Spectral Imaging Method for Reflective Media

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Abstract

An imaging process is described which captures spectral reflectance for reflective media. The ultimate target media are prints and photographs within the collection of the Library of Congress. The system is based on a fifteen channel LED source and a monochrome camera. The LED source sequentially illuminated reference and verification targets, with an image captured for each LED channel. From the measured data and images of reference targets, a model was developed to predict spectral reflectance. With that model, the 15 images of a test sample were combined to a single 31-band spectral image. Spectral images can be used to calculate colorimetric data for each pixel, or to better understand material properties. The colorimetric results show that the system predicts good color as compared to the most relevant FADGI guidelines.

Introduction

This work represents a continuation of the author's submission to Archiving 2021[1]. The focus in that paper was spectral imaging of transmissive media. The present paper extends that work both in terms of technique and the application to reflective media. The technique was extended, as will be described in detail below, by the addition of five spectral channels, for a total of 15 distinct channels. A new and inexpensive verification target is also described.

The balance of this paper will first describe and evaluate the camera used for this system, and the sequential LED illumination. After a description of the characterization and verification targets, the imaging process and spectral optimization will be reviewed. Finally, the results from imaging a set of independent CMYK prints will be presented. These prints are intended to be representative of the artifacts images within the Library of Congress Prints and Photographs department.

System Description

Monochrome Imaging System

The camera used for this research was a modified Sony α7 Mark IV with a Carl Zeiss Sonnar T* FE 55 mm f/1.8 ZA lens.[†] The modification was twofold: the RGB filter array was removed, leaving just the bare CMOS sensor; and the IR cut filter was replaced by a clear filter. While "single channel" and not "monochrome" might be more strictly correct for describing this camera, "monochrome" is nevertheless traditional, and we will continue that tradition here.

To determine the appropriateness of this camera for the task, two properties need to be evaluated: the uniformity of images across the three channels (this asks how complete the filter removal process was) and the linearity of the sensor. Two experiments were performed to verify these properties.

Camera Spectral Sensitivities

Regarding the first of these properties, it should be understood that the camera and software do not comprehend that the RGB filter array was removed. When imaging normally, the software exports a three-channel "RGB" file. However, if the filter removal was complete, the three image planes should be very nearly identical. One method of making this determination is to measure the spectral sensitivities of the system. The camera was therefore configured to image the output port of an integrating sphere, the input of which averaged the narrow band output of a monochromator. By sequentially adjusting the monochromator to output narrow wavelength bands across the visible spectrum, the sensitivity of the camera at each of these wavelengths is quantified. A schematic of the system is shown in Figure 1.

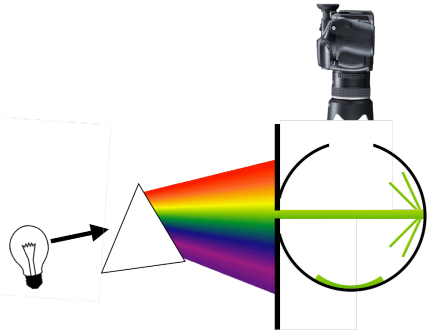

Figure 1. *Schematic of the spectral sensitivity measurement system. From the left, white light is dispersed into its component wavelengths, which are sequentially selected by rotating the prism past the vertical slit. The integrating sphere averages the light, and presents the camera with a uniform field of the given wavelength (shown by the example green field opposite the camera)..*

The results of the spectral sensitivity measurements are shown in Figure 2. The blue channel was slightly less sensitive; its mean level was about 3% below either the red or green channels. While this might not be ideal, for all imaging and analysis in this work the four pixels in each Bayer cell (two greens, one red, one blue) were averaged for digital count of each pixel in the final images.

Camera Linearity

To evaluate the linearity of the camera, a series of spectrally flat neutral patches were imaged and simultaneously measured with a PR740 spectroradiometer. The patches used were the central 13 neutral areas in the central region of the X-Rite Colorchecker DC. For a camera to be considered linear, the mean digital counts for

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[†] All imaging and testing described in this work were made with this lens in place, collectively referred to as "the camera."

each patch should be linearly related to the mean radiance measured off the patch. This is adequately shown by the good linear fit of the data in Figure 3. Note that even if the relationship in Figure 3 was curved (as through a gamma or similar function) the digital counts could be linearized at this stage, and the balance of the analysis described here could proceed with every hope of success.

