The Simultaneous Capture of Spectral and Textural Information

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Abstract

Digital archiving of cultural heritage has heretofore focused on capturing accurate color information via spectral imaging. We review a means of capturing topographical information entitled reflection transformation imaging. This paper discusses an experiment that attempts to merge these two techniques. Several paintings were imaged and color accurate, interactive texture maps were generated. Experimental deficiencies are identified and suggestions are made for remediation. A new dual-imaging technique with improved capability is discussed. Our conclusion is that the simultaneous capture of high-accuracy spectral and textural information is entirely feasible.

1. Introduction

Conservators and archivists have two conflicting responsibilities. The first is to conserve cultural heritage objects for future generations. The second is to make those same objects available to the public and scholars for appreciation and study. Physical access to objects unmistakably complicates the conservation process. Highly accurate, robust digital archiving methods promise the mutually beneficial advantages of reducing the need for physical access while offering an unprecedented level of accessibility to the public, students and scholars. These methods are becoming increasingly available with the advent of evermore capable digital cameras. [1,2,3] Heretofore, the emphasis has been on capturing highly-accurate color information via spectral imaging (SI). However, color accounts for a small fraction of the pertinent information associated with a particular work of art. Topographical information is also a key element worth capturing.

Hewlett-Packard (HP) Laboratories developed a method for capturing textural information by Reflection Transform Imaging (RTI). [4,5] Early uses of the technique, known as Polynomial Texture Mapping (PTM), with paintings took place at the National Gallery and the Tate Collection in London. [6,7] A new technique for acquiring PTMs of paintings, discussed in section 6, has been used by Cultural Heritage Imaging (CHI) and the conservators at the Worchester Art Museum (WAM) in Massachusetts. [8,9]. Both CHI and the Rochester Institute of Technology (RIT) have recently received grants to develop topographic imaging techniques. [10,11]

In this paper, we report on an experiment conducted by HP and CHI to simultaneously capture both spectral and textural information of oil paintings. We first review the principles of spectral and textural imaging, discuss the actual experiment, our results and required improvements. This will be followed by discussions of recent improvements in RTI, additional research opportunities and implications for conservators and museums.

2. Principles of Spectral Imaging (SI)

Reflective color measurement involves illuminating an object with a known illuminant at a specified angle of incidence (usually 45°) and measuring the reflection at a sequence of wavelengths with a light sensor located at a specified viewing angle (usually 0° or directly overhead). Color measuring equipment will sample the reflected light spectra in 3 to 100 channels, or wavelength increments. In general, more color channels results in higher color accuracy. Most commercial digital single-lens reflex (dSLR) cameras only have three channels. One way to increase the effective number of channels in a dSLR is to use two, well-chosen external filters, one at a time, while taking two images of the object. The external filters change the response of the internal on-chip filters. Hence, the dSLR now functions as a 6-channel device. Six channels of color information enable the mathematical estimation of the original spectra. Reconstructed spectra enable advanced color calculations such as converting from a daylight viewing illuminant to incandescent.

The digital output (D) of the camera is a function of several inputs, each of which is a function of wavelength (λ). Equation 1 shows that the camera integrates light energy which falls on the sensor. The impinging light energy is a product of the illuminant (I), the filters (F), the reflectance of the object (R), and the opto-electronic conversion function of the camera (OECF, or C).

$$\int I(\lambda) * F(\lambda) * R(\lambda) * C(\lambda)\, d\lambda = D \qquad (1)$$

The OECF accounts for the optics, the on-chip color filter array, the sensor responsivity and all electronic processing. When the wavelength range is uniformly sampled, the integral can be replaced by a summation. Consequently, Equation 1 can be rewritten in matrix form. The matrix, $\mathbf{\Omega}$, depicted in Equation 2, represents the integrated product of the illuminant, filters and OECF. The matrix, $\mathbf{\Omega}^T$, represents the transpose of $\mathbf{\Omega}$.

$$\mathbf{D} = \mathbf{\Omega}^T * \mathbf{R} \qquad (2)$$

The spectral reflectance to digital output transform matrix, $\mathbf{\Omega}$, can be found using a training target(s) in which the spectra have been measured It is important that the training target contains colorants as close as possible to those that are intended to be measured with the camera system. A more accurate method of finding the OETF is to use a monochromator to generate a sequence of known colors which are captured by the camera.

