High-Resolution Multi-Spectral Image Archives: A Hybrid Approach

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Abstract

We introduce an image capturing system that results in spectral image archives with sufficient spatial resolution and colorimetric accuracy for artwork imaging. In this system, a multi-band, low-spatial resolution multi-spectral image is combined with a high-spatial resolution lightness image (from either a monochrome digital or digitized photograph) to generate a high-spatial resolution spectral image. An alternative way to capture multi-spectral images by combining a trichromatic camera and absorption filters is also presented to overcome the technical problems inherent to the use of interference filters in this kind of imaging.

Introduction

The traditional techniques of image capture used to archive artwork in most of the museums of the world rely on conventional photographic processes. Photography has the advantages of high-resolution and optimal luminance (tone) reproduction and the disadvantage of poor color accuracy. The exception is the VASARI imaging system developed at the National Gallery, UK which employs a seven-channel multi-spectral 12 bit digital camera attached to a scanning device that traverses across the painting.[1] After appropriate signal and spatial processing, 20K × 20K 10-bit L*, 11-bit a* and b* encoded images result. The National Gallery has been very successful in developing colorimetric image archives and using them to provide the European community with accurate color reproductions in both soft-copy and hard-copy forms under a defined set of illuminating and viewing conditions (i.e., colorimetric color reproduction).

We have an interest in drawing upon the European experiences and making two enhancements. The first is alleviating the need to scan across the painting. This will greatly reduce the cost and complexity of the image acquisition system. The second is to define images spectrally and use the spectral information to provide printed color reproductions that are close spectral matches to the original objects producing high-quality color matching under different illuminations and observers. The advantages of spectral systems have been summarized by Berns[2] and Hardeberg et al.[3] Technical issues concerned with multi-spectral image acquisition have been exhaustively studied.[4–9] In particular, König and Praefcke[10] analyzed practical problems of designing and operating a multi-spectral scanner using a set of narrow-band interference filters and a monochrome CCD camera, the most common configuration for multi-spectral image capture. When using interference filters for image acquisition, a major problem is caused by the transmittance characteristic of the filters that depends on the angle of incidence. For example, in order to image a painting with horizontal dimensions of 1 meter with a distance of 2 meters between the painting and the filter, there is angle of incidence ~14° for points in the extremities. Simulations[10] have shown that this causes color differences of 2 ΔE^*_{ab} units in relation to the image obtained at 0° angle of incidence. Another problem is that the surfaces of the interference filters are not exactly coplanar resulting in spatial shift and distortion of the captured image. We also need to consider that there are inter-reflections caused by reflections between the spectral filters and the original image, and between the interference filters and the camera lens. These technical problems make it unrealistic and impractical for image acquisition using interference filters in museums without a considerable degree of expertise in multi-spectral imaging.

We believe that a conventional trichromatic digital camera combined with absorption filters can provide an alternative way to capture multi-spectral images. It makes the image acquisition easier and with relatively low cost since the performance-cost relation of commercial digital cameras has increased rapidly.

We have initiated research in multi-spectral image capture, spectral-based print modeling, and multi-ink printing algorithms. This article will focus on our enhancements of the European experience using trichromatic digital cameras to capture multi-spectral images.

