Experimental Evaluation of Museum Case Study Digital Camera Systems

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Abstract

A testing procedure was designed for characterizing both the color and spatial image quality of trichromatic digital cameras, which are used to photograph paintings in cultural heritage institutions for the purpose of creating archival quality digital master images. The testing procedure was target-based, thus providing objective measures of quality. The majority of the testing procedure followed current standards from national and international organizations such as ANSI, ISO, and IEC. The procedure was tested in the Munsell Color Science Laboratory, an academic research laboratory, as well as used to benchmark four representative American museum's digital-camera systems and workflows. The four museums were chosen because they were early adopters of digital-image archiving.

The nine quality parameters tested included system spatial non-uniformity, tone reproduction, color reproduction inaccuracy, noise, dynamic range, spatial cross-talk, spatial frequency response, color-channel registration, and depth of field. In addition to the characterization testing, two paintings were imaged and processed through each museum's normal digital workflow. The results of the four case studies showed many dissimilarities among the digital-camera systems and workflows, which caused a significant range in the archival quality of their digital masters. These differences point out the need for standardization of digital imaging in American museums, libraries, and other cultural-heritage institutions.

Introduction

For decades, museums, libraries, and other cultural-heritage institutions (referred to as "museums" in this publication) have been using analog photography as a means for documenting their collections and producing reproductions of their artifacts. Through the years, these institutions developed "best practices" for the process of documentation and reproduction, which included photographing the object, storing the image, and cataloging, so that a high quality image archive could be obtained and maintained for many years. Now that digital photography is well established and comparable to analog photography both in price and image quality, these cultural-heritage institutions have a choice of whether to continue imaging the traditional way or start imaging using digital technology.

Procedures for testing the quality of digital cameras have been established in the recent past, but they are not yet suitable and comprehensive enough to be used in a museum setting and have not been developed specifically for the direct digital capture of artwork. The ultimate goals of this research were twofold. First, it is beneficial to the cultural-heritage community because it might provide a possible guideline for high-quality-digital imaging and second, it benchmarked four camera systems and procedures currently used for digital imaging by the cultural-heritage community. Although the saying, "You get what you pay for" typically applies in the acquisition of imaging systems, there is no substitute for the careful and thorough testing and benchmarking of digital-imaging systems.[1] Benchmarking systems help to compare different camera systems, giving better information than the manufacturers provide, and should lead to a better understanding of the whole imaging process.[2]

The aims of the testing procedure were to follow current digital-photography standards to the greatest extent possible, provide only objective measures of image quality by imaging test targets, and be as automating as possible with the use of The MathWorks MATLAB® programming language analysis software. The outcome of this procedure was an extensive quantitative description of the digital-image-quality parameters, which characterized four museum digital cameras and procedures used for the direct-digital capture of cultural heritage paintings.

Case Study Descriptions

The cameras and lights used in the case studies in each of the four museums were different. The four museums were not chosen for the case studies for this reason. They were chosen because they were early adopters of digital-image archiving.

Case Study I:

The camera used at the museum's photography studio was a Leica S1 Pro digital camera, which is a 3-channel tri-linear-array-CCD scanning camera. The maximum native resolution of the camera is 5140p x 5140p. The lens used was a 100mm f/2.8 Leica lens. The filter used between the lens and CCD was a Leica daylight balancing/IR cut-off filter. There were four Lowel Scandles imaging lights used to light the scene. These lights had a correlated color temperature of approximately 5000K.

Case Study II:

The camera used at the museum's studio was a Phase One PowerPhase FX digital camera, which is a 3-channel tri-linear-array-CCD scanning-back camera. The maximum native resolution of the camera is 10,500p x 12,600p. The scanning back was on a TTI 4x5 view camera body. The lens used was a 150mm Schneider enlarging lens. The filter used behind the lens was a Phase One tungsten balancing/IR cut-off filter. The camera was set up on a copy stand. The imaging lights used were two TTI Reflective Lighting tungsten lights, which each had four OSRAM 250W Quartz Halogen photo optic bulbs. Their distances from the copy stand table were adjustable. These lights had a correlated color temperature of approximately 3000K.