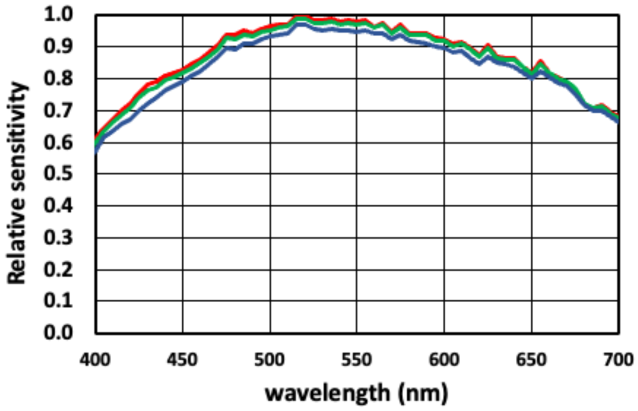

Figure 2. *Relative spectral sensitivity of the modified Sony α7 camera. The vertical scale is slightly exaggerated to show detail. Red and green channels are closely aligned; the mean difference between blue and red or green is about 2.5%.*

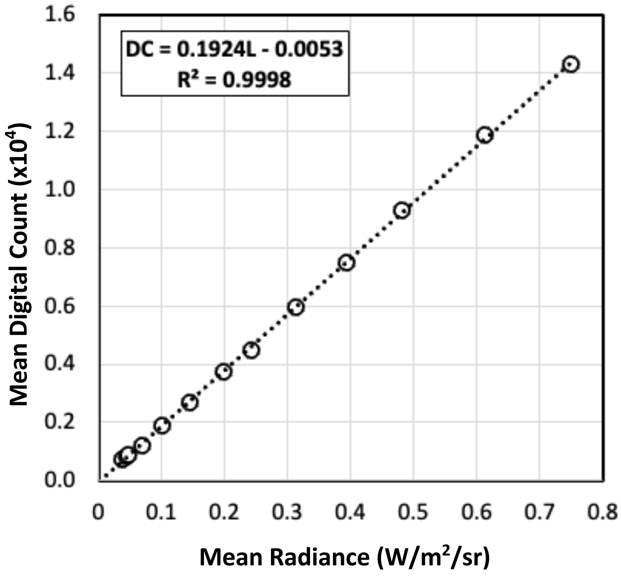

Figure 3. Linearity results, comparing the mean camera digital counts to measure radiance for a series of spectrally flat patches.

Illumination System

The illumination for this system consisted of 15 mostly narrow band LEDs. Ten channels were the same as those evaluated by the author in 2021, being a customized set of bands optimized for spectral image capture, products by LEDMotive. The additional channels were from a similar product, the stock (and uncustomized) version. All ten channels of both are shown in Figure 4a and 4b. The dashed lines in the Stock device (Fig 4b) indicate unused channels. These were found to be too similar, and in some cases identical, to channels in the Optimized device (Fig 4a).

Mechanically, the LEDMotive systems illuminate a circular piece of diffuse plastic. The approximately diffuse arrangement is directed towards the targets with a parabolic reflector. With two such lamps, this has shown to produce a bright and sufficiently uniform field for imaging.