Technical Approach

A possible solution to the desired enhancements mentioned above can be achieved by the fusion of a high-spatial resolution lightness image with a low-spatial resolution multi-spectral image. It is possible to interpolate each pixel of each multi-spectral image to high-spatial resolution while maintaining its color information and changing the original lightness for the lightness data of the corresponding high-spatial resolution image subpixels. This can be accomplished without noticing the expected decrease of tonal resolution in the hybrid image, because the modulation of the light in the eye becomes progressively smaller as the spatial frequency increases,[11] due to optical limitations and features of the retinal mosaic. As a consequence, the chromatic channels have much lower spatial resolution than the luminance channel. This visual feature of the human eye has been applied in broadcast television, and to devise very effective compression algorithms such as JPEG.[12] In fact, pyramidal data structures that exploit the eye's contrast sensitivity can be used for efficient data storage in the proposed system. Image fusion of a multi-spectral image with a high-resolution image has been intensively researched in the field of remote sensing.[13–15] The lightness and color information can be codified respectively as L* and a*, b* in order to allow the system to be easily optimized to have the least color difference in CIELAB ΔE^*_{ab} or ΔE^*_{94}. Therefore, it is important to assure that the high-spatial resolution image capture system produces very accurate L* and the multi-spectral image capturing system provides high-accurate chromatic information. Conventional photography followed by high-quality scanning results in very high spatial resolution, large dynamic range and low noise, and the photometric response of the film-scanning system can be easily determined using gray-scale targets alongside the imaged painting. A commercial digital camera with a set of filters can be used for the low-resolution chromatic data acquisition. This hybrid approach eliminates the need for scanning across artwork.

Hybrid Multi-Spectral Image Generation

We can divide the hybrid multi-spectral generation into four parts: image acquisition, spectral analysis, image fusion, and spectral reconstruction.

Image Acquisition

In the image acquisition system shown in Figure 1, the lightness information, *L**(x,y) is calculated for each (x,y) pixel of the high-resolution image from a scanned photograph after proper photometric and spatial calibration, where (x,y) denotes the coordinates of the high-resolution image pixels. After proper photometric and spatial calibration, the digital counts of the multi-spectral camera t_i, i = 1 to m, where m is the number of filters, are used to estimate the spectral reflectance, R(x',y',λ), and the colorimetric values of the image, L*a*b*(x',y'), where (x',y') denote the coordinates of the low-resolution image pixels.

One can model multi-spectral image acquisition using matrix-vector notation.[9] Expressing the sampled illumination spectral power distribution as

$$S = \begin{bmatrix} s_1 & & & 0 \\ & s_2 & & \\ & & \ddots & \\ 0 & & & s_n \end{bmatrix}, \qquad (1)$$

and the object spectral reflectance as $\mathbf{r}=[r_1, r_2, \ldots r_n]^T$, where the index indicates the set of n wavelengths over the visible range and T the transpose matrix, representing the transmittance characteristics of the m filters as columns of **F**

$$F = \begin{bmatrix} f_{1,1} & f_{1,2} & \cdots & f_{1,m} \\ \vdots & \vdots & \cdots & \vdots \\ f_{n,1} & f_{n,2} & \cdots & f_{n,m} \end{bmatrix} \qquad (2)$$

and the spectral sensitivity of the detector as

$$D = \begin{bmatrix} d_1 & & & 0 \\ & d_2 & & \\ & & \ddots & \\ 0 & & & d_n \end{bmatrix}, \qquad (3)$$

then the captured image is given by $\mathbf{t}=(\mathbf{DF})^T\mathbf{Sr}$ and the color vector can be represented as $\mathbf{c}=\mathbf{At}=(X, Y, Z)^T$ where *X, Y, Z* are the CIE tristimulus values. The CIELAB *L*, a*, b** are given by the non-linear transformation ξ, where ξ(*X, Y, Z*) = *L*, a*, b**.

Spectral Analysis

As shown in the figure 1, the spectral reflectance R(x',y') of the low-resolution image can be estimated using interpolation techniques such as cubic spline,[8] modified-discrete-sine-transformation (MDST),[7] or spectral reconstruction methods based on statistical analyses such as principal-component analysis (PCA).[16–18] The PCA method uses a set of *a priori* measured reflectance-based basis functions, E(λ,k), where k denotes the basis vector. Burns and Berns compared interpolation methods with PCA and found that PCA is more accurate than interpolation methods.[19] However, König and Praefcke[7] found that certain interpolation techniques such as the smooth inverse may produce acceptable results and should be considered. The accuracy of spectral reconstruction depends on the number of basis functions.[20] The number of basis functions necessary for accurate spectral reconstruction also depends on the database used for PCA. However, 5 to 8 basis vectors seem to be sufficient for an accurate spectral reconstruction of artwork. It is possible to optimize the filters[7] but it is not considered in this stage of the research. The L*a*b*(x',y') for the low-resolution image is calculated from the estimated spectral reflectance R(x',y') and the performance can be compared with direct linear transformation from the digital counts of the acquired multi-spectral image.[19]

