# Spectral reflectance estimation of ancient mexican codices, multispectral images approach

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Mexican codices are an ancient reading and writing system developed by the pre-Hispanic cultures of Mesoamerica. These pictorial documents are a cultural legacy, part of which dates from the $16^{th}$ century. The collection known as "Collection of Original Mexican Codices" is one of the most important codices collection around the world and it is under the custody of the National Library of Anthropology and History (BNAH, Biblioteca Nacional de Antropologia e Historia) in Mexico City. For preservation of the documents, the collection is kept under limited access and controlled illumination conditions, only tungsten lamps are allowed for illumination of codices and light intensity should no exceed 1000 Lux. In order to achieve accurate color reproduction of codices we have proposed to the BNAH a multispectral aproach. Our color reproduction method is based on the estimation of the spectral reflectance for every pixel in the image from a set of 16 bands multispectral images. Multispectral approach enables us to remove the original tungsten capture illumination and to carry out a color simulation under any arbitrary illumination, for instance CIE-D65, hence this approach enables us to reproduce the true colors of original codices. In this paper we present the results of several approaches for spectra estimation considering the illumination conditions established by the BNAH, and we show a color simulation of a codice replica under CIE-D65.

*Keywords:* Multispectral images; accurate color reproduction; spectral reflectance estimation; Mexican codices; ancient paintings preservation; simulation under daylight illumination.

Los códices mexicanos son un antiguo sistema de lectura y escritura desarrollado por las culturas pre-hispánicas de mesoamérica. Estos documentos pictóricos son un legado cultural, parte del cual data del siglo XVI. La colección conocida como "Colección de códices Mexicanos originales" es una de las más importantes colecciones alrededor del mundo y se encuentra bajo la custodia de la Biblioteca Nacional de Antropología e Historia (BNAH) en la Ciudad de México. Para la preservación de los documentos, la colección se encuentra bajo acceso limitado y las condiciones para su iluminación se mantienen controladas, únicamente se permiten lámparas de tungsteno para iluminación de los códices y la intensidad no debe exceder de 1000 luxes. Para llevar a cabo una reproducción exacta de los colores de los códices originales, hemos propuesto a la BNAH un enfoque multiespectral. Nuestro método para la reproducción del color esta basado en la estimación de la reflectancia espectral en cada uno de los píxeles en la imagen a partir de un conjunto de imágenes multiespectrales de 16 bandas. El enfoque multiespectral nos permite remover la iluminación original de tungsteno usado en la captura, y realizar una simulación de color bajo cualquier iluminación arbitraria, por ejemplo, CIE-D65, por lo tanto este enfoque nos permite reproducir los colores naturales (true colors) de los códices originales. En este artículo presentamos los resultados de diversas aproximaciones para la estimación del espectro bajo las condiciones de iluminación establecidas por la BNAH y mostramos la simulación de color de una replica de códice bajo CIE-D65.

*Descriptores:* Imágenes multiespectrales; reproducción exacta del color; estimación de la reflectancia espectral; códices mexicanos, preservación de pinturas antiguas; simulación bajo iluminación de luz de día.

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## 1. Introduction

There is an increasing number of applications where accurate color reproduction is becoming important and useful, for instance, in industry, electronic commerce, tele-medicine, digital cinema, digital archiving of fine art paintings, historical documents, and so on [1,2]. For this reason, there is a great interest from the color community in the development of both, international standards for the management and reproduction of color, as well as in the development of new technologies that will allow the common user to reproduce original colors with high accuracy on any personal computer connected to the world web.

Akasaka natural vision research center of TAO in Tokyo Japan is one of the research centers where these new technologies are being developed. The multispectral devices for image capture and display that have been developed in natural vision are designed to sense and reproduced information in the visible region with the main objective of reproducing colors as real and natural as original ones [3]. For instance, in nature, there are colors that present a high saturation level, and hence are said to be spectrally pure, it is not possible to capture these colors with their accurate color information by using conventional digital RGB cameras. On the other hand a set of multispectral images (usually more that the RGB bands) captured with the appropriate number of specially designed optical filters can be used for very accurate estimation of the spectral reflectance of the objects in an image. The accuracy in the estimation of the spectral reflectance is in proportion to the number of bands or multispectral channels. The experiments have shown that it is possible to achieve a good estimation by using the conventional RGB channels, but the accuracy greatly improves by increasing the number of bands in the set of multispectral images [4].

