Advances in Digital Imaging for Fine Art and Cultural Heritage

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Abstract

Digital imaging techniques have been applied to fine art and cultural heritage for decades. Due to continuing advances in technology and increases in funding, the application of digital imaging and digital reproduction to fine art and cultural heritage has recently exploded. To simplify the discussion of digital fine art, this paper will sub-divide digital imaging into five segments: digital image capture; archiving; conservation; restoration; and reproduction. The Hewlett-Packard Company, Cultural Heritage Imaging and the Rochester Institute of Technology have each been major participants in this digital imaging explosion. The author is familiar with many of the activities of these three institutions. Taken together, their activities form a storyboard of where digital fine art maybe headed. By way of example, the results of specific projects will be discussed. Advances in digital image capture include hyperspectral imaging and reflection transformation imaging and their use at the Worcester Art Museum. A striking innovation in archiving and conservation is demonstrated by the Kyoto International Culture Foundation shrine art conservation project. The rejuvenation simulation of a Seurat painting and the physical restoration of the vault at the Santos Juanes Church demonstrate amazing progress in the field of digital restoration. Finally, the Grand Tour in London is a great illustration of how digital fine art reproduction can involve the public in their cultural heritage. A widespread bibliography is provided.

1. Introduction

Vincent van Gogh's painting of *The Church in Auvers*, oil on canvas, can be seen in the Musée D'Orsay in Paris, France. If one is unable to travel to Paris, one can view a reproduction of the painting in the museum's published catalog [1] or in any number of art books, for example, Walther's Vincent Van Gogh: Vision and Reality [2]. The observer's experiences arising from the three observations are vastly different. The printed images of the painting were originally captured by a museum photographer. Firstly, the sizes vary dramatically. The original is 94cm X 74cm (37" X 29"), the catalog print is approximately 10cm X 7cm (4" X 3") – not much bigger than a thumbnail image, while the print in the book is 23cm X 18cm (9" X 7"). Secondly, the colors are dramatically different. Thirdly, and even more striking than the previous two differences, is that the prints are completely devoid of any appearance of texture. The catalog also depicts a 30cm X 23cm close-up of a segment of the painting at about a 5X magnification. It, too, has no appearance of texture whatsoever. The author had seen reproductions of van Gogh's paintings all his life. The compositions and color schemes were novel and interesting, but caused no exceptional interest. Later, after having observed numerous van Gogh paintings in person, the author was stunned by the interaction of the bold colors, the extreme impasto, and the museum lighting. Since then, van Gogh has been one of the author's favorite painters.

The discussion above points out several issues associated with the digital imaging. Digital imaging is defined here as the digital capture, archiving, conservation, restoration and reproduction of fine art and other cultural heritage objects. This paper will not address digital production of art. Digital capture involves converting an object into a digital format, whether two or three-dimensional (2D or 3D), that can be electronically processed. Since all of the other aspects of digital imaging ultimately depend on digital capture, this aspect of digital imaging will receive amplified attention. Archiving involves the efficient, reliable storage of the digital information along with a record of all processing procedures. Digital conservation encompasses the use of digital techniques to preserve existing information. Digital restoration attempts to restore lost information through materials analysis, color science, image processing, and so forth. For our present purposes, digital reproduction involves the 2D reconstruction of an image in either soft-copy form intended for viewing on video display devices or in hard-copy form intended for physical viewing of printed colorants on various media.

This paper will discuss (i) digital capture, (ii) archiving, (iii) conservation, (iv) restoration and (v) reproduction using contributions from Hewlett-Packard Company (HP), Cultural Heritage Imaging (CHI, pronounced 'chee') and the Rochester Institute of Technology (RIT). HP has historically had an interest in fine art reproduction and, in recent years, has taken in interest in fine art capture. CHI is a non-profit corporation based in San Francisco which is on the cutting edge of advanced cultural heritage imaging (www.c-h-i.org). RIT has been intimately involved in fine art imaging and reproduction for many years (www.art-si.org). This paper will elucidate some of the most important principles of digital imaging through the presentation of examples of work done by the aforementioned institutions.

Two primary goals of digital fine art should be to: (1), replicate and (2) enhance the interaction that an observer might have with the original object d'art in its displayed setting. A report on American museum imaging practices by the Rochester Institute of Technology makes the following recommendation regarding future imaging practices, "… the digital image should be a true surrogate for the object. We should be able to view it from different angles, to see it's surface properties, to look at it in magnified form, to see it rendered for different lighting, etc. (emphasis added)." [3] These recommendations are both laudable and daunting. Clearly, new imaging and reproduction techniques will be required to create "true surrogates" of cultural heritage objects.

2. Digital Image Capture

One of the prime objectives of digital image capture is to accurately capture the colors of a cultural heritage object. This is easier said than done. The previously mentioned RIT report benchmarked the ability of major museums to accurately capture color. A MacBeth Color Checker chart with 24 carefully selected color patches was sent to multiple institutions. Each museum digitally captured the target and sent their results back to RIT.

Figure 1 vividly shows some of the results. Each of the 24 color patches have 4 background squares and one centered, foreground square. The 4 outer squares depict the colors as captured by 4 different museums. The center square depicts the original target color. In the vast majority of cases, the colors captured by any one of the 4 museums neither matched the other 3 museums nor did they match the target color! This image dramatically demonstrates that capturing accurate color is not a simple matter.

