Invited Article: High resolution digital camera for infrared reflectography

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(Received 9 April 2009; accepted 14 June 2009; published online 15 July 2009)

This paper describes the characteristics of a high resolution infrared (IR) imaging system operating over the wavelength range of 830–1100 nm, based on a modified 8 Mpixels commercial digital camera, with which nonspecialists can obtain IR reflectograms of works of art *in situ* in a museum environment. The relevant imaging properties of sensitivity, resolution, noise, and contrast are characterized and the capabilities of this system are illustrated with an example that has revealed important new information about the working practices of a 16th century artist. © *2009 American Institute of Physics.* [DOI: 10.1063/1.3174431]

I. INTRODUCTION

Infrared (IR) reflectography[1] as a technique for the examination of works of art was introduced in the 1960s by van Asperen de Boer.[2] This technique makes use of the fact that IR light ($\lambda > 750$ nm) penetrates further into many pigments than does visible light ($400\ \text{nm} < \lambda < 750$ nm). Because of this, the presence of any underdrawings made with materials having different optical properties than those of the overlaying paint (e.g., graphite or silver point), often can be detected by photographing the artwork in the IR.

Although such IR reflectograms can provide valuable insights into the working practices of the artist,[3,4] the cost and specialized nature of the equipment available for acquiring the images has significantly restricted their use and as a result only a small percentage of paintings in museum collections have been examined with this technique to date.[5] This manuscript addresses this issue by describing the properties of an inexpensive, easy to use, high resolution instrument based on a consumer digital camera, allowing *in situ* acquisition of images in a way that is minimally disruptive to the operation of a museum. The capabilities of the camera are illustrated with a discovery made using it to acquire IR reflectograms from a painting in The State Hermitage Museum in St. Petersburg, Russia.

When IR reflectograms were first introduced, there were two ways of capturing the images: IR-sensitive photographic film, or videcon television tubes made with lead sulfide.[2] Both had limitations. In the case of film, even at a time when a wide variety of special emulsions were commercially available,[6] none had sensitivity to wavelengths longer than 900 nm,[7] whereas the optimal wavelength for examining some pigments extends up to 2200 nm.[8] In the case of vidicon tubes, the fairly low resolution required stitching together a number of separate images made of small sections of the painting, resulting in spatial distortions and artificial density variations in the final composite.

Improvements in detector materials and in electronics since the 1960s have resulted in the current availability of a 10 kg, 16 Mpixel camera system designed specifically for IR reflectography, offering 0.05 mm resolution at its closest focusing distance over the wavelength range of 900–1700 nm using an InGaAs sensor, with an image acquisition time of 2 min at an illumination level of 250 lx with its 150 mm $f/5.6$ lens.[9] Unfortunately, its cost of over $50 000 restricts the number of institutions that can afford it, and thus the number of works of art that can be studied. However, as discussed below, a commercial 8 Mpixel digital camera modified to operate in the IR and weighing only 1 kg can be acquired for a small fraction of the cost of the specialized instrument. Although this modified camera is limited to an upper wavelength of 1100 nm, the resolution is as high as 0.05 mm with an image acquisition time only a fraction of a second at 250 lx.

II. AN 8 MPIXEL CAMERA FOR IR REFLECTOGRAPHY

Recently the expected performance of cameras based on Si, InGaAs, HgCdTe, and InSb detectors was compared based on the relative transparency of various pigments in the wavelength range of 400–2500 nm.[8] The authors concluded that, although some pigments are better studied with detectors that are sensitive in the range of 1300–2200 nm, in most cases Si-based detectors provide good results. This present manuscript describes the relevant imaging properties of a system based on the Si detector in a modified commercial digital camera that can be easily operated by nonspecialists and costs less than $2000,[10] provides examples of IR reflectograms captured with it, and discusses its advantages and limitations for examining works of art.

A recent paper addressed use of a similar camera for acquiring IR reflectograms, but the implementation described in that paper requires bandpass filters in front of the lens.[11] Such filters eliminate all visible light from the viewfinder and from the autofocus and light metering systems, requiring that alignment and focusing be based on measured distances to the painting, and exposures determined entirely by trial and error.[12] The IR camera described in the current paper eliminates these limitations, resulting in a camera system that can be easily operated by nonspecialists. However, several technical issues affect the ability to capture IR images in the

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range of 830–1100 nm when modifying a camera that was designed for operation in the visible. These issues are addressed below.