Image Fusion

Figure 2 shows a flowchart of image fusion. Once the high-resolution L*(x,y) and the low-resolution L*a*b* (x',y') is obtained, the image fusion is performed. The initial step of this process is the geometric registration of the image (rotation, scaling, and translation, for example) that can be performed by a variety of commercial software such as ENVI. Among the fusion methods developed in the field of remote sensing, we decided to combine high-resolution lightness images with low-resolution colorimetric images in analogy to algorithms that use the hue, intensity and saturation (HIS) color space in remote sensing. We consider CIELAB as a reasonable first-order approximation to a vision model.

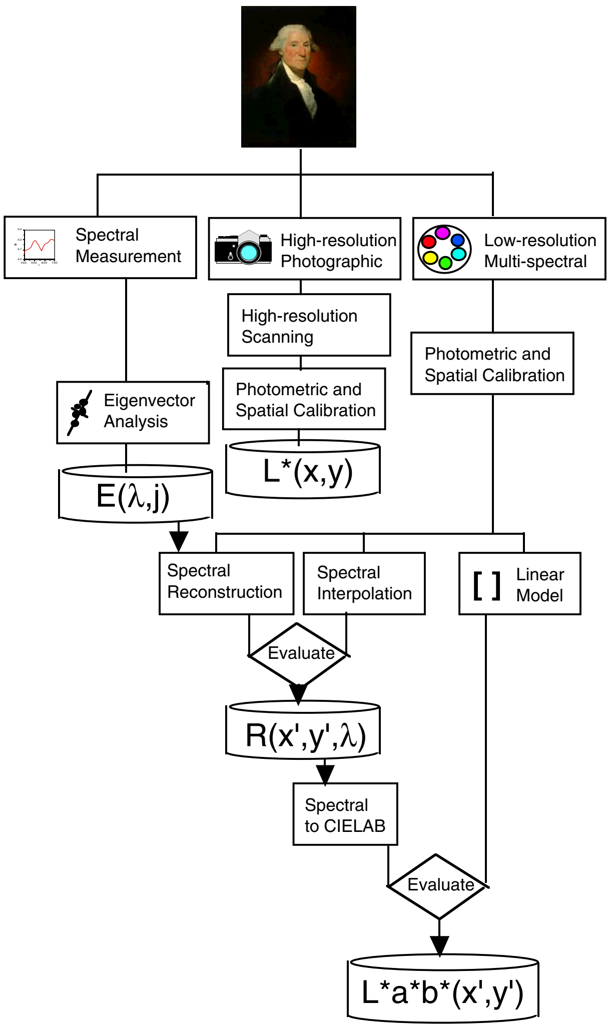

Figure 1. Image acquisition and spectral analysis flowchart

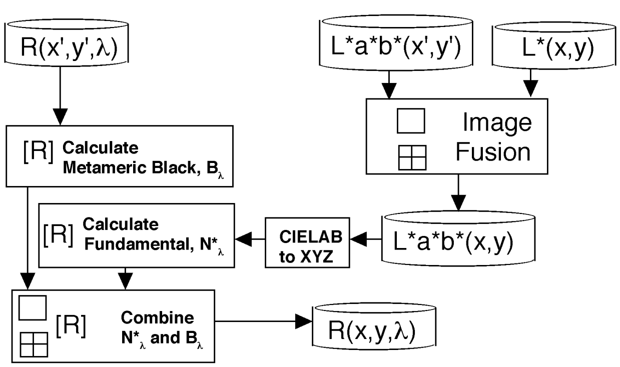

Figure 2. Image fusion and spectral reconstruction flowchart

Spectral Reconstruction of Hybrid Image

The estimation of high-resolution spectral reflectance R(x,y,λ) from low-resolution reflectance R(x',y',λ) is based on the Wyszecki hypothesis that any stimulus can be decomposed into a fundamental stimulus (with tristimulus values equal to the stimulus) and a metameric black (with tristimulus values equal to zero) whose mathematical technique, known as Matrix R, was developed by Cohen.[21] The metameric black from R(x',y') will be fused with the fundamental stimulus from L*a*b*(x,y,λ) resulting in a high-resolution spectral image R(x,y,λ), and the same techniques used to combine CIELAB images will be used to merge spectral information.

Preliminary Experiments

In this stage of the research we have sought to verify the feasibility of using a trichromatic digital camera with a set of absorption filters to capture multi-spectral images. An IBM PRO/3000 trichromatic digital camera system that provides 3,072 by 4,920 pixels image and a set of Kodak Wratten gelatin filters number 38 (Light blue) and number 44 (Light green-blue) were used to capture two trichromatic images that combined with the three channels without filters yielded nine channels. The spectral reflectance factors of the Macbeth color checker was measured and principal component analysis were performed to calculate the first nine eigenvectors. The chart was imaged in 12 bits and the