Case Study III:

The camera used at the museum's studio was a Sinar Sinarback 54H digital back camera, which is a 3-channel area array CCD camera. The maximum native resolution of the camera is 4,080p x 5,440p. The digital back was on a Horseman 4x5 view camera body, which had a Rollie electronic shutter. The lens was a 100mm f/4 Rodenstock Apo Sironar digital HR lens. The filter used between the CCD and the lens was a Sinar IR cut-off filter. There were four Speedotron Xenon strobe imaging lights in a 202VF light unit used to light the scene. These strobe lights had a UV correction filter over the bulb. These lights had a correlated color temperature of approximately 6700K.

Case Study IV:

The camera used at the museum's studio was a Better Light 6000-2 digital camera, which is a 3-channel tri-linear-array-CCD scanning camera. The maximum native resolution of the camera is 8,000p x 6,000p. The digital back was on a Sinar 4x5 view camera body. The lens was a 210mm f/5.6 MC Sinaron SE. The filter used between the lens and CCD was a Better Light daylight balancing/IR cut-off filter. There were four Broncolor HMI F 1200 imaging lights used to light the scene indirectly by bouncing the light off of white walls and a 12' ceiling. These lights had a correlated color temperature of approximately 5000K.

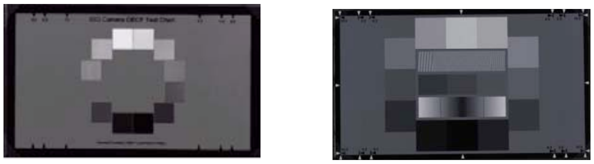
Case Study Testing Procedure

There were two main parts of the case study testing procedures. In the first part, two paintings (see Figure 1) which were painted with Gamblin Artist Oil paints, were imaged and processed through each museum's normal digital imaging workflow, which is typically used to create an archival quality digital master image. The colorimetric accuracy of these paintings was evaluated using 11 uniform areas of pigment on each painting and compared across the four museums.

Figure 1. Flower (left) and fish (right) paintings used for the analysis of each museum's digital imaging workflow. Uniform areas of pigment are marked with a white circle.

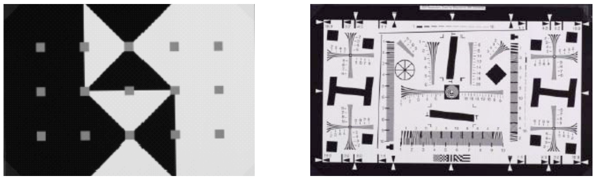
The purpose of the second part was to characterize each museum's camera system and imaging workflow. The images that were analyzed in the second part were representative of digital masters. In this part of the case study testing procedure, there were nine quality parameters tested. The first one, system spatial non-uniformity, which can be caused by uneven illumination of the scene and/or lens fall-off, was tested using a uniform gray card target. The second is tone reproduction, which was tested using an ISO standard grayscale target (see Figure 2a) and analyzed in the form of an opto-electronic conversion function, or OECF. The third is color reproduction inaccuracy, which is fundamentally caused by the inherent lack of correlation between the camera's spectral sensitivities and those of the average human observer. These spectral sensitivities were determined by imaging a monochromator instrument. Also, nine different color targets were imaged and analyzed. These targets included the Macbeth ColorChecker, the Macbeth ColorChecker DC, the Esser Test Chart, a cobalt blue pigment target, a Gamblin oil paint target, the IT8 target, the Kodak Color Separation and Grayscale targets, and a target made from ceramic BCRA spectrophotometer calibration tiles. The fourth and fifth parameters are noise and dynamic range, which were both tested using an ISO standard noise target (see Figure 2b), imaged eight times at the same exposure level. The sixth image quality parameter, spatial cross-talk, otherwise known as image flare, was tested using an IEC standard target (see Figure 2c). The seventh, spatial frequency response, (SFR) which is used to characterize a camera's ability to reproduce detail, and the eighth, color-channel registration were both tested using the knife-edges of an ISO resolution target (see Figure 2d). Depth of field, the ninth quality parameter that was tested, was tested using a three-dimensional target (see Figure 2e) that had a total depth of 6".