III. OPTICAL ISSUES

A. Overview

Obtaining suitable optics for focusing images in the IR is not a problem, since the glass used in consumer camera lenses transmits light from approximately 320 nm in the ultraviolet, through the visible of 400–750 nm, and into the IR. The specific camera system described here is based on a Canon EOS 30D body with $22.5\times15\ \mathrm{mm}^2$, 8 Mpixel sensor (i.e., 37.5% smaller in linear dimension than a frame of 35 mm format film). Unless otherwise stated, in all cases the images were made with an autofocusing Canon EF 35 mm $f/2$ lens.[13,14] This camera has a 2336×3504 silicon-based complementary metal oxide semiconductor (CMOS) array at the focal plane to convert the energy from incoming photons into electronic charge that is then processed to form the file for each image. Operation relies on the absorption of light by the silicon, which occurs for photon wavelengths up to the bandgap of 1.12 eV (1110 nm), beyond which the Si becomes transparent. It is this sensitivity to IR that makes the CMOS array useful for IR reflectometry. However, since IR comes to focus at a different distance than does visible light, this sensitivity to wavelengths longer than 750 nm is a problem for a camera intended only for the visible.[15] For this reason the manufacturer places a low pass filter directly over the CMOS array to eliminate all IR from reaching the detector.

B. Replacement of the low pass filter with a high pass one

As explained above, because of the intrinsic sensitivity of the CMOS array to wavelengths up to 1100 nm, Canon covers the sensor of their 30D camera with a low-pass filter to eliminate IR. However, to be useful for IR reflectometry, this IR must reach the detector, and instead all visible light must be blocked. Several companies offer the service of replacing the manufacturer's low pass filter with one of several choices of high-pass filters.[16] The results in this paper were obtained with a camera modified using an 830 nm high-pass filter (Schott RG 830 equivalent).

C. The focal plane for IR Light

The "achromat" designs of most standard camera lenses brings only two colors of the visible spectrum simultaneously into focus in the image plane. For applications where the residual chromatic aberration of an achromat results in insufficient image quality, "apochromatic" designs bring three colors into focus. However, in both cases the longer wavelength IR comes to focus behind the image plane. Because of this, many older lenses designed for film cameras have a red mark indicating the amount of "focus offset" required to bring the IR into focus after having initially focused on the visible image. However, since "IR" is not a single color, but rather is a range of wavelengths, presumably the red mark is a compromise position based on the sensitivity of commercial IR photographic films which, as mentioned earlier, do not have sensitivity beyond 900 nm.[6]

Since focus is controlled by visible-light sensors in the camera body, the necessary offset to bring IR light to correct focus on the imaging sensor can be adjusted into the circuitry. That is, exactly as for the unmodified camera, the autofocus system determines the point of correct focus using visible light. However, a fixed electronic offset then sets the lens at the slightly further distance from the focal plane that is necessary for the IR.[17] With this offset, my measurements found the actual distance where the autofocus system of my camera focused the lens to capture the IR image was within ±1 mm of the ideal point at the object plane. This is within the depth of field of this lens even at maximum aperture.[18] Using a $2\times$ magnifier on the eyepiece, I found that for the Canon 35 mm $f/2$ lens, the distance of correct focus in the visible (i.e., in the viewfinder) is several mm different than where the autofocus mechanism on this specific camera had been adjusted for the IR. However, given how well the autofocus system works, there would be no reason to focus manually.[19]

D. Transmission of blue, green, and red sensor filters

Each of the 8×10^6 sensors in the camera includes a blue, green, or red filter, with the signals from the sensors appropriately combined by the internal processor to provide a color image in an unmodified camera. If each of these filters blocked all light of wavelength outside its bandpass, the sensors would be totally insensitive to IR, and the IR-modified camera would be useless for IR reflectography. However, as discussed below, measurements show that each of the filters transmits some IR, with the relative transmission with respect to each other varying by a factor of approximately 3. Using a gray-painted wall uniformly illuminated with indirect sunlight, the camera's exposure histogram showed the blue channel to have received 0.50 ± 0.12 less exposure than the red (i.e., $1\pm\frac{1}{3}$ stops), and the green 0.31 ± 0.06 less exposure ($1\frac{2}{3}\pm\frac{1}{3}$ stops). Other than the differences in relative transmission, the detailed shapes of the three exposure histograms showed similar structure, indicating roughly identical behavior in the IR for all three filters on the sensor.

The previous paragraph addressed the relative transmission of IR light by the blue, green, and red filters. To estimate the total transmission, I photographed a poster[20] illuminated at a level of 42 lx by four tungsten bulbs of measured color temperature 2700 K. For this test I used the same Canon 35 mm $f/2$ lens on the IR-modified Canon 30D and on an unmodified Canon EOS 1Ds Mk II. Both cameras were set at ISO 100 and the lens aperture at $f/4$. Integrated over the band of 820–1100 nm for which the modified camera is sensitive, the power radiated by a 2700 K black body source is 3.25 more than it is over the visible range of 400–750 nm for which the unmodified camera is sensitive. Hence, assuming the blue, green, and red filters are uniformly transparent across the IR, but only respond to their respective 1/3 of the light in the visible, an average of 10% transparency for each filter in the IR would result in requiring the same exposure time for both cameras under these illumination conditions.

