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Color Accuracy-Guided Data Reduction for Practical LED-based Multispectral Imaging

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Abstract

The color accuracy of an LED-based multispectral imaging strategy has been evaluated with respect to the number of spectral bands used to build a color profile and render the final image. Images were captured under select illumination conditions provided by 10-channel LED light sources. First, the imaging system was characterized in its full 10-band capacity, in which an image was captured under illumination by each of the 10 LEDs in turn, and the full set used to derive a system profile. Then, the system was characterized in increasingly reduced capacities, obtained by reducing the number of bands in two ways. In one approach, image bands were systematically removed from the full 10-band set. In the other, images were captured under illumination by groups of several of the LEDs at once. For both approaches, the system was characterized using different combinations of image bands until the optimal set, giving the highest color accuracy, was determined when a total of only 9, 8, 7, or 6 bands was used to derive the profile. The results indicate that color accuracy is nearly equivalent when rendering images based on the optimal combination of anywhere from 6 to 10 spectral bands, and is maintained at a higher level than that of conventional RGB imaging. This information is a first step toward informing the development of practical LED-based multispectral imaging strategies that make spectral image capture simpler and more efficient for heritage digitization workflows.

Introduction

Spectral imaging is a powerful tool for the scientific examination, documentation, and visualization of cultural heritage materials. The rich information captured in a single visible-range spectral imaging dataset can be used to estimate materially-diagnostic reflectance curves, to create highly-accurate color reproductions, and to simulate changes in appearance upon changes in viewing and illumination conditions [1], [2]. These features of spectral imaging render it more comprehensive and versatile than conventional RGB imaging and lend to its growing popularity in cultural heritage settings. LED-based spectral imaging is of particular interest, especially as LEDs become increasingly more common, and they continue to improve in flexibility, efficiency, and cost-effectiveness over filter-based methods [3], [4].

Despite the recognized advantages of spectral imaging, it is still largely employed as a scientific tool used in one-off technical studies, carried out with complex instrumentation and requiring computationally-intense data processing [5]–[7]. As such, it has not yet found a place within more routine cultural heritage digitization workflows. In order for spectral imaging to be effectively translated from lab to studio, considerations balancing complexity, efficiency, quality, and cost must be made.

The investigation presented here explores the first step of a needs-based approach for implementing spectral imaging more practically as a routine imaging technique. This involves determining the number of image bands necessary for high color accuracy in the final rendered image. Reducing the number of bands while maintaining a specified level of color reproduction quality is a simple means of reducing capture and processing complexity while increasing workflow efficiency. Finally, in consideration of budget and space allowances, the system used in this investigation consists of a commercial camera and LED light sources that are already found in or easily added to studio equipment setups.

In the context of this research, “multispectral” is used to describe the number of spectral image bands captured. This will range from 10, when the LED lights are used to their full capacity, down to 6, when investigating reducing the number of bands. Additionally, all of the image bands fall within the visible range, with peak wavelengths ranging from 385 nm to 725 nm. Because this research is focused on color rendering, imaging bands in the UV and NIR ranges, which are commonly included in other spectral imaging approaches, are not considered here.

Equipment

A more practical spectral imaging strategy necessitates the use of familiar and affordable tools. The first is a commercially available RGB camera. The imaging presented here has been carried out using a modified Sony α7R III digital camera. The camera was modified to have its internal IR filter removed, which extends the sensitivity of the camera’s red channel (Figure 1). This improves the spectral estimation accuracy over longer visible wavelengths.

The lights used for imaging are SPECTRA TUNE LAB (LEDMotive) spectrally tunable LED light sources [8]. Each light contains 10 independently addressable LED color channels. The spectral power distributions of the LEDs are plotted in Figure 2, and the peak wavelength of each LED reported in Table 1. The sources were custom-made to contain 10 channels that would enable optimal color reproduction for artists’ materials. The specific LEDs were originally chosen according to simulations performed using the LED spectral power distributions and color target reflectance spectra when coupled with a monochrome camera [4]. The work presented here generalizes their use by pairing them with a color sensor rather than a monochrome sensor, and by characterizing the color reproduction achieved using fewer than the full set of 10 LEDs.

Each light contains the LEDs within a small (16 x 12 x 12 cm), lightweight casing. Each incorporates an internal integrating sphere and is outfitted with an external reflector to ensure uniform illumination. The imaging is performed with a typical camera/light source 0˚/45˚ studio setup (Figure 3).