Once $\mathbf{\Omega}$ has been found, then Equation 2 can be rewritten to estimate unknown reflectance spectra given the camera's digital outputs.

$$\check{\mathbf{R}} = \mathbf{\Omega}^{T-} * \mathbf{D} \qquad (3)$$

$\check{\mathbf{R}}$ represents the estimated spectra while $\mathbf{\Omega}^{T-}$ represents the pseudo-inverse of $\mathbf{\Omega}^T$. In practice, there are more accurate mathematical techniques than computing the pseudo-inverse, notably, principle component analysis (PCA) and independent component analysis (ICA).

3. Principles of Reflection Transform Imaging (RTI) and Polynomial Texture Mapping (PTM)

RTI is an imaging method that utilizes reflective light energy to create transform information about some characteristic of an object. HP Labs invented polynomial texture mapping (PTM) which transforms reflective information into surface normals which are mathematically encoded as polynomials. [4,5]

The basic idea behind PTM imaging is the capture of successive images, each successive image being illuminated from a different direction. The illuminants are placed inside a hemispherical dome in rings located at various elevation angles. The camera is fixed at the zenith. This arrangement results in a set of N images illuminated from N known directions and distances. Typically, lower illumination angles generate more shadows in the images as a result of object texture.

The surface luminance information from the N images is processed for all pixel locations to generate normal vectors for each pixel, now referred to as a textel. The number of illuminators, N, can vary upwards from a minimum of about 12-16. Equation 4 shows the textel components.

$$L(u, v; l_u, l_v) = a_0 l_u^2 + a_1 l_v^2 + a_2 l_u l_v + a_3 l_u + a_4 l_v + a_5 \quad (4)$$

L is the surface luminance; u, v are the textel coordinates; a_0-a_5 are fitted coefficients; and I_u, I_v are the projections of the light direction onto the u-v plane. There is an L associated with each of the N light sources. Let $L_i = [L_0, L_1, \ldots, L_{N-1}]$, $I_i = [I_{ui}^2, I_{vi}^2, I_{ui}I_{vi}, I_{ui}, I_{vi}, 1]$, and $a^T = [a_0, a_1, a_2, a_3, a_4, a_5]$. Equation 4 can be rewritten in matrix form.

$$\mathbf{L} = \mathbf{I} * \mathbf{a}^T \quad (5)$$

Once $\mathbf{a}^T$ has been derived, the surface luminance, L_i, can be derived for any illuminator, I_i. Freely available viewers have been created which reconstruct the image for any desired illuminance direction.

Image and textel data are generated and stored in either of two formats, LRGB or RGB. The LRGB format stores a single textel channel and the usual three color channels. The RGB format combines three textel channel data along with their respective color channels. The LRGB format assumes that L is not a function of the pixel color while the RGB format assumes that it is. The latter situation is certainly the case for highly reflective objects such as gold coins.

4. Merging PTM and SI (PTM+SI)

SI techniques were developed without any intent to capture textural information. The PTM technique was not intended to capture more than three channels of color information. Our experiment consisted of modifying the PTM imaging apparatus and procedures to enable simultaneous spectral imaging.

4.1. CHI's System Description and Modification

CHI worked with HP Labs to create their own PTM imaging apparatus based on a fiber optical illumination system. This system used a tungsten-halogen lamp to illuminate 32 optical fibers. The fibers were directed to 32 locations within a metal framework. See Figure 1. The apparatus was designed to image objects smaller than 5" in diameter though it can be extended up to about a 12" object diameter. The sole hardware modification to the apparatus was the introduction of either of two filters into the illumination system to generate 6 channels of color data. Filtering the illuminant versus the camera lens has several advantages, principle of which is the ability to control the wavelengths that strike the object under study. This is clearly desirable in an archival and conservation setting. The selected filters were those used in an RIT study, Schott BG39 and GG475 combined with a Unaxis Balzaars Calflex-X visible bandpass interference-based filter. [2,11]

***Figure 1**. Reflection Transformation Imaging apparatus modified for spectral imaging*

4.2. Camera Modification

The Canon EOS d60 dSLR had an internal BG39-like color and anti-aliasing filter. The use of external filters necessitated that this filter had to be removed. It was replaced with a Schott N-WG295, long-pass, non-colored filter to preserve the optical path length to the camera's sensor. The camera modification was carried out by David Burren.