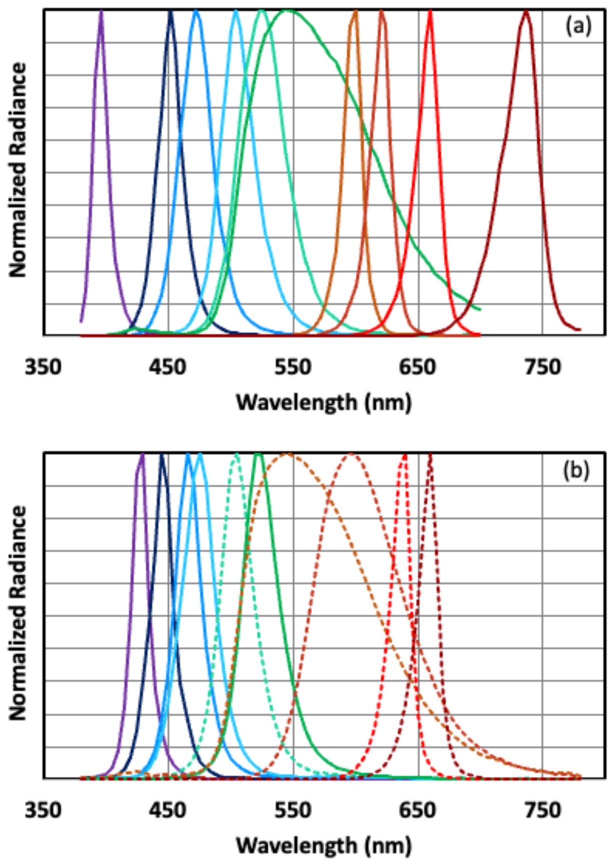

Figure 4. Normalized spectral radiance of the two systems used in this work. All ten channels in 4a, the five solid lines in 4b were used for this 15 channel system.

Reference and Verification Targets

The system was calibrated against the DT-NGT2,[2][3] and verified with a custom matte paint target using patches from Coloraid. This was assembled using 144 patches from the Coloraid “Color Chart” [4]. This verification target is a good test for the system, as the patches have a large chromatic range. Also, they are very diffuse, and so stress the geometry of the system after calibration with the glossy DT-NGT2. The CIELAB a*-b* distribution of the Coloraid target is shown in Figure 5.

A second verification target consisted of four printed targets, each with 24 patches and generally similar to the X-Rite Color Checker Classic. These were printed on four different CMYK print processes, with the goal being to provide a range of CMYK spectral primaries. It is important to note that paper selected for printing this the target had no optical brightening agents (“OBA”). Researchers attempting to replicate the results in this paper are cautioned against using typical office papers, even of very high quality. (Indeed, “high quality” office paper often means “high brightness” indicating the presence of OBAs.)

The reflectance of the cyan, magenta, and yellow patches (third row, patches 4-6) and black (row 4, patch 6) of each of four prints are shown in Figure 6a and b. The intention of including these prints was to show that the spectral imaging system can reproduce a variety of underlying colorants. Note the expanded ordinate axis to show detail of the black patches in Figure 6b.

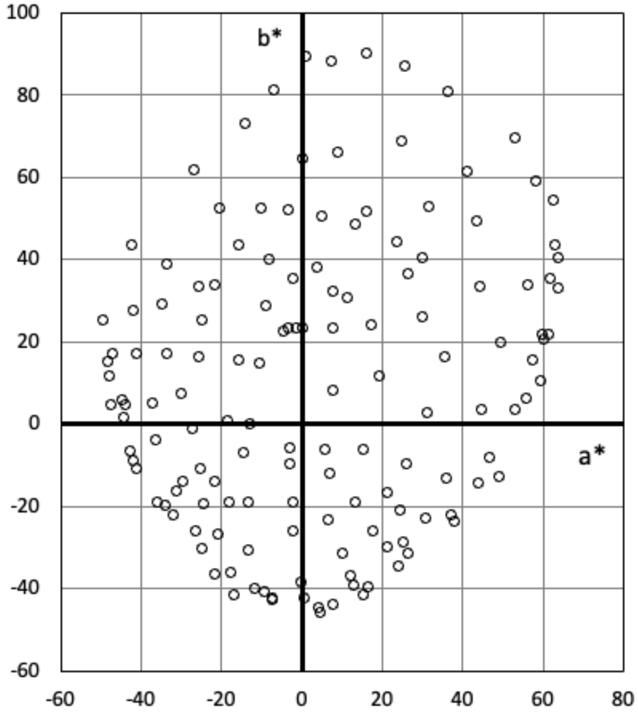

Figure 5. Color distribution of 144 patches in the Coloraid verification target.

Test Procedure

The camera was mounted in a typical copy stand above the targets with the lights positioned at approximately 45° from the normal. For all imaging the camera was set to F8/ and ISO 100. LED channels were always set to full output, and the camera exposure was adjusted to maximize the level of the NGT2 white patches without clipping. A large Coloraid matte white sheet was used as the flat fielding target. Its reflectance is a nearly uniform 85% throughout the visible spectrum.