Consistent with this estimate, the measured exposures were essentially identical: 1/3 s for the IR photograph and 1/4 s for the visible.[21] From these results I infer that the overall average transmission of each the filters in this camera to IR is approximately 10% of the transmission of a given filter within the appropriate blue, green, or red band in the visible. However, thanks to the IR-rich spectra of the tungsten lights used in nearly all museums, this level of transparency is completely adequate for our purposes.

E. Multilayer antireflectance coating

The multilayer coatings applied to all modern photographic lenses are designed to minimize reflections at the various interfaces, not only to increase the overall amount of light transmitted by the lens, but also to reduce scattering and stray light that otherwise would reduce contrast at the image plane. Since the design of any multilayer antireflectance coating can be optimized only over a finite wavelength range,[22] even for lenses intended for dual use on film and digital cameras, there is no reason for the designer to take into consideration wavelengths longer than 900 nm, beyond which no commercial emulsion has sensitivity. Consequently, we can expect the coatings used on the Canon lens to result in excess scattering in the IR, resulting in reduced contrast of the image. Consistent with this, with a target designed to provide very high contrast in the IR,[23] the brightness range captured by the IR camera and lens system was only $7\frac{1}{2}$ stops, whereas in the visible the same lens on an unmodified Canon 5D captured the full 9 stops of the target under the illumination conditions of these measurements.

To determine whether the limited range of intensity values captured by the IR camera was due to stray light caused by scattering within the lens, I substituted an uncoated lens using a temporary bellows to connect it to the camera.[24] Under lighting conditions where the target provided a luminance range of $7\frac{1}{2}$ stops in the visible, the IR camera with this uncoated lens produced an image of range of $7\frac{1}{2}$ stops, but only 6 stops with the 35 mm Canon lens. These measurements indicate the cause of reduced contrast in the IR lies within the lens, rather than with the CMOS sensor. However, as Sec. III F shows, even with this limitation, the overall system performs very well for the purpose of *in situ* analysis of paintings.

F. Resolution

Figure 1 shows the ability of this camera system to resolve small features on a target of medium contrast, consisting of narrow black, brown, and red lines on a tan background, in turn on dark brown wood. I used this target, rather than a high contrast one, to mimic the intended application of the camera.[25] The top image was taken at the camera's lowest noise setting of ISO 100,[26] and the bottom at ISO 400, with the target focused using the camera's autofocus system. Measured in the visible, the lighter region (brown) on the target between the two dark lines (black) to the left of the superimposed 1 mm bars has a reflectivity of 19%. The images in Fig. 1 are direct enlargements of portions of the as-captured images, without any adjustments made other than stretching the range of levels to cover a full 8 bits from black to white. As can be seen, the resolution is better than 0.5 mm at the lowest noise setting, and roughly 25% worse at ISO 400. Not shown is that noise continues to increase at even higher ISO values, degrading resolution further, to approximately 1 mm at the camera's maximum of ISO 1600.

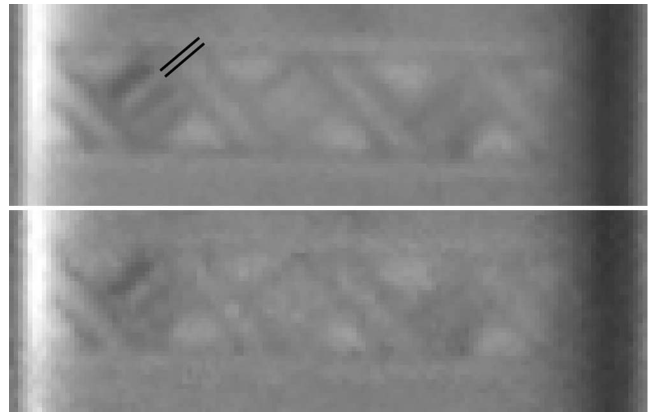

FIG. 1. Enlarged detail of IR images of a medium contrast target located 2 m from the focal plane, with aperture set to $f/4$. Spacing of superimposed bars is 1 mm. Camera set to: (top) ISO 100; (bottom) ISO 400.