Accurate color reproduction of saturated colors on also specially designed, multi-primary displays (more than the conventional RGB primaries) can be achieved from the color information in a set of multispectral images . Natural vision has developed a sixteen band automatic multispectral camera for still images, a six band multispectral motion camera, and also six and four primary display systems for accurate color reproduction [4].

From the estimation of the spectral reflectance of the objects, the spectral distribution of the capture environment illumination and the color matching functions for the CIE standard observer, it is possible to compute the tristimulus values CIE_XYZ. The tristimulus values CIE_XYZ are independent from the image capture and display devices which have a limited color gamut. The more accurate the estimation of the spectral reflectance, the more accurate the estimation of the tristimulus values CIE_XYZ. If the color profile of the output device is known, such as a PC-monitor, images projector or printer, a transformation of the tristimulus values CIE_XYZ to the color space of that output device will produce a faithful color reproduction.

One of the advantages of multispectral images over the digital counts RGB is that working with spectral data, such as spectral reflectance, spectral distribution of illuminant and color-matching functions, it is possible to remove digitally the component of the capture environment illumination, for instance, the incandescent spectrum produced by tungsten lamps used for codices illumination. It also is possible to carry out a simulation, incorporating another light source different from the capture one, for instance CIE average daylight D-65. This digital image processing enables us to reproduce the true colors of the objects defined as the colors that are observed under a source light that radiates approximately the same quantity of energy in every wavelength [5].

One important advantage of multispectral images over photographic emulsions is the faithful color reproduction that is almost impossible to achieve from films since the development of emulsions requires chemical processes that are difficult to control. On the other hand, digital images do not suffer deterioration with the passage of time, which is the case of photographic emulsions that strongly deteriorate due to environmental factors.

For preservation of ancient objects and historical remains of many ancient world cultures, some museum collections are kept under limited access and restricted illumination conditions, even some of these collections can no longer be exhibited due to damage caused by handling and light exposure. The codices collection kept by the BNAH is under a preservation management plan. For scientific photography of this collection only tungsten lamps are allowed, and the maximum illumination intensity permitted should not exceed 1000 Lux. The multispectral image approach enables us to remove the original tungsten capture illumination and to carry out a color simulation under any arbitrary illumination, for instance CIE-D65. We present the results of several approaches for spectra estimation when capturing under the illumination conditions imposed by the BNAH, for this experiment we have used a codice replica. We also show a color simulation of the replica under CIE-D65 after removing the capture illumination spectrum of tungsten-halogen light produced by relatively new SOLUX lamps.

The advantages of multispectral images in accurate color reproduction, and the analysis of surface physical properties might support the efforts on preservation and restoration of fine paintings and historical documents. For instance, in preservation efforts, multispectral images can provide digital images with accurate reproduction of true colors for historical and ethnological studies, avoiding constant handling of the original ones. In restoration, from multispectral images it is possible to derive useful information about the optical properties of colors and surface, which can be used for recoloring the damaged sections of historical documents [6].

## 2. Spectral reflectance estimation

The output $v(x,y)_i$ from a multispectral camera with $m$ optical filters can be modeled in the pixel coordinates $(x,y)$ of the i-th image $(i = 1 \cdots m)$ as [7,8]:

$$v(x,y)_i = \int f_i(\lambda; x,y) E(\lambda;, x,y) r(\lambda; x,y) d\lambda + n_i(x,y), \tag{1}$$

where $f_i(\lambda; x,y)$ is the i-th spectral sensitivity of the multispectral camera in the coordinates $(x,y)$, $E(\lambda; x,y)$, and $r(\lambda; x,y)$ are the spectral power distribution of the capturing illumination and the spectral reflectance of the object, respectively, both in the location of the corresponding sampled point in the original image, and $n_i(x,y)$ is the noise in the pixel coordinates $(x,y)$ for the i-th image. For simplicity, we will assume uniform illumination field along with the whole image and also uniform spectral transmittances along with the surface of all optical filters, in such a way that:

$$E(\lambda) = E(\lambda; x,y) \quad , \tag{2}$$

and

$$f_i(\lambda) = f_i(\lambda; x,y), \tag{3}$$

The same applies for every pixel in the image and we will omit the $(x,y)$ pixel coordinates. The equation (1) becomes:

$$v_i = \int f_i(\lambda) E(\lambda) r(\lambda) d\lambda + n_i \tag{4}$$

In the discrete space, the equation (4) can be represented as:

$$v_i = \mathbf{s_i^T} \mathbf{r} + n_i, \tag{5}$$

where, $\mathbf{s_i^T}$ and $\mathbf{r}$ are vectors of $\ell$ spectral resolution elements usually along with the interval from $380nm$ to $780nm$, T is the transposition operator, $\mathbf{r}$ is the spectral reflectance, and $\mathbf{s_i^T}$ is expressed by:

$$\mathbf{s_i^T} = \mathbf{f_i^T} \mathrm{E}, \tag{6}$$

where, $\mathbf{f_i^T}$ is the transposed vector of the i-th spectral sensitivity of the multispectral camera, and E is a diagonal matrix where diagonal elements represent the spectral distribution of the capture illumination environment.

The output from the multispectral camera can be represented as:

$$\mathbf{v} = \mathrm{S}\mathbf{r} + \mathbf{n}, \tag{7}$$

where $\mathbf{v}$ is a vector composed of m digital counts, $\mathbf{s_i^T}$ is the i-th row of the matrix S and $\mathbf{n}$ is the noise vector. The generalized inverse estimate is given by[9,10]:

$$\hat{\mathbf{r}} = \mathrm{S}^{\mathbf{T}} \left(\mathrm{S}\mathrm{S}^{\mathbf{T}}\right)^{-1} \mathbf{v}, \tag{8}$$

where $\hat{\mathbf{r}}$ is the estimated spectral reflectance from the multispectral camera output $\mathbf{v}$. The generalized inverse estimate with a smoothing matrix M is expressed by the following linear inverse operation[9,10]:

$$\hat{\mathbf{r}} = \mathrm{M}^{-1}\mathrm{S}^{\mathrm{T}}(\mathrm{S}\mathrm{M}^{-1}\mathrm{S}^{\mathrm{T}} + \mathrm{N})^{-1}\mathbf{v}, \tag{9}$$

where N is the noise matrix.

The Wiener estimation method minimizes the error $\varepsilon$ between the original $\mathbf{r}$ and the estimated spectral reflectance $\hat{\mathbf{r}}$ [11]. The spectral reflectance in every pixel is estimated from a priori statistical information about the object by using the covariance matrix of a set of reflectance samples. If the covariance matrix and hence the a priori information about the spectral reflectance is well chosen, the error in the estimation of the spectral reflectance will be relatively small, and a poor election of the covariance matrix will produce a larger error in the estimation of the spectral reflectance. In the Wiener estimation method the estimated spectral reflectance is given for the expression[9,10]:

$$\hat{\mathbf{r}} = \mathrm{K_r}\mathrm{S}^{\mathrm{T}}(\mathrm{S}\mathrm{K_r}\mathrm{S}^{\mathrm{T}} + \mathrm{K_n})^{-1}\mathbf{v}, \tag{10}$$

where $\hat{\mathbf{r}}$ and $\mathbf{n}$ are assumed to be unknown random vectors with known covariance matrix $\mathrm{K_r}$ and $\mathrm{K_n}$ respectively. $\mathrm{K_r}$ can be modeled as a first order Markovian process with a covariance matrix given by[9]:

$$\mathrm{K_r} = \begin{pmatrix} 1 & \rho & \rho^2 & \cdots & \rho^{m-1} \\ \rho & 1 & \rho & \cdots & \rho^{m-2} \\ \rho^2 & \rho & 1 & \cdots & \rho^{m-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho^{m-1} & \rho^{m-2} & \rho^{m-3} & \cdots & 1 \end{pmatrix}, \tag{11}$$

where $0 \leq \rho \leq 1$.