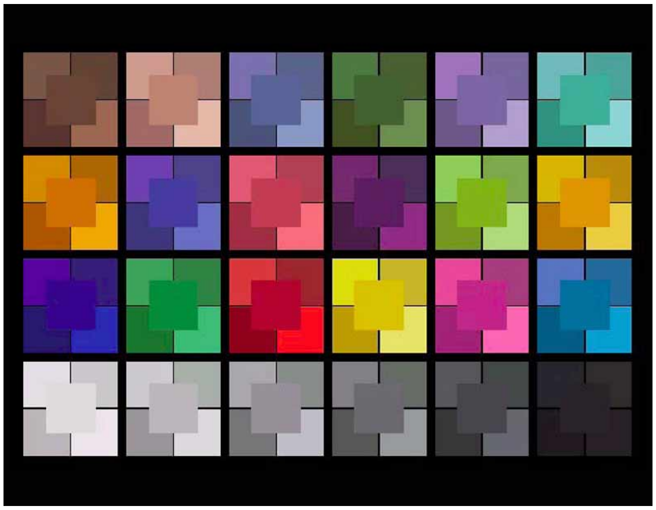

Figure 1. The MacBeth ColorChecker Chart with 24 color patches. Each patch has 4 background segments which represent the colors captured by 4 major museums. The center segment is the original patch color. [3]

2.1. Accurate Color Capture

All color imaging systems require a digital sensor of some type, usually a silicon-based sensor. These systems also require filters which transmit or reflect restricted regions of the visible spectrum. Some of the most important system design issues include the following: (1) will the system use a linear or an area sensor; (2) will the system use external filters or internal filters; and (3) how many filters will be used? With linear sensors, the object must be scanned in a line-by-line manner. With external filters, each filter must be positioned in front of the camera's lens and a separate image captured. Single image capture times can require tens of minutes for imaging systems with linear sensors and external filters. For area sensors with on-chip color filter arrays (CFA), single image exposure times can be less than a tenth of a second.

Most CFA area sensors have alternating filters on adjacent sensor elements, such as a RGRGRG pattern on one row and a GBGBGB pattern on the adjacent rows. This pattern is the ubiquitous Bayer filter pattern. A single image, therefore, has 50% green pixels, 25% red pixels and 25% blue. Consequently, the image associated with each filter type must be interpolated or demosaiced. If demosaicing is undesirable, there are camera systems in which the CFA sensor has a different filter pattern, such as RGBG and GRGB on adjacent rows. The camera's backplane has a micro-positioner which can move the sensor horizontally one pixel at a time. After 3 movements and 4 exposures, one has full R and B images with two G images. The following discussion will concentrate on standard RGB cameras with simple modifications.

Unfortunately, three color sensors are generally not adequate for high accuracy color capture. The literature cites the required number of color channels to be between 3 and 18, with most suggesting 5-8 channels. [4,5] Recent work at RIT suggests that with proper system design, a 6-channel camera can perform as well as a 31-channel camera. [6,7,8,9] The result is a highly accurate 6-channel color imaging system with colorimetric accuracy of ~ 1 ΔE_{00} and spectral accuracy of ~ 1.5% RMS. The comparable accuracy is accomplished through non-linear signal processing for the 6-channel system which is not practical with a 31-channel system. The ability of a 6-channel color system to rival a 31-channel system is also due to the fact that natural colorants, including inks, dyes and pigments tend to be well-behaved spectrally. That is, natural objects have reflectance spectra that are smooth, change gradually and do not have spikes or discontinuities.

The most-accessible, least-expensive and easiest-to-use 6-channel camera consists of a slightly modified digital SLR RGB camera. Digital cameras use silicon-based sensors which are more sensitive to long wavelengths than to short wavelengths. Therefore, dSLR's incorporate internal IR-cut filters which reduce the signal in the red regions of the spectrum. This internal filter must be removed and replaced with a visible bandpass filter to preserve the optical path length. Subsequently, two different filters are placed in front of the camera lens or the illuminant, one-at-a-time, and two images are captured. These filters must be optimized for each individual camera's CFA and associated electronics. For RIT's camera, one filter consisted of a BG-39 and IR/UV cut filter combination while the other filter consisted of a GG-475 and IR/UV cut filter combination. The filter sets shift the peak transmittance wavelengths and change the area-under-the curve for each of the RGB filters effectively creating two sets of filters.

2.2. Spectral Estimation

With 6-channels of color information, it is mathematically possible to estimate or reconstruct the original spectra of the object. The existence of a reconstructed spectra enables advanced color calculations, such as converting from one viewing illuminant into another, e.g., daylight 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 demonstrates that the camera integrates the 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 transfer function of the camera (OETF).

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

If the spectra are uniformly sampled, the integral can be replaced by a summation and Equation 1 can be rewritten in matrix form. The matrix, **Ω,** depicted in equation 2, represents the integrated product of the illuminant, filters and OETF. The matrix, $\mathbf{\Omega^T}$, represents the transpose of **Ω**.

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

The spectral reflectance to digital output transform matrix, Ω, can be found using a training target(s) in which the spectra of the patches have been spectrally measured. It is important that the training target contain colorants as close as possible to those that are intended to be measured after characterization. [4,10,11,12] A more accurate but more complicated and expensive method of finding the OETF is to use a monochromator to generate a sequence of wavelengths which are measured by a spectroradiometer and captured by the camera.

Once Ω has been found, then equation 2 can be rewritten to estimate unknown reflectance spectra given the camera's digital outputs.