To mimic capturing a full "typical" painting in a single image, the target for these measurements was located 2.0 m from the focal plane of the camera, at which distance the field of view captured by the 2336×3504 pixels of the sensor is $0.87\times1.3\ \mathrm{m}^2$, corresponding to a linear magnification of 0.37 mm/pixel. Comparing this with the measured $\sim$0.5 mm resolution at this distance, this IR camera and lens system appears to have a resolution limited by the pixel density in the 8 Mpixel sensor, not by any properties of the lens, or by degradation due to focusing error.[27]

To put these results in the context of the intended application, an IR reflectogram of the entire $0.83\times0.60\ \mathrm{m}^2$ "Arnolfini Marriage" by Jan van Eyck would resolve features as narrow as 0.3 mm, i.e., the width of a line made with a freshly sharpened pencil. At the closest focusing distance of this lens, 0.25 m, the camera captures a field of $6.7\times10\ \mathrm{cm}^2$, resolving features as fine as 0.05 mm.

IV. GENERAL PHOTOGRAPHIC ISSUES

A. Overview

Four factors are involved in creating a properly exposed image with any imaging system: the intensity of the illumination, sensitivity of the sensor (or film), shutter speed, and lens aperture. Since each of these factors has a different effect on the relevant properties of IR reflectograms captured by this camera system, I briefly examining each of them. Readers interested in more details on the photographic process should consult one of many books on the topic.

B. Illumination level

My measurements made in a selection of art museums shows the illumination level in rooms containing tempera and oil paintings is 200 lx, or somewhat less. This illumination is typically provided by a mix of tungsten ($\sim$2700–2800 K), or tungsten-halogen ($\sim$3100–3200 K) bulbs, and indirect sunlight (~3500–7000 K), with the relative percentages of each type of illuminant varying greatly depending on museum design and on time of day.

In general there is no relationship between the intensity of lighted emitted by a source in the IR, and the intensity in the visible. For example, a common fluorescent light fixture emits practically no IR, while a 40 W household bulb emits three times as much power over the IR range of this camera as it does in the visible. In the case of indirect sunlight, the amount of IR depends not only on the time of day, with early mornings and late afternoons being more IR-rich, but also on the surfaces from which the sunlight has reflected before reaching the paintings. However, since tungsten and tungsten-halogen bulbs typically provide a significant fraction of the illumination in many museum galleries and since their emission peak is around roughly 1000 nm,[28] taken together, these factors mean that we can expect the necessary exposure times for this IR-modified camera in a museum setting to be comparable to those for an unmodified camera.

C. ISO setting

My measurements described above in Sec. III A show that setting the ISO of this camera at its lowest sensitivity of 100 produces the highest resolution reflectograms.[26] Although this lowest level of sensitivity necessarily results in the longest exposures, this is not a problem since museum staff will be able to mount their cameras on tripods. However, as discussed above, in cases where it is necessary, increasing the setting to ISO 400, which reduces the exposure time by a factor of 4, only degrades the resolution of this camera by about 25% (e.g., from 0.5 to 0.6 mm for a painting located 2 m from the focal plane).

D. Shutter speed

Even without exposure to light, charges are thermally generated within the CMOS sensor. Although this "dark current" can be significantly reduced by cooling the sensor, doing so is not practical for the present application. Fortuitously, this source of noise is small compared to the photon-generated signals for shutter speeds down to 0.5 s. However, if longer exposures are required due to even lower light levels, or use of smaller lens apertures, there will be an increase in noise due to heating of the CMOS sensor during operation. Although the Canon 30D has a "long exposure noise reduction" feature[29] that digitally subtracts some of this noise, thereby increasing the signal/noise of the image, there should be no need for shutter speeds slower than 1 s under typical museum lighting conditions if my recommendations given below are followed.

E. Aperture

Although the depth-of-field of any lens increases as the aperture is decreased, since paintings are two-dimensional, depth of field issues are not relevant as long as the lens is accurately focused on the object and the image plane oriented parallel to it. However, when closed down a few stops from wide open, most lenses will provide measurably sharper images. In the case of the Canon 35 mm $f/2$ lens,

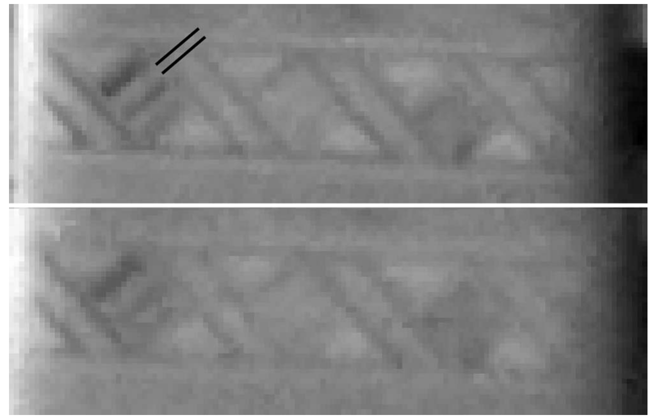

FIG. 2. Enlarged detail of IR image of a medium contrast target located 2 m from the focal plane with the camera set to ISO 100. Spacing of superimposed bars is 1 mm. (Top) Lens at $f/4$; (bottom) $f/2$.

measurements with a moderate contrast target show an improvement in resolution when stopped down to $f/4$, beyond which there is no discernable further change until $f/16$, at which point the resolution begins to degrade again. This is shown in Fig. 2 for two apertures. For this reason, this lens should be operated in the range of $f/4$–$f/16$ if the maximum resolution is required.