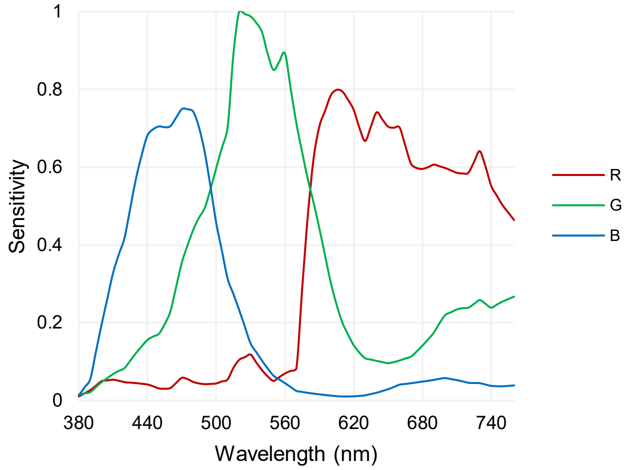

Figure 1. *Spectral sensitivity of the modified RGB camera.*

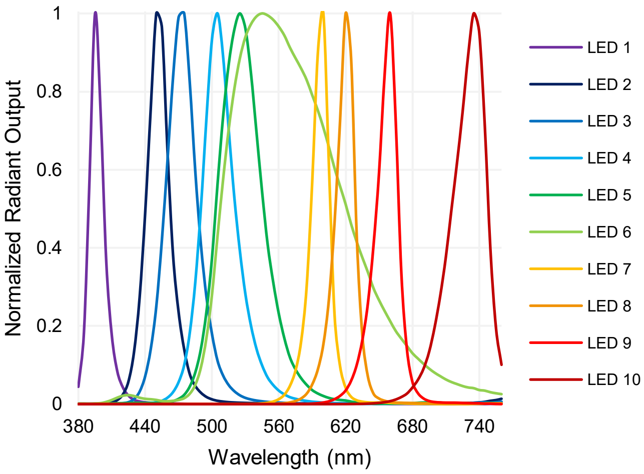

Figure 2. *Normalized spectral power distributions of the 10 LEDs in the custom SPECTRA TUNE LAB LED light sources.*

Table 1. Peak wavelength of each LED.

LED ID	Peak Wavelength (nm)	LED ID	Peak Wavelength (nm)
1	395	6	545
2	450	7	600
3	475	8	620
4	505	9	660
5	525	10	735

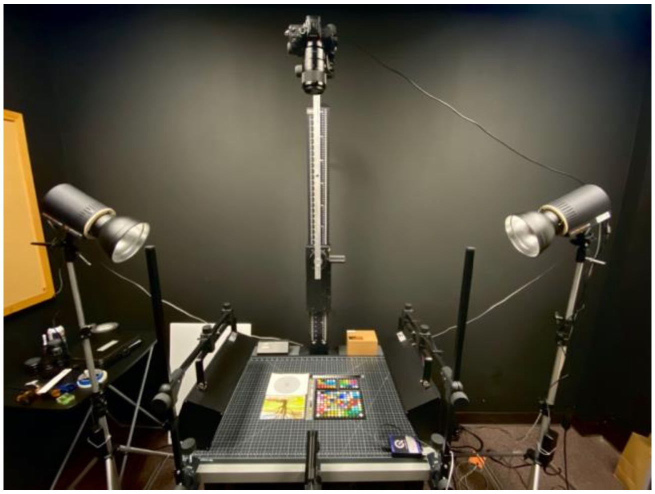

Figure 3. *Studio setup for imaging.*

Methods

Imaging

A scene containing several color targets, followed by a flatfield, were imaged using each LED in turn for illumination. This resulted in the collection of 10 3-channel RGB images of both the target and the flatfield. The same scene and flatfield were then imaged under illumination by strategic combinations of LEDs, further explained below. Dark images of equivalent exposure times were also captured. Finally, the lights were tuned to approximate D50 illumination, and a single RGB image captured to enable comparison between conventional RGB imaging and the various multispectral combinations to be evaluated.

Band Reduction

The RGB camera captures in three bands with relatively broad spectral sensitivities. The LED lights can provide illumination in up to 10 distinct channels. Capturing an RGB image illuminated by each LED in turn results in the collection of 10 3-band (RGB) images, with 30 total bands in the set. This is more than is either necessary or useful for practical processing and accurate color rendering. Because of the narrowband output of a majority of the LEDs, in most of the RGB images, only one of the channels contains a majority of the signal. For instance, when lit using the 450 nm blue LED, only the blue camera channel has high sensitivity at this wavelength, and as such contains much more signal than either the green or red channels. The camera channel with the highest sensitivity where the LED output peaks will contain the most signal. Following this logic, the set of 30 bands was reduced to 10 by selecting the channel containing the most signal from each RGB image. This 10-band collection comprised the initial multispectral band set. The resulting system spectral sensitivities are plotted in Figure 4.

