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Spectral Imaging Method for Transmissive Media

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Abstract

An imaging process is described which captures spectral transmittance for transmissive media. The specific application is positive and negative large-format film. The system is based on a ten channel LED backlight source and a monochrome camera. The LED source sequentially back-illuminated reference targets and film samples, with an image captured for each LED channel. From the measured data and images of reference targets, a model was developed to predict spectral transmittance. With that model, the 10 images of a sample were combined to a single 31-band spectral image. Spectral images can be used to calculate colorimetric data for each pixel. These colorimetric results show that the system produces good colorimetric predictions when compared to the most relevant FADGI guidelines. Some improvement is required for the spectral model particularly in the red region.

Project Summary

The Library of Congress has innumerable positive and negative film samples that are in danger of unrecoverable degradation. Since these samples are all based on three primaries, in principle, RGB imaging should be sufficient to capture spectral transmittance. This has been demonstrated if the spectral nature of the three primary colors is known. [1] However, for the case of multiple film types, and those that may have been aged or degraded in different and indeterminate ways, it is not possible to know the baseline data for the three primaries. Therefore a spectral approach is required. This paper proposes a technique for spectrally imaging these materials in transmission mode, using a monochrome camera and backlighting the samples via a series of narrow band LEDs.

Introduction

Historically there have been many types of film developed, each with different strengths and weaknesses, and more importantly different chemical characteristics. These differing characteristics mean that the three fundamental primaries present in any given film, while generally CMY for positives or RGB for negatives, are not necessarily the same CMY or RGB as found in any other film. This is compounded by the fact that negative film is generally designed in concert with a specific photographic paper, that has its own chemical signature and therefore yet another set of color primaries. Finally, the problem might be tractable if all of these properties remained the same over time, or at least they all changed in some consistent, predictable way. But that is not the case, as the aging process (fading, yellowing, or other deterioration) happens differently for the various materials involved, or at best the aging behaviors are not fully characterized for all media of interest.

Therefore we recommend a spectral approach, since the application of any three-color imaging system will be either applicable to at most one film type. For the general case, a system is needed that can handle any film technology. The alternative is a spectral technique that will yield material properties, in this case spectral transmittance, that are independent of the underlying chemistry for any given film. (We recognize that the definitions of "spectral," "multispectral," and "hyperspectral" may be fluid across imaging application domains, and we will not enter that debate here. All of the above will simply be referred to as "spectral" in this paper.)

Imaging and Lighting Apparatus

Spectral imaging hardware must by its very nature capture more than three dimensions of data. The exact number of planes required depends on the imaging technology and the samples. The literature suggest a lower bound of five or six channels that are required for reasonable spectral estimation, [3] and for an upper bound so-called hyperspectral systems containing hundreds of channels.

The system described for this research uses a 10-channel LED illumination system manufactured by LEDMotive [4]. The particular source had a set of custom LEDs installed that were optimized for reflective spectral reproduction and colorimetric accuracy.[5] The series of LEDs are in a single package, and packaged into a traditional photographic illumination system with parabolic reflectors. To create a uniform back-illumination system, the two source assemblies were positioned behind a large (250mm x 250mm) plate of diffusely transmitting material. This material was designed specifically for this purpose, having been removed from a GTI light booth intended for viewing backlit transmissive materials. For simplicity, the diffuser and illumination system will collectively be referred to as the "backlight." Refer to the schematic in Figure 1 and the normalized LED spectral output in Figure 2.

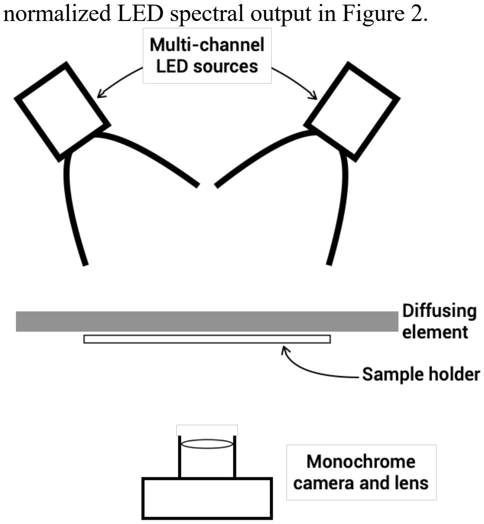

***Figure 1**. Schematic showing top view of the LED illumination, diffuser, sample holder, and camera*

The camera was a Phase One IQ4 150MP Apochromatic camera. This monochrome camera has a single 14204x10652 pixel sensor without any color filter array. The lens used was a Rodenstock HR-Digaron Macro 105mm f/5.6. The camera was controlled by Capture One, v14.1, producing 16-bit TIFF files with an approximate L* (cubic) gamma encoding. That curve was included in the TIFF profile, and all image data are subsequently linearized using its inverse.