The test targets and paintings were approximately the same size, so the camera and lights set-up remained consistent throughout the imaging process, with the exception of the imaging of the monochromator instrument and depth of field target. Although the basic imaging procedure was consistent for all four of the museum case studies, they were each still unique because the photographer had the freedom to follow his normal imaging procedure.



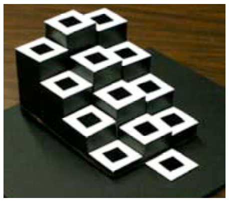
a.) ISO OECF target

b.) ISO Noise target



c.) IEC spatial cross-talk target

d.) ISO Resolution target



e.) Depth of field target

Figure 2. Test targets used in the characterization of each museum's digital camera system and imaging workflow.

Part I: Paintings Analysis

The paintings in Figure 1 were imaged in each case study as if they were one painting, because they both contained the same pigments. The circled areas of the paintings in Figure 1 were evaluated for colorimetric accuracy by comparing the image data to the measurements made with a spectrophotometer after the lightness differences caused by the different exposure levels of the images at each museum were corrected. Figure 3 shows the hue and chroma errors between the measured data (dots) and image data (vector arrows) of the fish painting in the CIELAB color space. The longer the vectors, the more error there was. Included in each plot is the mean ΔE_{00} (a CIELAB color difference metric) value between the measured and image data of both the flower and fish paintings. The analyzed images were digital masters, and no visual corrections were performed on these images, so the color errors were mostly attributed to the camera's spectral sensitivities.

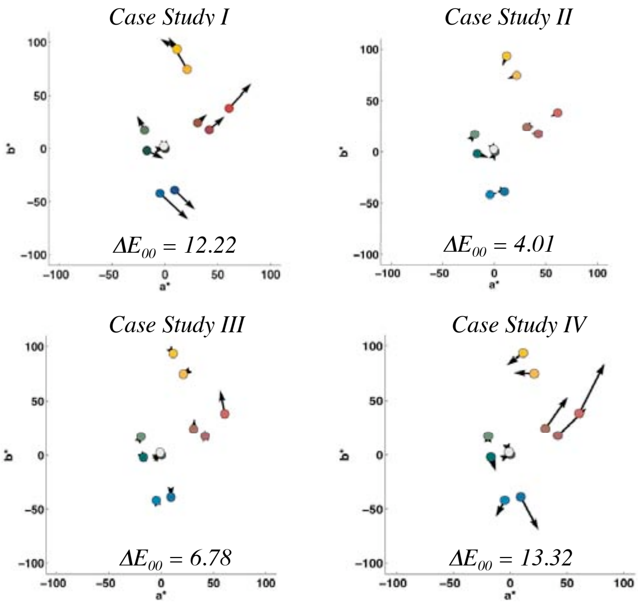


Figure 3. CIELAB a* (green (-) to red (+)) vs. b* (blue (-) to yellow (+))of the fish painting of the four case studies. Dots are measured values and vector arrows point to image values. Also included are the mean ΔE_{00} values of the flower and fish paintings.

Part II: Characterization Analysis

System Spatial Non-uniformity

Figure 4 shows the system spatial non-uniformity results of the four case studies.

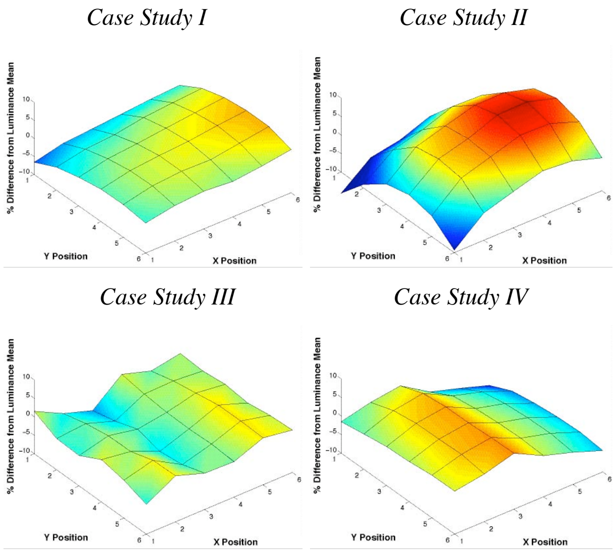


Figure 4. System spatial non-uniformity results case study comparison.