F. Exposure recommendations

Although the exposure meter in the Canon 30D is filtered to be sensitive only to visible light, the approximately 10% transmission of IR light by the blue, green, and red filters, coupled with the IR-rich output of tungsten light bulbs, means that under typical museum lighting conditions, the exposure meter will result in an IR image that is exposed roughly correctly. Since images and exposure histograms are available on the camera's liquid crystal display (LCD) for inspection immediately after capture, exposure compensation can be made if necessary, and another image immediately captured. What this means is that in a typical museum setting the IR-modified Canon 30D camera and 35 mm $f/2$ lens can be used on a tripod in aperture priority mode with its optimum settings of ISO 100 and $f/4$. To within the necessary accuracy, the camera will autofocus the 35 mm lens to the correct distance, and the shutter speed will be automatically set by the internal light meter to a value that will be faster than 0.5 s. The image and histogram of intensity will be displayed as soon as the image is captured, allowing the operator to fine-tune the exposure time, if necessary.

G. Miscellaneous issues

1. LCD resolution

The 12 pixels/mm spacing of the LCD screen on this camera is 13× coarser than the 156 pixels/mm pixel spacing on the CMOS sensor. In addition, under ambient lighting conditions, the dynamic range of the LCD screen is less than the $10f$-stop dynamic range of the CMOS sensor. In practice, what this means is that features that are not even discernable on the LCD will be quite apparent on the IR reflectogram once it is transferred to a computer and opened in an image editing program. Although the histogram on the LCD is im-

FIG. 3. Detail of a painting described in the text. (Left) Full 830–1100 nm range of the IR system; (right) at $f/8$ with 1000 nm high-pass filter over the lens, but without manually offsetting the focus to compensate for the additional focus shift at the longer wavelength.

portant for judging the correct exposure, the actual image on the LCD serves only as a rough guide to what will be seen once the image is opened on a computer.

2. Use of an external 1000 nm high-pass filter

The IR-modified camera described here produces IR reflectograms integrated over all wavelengths from 830 nm to the silicon cutoff of ~1100 nm. Depending on the optical properties of the pigments involved,[8] in certain cases additional features can be revealed if the shorter wavelengths in this range are eliminated. This can be done by placing a 1000 nm high-pass filter over the lens,[30] resulting in only the longest wavelengths being recorded. However, since this filter eliminates all visible light from reaching the camera's meter and autofocus sensors, a few extra steps are required for its use. First, in aperture priority mode with the lens at $f/4$ use the camera to autofocus the lens on the painting and acquire a properly exposed image, noting the exposure time. Next, switch the lens to manual focus and the camera to manual exposure control, attach the 1000 nm filter to the lens, and offset the point of focus closer by rotating the focusing ring by 5°, i.e., move the lens further from the sensor to allow the longer wavelength IR to come to proper focus.[31] Under typical museum lighting conditions, the image with this filter will require approximately 3 stops more exposure than without it. Thus, with the lens set at the same $f/4$ aperture as before, set a three-stop longer exposure and acquire a new image. The exposure obtained this way should be close to the shutter speed needed for the final, properly exposed IR reflectogram.

Since the procedure for using the 1000 nm filter requires additional expertise that not all operators may have, Fig. 3 (Ref. 32) shows the quality of an image obtained with this 1000 nm filter without manually offsetting the point of focus. Despite the lower contrast and reduced resolution of this image acquired under nonoptimum conditions,[33] it can be seen that the additional transparency of certain pigments at this longer wavelength reveals useful information. Note in Fig. 3 that the background, a blue-green color in the visible, is lighter due to increased transparency at 1000 nm. This results in small triangular regions becoming visible at the upper, left corner and at the upper edge directly over the man's head.

3. Video output

This camera has a video output port, making it possible to tether it to a television set to display the images as they are acquired. Although the resolution of a television signal is fairly low,[34] it is still sufficient for the IR underdrawings in some paintings, allowing the camera to also serve as a teaching tool in museum educational programs. In this way, real-time displays of IR reflectograms can be viewed in the gallery while people are standing in front of an actual painting as it is being discussed.

4. White balance

When using the camera's standard settings, the images will have a strong red tint because of the higher transmission of IR light through the red filter than through the blue and green. Although this tint can be eliminated later in an image editing program, I find it useful to adjust the settings to produce a neutral gray for the images as they are captured and displayed on the LCD screen. Although it can be done more precisely, if desired, it is easily accomplished to quite reasonable accuracy with the camera's "custom white balance" control, setting the white balance by using an image of healthy foliage, since such foliage broadly reflects across the IR spectrum.