For each of the reference target and sample types (described below) a mask was created to cover the backlight except for the areas of each respective target. This was to reduce scattered light. To further reduce scatter, the LED sources themselves were covered with black fabric, sealing the sources behind the frame supporting the backlight. The mask also served to ensure consistent alignment of the film samples, reducing the processing time by permitting the use of a single patch location reference file for all film images.

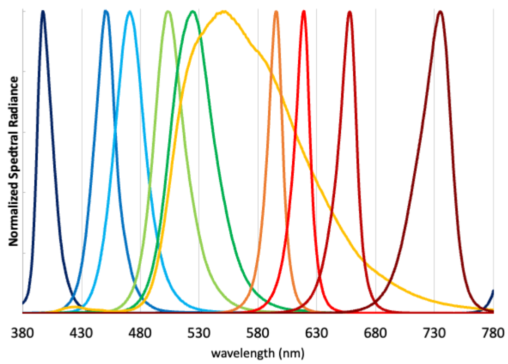

Figure 2. *Normalized spectral radiance of the 10 LED channels. The peak measured wavelengths (nm)are: 397, 450, 471, 503, 524, 552, 595, 619, 658, 735.*

Reference Targets and Samples

The prototype reference transmittance target is shown in Figure 3. [6] It consists of 12 absorption filters, each 25mm square and 2mm thick. A secondary target (not shown) held an additional 9 absorption filters; these are 50mm square, and 1mm thick. The secondary filters were added to help to fill in some regions not covered well by the prototype target, particularly in the less transmissive range. All filters were measured using an X-Rite Coloreye 7000A spectrophotometer, configured for total spectral transmittance. The transmittance measurements for both reference targets are shown below under Model Performance.

The film samples were all 4x5 format, with some positives and some negatives. Examples are shown in Figure 4. The solid patches down the left side of the film were measured on the Coloreye 7000A, and were used to evaluate the imaging system. The transmittance measurements are also shown below under Model Performance. In total there were four positive film samples (two Kodak Ektachrome 100, one Fuji Fujichrome Provia, and one AGFA RSX) and one negative (Kodak Portra).

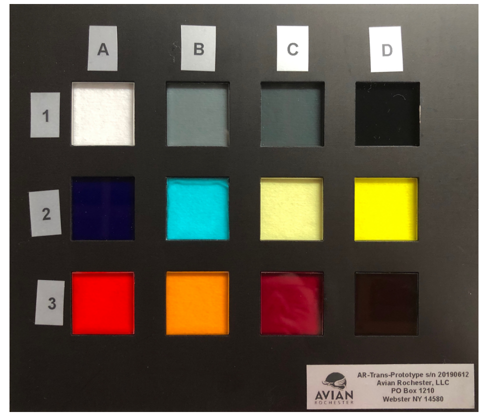

Figure 3. *Prototype Transmittance Calibration Tool. [7] Note that irregularities in the filter appearance are due to the background used for this image.*

Figure 4. *Example positive and negative film. The six patches along the left side were measured and used to evaluate the transmittance imaging system.*

Test Procedure

For the imaging sequence, the steps were:

1. Position the camera such that it was as close as possible to the sample while remaining in good focus and maintaining the field of view large enough to encompass all targets. The lens was set at F8 for this and all subsequent imaging.
2. After setting the dimmest LED channel (in this case, 397nm) at full output (maximum energy), the camera exposure time was determined to maximize the digital counts without a risk of clipping. This single exposure time was used for all the channels.
3. For each of the other LED channels, determine the output level yielding similar values to Step 2. These 10 LED output levels are recorded and used for all subsequent imaging.
4. Using the recorded LED levels, image the white diffuser under each LED channel. This was used for flat fielding.
5. Similarly image the calibration targets and the samples.
6. Using CaptureOne, all images were exported as 16-bit TIFF files.

To process the images:

1. All images were linearized using the inverse gamma curve using code provided by Digital Transitions. This and all subsequent calculations were preformed using Matlab.
2. Each image was flat-fielded by dividing the image by the white diffuser image (one flat fielding image per LED channel).