The initial 10-band set was further reduced by systematically removing first single bands, to create 9-band sets, then pairs of bands, to create 8-band sets, and eventually entire groups of bands to create 7- and 6-band sets. The color rendering was evaluated for every combination to determine which combination for each total number of bands resulted in the smallest loss in color accuracy. As an example, the system spectral sensitivities of the optimal 8-band set determined in this way are plotted in Figure 5. Comparing the system sensitivities of 8- and 10-band sets reveals that the optimal 8-band system is missing the bands corresponding to the 505 and 620 nm LEDs (LEDs 4 and 8).

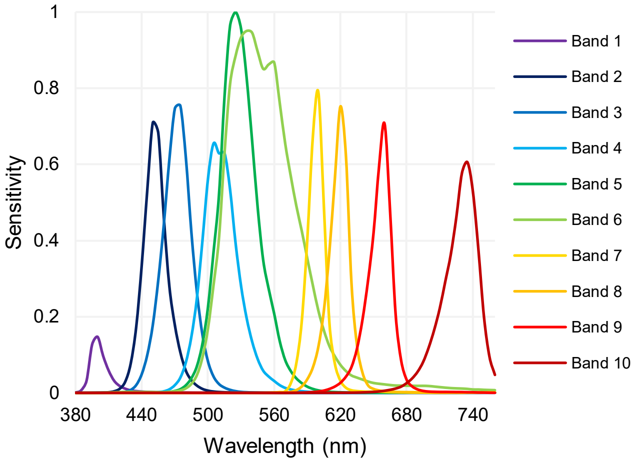

Figure 4. *10-band multispectral system spectral sensitivities.*

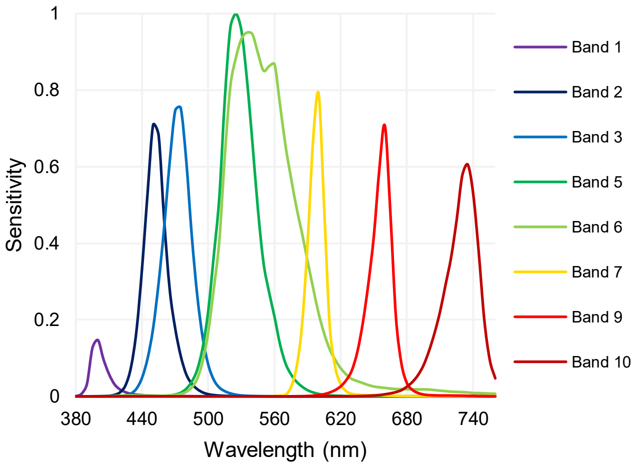

Figure 5. *System sensitivities of the optimal 8-band set obtained through band removal.*

In a second band reduction strategy, the 10-band set was reduced to smaller sets of 9, 8, 7, and 6 total bands by capturing images under illumination by systematically paired and grouped LEDs at the same time. The color rendering was again evaluated for every combination to determine which combination for each total number of bands resulted in the smallest loss in color accuracy. For example, the optimal 8-band set obtained using this method resulted from combining the 600, 620, and 660 nm LEDs (LEDs 7, 8 and 9) in a single capture. The red camera channel collects the most signal at these wavelengths, and as such, is that which is included in the overall set of 8 bands. The resulting system sensitivity for this 8-band set is plotted in Figure 6. Note the differences in the sensitivity profiles of the 8-bands set obtained using the two different band reduction methods.

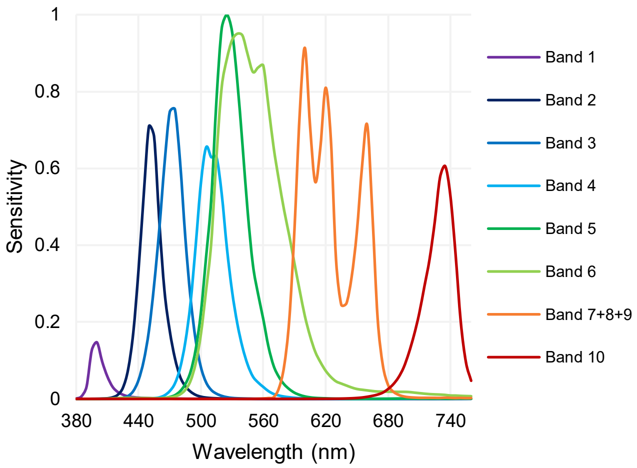

Figure 6. *System sensitivities of the optimal 8-band set obtained through LED combination.*