The Y tristimulus value (luminance factor) data for each of 36 (6 x 6) evenly spaced patches of the gray card target were compared to the mean image Y tristimulus value of all 36 patches and a percent difference was calculated between them. In Case Study I, light metering was performed during the imaging system set-up; in Case Study II, no uniformity correction was done; in Case Study III, the non-uniformities were corrected using the image capture software; and in Case Study IV, the uniformity was checked in the image capture software during set-up.

Tone Reproduction

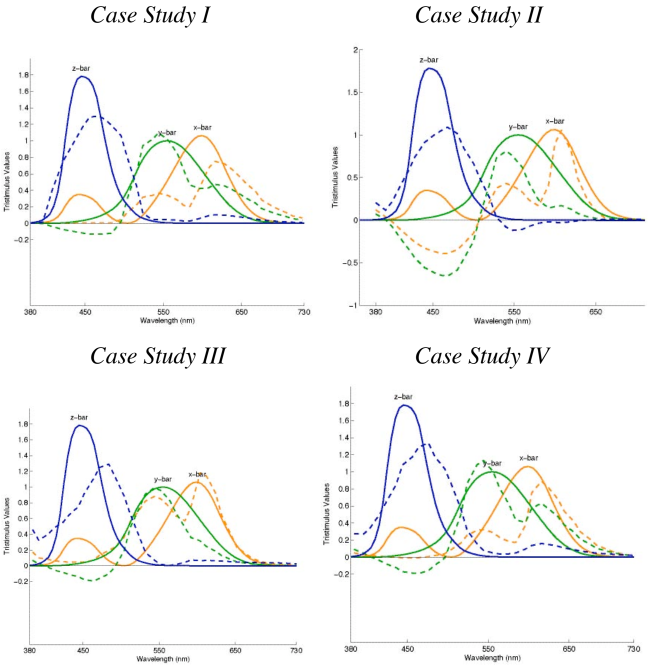
During the case studies, the target in Figure 2a was imaged at the nominal exposure, underexposed, and overexposed, so that the target patch image data over the full range of possible digital count values were obtained. The average image target patch values were determined for each exposure level and rescaled to match the nominal exposure level. The OECF functions (digital counts vs. adjusted luminance in cd/m^2) for each channel were fitted with gamma encodings. The mean gammas of the three channels are listed in Table 1 for the four case studies. The OECF results from one case study was not necessarily better than that of any another case study. The gamma encoding could have been imposed on the images by the camera's profile or image software. Some of the case studies had different OECF curves for each channel. If the OECF or gamma encoding is known, it can show what the actual gamma encoding of each channel is and if there is any unwanted clipping.

Color Reproduction Inaccuracy

Spectral Sensitivity

Most digital camera spectral sensitivities are not linear transformations of an average human visual system's spectral sensitivities. This is the underlying reason why color inaccuracies exist in digital images. In the case studies, a monochromator instrument was imaged 36 times from bandpass peaks of approximately 360nm to 730nm in 10nm increments with the imaging lights turned off. After the images were taken, the radiance of the same bandpass peaks were measured with a spectroradiometer. The average image values of the spot of monochromatic light in the centers of each of the 36 images were divided by the radiance values to obtain relative spectral sensitivities. Figure 5 shows the relative spectral sensitivities rotated to fit the CIE standard 2° 1931 standard observer "sensitivities."

The lack of fit to the 2° observer can be summarized using a quality metric, μ-factor.[3] The μ-factor was calculated for each case study using the imaging illuminant and camera spectral sensitivities, a D50 viewing illuminant, and the 2° observer. These results for the four case studies are shown in Table 1. The closer that this value is to unity, the better the correlation of the camera's spectral sensitivities to the 2° observer. A value of zero signifies no correlation.


Case Study I

Case Study II

Case Study III

Case Study IV

Figure 5. Spectral sensitivity case study comparison of relative spectral sensitivities (dotted lines) rotated to fit the CIE 2° standard observer (solid lines).