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

$\check{\mathbf{R}}$ represents the estimated spectra while $\Omega^{\mathbf{T-}}$ represents the pseudo-inverse of $\Omega^{\mathbf{T}}$. In practice, other mathematical techniques such as principal component analysis (PCA) [13,14,15], independent component analysis (ICA) [15,16,17], matrix R processing [18] and data preprocessing [19] may prove more accurate than using the pseudo-inverse.

Rather than using reconstructed spectra, multiple transformation matrices can be used to convert between illuminants. It should be noted that optimizing colorimetric accuracy (ΔE) does NOT optimize spectral accuracy (RMS), and vice versa. Consequently, one must decide which color metric one wants to optimize for. [20] Alternately, one could create multiple transformation matrices based upon multiple optimizations. [9,20]

2.3. Accurate Surface Texture Capture

Capturing accurate surface texture is a much more difficult undertaking than capturing accurate color. Historically, the most common technique is to measure Bidirectional Reflectance Distribution Functions (BRDF). The BRDF, ρ, represents the interaction between two hemispheres, the incident light hemisphere and the reflected light hemisphere. Basically, it is a measure of the amount of light reflected into each outgoing angle for a given incoming light angle. [21]

$$\rho\ (\theta_i, \varphi_i, \theta_r, \varphi_r) = dL_r\ (\theta_r, \varphi_r) / dE_i\ (\theta_i, \varphi_i) \qquad (4)$$

i = incidence;
r = reflectance;
E = incident irradiance (flux/area);
L = reflected radiance (flux/area/solid angle).

BRDF measurement is fraught with technical difficulties, partly because of the four dimensions. The BRDF may also be a function of wavelength, i.e., color, which increases the number of dimensions and complicates things further. Measurement values typically are highly variant with large noise components. RIT has recently received a grant from the Andrew W. Mellon Foundation to develop more robust, color accurate, easy-to-use equipment and methods to capture not only surface texture but 3D structure. They plan to develop an imaging gonio-spectrophotometer in which the light source and the camera can be moved independently in 3D space. [22]

Several years ago, HP Laboratories (HP Labs) developed Reflection Transformation Imaging (RTI), a novel method of capturing highly accurate textural information. Measurements are confined to 20-50 fixed locations on the incoming hemisphere and to one fixed location for the outgoing hemisphere. Hence, the dimensionality of the problem is reduced. The texture is mathematically modeled using surface normal information encoded in polynomial format, referred to as polynomial texture mapping (PTM). [23,24]

The basic idea behind PTM imaging is the capture of successive images, each successive image being illuminated from a different direction. Using altitude-azimuth coordinates, the illuminants are placed inside a hemispherical dome at various azimuths, e.g., 6 illuminants placed at 0°, 60°, 120°, etc. around the object to be imaged. In turn, there is a set of 6 illuminants at various altitudes, e.g., 15°, 30°, 45° and 60° from horizontal. The camera is fixed at the zenith. This arrangement results in a set of 24 images illuminated from 24 known directions and distances. Typically, lower illumination angles generate more shadows in the images as a result of object texture.

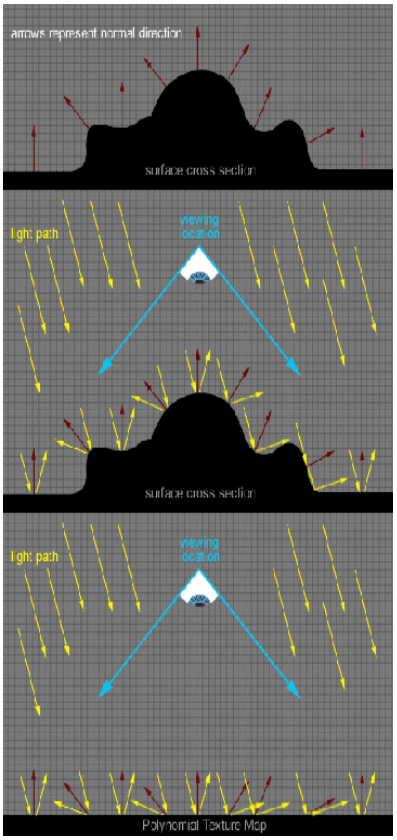

Figure 2. The top image shows a representative surface texture with its surface normals. The middle image depicts the incident light and its reflection at sample points. The bottom image shows how the normals are mapped to a 2D surface.

The surface luminance information from all of the 24 images is processed for all pixel locations to generate normal vectors for each pixel. The pixel-normal information is referred to as a textel. Figure 2 illustrates the textel-generation process. Equation 4 shows the textel components.

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

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 $a^T = [a_0, a_1, a_2, a_3, a_4, a_5]$. For i = 0 to n-1, L_i and I_i become the matrices **L** and **I**. Consequently, equation 4 can be rewritten in matrix form.

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

Using equation 5, the surface luminance, L_i, can be derived for any I_i. An interactive PTM viewer application has been created which will reconstruct the image on a computer monitor for any desired illuminant location in near-real time.

Image and textel data are generated and stored in either of two formats, LRGB or RGB. [25] The LRGB format stores one textel channel (L) and 3 color channels (RGB). The assumption here is that the RGB values do not change significantly with illumination angle. Typically, the color does change somewhat with illumination angle, hence, the insistence on given geometries for interchangeable color measurements. One of the most common illuminant/sensor measurement geometries is 45/0 (illumination at 45 degrees and the sensor directly overhead). The RGB format uses the RGB channels to store 3 sets of PTM's from which the RGB color values can be calculated once the illumination angle is selected. This means that color is a function of the illumination angle. This latter situation is certainly the case for highly dielectric objects such as gold coins. For many objects such as an oil painting the color does not change dramatically within a reasonable range of illumination. The average of all the illuminants in an RTI system tends to be between 45-55 degrees. This is a 0-10 degree angular error versus the reference color measurement angle. This amount of angle error does not produce objectionable color errors for many applications.