5. Comparison with visible light images

It is very helpful to take images of the paintings at the same time with an unmodified camera as well. If a quick-release system is used on the tripod and if an identical but unmodified camera body is used, this easily permits having both the visible and the IR image available in separate layers in an imaging editing program, where quickly moving back and forth from one to the other makes it easy to see where new information has been revealed in the IR.[35] I find it helpful to have three such layers in an imaging program: color, as captured by the unmodified camera; monochrome, converted from the color image; and IR.

V. EXAMPLES OF IR IMAGES OF UNDERDRAWINGS

To test the IR-modified camera under its intended operating conditions, I took it, a remote cable release (to minimize vibration when tripping the shutter) and a small tripod in my carry-on luggage to St. Petersburg, Russia, where arrangements had been made to capture IR reflectograms in the State Hermitage Museum. As very brief background, several years ago the artist Hockney[36] observed features in a number of paintings that lead him to conclude some artists began using optical projections as aids as early as c1425. Together Hockney and Falco[37] subsequently found a variety of optical evidence in a number of paintings that demonstrated artists as important as Robert Campin, Jan van Eyck, and Hans Holbein the Younger used projected images from lenses or concave mirrors as direct aids for producing some features of some of their paintings. One painting, "Family Portrait" by

FIG. 4. (Color) Family Portrait, Lorenzo Lotto, 1523/1524 (96×116 cm^2 oil on canvas). Image captured *in situ* using a Canon 5D with 35 mm $f/2$ lens.

Lorenzo Lotto (1523/1524),[38] provided important evidence for our thesis, since it contains an octagonal pattern in the table covering that we showed to an accuracy of better than 1% is a composite of three segments, at three magnifications, resulting from the refocusing necessitated by the depth-of-field of a lens. This allowed us to calculate the focal length and diameter of the lens Lorenzo Lotto would have had to use.[37]

Figure 4 is the full image of this painting in the visible, captured *in situ* at the Hermitage by an unmodified Canon 5D camera using a Canon 35 mm $f/2$ lens. Examination of this image reveals some of the obstacles facing *in situ* image capture in a museum environment. The painting was illuminated by a combination of indirect sunlight from windows to the left and overhead tungsten lights, each having its own color temperature. The roughly equal darkness of shadows visible along the left and top borders, cast by the ornate frame in which the painting is mounted, indicate that the level of illumination from both types of sources was approximately equal. Closer inspection shows that the illumination across the surface of the painting is not uniform. This can be most easily seen in the region of the man's chest, which is too bright due to a partial specular reflection of one of the light sources that could not be eliminated by repositioning the camera within the constraints of the room. However, in spite of these obstacles, I was easily able to obtain IR reflectograms that have revealed important new information about this painting. A full discussion of the information extracted from the IR reflectograms will be submitted for publication elsewhere.[39]

FIG. 5. IR reflectogram of Family Portrait, Lorenzo Lotto, 1523/1524 (96×116 cm^2 oil on canvas) captured *in situ* using modified Canon 30D with 35 mm $f/2$ lens.

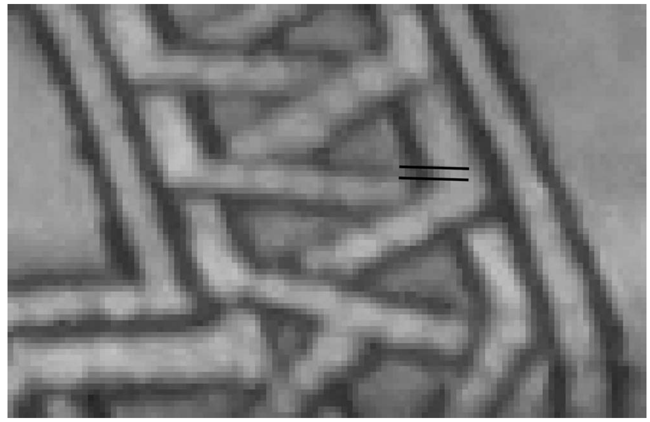

FIG. 6. Enlargement of the nearest, left portion of the octagonal pattern in Fig. 5. The superimposed bars have a spacing of 1 mm, showing the resolution under these *in situ* conditions is better than 0.5 mm.