Target-based Color Reproduction Inaccuracy

The color reproduction inaccuracies of the four case studies can be summarized using ΔE_{00}. The ΔE_{00} value was determined between the average image data of each patch of nine color targets and the spectrophotometrically measured data. The mean 90th percentiles of all of the patches of each case study are listed in Table 1. The higher this value, the more color error there was. The amount of color difference errors resulting in all four case studies is mostly dependent on the spectral sensitivities of the camera system and the accuracy of the profiles used in each case study. Since the spectral sensitivities of the camera cannot be changed, except with the use of filters, it is easier to create a profile that is as accurate as possible. The profiles should be optimized using a target representing the pigments and materials being imaged with the camera.

Noise

The center three patches of the ISO Noise target, shown in Figure 2b, were used to evaluate the image noise. The total signal-to-noise ratios, SNRs, of each case study are listed in Table 1. These values were calculated according to the ISO 15739 standard.[4] The higher this value, the less noise the image had. In order to produce images with a low amount of noise, at least one dark correction image should be subtracted from the digital master images. This was done automatically in the image capture software in Case Study III and not at all in the other case studies. Also, using a low ISO and short exposure time when imaging will help in the reduction of the image noise level.

Table 1. Case study characterization results of eight of the quality parameters.

Quality Parameter	***Case Study I***	***Case Study II***	***Case Study III***	***Case StudyIV***
Tone Reproduction *Mean gamma*	2.80	2.03	1.70	3.70
Spectral Sensitivity *μ-factor*	0.68	0.79	0.81	0.80
Target-based Color Reproduction Inaccuracy *Mean* ΔE_{00} 90^{th} *percentile of 9 targets*	12.74	6.73	5.05	16.34
Noise *Total SNR*	35.85	14.16	14.11	22.79
Dynamic Range *Density*	2.86	2.81	2.65	2.87
Spatial Cross-talk *Relative maximum % difference*	5.83	6.52	6.43	3.97
Spatial Frequency Response *Mean area under the RGB curves across all 4 edges from frequencies of 0.0 to 0.5 cy/pixel*	0.484	0.616	0.862	0.592
Color Channel Registration *Mean registration shift RGB channels and across 4 edges*	0.130	0.136	0.035	0.027

Dynamic Range

The dynamic range, otherwise known as tonal range, of a digital camera system is the capacity of the camera to capture extreme density variations. The darkest and second darkest patches of the ISO noise target were used to calculate the dynamic range as a luminance ratio according to ISO standard 15739.[4] The log10 of this ratio was calculated to determine the dynamic range density values listed in Table 1 for all four case studies. It is desirable to have a high dynamic range. A density of 0.3 is equal to one stop of light ($\log_{10}2$). In order to obtain the most dynamic range achievable by a digital imaging system, the amount of spatial cross-talk or flare should be reduced as much as possible.

Spatial Cross-talk

In order to evaluate spatial cross-talk, the target shown in Figure 2c was imaged twice. In the second image, the target was rotated 180° so that, for example, a gray patch with a black background in the first image had a white background in the second image. The spatial cross-talk results listed in Table 1 for the four case studies are the relative maximum percent differences of the 30 gray patches between the two target image rotations. The lower this value, the less spatial cross-talk the digital masters had. In order to reduce the amount of spatial cross-talk, or image flare, in a digital image, the image area surrounding the painting being imaged should be as dark as possible.

Spatial Frequency Response

The central horizontal and vertical knife edges, along with the upper left corner square knife edges of the ISO resolution target, shown in Figure 2d, were used to determine the digital master images' SFR curves. The knife-edges were evaluated using Burns' sfrmat2 program.[5] The areas under the SFR curves, which are normalized between zero and unity, are listed in Table 1 for the four case studies. The higher this value, the better the target's detail was preserved. Un-sharp masking was performed on the digital master in Case Study III, which is why the SFR area was very high (the SNR was very low as a consequence of the un-sharp masking). The SFR results of the case studies could have been affected by the tool used for focusing the images before capture. In Case Study I, the photographer focused by looking through the ground glass, whereas in the other three case studies, a magnification tool or frequency focusing tool in the image capture software was used to focus the images.