4.3. Oil Paintings

Several oil paintings were required which did not require special handling. Michele Stapley graciously supplied several paintings created during a portraiture class. [12] One painting was on board (Masonite) while the other was on canvas. The former support tends to magnify impasto while the latter tends to smooth brushstroke and paint thickness variations.

4.4. Targets

Targets were required for training, verification and flat-fielding. The training targets used to generate Ω in Equation 2 consisted of a Macbeth CCDC target and half of a hand-painted acrylic paint target. Michele graciously consented to paint a target with 30 squares, each square painted with her favorite paints. Color accuracy verification used a Macbeth CC (Color Checker) target and the other half of the painted target. A conventional 10"x8" photographic gray card was used as a flat-fielding target.

4.5. Procedural Modification

The normal workflow for utilizing the CHI apparatus is discussed below. An object is placed inside the hemispherical array of lights. Exposure and depth-of-field are calculated by sampling the highest and lowest illumination inclinations. Aperture and shutter speed parameters are selected that provide sharp focus and avoid clipping of highlight values and excessive noise in the shadows. Once the values are passed to the control software, image capture occurs automatically. Using conservator- friendly low-light intensities, thirty-plus images can be captured in less than fifteen minutes. Camera outputs were set to 12-bit RAW. RAW output prevents the camera from performing any color processing on the raw pixel data. Batch processing of the images was done in Adobe Photoshop. HP Labs' Fitter software requires two inputs: a file that specifies the physical locations of the light emitting fiber fixtures and a folder that contains the images themselves. Tests by CHI's Marlin Lum showed that the time required for the entire imaging process was between one and two hours.

PTM+SI generation requires several critical additions to the above procedure: (1) instead of one set of images, two sets of object images must be generated, one for each filter, each with its own exposure; (2) two sets of gray card images must be generated, one for each filter, with the same exposure as step one; and (3) the training and verification targets must be imaged with all the fibers turned On, one image for each filter.

4.6. Post-Processing

Post-processing of the images was required to de-mosaic the images and to compensate for the non-uniformity of the illumination. De-mosaicing was accomplished using Adobe's Camera Raw Photoshop plug-in. Flat-fielding was conducted as follows: Flat-field = (Image – Ambient)/(Gray – Ambient). An ambient image is subtracted from the object and gray card images instead of the usual dark-field image. This is because CHI's illumination system uses a set of solenoid-activated, mechanical valves to turn the individual fibers On or Off. There is some light leakage even when all of the valves are presumably Off. The magnitudes of the dark-field image and the ambient images were 2-3% and 4-7% of the maximum digital count, respectively.

5. Results of the PTM+SI Merger Experiment and Future Improvements

The results of the PTM+SI experiment were highly encouraging. We conclude that the simultaneous capture of both spectral and textural information is unquestionably feasible. The ability to interactively view full-size and close-up images with accurate texture and color reproduction has enormous appeal. Figure 2 is a sample image obtained from the PTM viewer with high-angle illumination.

In the future, PTM equipment and procedures need to be modified to facilitate SI. The most obvious needs are to physically accommodate larger objects and to incorporate more uniform lighting. The current PTM file formats can only accommodate 3 color channels of data, The PTM Fitting code and file formats must be modified to accommodate 6 channels of color data.

The hand-painted target proved problematic because of thickness variations and impasto. In the future, targets should be made as uniformly thick as possible with a smooth, flat surface,

With these improvements, the simultaneous capture of images suitable for both PTM and SI will become more efficient. The resulting PTM+SI archives should provide museum quality information that can be used for a variety of purposes.