3. The mean digital counts were extracted from the calibration target filter images.
4. A model was developed (see below) relating camera output to the reference transmittance data for the reference and secondary targets.
5. The measurements from the verification images were compared to the rendered images by spectral and colorimetric difference.
6. The model was applied to all test images to predict spectral transmittance for each pixel of each image

Model Development

The prediction model will take as input the flat-fielded digital counts of the test image when imaged under each of the 10 LED channels. These 10 images are processed through an optimized matrix yielding the predicted spectral transmittance of each pixel. For pixel $P_{x,y}$ of the image, the corresponding estimated spectral transmittance T_{est} is:

$$\boldsymbol{T}_{est} = \boldsymbol{M} \cdot \boldsymbol{DC}, \qquad (1)$$

where $\boldsymbol{M}$ is the optimized 31x10 transformation matrix and $\boldsymbol{DC}$ is the 10x1 matrix of flat-fielded digital counts for $P_{x,y}$ when imaged under each LED channel. T_{est} is therefore a 31x1 matrix, corresponding to the spectral transmittance from 400 to 700nm, sampled every 10nm. Equation 1 is applied for each film sample using the set of 10 input digital counts (one from each of the 10 LED channels).

The inputs to the optimization of the transformation matrix $\boldsymbol{M}$ are the 21 spectral transmittance curves for the reference filters (shown below in Figure 5) and the 10 mean flat-fielded digital counts for each of those filters when illuminated by each LED channel. The non-square matrix $\boldsymbol{DC}$ is inverted using the Moore-Penrose pseudoinverse:

$$\boldsymbol{T}_{ref} \cdot pinv(\boldsymbol{DC}_{ref}) = \boldsymbol{M} \qquad (2)$$

where T_{ref} is the 31x21 matrix of reference filter spectral transmittance, and $\boldsymbol{DC}_{ref}$ is the 10x21 matrix of flat-fielded digital counts for each filter under each LED channel. This yields the 31x21 transformation matrix $\boldsymbol{M}$ applied in equation 1, which will be for predicting the transmittance of arbitrary samples.

Model Performance

The first test for the model is to examine how well it performed against the input data, in this case the reference filters. Figure 5 shows the measured (solid lines) and estimated (dashed lines) transmittance for the reference target (upper plot) and the secondary target (lower plot). Figure 6 shows the measured CIELAB of the reference filters (filled circles), and the corresponding estimated values (arrow points). Figure 6 shows the b* vs a* (upper) and L* vs C* (lower). The mean and standard deviation of the ΔE_{00} color differences are 1.53 and 1.58, respectively.

A more critical test of model performance applies independent data. As described above, the solid are patches of the film samples were measured and then imaged to predict spectral transmittance. Figures 7 and 8 show the spectral and color results for the film samples, analogous results to Figures 5 and 6 for the filter results.

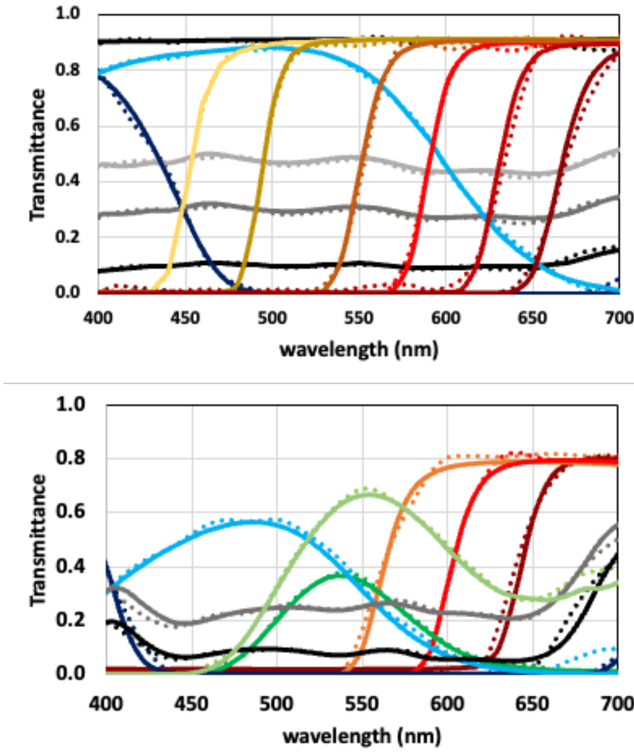

Figure 5. Measured (solid lines) and estimated (dotted lines) spectral transmittance for the 12 filters in the reference (upper) and the nine filters in the secondary target (lower).

Discussion

The spectral transmittance predictions are reasonable, especially given the simplicity of the model. Some of the reference filters and film samples show more error than expected on the red region. It is not clear why the fits are not better since there is an LED (and hence some expected signal) in that spectral region, although that LED does not peak until 735nm (refer to Figure2). We also note that this error is not present in all reference filters, nor in all film samples. The three neutral filters in the upper plot of Figure 5, as well as the film in Figure 7(c) show very good performance in the 650-700nm range. Further investigation will be required.