2.4. Simultaneous Color and Textural Capture

As originally conceived, RTI was not designed to capture highly accurate color information along with textural information. Recent modifications have made it possible for RTI to simultaneous capture both accurate color and textural information on a pixel-by-pixel basis. [26] Basically, two PTM's are created, one with one filter set and on with a second filter set. It is possible to filter either the camera lens or the illuminant. The resulting 6-channels of color information are processed similarly to that done for spectral imaging only. The result is a highly color accurate PTM.

2.5. Recent Improvements in RTI

In 2006, CHI and HP Labs collaborated to develop an improved RTI technique referred to as Highlight-RTI (H-RTI) [27]. RTI relies on a rigid structure to support the camera and the many light sources. The advantages of a fixed structure are that the illuminants and the camera are stable and in known positions and image capture is very rapid. Unfortunately, a rigid structure is expensive, limits the size of objects that can be imaged, is difficult to move and is unusable in many contexts (cramped spaces, vertical positions, etc.). H-RTI, on the other hand, has many advantages. These include low cost,, ease-of-use, more standardized equipment and flexibility regarding subject size and context. Hopefully, these characteristics may lead to the method's widespread adoption by cultural heritage professionals.

Figure 3. A high-resolution PTM screen capture of a painting of Wilhemine with Braids by Lovis Corinth located in the Worcester Art Museum, Worcester, Massachusetts. (2005.202). A gift from Wilhemine Corinth Klopfer, at the request of her children. The painting is approximately 0.7 m tall. This PTM was captured by Cultural Heritage Imaging.

The method is remarkably simple and amazingly effective. H-RTI relies on the user to position a handheld light source. The lighting direction for 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 field-of-view captured by the camera. Light intensity is controlled by keeping a constant radius between the light and the center of the subject in the camera's view. 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 method permits RTI acquisition with the photographic equipment contained in a basic wedding photographer's kit. H-RTI is able to capture a large size range of objects. Research conducted by the Worcester Museum of Art in collaboration with CHI and funded by the Andrew W. Mellon Foundation, has demonstrated the ability of H-RTI to effectively capture the surface characteristics of very large (> 2m) and very small (< 5cm) cultural heritage material. See Figures 3, 4 and 5.

H-RTI can be made more color accurate by using a portable light which has two identical illuminants physically close together instead of a single illuminant, each with its own filter. Once the illuminant is held in a given position, two successive images can be captured, one with each illuminant turned on. A color target can be affixed to the shiny black sphere or spheres which will be captured in every usable image.

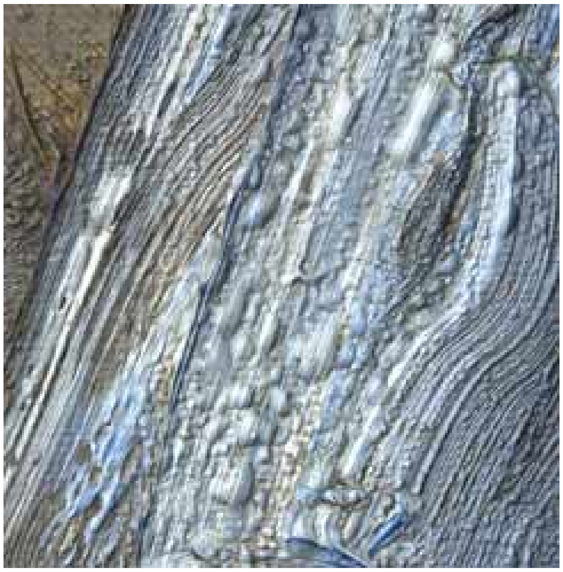

Figure 4. A close-up of the Corinth painting. This section of the original painting is approximately 5 cm square. This image has a resolution of about 6000 pixels/mm^2. The PTM was captured by Cultural Heritage Imaging.

2.5.1 Observer Preference for Perceived Texture

A color-accurate reproduction of a captured image can be made for a chosen illuminant type. The colors can also be modified so that they appear close to the original when viewed under a different illuminant. In other words, the color appearance can be maintained. However, how does one reproduce texture or maintain textural appearance? Currently, it is expensive and difficult, if not impossible, to reproduce color accurate textures (up to several mm). The author refers to this as 2.5D printing. It is possible, however, to make 2.1D prints. A 2.1D print is defined as one which gives the appearance of texture to a conventional 2D print.

A 2.1D print can be created as follows. The PTM Viewer permits an observer to move the virtual light source around and view the effects on the image. An observer moves the mouse pointer around within a circle located next to the image. If the pointer is in the center of the circle, the virtual light source is directly overhead the object. If the pointer is on the edge of the circle, the light source is at a very high grazing angle (~80° from vertical). See Figure 6. Theoretically, a uniform bump on the surface of an object should create longer and longer shadows at higher and higher grazing angles.