## 3. Experiment

For this experiment, the replica of a codice was used, this replica was acquired at the BNAH's shopping store, and it is made from materials that are intended to simulate the amate paper that was used for the elaboration of some of the original codices. The replica was digitally captured by a sixteen bands multispectral camera that has an attached rotating wheel with the same number of narrow bands optical filters, the multispectral camera is shown in the Fig. 2, and the spectral sensitivities of the camera and narrow-band optical filters are shown in Fig. 2. The spatial resolution of the CCD image sensor is 2048x2048 pixels with 12 bits dynamic range.

In the capture process, the codice replica was illuminated by SOLUX 3700 tungsten lamps that increase the intensity of the short wavelengths in the visible region by means of a special optical coating. The SOLUX lamps that were used in this experiment have a correlationed color temperature of 3700 Kelvin degrees. These lamps were chosen because of the low emission in the ultraviolet region that is produced from tungsten filament lamps, and because of the improved emission on the short wavelengths of the spectrum. In Fig. 3

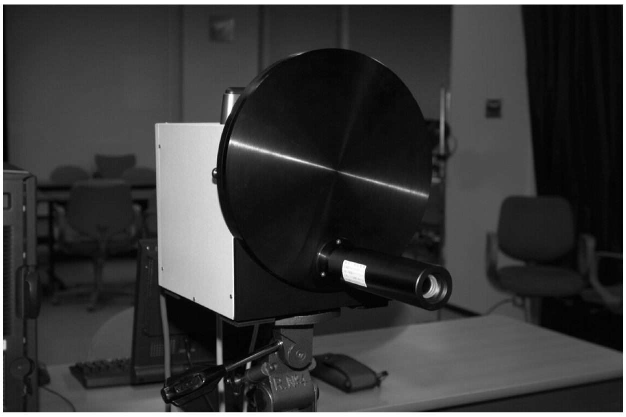

FIGURE 1. Sixteen bands multispectral camera developed in Natural Vision Research Center.

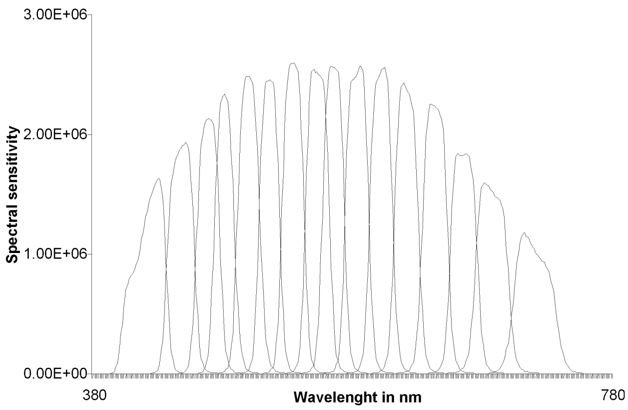


FIGURE 2. Spectral sensitivities of sixteen bands multispectral camera.

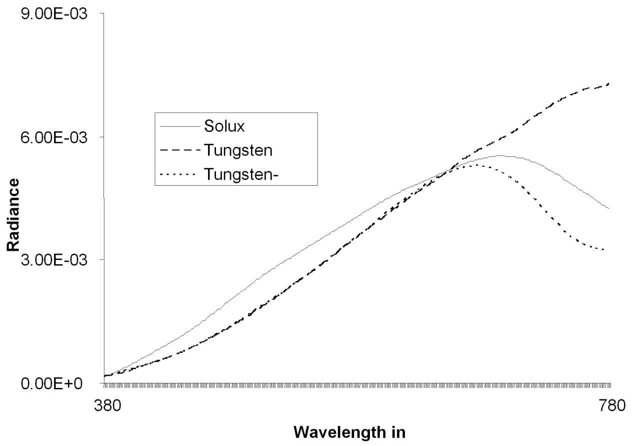


FIGURE 3. Spectral power distributions of SOLUX 3700, tungsten and tungsten-halogen lamps.