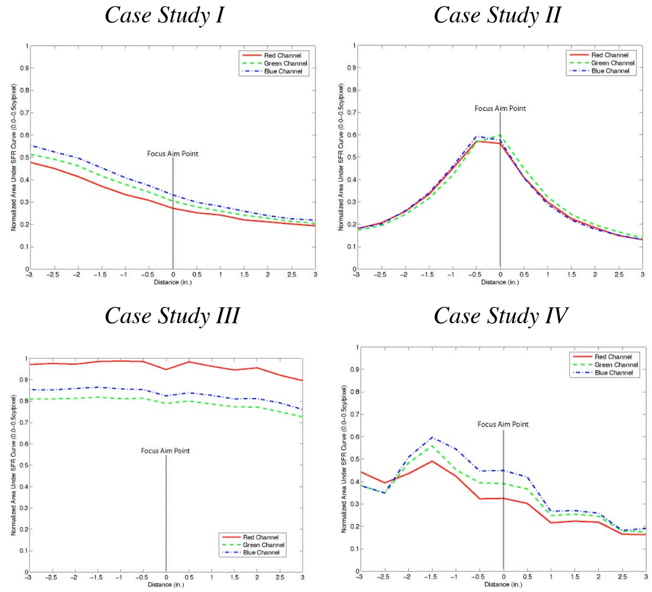
Color Channel Registration

The color channel registration was evaluated using the same four knife-edges as in the SFR analysis. It was also evaluated using Burns' sfrmat2 program.[6] The mean amounts of color channel mis-registration of all three color channels across the four knife-edges are listed in Table 1. The mis-registration errors in all for case studies were very low. Mis-registration in images from both scanning and area array CCD cameras can be caused by chromatic aberration of the lens or color filter array lenslets.

Depth of Field

Depth of field is the range of distance for which the subject is rendered acceptably sharp in an image. It increases as the lens is closed down (f-stop increases). It is greater for short focal lengths than for long ones, and it increases with the subject distance. A digital imaging system should have a suitable depth of field when it is used to image paintings because a painting is a three dimensional object that has some depth and a large painting could be warped. The center column of the depth of field target, shown in Figure 2e, was focused on when the image of this target was taken in each case study. The other columns are a total of 3" in front of and behind the center column in 0.5" increments. The SFR of each square's knife-edge on top of each of the 13 columns was determined.

Figure 6 shows the depth of field results of the four case studies as plots of the areas under the SFR curves from frequencies of 0.0 to 0.5cycles/pixel vs. distance. The steeper the sides of the curves are, the less depth of field the case study images had. Also, if the peaks are shifted with respect to the focus aim point, then the focusing tool was not accurate.


Case Study I

Case Study II

Case Study III

Case Study IV

Figure 6. Depth of field results comparison of the case studies.

Further Details

A research project, of which this research was a part, entitled "Direct Digital Image Capture of Cultural Heritage – Benchmarking American Museum Practices and Defining Future Needs," also surveyed American museums about their involvement with digital photography and performed six American museum on-site case study interviews to document their current digital-imaging workflows.[7] See www.cis.rit.edu/museumSurvey for more details about the findings of this project.

A full report, in the form of a Master's thesis[8] contains a review of standards, a detailed description of how each case study was performed at the museum, a detailed description of how the data was analyzed, the results of each case study, and a comparison of the four case studies.

Conclusions

The testing procedure described here can be used to provide objective measures of a range of performance characteristics of digital-camera systems and workflows, which are used in cultural heritage institutions to document archival quality digital master reproductions of their painting collections. Cultural heritage institutions can store future characterization data as metadata with their images. Also, digital camera manufacturers can use this characterization data to see where imaging systems need improvements for cultural heritage applications.

As a result of these case studies, many differences were discovered among their current digital-imaging practices, which points out the need for standardization in American museums. None of the four museum case studies had the best results for all of the quality parameters tested.

Ideally, a raw digital image should be captured and stored as a digital master with the characterization metadata of the digital-imaging system. This way, the digital information is as accurate as possible and if, in the future, there is an improvement in the way digital data are interpreted, the raw data and information about the means by which it was formed can be retrieved. Cultural heritage institutions should also document their digital-imaging workflows for future reference. When a painting is digitized, an accurate archival quality reproduction of the painting should be the goal of the photographer. In other words, the photographer should be careful not to image the painting with a specific reproductive purpose in mind. After a painting is imaged and the raw data stored, derivatives can then be made in the form of reproductions.

Acknowledgements

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Biography

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