With the exposure setpoints established, the image sequences can be completed:

1. Turn on an LED channel to 100%.
2. Image the target(s).
3. Image the white flat field.
4. Repeat until all channels and targets are imaged.

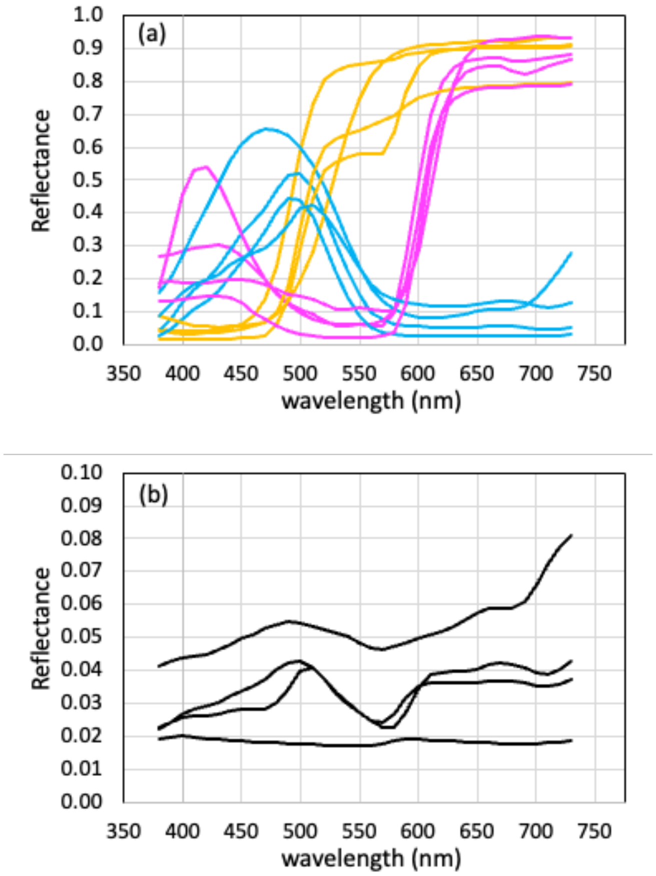

Figure 6. Spectral reflectance of four patches of the printed targets. (a) shows cyan, magenta, and yellow reflectance, and (b) shows black reflectance on an expanded scale.

The images were exported in the Sony proprietary ARW format, This linear camera raw format was converted to 16 bit TIFF using dcraw.[5] dcraw is a public domain tool that was interfaced with Matlab for automated processing of all images. As described above under *Camera Spectral Sensitivities*, dcraw was configured to dark correct the raw images, and then to produce a 25% sized output image, meaning the output RGB of the 25% image was simply the R, B, and mean G of each 2x2 Bayer pattern cluster. This is still a three plane image, and the RGB digital counts were then averaged for the final processing into a single plane image. Once all images are processed in this manner, each single plane image is divided by the corresponding flat fielding image. These images are analogous to reflectance.

The final step of image processing is to normalize each image such that one reference white patch in the NGT2 image matches the reference measurement data. This was done on a per-channel basis:

$$DC'_i = DC_i \frac{R_{white,i}}{DC_{white,i}}, \tag{1}$$

where: i indicates the LED channel, DC'_i are the normalized digital counts for the i^{th} channel; $R_{white,i}$ is the reflectance of the reference patch at the wavelength where the i^{th} LED channel peaks; and $DC_{white,i}$ is the digital count of the white reference patch when imaged under the i^{th} LED channel.

The flat fielded and normalized digital counts for the DT-NGT2, the Coloraid target, and the printed Color checkers form the basis of all subsequent calculations. For the balance of this paper, “digital counts” or “DC” will indicate these processed values.

Model Calculations and Results

Using the NGT2 reference reflectance and digital counts, a simple matrix model was developed. Considering the linearity results summarized in Figure 3, it is reasonable to include an offset in the model. We conclude this because the offset term of the linear fit in that figure is 0.0053. This term, although small, is still about 3% of the white used for those measurements.