The author created prints with increasing amounts of virtual texture (more shadows) by positioning the pointer along a line going to the left of an oil painting. The best light direction is a function of the painting. Grazing angles of 20°, 40° 60° and 80° were selected. See Figure 7. A study was conducted which asked subjects to rank order images from their most preferred to their least preferred. The Comparative-Judgment Method was used to analyze the data. [28] The results are depicted in Figure 8. Observers universally preferred images with greater perceived texture. The finding that more shadows are perceived as having more texture is consistent with another study by Ho et al. [29]

Figure 5. This is an H-RTI image of a large stone carving housed in the Worcester Art Museum. The original is over 2m in height. The PTM was captured by Cultural Heritage Imaging.

2.6. Accurate 3D Structure Capture

The next evolutionary imaging step would be to extend accurate 2D color and surface texture imaging into 3D imaging. 3D scanners have been used to capture digital models of objects. Predominantly, these models have been used for animation, games and virtual reality. While the 3D spatial resolution may be high, fine surface texture is usually not captured. Most often, externally generated texture maps are wrapped around the models at a later time. [30]

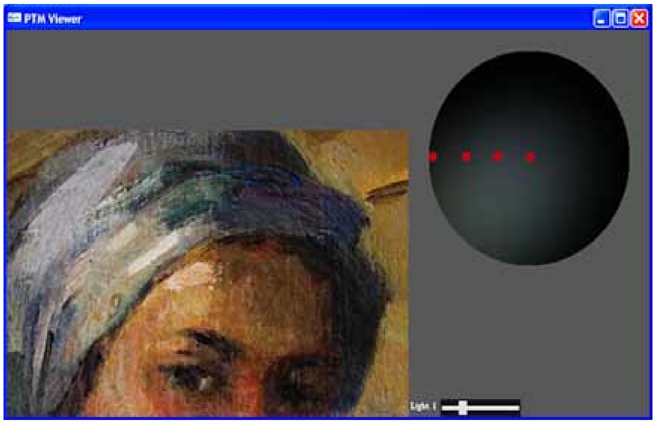

Figure 6. The PTM Viewer showing the selected locations of the light sources. Painting by Michéle Stapley

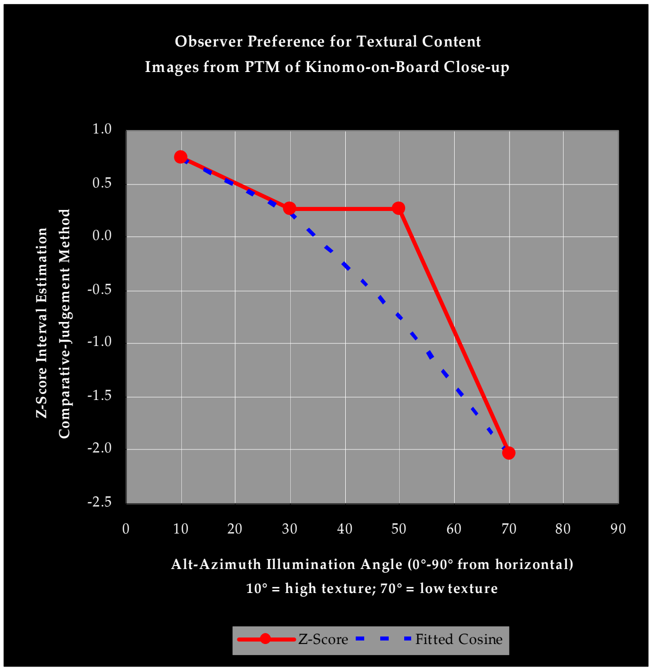

Figure 8. This graph depicts the results of the preference for perceived texture psychometric study. The angles on the abscissa correspond to the images shown in Figure 7. The increasing negative z-score indicates an increasing preference for perceived texture produced by PTM screen captures which contain more shadows.