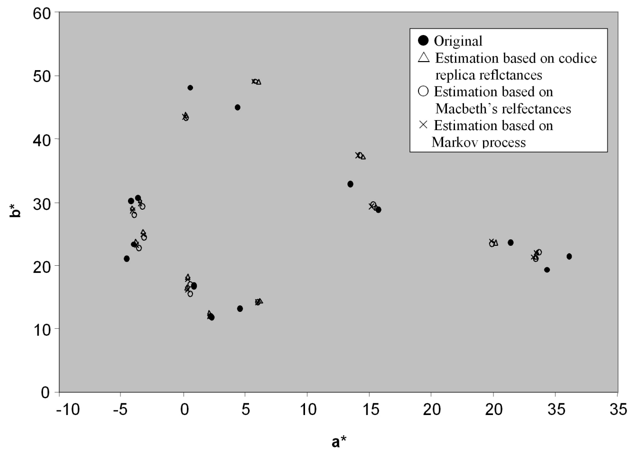


FIGURE 4. a*b* color coordinates of 14 sample points measured on the surface of the codice replica and the corresponding estimated a*b* color coordinates obtained fron each different approaches for spectra estimation.

are s rom the spectral reflectances of the Macbeth color test chart, which consist of 18 chromatic and 6 achromatic sample pads. In the third approach, we used a Markov process expressed by equation (11).

All spectral reflectance measurements were done by using Photoresearch PR-650 spectro-photometer that has a spectral resolution of 1 nm, and senses along with the interval from 380nm to 780nm. The spectral distribution of the capture illuminant was measured by means of a standard reflectance diffuser Photo research SRS-3. In order to satisfy the regulations of the BNAH for the preservation of the Mexican codices, we used an illumination level of about 900 Lux for multispectral digital capturing, 100 Lux less than the maximum allowed illumination for scientific photography of the codices collection.

## 4. Results

In Fig. 4 the a*b* color coordinates of 14 sample points are shown in the Cie-Lab color space. The 14 sample points were measured on the surface of the codice replica. In the figure are also shown the corresponding estimated a*b* color coordinates that were obtained from the three different approaches for spectra estimation used in this experiment.

In Table I we present the average, maximal and minimal color differences in $\Delta E_{a*b*}$ units that were obtained from each of the different approaches.

In Fig. 5 the image of the codice replica is showed under the capture illumination of the solux 3700 lamps that are based on tungsten filament, even so the radiance of solux lamps 3700 has been increased in the short wavelengths, it is still possible to appreciate the reddish appearance that is characteristic of the captured objects illuminated by tungsten-halogen lamps.

In Fig. 6 the simulation of the codice replica that was obtained from the Fig. 5 is showed by previously removing the spectral power distribution of the original capture illumination of solux 3700 lamps. The digital simulation was achieved by incorporating the spectral power distribution of average daylight D-65. Figure 6 exhibits the true color of the codice replica within the color reproduction error presented in Table I.

TABLE I. Average, maximal and minimal color differences in $\Delta E_{a*b*}$ units that were obtained from each of the different approaches used in this experiment.

| Spectra estimation approach | Average color difference | Maximal color difference | Minimal color difference |
|---|---|---|---|
| Estimation based on codice replica reflectances | 1.90239 | 4.24824 | 0.184755 |
| Estimation based on Macbeth's reflectances | 1.90712 | 4.65882 | 0.390613 |
| Estimation based on Markov process | 1.88555 | 4.92584 | 0.443758 |

## 5. Conclusion

The three different approaches for spectrum estimation practically produced the same color difference results. There is not visual color difference between each one of the three different approaches. As shown in Table I, the results achieved by each one of the approaches satisfy the established criterion of the just noticeable color difference corresponding to $2.5\Delta E_{a*b*}$ units. This experiment was carried out as part of a training for the real capture of original codices that will be performed by the Natural Vision Research Center in the security vault of the BNAH in Mexico City. The level of illumination used for this experiment was approximately 900 Lux, this means about 100 Lux less than the illumination

FIGURE 5. Image of codice replica under the capturing illumination of solux 3700 lamps.

FIGURE 6. Simulation of the codice replica under D-65 illumination.

level allowed by the BNAH for scientific photography of codices. Since we are using narrowband optical filters, the capture illumination spectrum, and the low intensity level used in this experiment seems to be affecting the spectra estimation mainly in the short wavelengths (blue region) where the noise becomes higher than in the middle and long wavelengths (green and red regions). In future work it will be intended to improve the spectra estimation in the short wavelengths of the visible region, while keeping almost the same intensity level of the capture illumination in order to avoid causing damage to the original codices. We are aimed to achieve satisfactory results on accurate color reproductions under these restricted digital capturing conditions.

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