Figure 5 is an IR reflectogram of the entire painting, captured under the less than ideal lighting conditions described in the previous paragraph. The exposure was 1/4 s at $f/4$ with an ISO of 100. As discussed earlier in this paper, these represent optimum conditions for noise and resolution from this imaging system. Also, the same 35 mm $f/2$ lens as used for Fig. 3 was used here as well. Although many features are revealed by this IR reflectogram, it is immediately apparent that Lotto used a different pigment for the woman's dress than he used for the man's jacket, providing us with previously unknown information about the artist's working technique that we will discuss elsewhere.[39]

To test the resolution under these conditions, Fig. 6 is a direct enlargement, without smoothing, from the IR image of the full 96×116 cm^2 painting, of the nearest, left portion of the octagonal pattern. As can be seen, the resolution of this IR imaging system under these *in situ* conditions is better than 0.5 mm.

Figure 7 shows the octagonal pattern in greater detail, enlarged from an image taken from approximately half the distance (so the resolution at the plane of the painting is ~ 0.25 mm). As can be seen by comparison with Fig. 4, the red and yellow pigments Lotto used are largely transparent in the IR, providing us with a clear view of the black lines he used to create this feature on the painting. Three distinct types of markings can be seen for the lines making up the triangular pattern within the borders of the pattern: well defined lines in the region nearest the front of the image, con-

FIG. 7. (Color online) IR reflectogram of the octagonal pattern. The arrows superimposed to the right indicate the three regions, which our previous analysis of this painting has found. Compare this with Fig. 1 of Ref. 37.

sistent with tracing; abruptly changing to tentative lines in the middle region, where our previous analysis showed the magnification was reduced by $12.6\% \pm 1.5\%$ due to refocusing (compare this figure with Fig. 1 of Ref. 37) and hence where Lotto would have had significant difficulty creating a plausible match for this geometrical pattern between the two regions; again abruptly changing to only short marks in the region farthest into the scene, where our previous analysis shows the magnification was reduced by an additional $13.5\% \pm 1.6\%$ due to needing to refocus a second time after again reaching the limit of the depth-of-field. These new results, combined with those of our previous analysis, provide important new insights into the actual working practices of an artist, revealing details about how he made use of projected images over 150 yr prior to the time of Galileo. For the purposes of the present manuscript, the important point is these high resolution IR reflectograms were captured *in situ* in a museum using only the ambient, nonuniform lighting.

VI. OTHER CAPABILITIES

At times it may not be possible to use a tripod, requiring the camera to be operated handheld. Under these conditions, it will not be possible to achieve the maximum resolution, since to minimize blurring due to unavoidable shaking of the camera by the operator, the highest ISO setting (i.e., highest noise) for the sensor will have to be used, along with the widest aperture of the lens. To demonstrate the capabilities of the camera under these conditions, Fig. 8 is a detail of a full IR reflectogram of a 115×122.5 cm^2 painting in the National Museum of Western Art in Tokyo, captured handheld at 1/30 s and $f/2$ with the ISO at 1600. The measured resolution of the IR reflectogram under these conditions is 1.2 mm, which is a factor of 2 and 3 worse than was the case for the optimum conditions of Fig. 6. However, in spite of the reduced resolution, quite useful information about the degradation of the underlying panel of this painting is clearly revealed in the IR.

The usefulness of this camera is not limited to two-dimensional works of art. Figure 9 shows a three-dimensional suit of armor enclosed in a protective plastic box in the New Orleans Museum of Art. As can be seen, the optical properties of the different materials used in the armor are such that it is much easier to distinguish between some of them in the IR than it is in the visible. Finally, I note that the camera is also useful for IR photomicroscopy.[40]

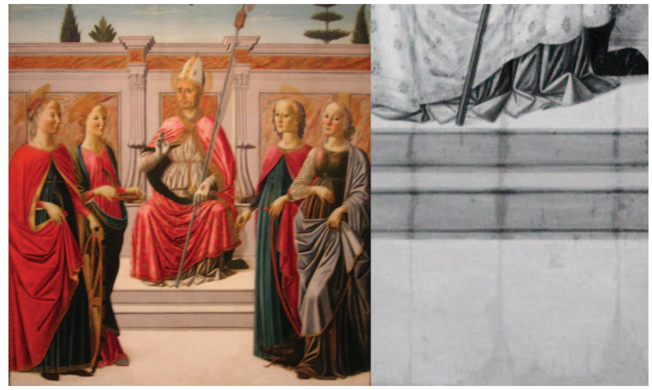

FIG. 8. (Color) (Left) "Saint Nicolas and Saints Catherine, Lucy, Margaret, and Apollonia," Francesco Botticini, late 15th century (115×122.5 cm^2 tempera on panel). (Right) 34×45 cm^2 detail of the lower center of the IR reflectogram of the full painting, captured handheld at 1/30 s with ISO at 1600. The measured resolution under these conditions is approximately 1.2 mm.