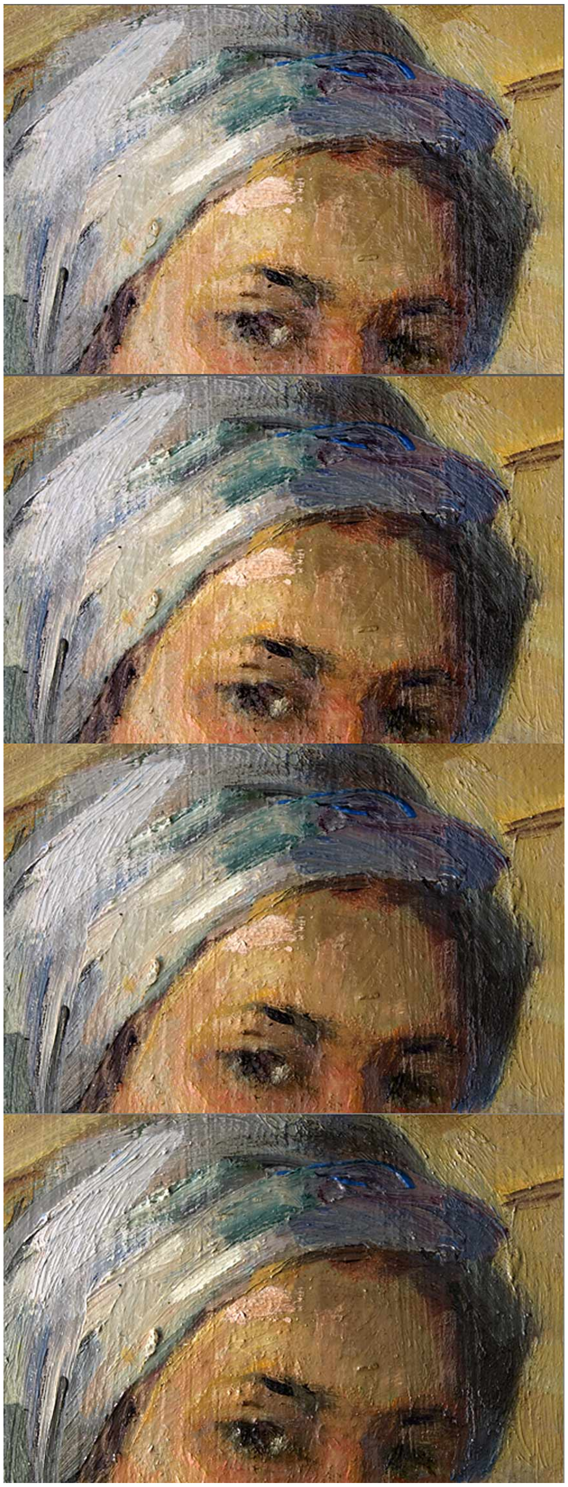

Figure 7. This collage of images shows PTM screen captures for 20°, 40°, 60° and 80° incident illumination angle with respect to vertical (0°).

For cultural heritage use, 3D capture methods must become easier-to-use while capturing 3D structure, surface texture and surface color simultaneously. The RIT grant mentioned previously incorporates an investigation into improved 3D imaging methods. [22] CHI and the University of Southern California (USC) have received a similar grant. [31] One goal of the CHI/USC project is to develop methods for capturing high-quality, detailed 2D and 3D representations of cultural heritage objects. The general idea is to modify the H-RTI technique further by utilizing multiple cameras from which 3D structure can be derived. Accurate color could be captured by filtering the illuminant and capturing the 2-3 images from different camera locations simultaneously.

3. Digital Image Archiving

Once an image is captured, it must be archived. Archiving means different things to different people. To a professional archivist, archiving generates a multitude of questions, such as: (1) what storage format to use; (2) what is the likelihood that the storage format will still exist in a decade; (3) should the data be compressed; (4) what storage medium to use; (5) what is the likelihood that the storage medium will still exist in a decade; (6) what is the permanence of the data on the medium and what is its susceptibility to environmental factors; (6) are there copyright issues; (8) is the data authentic; (9) what metadata should be stored with the data; (10) has the data experienced any processing; and (11) is there a history of the processing; and (12) can the processing be reversed? The history of the ownership of a painting is referred to as the painting's provenance. Items 9-12 can be referred to as 'digital provenance,' or 'empirical provenance,' terms coined by CHI. Each of the above questions has a deeper set of questions associated with it. For example, if any processing was conducted on the data, was it proprietary? For example, the demosaicing algorithm integrated into Adobe's Photoshop CS2 is proprietary and undocumented. When CS2 is no longer available, the empirical provenance chain is broken. The same comments can be made with regard to compression algorithms.

Both RIT and CHI are addressing digital provenance issues. All RTI image metadata, for example, carries "empirical provenance" information. Empirical provenance documents the entire digital image generation process history. Beginning with the raw empirical data captured by the photographic sensor, every operation until the completion of the digital representation is documented. This empirical provenance data is structured to comply with ISO 21127 [32] cultural heritage documentation standard. ISO 21127 describes the Conceptual Reference Model (CRM) ontology developed by the Committee On Documentation (CIDOC) of the International Council of Museums (ICOM) [33]. When linked to the archived raw empirical data, empirical provenance documentation permits independent confirmation of the trustworthiness and quality of digital representations through process transparency and possible replication. RTI empirical provenance also meets the requirements of the 2006 London Charter [34] on three dimensional digital representations calling for source clarity, process transparency, documentation completeness, and standards-driven metadata structures.

Figure 9. A before and after image of the restoration of the frescoes on the vault of the Santos Juanes Church in Valencia, Spain. Photograph provided by HP in Barcelona.

4. Digital Image Conservation

Kyoto is the cultural heart of Japan. There are over 3500 shrines is Kyoto with thousands of works of art dating from the 13th to 17th centuries. The works of art are very delicate and are being destroyed by age, climate and air pollution. As a result, the public has never seen the artwork. [35] In March of 2006, it was reported that the Kyoto International Culture Foundation had collaborated with HP to reproduce the artwork for display. The originals had been stored in a controlled climate. HP had to accurately capture the images, create special media made from mulberry bark similar to the originals, design special inks, and accurately reproduce the images. According to one report, "the results are remarkable, producing images that look strikingly similar to the originals, capturing the look and feel of ink on paper, down to the distressed effects of deterioration present in the original works." [36] This is a wonderful example of how the development of technology can preserve our cultural heritage.

