Instrumentation system transformation coefficients between camera signals and spectral reflectance factor, normalized to peak height based on the APT.*

The difference in spectral accuracy between the two systems is shown in Figure 11, where four samples from the ColorChecker SG are compared. The main difference is poor estimation accuracy at long wavelengths for the S-CTM system. The FLI system estimated spectra more closely, tracking the measured spectra using a contact spectrophotometer. The FLI system is using seven channels for spectral estimation whereas the S-CTM system uses five channels (wide and narrow red and blue, and one green).

Using the same target to derive and evaluate the transformation was deliberate. This assumes that the majority of samples were produced from the same set of pigments. Thus, the target is tuned to the spectral properties of the object. Similar to the colorimetric results, the differences between systems will be more pronounced with independent verification.

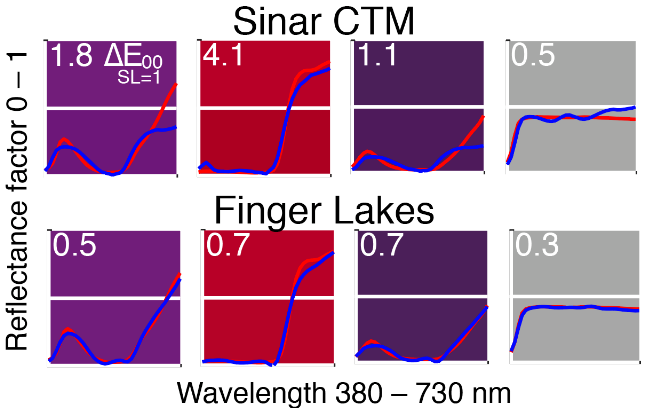

Figure 11*. Examples of spectral estimation accuracy for the Sinar CTM and Finger Lakes Instrumentation systems. Red lines are reference measurements using a contact spectrophotometer and blue lines are camera estimates.*

Conclusions

The FLI system is an effective multispectral system for high resolution studio photography. The total cost including lens, filter, and software was just below $29,000. Because seven separate images are combined, each with different magnification, position, and focus, a reduction in image quality was anticipated compared with an RGB or Dual-RGB system. This did not occur because of effective registration software and channels with poor focus did not contribute to the colorimetric rendering. If images are required in the UV-VIS-NIR wavelength region with high sharpness, a different lens will be required. It would be interesting to refocus for each wavelength in the MV system and see whether wavelength dependent blurring can be reduced.

The colorimetric accuracy of the FLI system was excellent exceeding the S-CTM system. The improvement was dramatic when analyzing independent data. Both systems have superior performance to RGB systems.

The spectral estimation accuracy of the FLI system was dramatically improved compared with the S-CTM Dual-RGB system. It viability for pigment mapping has yet to be tested.

These improvements come at an operation cost. There is greater time for set up including focusing and setting exposure for seven channels rather than one. Separate software is required to control the camera and process the images. The processing software is academic based and some knowledge of programming is beneficial. Finally, the system is not a commercial product. It is the author's hope that this research may lead to a commercial product.

References

[1] R. S. Berns, "Color accurate image archives using spectral imaging," in *Scientific Examination of Art: Modern Techniques in Conservation and Analysis*, National Academies Press, 105-119, 2005.

[2] R. S. Berns, L. A. Taplin, M. Nezamabadi, M. Mohammadi, "Spectral imaging using a commercial color-filter array digital camera," *Proc. 14th Triennial Meeting The Hague, ICOM Committee for Conservation,* 743-750 (2005).

[3] R.S. Berns, Cox B.D, Abed F.M, "Wavelength-dependent spatial correction and spectral calibration of a liquid crystal tunable filter system," *Applied Optics,* 54 3687-3693 (2015).

[4] Y. Wang Design and Construction of a Multispectral Camera for Spectral and Colorimetric Reproduction, M.S. Thesis Rochester Institute of Technology (2016).

[5] R.S. Berns and S. Smith, "Analysis of color management default camera profiles for museum imaging applications," *IS&T Archiving 2012*, 111-115 (2012).

[6] F. M. Abed, Pigment Identification of Paintings Based on Kubelka-Munk Theory and Spectral Images, Ph.D. Dissertation Rochester Institute of Technology (2014).

Acknowledgements

This research was supported by a grant from the Andrew W. Mellon Foundation. The author acknowledges the excellence of the many students and staff who have contributed to this research over the years. Dr. Gregory Heyworth kindly imaged targets using the the Lazarus Project's MegaVision EV system at the University of Rochester.

Author Biography

Roy S. Berns holds the Richard S. Hunter Professorship in Color Science, Appearance, and Technology at Rochester Institute of Technology (RIT). He has directed the Munsell Color Science Laboratory and graduate programs in Color Science at RIT. He is the director of the Andrew W. Mellon sponsored Studio for Scientific Imaging and Archiving of Cultural Heritage. Berns is an IS&T Fellow with lifetime achievement awards from the International Association of Colour, the U.S. Inter-Society Color Council, and the Colour Group of Great Britain.