Color Rendering Evaluation

Color rendering was evaluated through cross profiling based on the targets pictured in Figure 7: the Next Generation Target V2 (Avian Rochester, LLC) and the Artist Paint Target (Image Science Associates, LLC). Together, these targets offer a wide distribution of colors to test over, as well as materially and spectrally relevant paint samples. All images were flat-fielded and dark current-corrected prior to building the color profiles. For a given image set, a color transformation matrix was estimated based on the relationship between the camera signals captured for each target, and reference tristimulus values obtained from spectrophotometric measurements. A colorimetric calibration was chosen over a spectral calibration in order to compute a direct transformation from recorded signal to rendered color. A spectral calibration, in which target reflectance spectra are estimated first and then used to compute the color rendering was not performed as part of this experiment.

The color transformation matrix was constructed using all available bands in each set. As such, the matrix varied in size from a 3-by-10 for the 10-band multispectral set to a 3-by-6 for the 6-band multispectral sets, and a regular 3-by-3 for the conventional RGB image, where the second dimension of each of the matrices corresponds to the total number of bands. In accordance with the direct colorimetric calibration, this matrix was then iteratively optimized to give the minimum mean ΔE_{00} across all of the patches in the target. The final optimized, matrices obtained for each target were used to cross-profile the band set, predicting the $L^*a^*b^*$ values for the opposite, verification target. The band set having the lowest mean and 90th percentile verification target ΔE_{00} values for each reduction strategy and each total number of bands were identified as the optimal band sets for those requirements and are reported below.

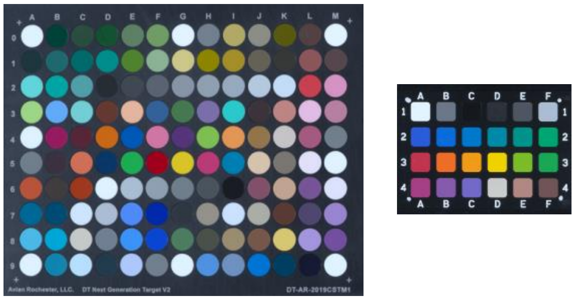

__Figure 7.__ Next Generation Target V2 (NGT) and Artist Paint Target (APT) used in cross profiling for color rendering evaluation.

Results

Table 2 summarizes the results of the band reduction experiment. The band sets are classified in the top row by total number of bands. The next row identifies the bands that were either removed from the set, or LEDs that were combined during capture to obtain the total number indicated in the first row. The combinations reported are those which gave the lowest mean and 90th percentile ΔE_{00} values for each reduced band set size (9, 8, 7, and 6) and for each band reduction method (removing bands versus combining LEDs). The max ΔE_{00} values are also reported for each combination.

Overall, the results indicate that reducing the number of bands had little effect on the mean color accuracy, regardless of band reduction method. This can be read from the table by examining the mean ΔE_{00} values from left to right. As the number of bands grows smaller, the mean does not increase significantly for either target. In fact, it remains nearly constant, with the mean for the NGT increasing from 1.1 to only 1.2 in either of the 6-band scenarios, and the APT from 1.1 to 1.3 in the 7-band and 6-band scenarios obtained through band removal. The 90th percentile and max ΔE_{00} values do increase as the number of bands decreases, indicating that there are some outlier patches that become more difficult to reproduce accurately with less spectral coverage, though the increase is not monotonic. Finally, note that the mean and 90th percentile ΔE_{00} values are comparable between the two targets, indicating good target-independence in the cross-profiling.

The mean and 90th percentile ΔE_{00} values for all of the test cases fall below the limit of perceptible color difference for digital images, indicating that 90% of the patches are rendered with less-than-perceptible color difference errors [10]. In most cases, the max ΔE_{00} represents only a single patch which was not well characterized. There is no perceptibly significant increase in the mean and 90th percentile ΔE_{00} values when band sets ranging in size from the full 10 to the most reduced number of 6 are used to create

Table 2. Best-case verification target mean and 90th percentile ΔE_{00} values for each indicated image set. Next Generation Target (NGT) and Artist Paint Target (APT) are abbreviated.