5. Digital Image Restoration

Just as digital imaging technology can make previously impossible conservation projects possible, it can make previously unthinkable restoration projects possible. Using careful color analysis, RIT was able to do analysis of pigments that had aged. [37] Through this analysis, they were able to identify what the pigments originally looked like. Using this information, they were able to simulate a rejuvenation of Seurat's *A Sunday on La Grande Jatte* to make it appear like what it probably looked like when it was originally created. [38]

In 1700, the vault of the Santos Juanes Church in Valencia, Spain, was decorated with fresco paintings. In 1936, the paintings suffered significant damage as a result of a fire during the Spanish Civil War. Several subsequent attempts at restoration did more damage than good. The first step in the current restoration project was to digitally image the entire ceiling (1200 m^2). HP assisted with the photography. Using computer imagery, attempts were made to fill in the missing fragments. The entire process was complicated by the highly irregular geometry of the vaulted ceiling, somewhat akin to the Sistine Chapel. Once the mosaic of images were generated, specially developed inks were deposited on a specially developed transfer gel. The locations of the missing fragments on the ceiling were then filled in with wet lime and sand. While still wet, the images on the support gels were transferred to the ceiling. The saturation of the restored images was deliberately changed versus the surrounding original images. The intent was to enable observers to get a sense of the total image while enabling them to differentiate the restored portions of the image from the original. The restoration is on-going, however, some preliminary results can be seen in Figure 9. [39,40]

6. Digital Image Reproduction

Industry and cultural heritage institutions are interested in digital fine art reproduction for what appears to be exclusively different reasons. Industry is primarily attracted to art reproduction for financial reasons, and for good reason. The art reproduction market has been estimated to be a $7.5B market which is growing at 30% per year. [36] Museums are interested in art reproduction for the following reasons – listed in priority order: (1) to make collections accessible over the Internet; (2) to include in collection management system; (3) to produce reproductions for sale; (4) to protect the original from unnecessary use; and (5) to document conservation treatment. [3] Fortunately, the interests of industry and museums need not be as disparate as they appear at first glance. First, financial incentives drive improvements in technology which can help fulfill the wishes of the cultural heritage establishment. Second, the promotion of fine art reproduction by museums can create markets for industry. Third, there is actually some overlap in the interests of industry and museums. Though the reproduction of art for sale is ranked third while making collections accessible over the internet is ranked first, it seems likely that better internet accessibility will promote increased sales of reproductions. It is also likely that cultural heritage promotions supported by industry can be mutually beneficial.

An example of the interests of the cultural heritage community being promoted by industry is HP's Art-on-Demand program. It has had as its focus the development of systems that facilitate the reproduction of fine art. This program also been referred to by the more descriptive title, the 'Masters to the Masses' program. The ability to make the masters available to the masses will certainly enrich the lives of individuals while benefiting both cultural heritage institutions and industry. More recently, HP began another program called HYPE. The idea motivating HYPE is to print and project art in association with galleries in London and Paris. The Grand Tour just ended in London. For 12 weeks, approximately 30 full-size reproductions from the National Gallery of Art were displayed in the streets of London. Even the frames were replicas of the originals. The aim of the program was to encourage people to visit the nearby National Gallery of Art to see the originals displayed in the streets of London as well as all the other works of art in the gallery. Future exhibitions are planned for Moscow, Milan and Singapore. [41] This project certainly promotes our cultural heritage while benefiting the National Gallery of Art whose task it is to preserve our cultural heritage and make it accessible to the public. Again, this program should be mutually beneficial to the public, the museum and industry. Digital imaging reproduction and programs such as the these can bring our cultural heritage closer to our homes and offices and enrich the lives of art lovers worldwide.

7. Future Digital Imaging Opportunities

This is an exciting time to be involved in the digital imaging arena. The technology is advancing rapidly. The existence of highly accurate 3D structural, 2D surface textural, 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 Alaska can soon have better access to more detailed information about van Gogh's *The Church in Auvers* than a doctoral student residing in Paris and studying the original at the Musée D'Orsay.

References

[1] V. Mettais, Your Visit to Orsay – ENGLISH,, art lys, Versailles (1999), pp. 126-127.

[2] I. F. Walther, Vincent VanGogh (1853-1890): Vision and Reality, Barnes & Noble Books by arrangement with TASCHEN GmbH, Germany (2001), p. 62.

[3] R. S. Berns and F. S. Frey, Final Report 2005: Direct Digital Capture of Culture Heritage – Benchmarking American Museum Practices and Defining Future Needs (2005).

[4] J. Y. Hardeberg, Acquisition and Reproduction of Color Images: Colorimetric and Multispectral Approaches, Dissertation.com (2001)

[5] D. Connah, A. Alsam and J. Y. Hardeberg, Multispectral Imaging: How Many Sensors Do We Need? Journal of Imaging Science and Technology 50 (1):45-52, 2006.

[6] R. S. Berns and L. A. Taplin, Practical Spectral Imaging Using a Color-Filter Array Digital Camera, July 2006, Final Report, www.art-si.org (2006)

[7] R. S. Berns, L. A. Taplin, M. Nezamabadi, M. Mohammadi and Y. Zhao, Spectra imaging using a commercial colour-filter array digital camera, ICOM Committee for Conservation Preprints: 14th Triennial Meeting The Hague: 12-16 September, 2005, Vol. 2 of 2 (2005), pp. 743-750.

[8] R. S. Berns, L. A. Taplin, M. Nezamabadi and Y. Zhao, Modifications of a Sinarback 54 camera for spectral and high-accuracy colorimetric imaging: Simulations and experiments, June 2004, www.art-si.org (2004), pp. 1-23.

[9] Jeffrey M. DiCarlo, N. Sampat, M. Bhachech, M. McGuire and G. Dispoto, Building a Fine Art Reproduction System from Standard Hardware, HP Internal Document (2007).

[10] R. S. Berns, The Science of Digitizing Paintings for Color-Accurate Image Archives: A Review, Journal of Imaging Science and Technology 45 (4), pp. 305-325 (2001).

[11] H. Maitre, F. Schmitt, J. Crettez, Y. Wu and J. Y. Hardeberg, Spectrophotometric analysis of fine art paintings, 4th Color and Imaging Conference: Color Science, Systems and Applications (1996), pp. 50-53.