resulting digital counts were used to estimate a linear transformation matrix from digital counts to the eigenvalues corresponding to the eigenvectors of the sampled spectral reflectances. The resulting matrix was used to predict the spectral reflectance for the chart and the spectral and colorimetric accuracy was calculated for illuminant D50 and CIE 10 degree standard observer. Figure 3 shows the comparison between measured and estimated spectral reflectance of the Cyan patch of the Macbeth Color Checker.

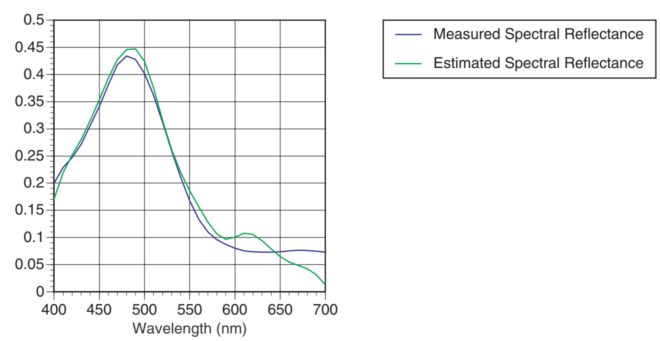

Figure 3. The spectral reconstruction from camera signal values for the Cyan sample of Color Checker.

The average spectral mean error was 0.029 and the average RMS error was 0.049. The mean ΔE^*_{ab} was 2.2. As a comparison, Burns and Berns[19] performed spectral reconstruction by PCA from camera signals using seven interference filters and a monochrome camera. Their mean ΔE^*_{ab} was 2.2 for the Color Checker presenting similar performance to the proposed scheme that combines a trichromatic digital camera with Wratten filters.

At the present stage interactive and non-linear methods to reduce the number of channels is in progress and it will be applied for paint patches, too. As a pilot experiment to test image fusion, instead of using scanned photography, the original image will be blurred to produce a lower spatial resolution image and the estimated colorimetric values and spectral reflectance will be fused with the lightness information of the original image.

Conclusions

A hybrid image capture system has been proposed. It consists of a high-resolution conventional photographic and digital scanning system and a low-resolution trichromatic digital camera system. Using a priori spectral analyses, linear modeling techniques, and exploiting the human visual system's spatial properties, high-resolution spectral and colorimetric images can be generated. Preliminary experiments are promising and suggest that a practical solution to multi-spectral image capture has been identified. These techniques should be able to be used in many of the photographic departments of typical museums. Future research is aimed at further experimental optimization, verification, and testing within a museum context.

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