***Figure 2**. PTM image captured with raking angle illumination*

6. Recent Improvements in RTI

In 2006, CHI and HP Labs collaborated to develop a complimentary extension of the existing, fixed-light RTI technique. [9] Highlight RTI (HRTI) has many advantages including low-cost ease-of-use, and subject size and context flexibility.

HRTI is remarkably simple and amazingly effective. It relies on the user to position a handheld light source. The lighting direction from each image is recovered after the imaging session. It is calculated from the specular highlights produced by the user positioned light on a shiny black sphere included in the camera's field-of-view. Light intensity is controlled by keeping a constant radius between the light source and the center of the subject. The radius is controlled by tying a string to the light and holding the other end of the string next to the center of the subject. Once the proper distance is established, the string is removed from the field-of-view. The ball-and-string, or Egyptian, method permits RTI acquisition with the photographic equipment contained in a basic wedding photographer's kit.

HRTI is able to capture a large size range of objects. Mellon Foundation funded research conducted by the conservation department of the WAM in collaboration with CHI has demonstrated the ability of HRTI to effectively capture the 3D characteristics of very large (over 2 meters) and very small (less than 3 cm) cultural heritage objects. See Figure 3.

All HRTI image metadata carries 'empirical provenance' (EP) information which documents the entire digital image generation history. Beginning with the raw empirical data captured by the photographic sensor, every operation until the completion of the digital representation is documented. This EP data is structured to comply with ISO 21127 cultural heritage documentation standard [13]. ISO 21127 describes the Conceptual Reference Model (CRM) ontology developed by the Committee On Documentation (CIDOC) of the International Council of Museums (ICOM). [14] When linked to the archived raw empirical data, EP documentation permits independent confirmation of the trustworthiness and quality of digital representations through process transparency and possible replication which meets the requirements of the 2006 London Charter. [15]

***Figure 3**. PTM image (1" x 0.5") captured using the Highlight RTI technique*

7. Future RTI+SI Research Opportunities

CHI and the University of Southern California are conducting IMLS-funded research to generate more robust 3D digital representations from multiple RTI and HRTI views of a subject, to automate the image and EP documentation process, and to capture spectrally accurate color information. [10]

The color accuracy of this paper's PTM+SI experiment suffered from non-optimized filters, extensive flat-fielding, and a difference in the reference spectra and average PTM illumination angles These issues will be resolved by: (1) selecting optimized filters; (2) providing more uniform illumination which is already the case with HRTI; and (3) collecting color data from illuminators located at 45° to match reference spectra conditions.

HRTI is being enhanced through the use of two specular balls and two cameras. Two light-locating balls provide better illumination angle and surface normal accuracy. Two cameras are being explored to generate stereo 3D object information. The intent is to generate an authentic and informationally rich 3D representation of an object in addition to its surface texture. A color reference target will be incorporated in every image in which accurate color data is desired. The addition of two filters, either on the illuminant or on the camera(s), will enable HRTI+SI.

Our aspiration is that RTI+SI and HRTI+SI techniques will be widely adopted by cultural heritage professionals.

8. Implications of RTI+SI

The existence of highly accurate 3D structure, surface texture, and spectral color information of cultural heritage objects accompanied by detailed, standards-based, empirical provenance documentation has tremendous implications for the public, students, and scholars. In the near future, a high school student in Idaho could have greater access to more detailed information about Munch's 'The Scream' than today's doctoral student residing in Norway and studying at the National Gallery in Oslo.

There could be additional opportunities for fund raising to support cultural heritage activities. For example, a customer could log onto the internet and view a color and texture accurate image of a painting they want to own. The customer could select the direction of the light source which produces the level of texture appearance they like, specify the type of lighting that the image will be viewed under, and select the supporting medium. The object d'art can then be printed on canvas, for example, which will have the appearance of the original texture and which will be color accurate when displayed in their home.

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Mark Mudge received his BA is Philosophy from New College of Florida (1979) He has worked as a professional sculptor and has been involved in photography and 3D imaging for over 20 years. He has published 10 articles related to cultural heritage imaging and serves on several international committees. In 2002, Mark founded Cultural Heritage Imaging, a non-profit corporation, in which he serves as President. He is a co-inventor of Highlight RTI.