[12] E. P. M. Smoyer, L. A. Taplin and R. S. Berns, Experimental evaluation of museum case study: Digital camera systems, www.art-si.org.

[13] D. Tzeng and R. S. Berns, A Review of Principle Component Analysis and Its Applications to Color Technologies, Color Research and Application 30 (2), April 2005 (2005), pp. 84-98.

[14] I. T. Jolliffe, Principal Component Analysis, 2nd Ed.,, New York: Springer (2002).

[15] Z. Li and R. S. Berns, Evaluation of Linear Models for Spectral Reflectance Dimensionality Reduction, ICIS ’06 International Congress of Imaging Science, 288-291.

[16] J. V. Stone, Independent Component Analysis – A Tutorial Introduction, Cambridge: The MIT Press (2004).

[17] J. A. Hyvärinen, J. Karhunun and E. Oja, Independent Component Analysis, New York: John Wiley & Sons, Inc. (2001).

[18] Y. Zhao, L. A. Taplin, M. Nezamabadi and R. S. Berns, Using the Matrix R method for spectral image archives, AIC Colour 05: 10th Congress of the International Colour Association (2005), pp. 469-472.

[19] D. Tzeng and R. S. Berns, Deriving a suitable vector space describing a subtractive color mixing for multi-primary printing systems, MCS07 Symposium, Taiwan, June 2007 (2007).

[20] F. H. Imai, M. R. Rosen and R. S. Berns, Comparative study of metrics for spectral match quality, CGIV 2002: The First European Conference on Colour Graphics, Imaging and Vision (2002), pp. 492-496.

[21] S. Rusinkiewicz, A survey of BRDF representation for computer graphics, class notes, CS348c, Winter 1997 (1997).

[22] R. S. Berns, Improving Artwork Reproduction Through 3D-Spectral Capture and Computer Graphics Rendering: Project Overview – May 2006, www.art-si.org (2006).

[23] T. Malzbender, D. Gelb and H. Wolters, Polynomial Texture Maps, Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques, 519-528 (2001).

[24] http://www.hpl.hp.com/research/ptm/index.html (2007).

[25] Tom Malzbender and Dan Gelb, Polynomial Texture Map (.ptm) File Format, Version 1.2, Hewlett-Packard Laboratories, November 2001.

[26] John Redman and Mark Mudge, The Simultaneous Capture of Spectral and Textural Information, Archiving 2007: Final Program and Proceedings (2007), pp. 2-5.

[27] Mark Mudge, Tom Malzbender, Carla Schroer and Marlin Lum, New Reflection Transformation Imaging Methods for Rock Art and Multiple-Viewpoint Display, Proceedings of the7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST2006), M. Ioannides, D. Arnold, F. Niccolucci, (Eds.), Eurographics Association, pg 195-200 (2006).

[28] C. J. Bartleson, Optical Radiation Measurements, Vol. 5, Chapter 9: Direct Ratio Scaling, pp. 491-507.

[29] Y. Ho, L. T. Maloney and M. S. Landy, The effect of viewpoint on perceived visual roughness, Journal of Vision 7(1):1, pp. 1-16 (2007).

[30] F. Bernardini, I. M. Martin and H. Rushmeier, High-quality texture reconstruction from multiple scans, IBM T. J. Watson Research Center.

[31] Mark Mudge, Developing Advanced Technologies for the Imaging of Cultural Heritage Objects, a partnership including Cultural Heritage Imaging, the University of Southern California and Hewlett-Packard Laboratories, National Leadership Grant sponsored by the Institute for Museum and Library Services, www.c-h-i.org (2007).

[32] http://www.iso.org/iso/en/CatalogueDetailPage.(continued) CatalogueDetail?CSNUMBER=34424&scopelist=PROGRAMME

[33] http://icom.museum/

[34] http://www.londoncharter.org/

[35] HP Newsroom, Releasing the spirit of Kyoto, http://www.hp.com/hpinfo/newsroom/presskits/2006/kyoto/news_html (2006).

[36] A. Cantrell, HP’s new big business: art reproduction?, CNNMoney,com, 2 March 2006.

[37] R. S. Berns and F. H. Imai, The use of multi-channel visible spectrum imaging for pigment identification, ICOM Committee for Conservation Preprints: 13th Triennial Meeting, Rio De Janeiro, 22-27 September 2002, Vol. 1 of 2, pp. 217-458 (2002).

[38] R. S. Berns, F. H. Imai and L. A Taplin, Rejuvenating the appearance of Seurat’s A Sunday on La Grande Jatte – 1884 using colour and imaging science techniques: a simulation, ICOM Committee for Conservation Preprints: 14th Triennial Meeting The Hague: 12-16 September, 2005, Vol. 1 of 2, pp. 452-222 (2005).

[39] M. Sanchez Pons, Study about materials and criteria in the compensation for losses in mural painting – Application in the frescoes of Antonio Palomino in the Santos Juanes Church of Valencia [in Spanish], Ph.D. Thesis, Universidad Politechnica de Valencia (Spain), January 2005 (2005).

[40] J. L. Abad and J. F. Plante, Exhibiting the Remaining Fragments in the Vault of Santos Juanes Church in Valencia, HP internal presentation (2005).

[41] HP Newsroom, Picture Perfect, http://www.hp.com/hpinfo/newsroom/presskits/2007/london/news_html (2006).

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