In spite of the spectral error shown in 650-700nm range, colorimetric results are quite good in all but a few points. The two filters with the largest color differences (green highlighted circles in Figure 6) are both dark reds. We attribute these two large differences to the larger spectral error in the red region.

The film samples will be applied as independent data to test the model. As described above, each test film sample has six solid area patches which were measured using the Coloreye 7000A. They were imaged identically as the filters, and processed as described above. After flat fielding those film images, the digital counts of the central region of each solid area patch were averaged for each of the 10 images. these constitute the 10x1 matrix $\boldsymbol{DC}$ applied in equation 1 to estimate one of the six transmittances for each film sample.

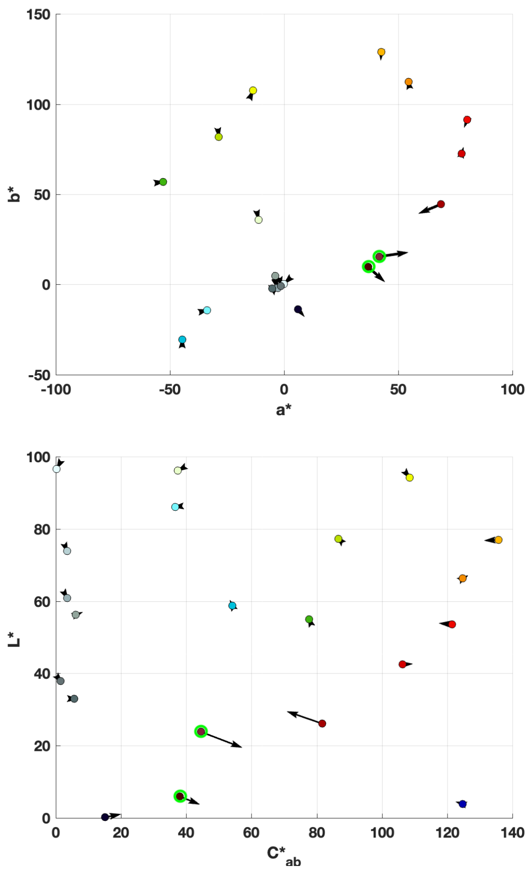

***Figure 6**. Measured (filled circles) and estimated (arrow points) b* vs a* (upper) and L* vs C* (lower) for the 21 filters representing both the reference and secondary targets. Green highlighted points have the highest color differences, and are described in the text.*

Figures 6a-e show the measured (solid lines) and estimated transmittance (dashed lines) for each patch of each film sample.

Table I shows the CIELAB for the model performance for the independent film data.. Overall these color and spectral differences are reasonable. While FADGI [7] does not provide color difference metrics for transmissive targets, that metric for (reflective) Prints and Photographs is <4 and <2 for FADGI three- and four-star performance, respectively.

Conclusions and Future Work

A prototype spectral imaging system has been demonstrated and applied to transmissive media. The specific samples used here were historic film targets. Predicted transmittance compared favorably to the reference measurements, for both the model fitting and independent data sets. Colorimetric results were similarly favorable, and when the FADGI rating for reflective media is applied, all five film samples were either 3- or 4-star.

***Table 1**. Mean and standard deviation of the six patches in each of the five film samples (a) through (e) as denoted in Figure 7. FADGI star rating uses reflective metrics, described in the text.*

ΔE_{00}	mean	std dev	FADGI rating
(a)	1.90	0.92	****
(b)	1.97	1.02	****
(c)	3.89	1.76	***
(d)	1.57	0.63	****
(e)	3.06	1.32	***

Spectral transmittance in the 650-700nm region was poorly predicted for several of the reference filters and independent film data. This will require further investigation, and possibly adjustment in the imaging system by the use of a different LED in that region.