Total Number of Bands	10	9	9	8	8	7	7	6	6	3 (RGB)
Bands Removed or Combined	-	8+9 (combined)	7 (removed)	7+8+9 (combined)	4, 8 (removed)	3+4+5, 7+8 (combined)	3, 5, 8 (removed)	1+2, 3+4, 7+8, 9+10 (combined)	3, 4, 7, 9 (removed)	-
NGT mean ΔE_{00}	1.1	1.1	1.1	1.1	1.2	1.1	1.2	1.2	1.2	2.0
NGT 90th pctl ΔE_{00}	1.5	1.5	1.6	1.6	1.7	1.7	1.8	1.7	1.9	4.4
NGT max ΔE_{00}	2.5	2.6	2.5	2.4	2.7	3.4	2.6	2.5	4.1	7.5
APT mean ΔE_{00}	1.1	1.1	1.1	1.1	1.2	1.2	1.3	1.1	1.3	3.3
APT 90th pctl ΔE_{00}	1.7	1.6	1.5	1.7	1.6	1.9	1.9	1.6	2.2	5.9
APT Max ΔE_{00}	2.3	2.0	1.9	2.2	2.1	2.4	2.0	2.1	3.0	9.1

the profile. All test cases clearly outperform conventional RGB imaging, for which metrics are reported in the final column of the table. Considering the APT in particular, this indicates that typical artist's paints are better characterized when imaging with greater spectral coverage than is achieved using 3-channel RGB imaging. Comparing the results for the 6-band sets and RGB reveals that doubling the number of bands to 6 reduces the mean and 90th percentile ΔE_{00} values by more than a factor of 2. For both targets, the relatively large value obtained from RGB imaging with respect to those obtained in any of the multispectral band sets indicates that a larger majority of the patches are reproduced with higher accuracy using multispectral imaging than in RGB. Visualizations of the APT comparing the color rendering obtained from 10-band, 6-band combined, and RGB imaging can be found in Figures 8 and 9.

Figure 8. *Color rendering visualization of the measured color (left half of each square), the color rendered from the RGB image (top right quarter of each square), and the color rendered from the 10-band image (bottom right quarter of each square).*

Figure 9. *Color rendering visualization of the measured color (left half of each square), the color rendered from the RGB image (top right quarter of each square), and the color rendered from the 6-band combined image (bottom right quarter of each square).*

Observations can be made based on the relationship between the spectral coverage provided by this particular set of LEDs, the sensitivity of the camera, and the ΔE_{00} values obtained. When creating the 9-band sets and then the 8-band sets, the optimal combinations involved removing or combining amber and red LEDs, namely those with peak outputs at 600, 620, and 660 nm (LEDs 7, 8, and 9). This indicates that coverage by adjacent LEDs in this region, likely the broadband LED that peaks at 545 nm (LED 6) but has output throughout the 600-700 nm range, was sufficient to maintain color accuracy. Having first modified the spectral coverage in the amber-red region, when creating the further reduced band sets of 7 and 6 bands, removing/combining LEDs with peaks in the green and blue gave the best results. For example, the optimal 6-band set creating by removing channels came at the loss of the 475, 505, 600 and 660 nm LEDs (LEDs 3, 4, 7, and 9). This can be rationalized by observing the overlap between adjacent LEDs, particularly for the 475, 505 and 600 nm LEDs. Note that none of the sets created through band removal dropped the 395, 545, or 735 nm LEDs (LEDs 1, 6, and 10). The LEDs at either end of the set are essential for anchoring and provide necessary coverage to the edges of the visible range. The broadband 545 nm LED in the middle of the set provides coverage when adjacent bands are removed, and furthermore, and mimics the peak of the luminous efficiency function ($V(\lambda)$) of the human visual system, important to color accuracy [9].

Conclusions

This research explored the limits of color rendering accuracy attained through LED-based multispectral imaging. The effect of reducing the number of bands during construction of the color profile was investigated, and it was determined that while the LED lights used in the imaging for this experiment contain 10 channels, as few as 6 can be used to achieve nearly equivalent mean color accuracy in the resulting rendered image. This suggests that a practical LED-based multispectral imaging strategy could be carried out using further simplified lights with fewer LEDs, thus reducing manufacturing cost. It also demonstrates that reducing the number of bands while maintaining average color accuracy is possible, providing a simplified framework for constructing simplified multispectral imaging strategies for color accurate reproduction of cultural heritage materials. Band sets of fewer than 6 were not investigated using the band reduction approaches described here. This is because a capture strategy utilizing the inherent 3-channel sensitivity of RGB camera channels is more efficient for the capture of 6 or fewer bands than are capture sequences that step through the spectral range, like that used in this research. Future work will address maximizing the information captured in all three camera channels using specific LED combinations, enabling the capture of 6 useful spectral bands in only two capture bands [11], [12]. Additionally, combining spectral and colorimetric calibration processes will be investigated, such that the system is profiled to minimize root-mean squared spectral reflectance error, and the estimated spectra used to compute the color rendering.

The findings from this investigation will be used toward informing the development of practical systems and strategies that reduce the complexity of multispectral imaging for routine cultural heritage imaging.

Acknowledgements

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