The matrix M is derived by use of the Moore-Penrose pseudoinverse,[6] symbolized by the superscript $^{+}$:

$$\boldsymbol{M} = \boldsymbol{DC}^{+} * \boldsymbol{R}_{\boldsymbol{meas}}, \tag{2}$$

where DC are the mean digital counts of the 130 reference target patches (the DT-NGT2) and R_{meas} are the spectral reflectances of the reference target. M can now be used to transform arbitrary digital counts (after flat fielding and normalization, as described above) into estimated spectral reflectance using this relationship:

$$\boldsymbol{R}_{\boldsymbol{est}} = \boldsymbol{DC} * \boldsymbol{M}, \tag{3}$$

Note that in equations 2 and 3, bolded quantities are matrices, and the * symbol represents matrix multiplication.

Model Results

Given that the goal of the model is to predict spectral reflectance, the emphasis of reporting should be on those results. Nevertheless, for many communities color differences are also of great importance, so they are also included in Table I.

Table I. Color difference statistics for three targets

Target	Color Difference (ΔE00)				% Passing FADGI†	
	mean	max	stdev	90th	★★★★	★★★
NGT2	0.50	3.01	0.49	0.81	97	100
Coloraid	1.49	5.83	0.75	2.26	86	98
CC24	1.02	3.96	0.68	1.79	93	100

† Prints and Photographs “Color Accuracy”

There are fewer statistics relating to the spectral performance of the model. The average RMS (root, mean, square) between the measured and estimated reflectance values is precisely what the pseudoinverse in equation 2 is optimizing. For the three targets evaluated here: 0.0524, 0.2010, 0.2279, for NGT2, Coloraid, and CC24, respectively.

Discussion of Model Performance

The color performance in Table I is reasonable, especially when compared against current FADGI Color Accuracy metrics for Prints and Photographs [7]. This is established by the use of the mean data only, in the second column of Table I, all of which meet FADGI 4★. Additionally, the rightmost two columns of Table I examine the FADGI performance of individual patches, and show that there are only a few patches in the reference target and the CC24 CYMK target. The Coloraid performance is somewhat lower, although still FADGI 4★ on average. Regardless, the objective of this work is to improve the imaging performance of Prints and Photographs (generally CMYK artifacts) and the slightly reduce performance for the Coloraid target is acceptable, especially given that it is a stress case.

Spectral accuracy is somewhat more difficult to evaluate for the general imaging case. The specific application of full spectral imaging (as opposed to spectral imaging with the goal of improved color, and/or relighting) will affect the interpretation of any metrics. For example, the evaluation of spectral imaging towards determine material properties will depend on the specific material properties in question. Similarly, when considering sample fading a different set of spectral metrics may apply.

Conclusions

A spectral imaging system using a monochrome camera and 15 narrow band LED channels has been described. Applying the system and the associated processing techniques produced good colorimetric results when evaluated against the FADGI guidelines. The CMYK target, intended to simulate some of the requirements of Prints and Photographs, also performed quite well.

Acknowledgements

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References

[1] Wyble, DR. “Spectral Imaging Method for Transmissive Media,” in IS&T Archiving 2021 (held virtually) (2021).

[2] Wyble, DR. “Next Generation Camera Calibration Target for Archiving,” in IS&T Archiving 2017, Riga, Latvia (2017)

[3] Available from Digital Transitions Heritage, see <heritage-digitaltransitions.com/product-catalog/>

[4] See <coloraid.com/colorchart.aspx>

[5] See <www.dechifro.org/dcraw>

[6] Penrose, Roger "A generalized inverse for matrices". Proceedings of the Cambridge Philosophical Society. **51** 3: 406–13 (1955).

[7] Technical Guidelines for Digitizing Cultural Heritage Materials, Federal Agencies Digitization Guidelines Initiative (FADGI), Still Image Working Group, 2010 revised 2016, <digitizationguidelines.gov/>

Author Biography

David R. Wyble is president and founder of Avian Rochester, LLC, and president and co-founder of Gray Sky Imaging. Avian Rochester provides color standards; traditional and custom measurements; and consulting services to the color industry. Gray Sky Imaging focuses on improved imaging techniques and products for the museum/library/archive sectors, and other markets. Wyble holds a BS in Computer Science and MS and PhD degrees in Color Science from RIT and Chiba University, respectively.