Future imaging will include a more extensive set of film samples, including formats beyond 4x5 (e.g.: 35mm, and others). Improved imaging techniques (e.g.: flatness) will also be applied, permitting a more stringent evaluation of image quality

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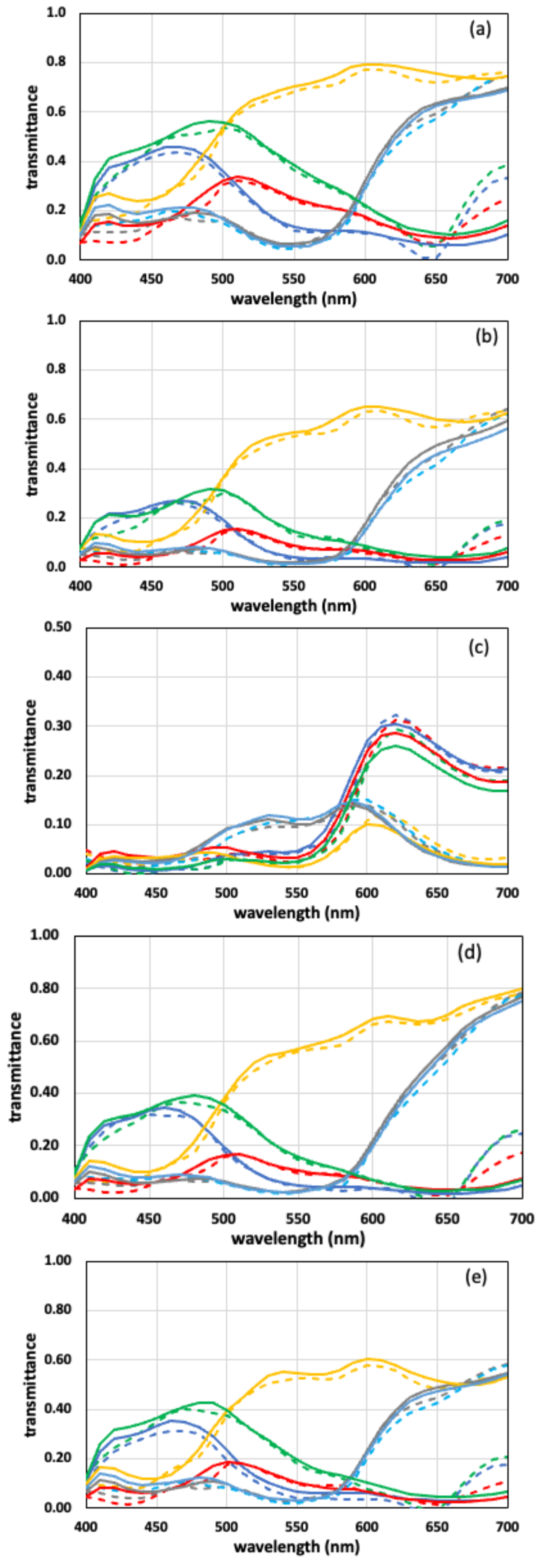

Figure7. *Measured (solid lines) and estimated (dotted lines) spectral transmittance for the six solid patches in each of five types (a)-(e). Note expended ordinate axis scale in (c).*

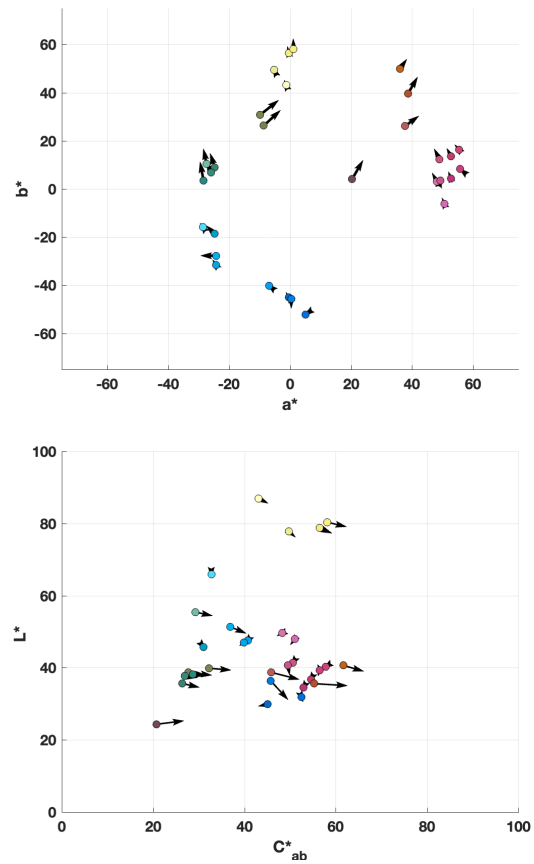

Figure 8. *Measured (filled circles) and estimated (arrow points) b* vs a* (upper) and L* vs C* (lower) for the 30 solid are patches representing all five film types. Note that the axes are expanded from those in Figure 6 to show better detail.*

Author Biography

David R. Wyble is president and founder of Avian Rochester, LLC. Avian Rochester provides color standards; traditional and custom measurements; and consulting services to the color industry. Recently he was involved in co-founding a new venture, Gray Sky Imaging, which will focus 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.