VII. DISCUSSION

Although this IR-modified camera does not cover the full range of wavelengths possible with a specialized camera that uses a sensor other than silicon,[9] and does not produce the same quality that would be possible if a painting were examined under ideal conditions of uniform lighting, its high resolution, low cost, portability, and ease of use by nonspecialists represents a significant advance over what has been

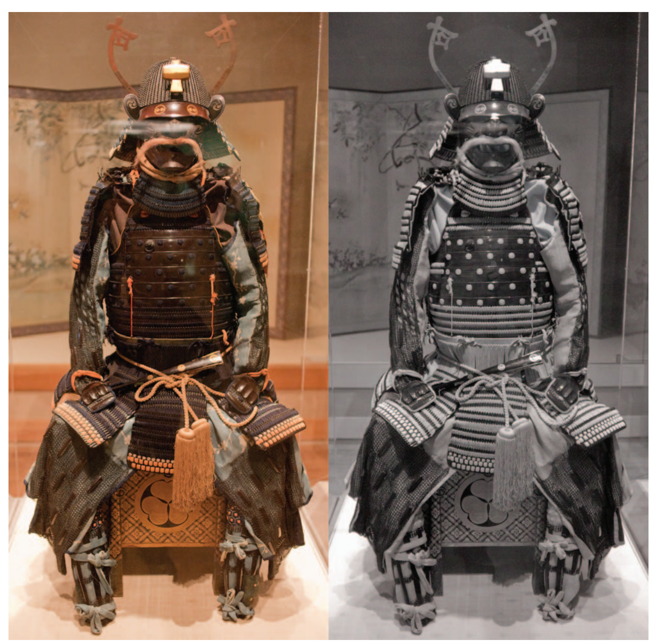

FIG. 9. (Color) (Left) Visible light image of a set of Japanese armor located within a protective glass enclosure. (Right) IR reflectogram of the armor. The various materials used in the armor are much more apparent in this image than in the visible due to their optical properties in the IR.

possible prior to this. Such a modified commercial digital camera for the first time makes it possible for a museum to capture high resolution IR reflectograms of their entire collection *in situ* without significant expenditure of staff time, and without disrupting the exhibition requirements of the institution.[41] In cases where analysis of an IR reflectogram revealed new information, the camera could be immediately returned to the painting in question to capture additional details. Further, the information revealed by these IR reflectograms could help curators decide if certain paintings warranted further detailed study by other scientific techniques.

The 1100 nm upper limit of sensitivity of this camera means some features in paintings cannot be imaged, because not all pigments are semitransparent in this wavelength range. However, the relevant point is that currently all such features of nearly all paintings are unavailable for study because only a small percentage of paintings in museums ever have been studied in the IR.[5] As the Lotto example illustrates, important information that otherwise simply would not be known can be revealed in IR reflectograms acquired *in situ* with this portable imaging system, at an average time of less than a few minutes per painting.[41]

It is worthwhile discussing improvements of similar imaging systems that might be made in the future. Within the limitations of the 1100 nm upper limit for sensors based on silicon, some useful advances could be made. While higher resolution is always desirable, linear resolution only scales as the square root of pixel number. Hence, all other factors being equal, a 16 Mpixel camera would only improve resolution to 0.35 mm from the 0.5 mm of the system discussed here. The ability to individually fine tune the electronic focus offset would be of significant help in achieving the maximum possible resolution allowed by the lens. Ideally, a manufacturer would supply lenses with multilayer coatings optimized for the IR. Failing this, an uncoated lens might offer an improvement in contrast over current lenses. Sensors without blue, green, and red filters would increase IR sensitivity by about a factor of 10 which, coupled with improvements in noise reduction at higher ISO settings, would enable high resolution IR reflectograms to be acquired without the need of a tripod. Finally, a full high definition television output would provide more than twice the resolution currently available, which would be a useful improvement for displaying images to audiences as they were captured.

VIII. CONCLUSIONS

This paper describes the relevant characteristics of an inexpensive, highly portable, IR imaging system, based on a modified digital camera, with which nonspecialists can obtain high resolution IR reflectograms of works of art *in situ*. The capabilities of this system were illustrated with several examples, including one that confirmed conclusions reached by a completely different type of analysis, as well as revealed important new information about a 16th century artist's working practices.

ACKNOWLEDGMENTS

I am grateful to Donghwan Har for reprints of several of his papers, Robert Edmund of Edmund Optics for donating the magic lantern lens, Richard McCoy and David Miller of the Indiana Museum of Art for arranging an early test on three paintings for which IR reflectograms already exist, Dr. Vladimir Matveyev, Deputy Director of The State Hermitage Museum, for permission to capture IR reflectograms of the Lorenzo Lotto painting, Sophie Faudel and Joël Calmettes for arranging the work at the Hermitage, and David Hockney and David Graves for a variety of invaluable advice related to the practice of art. My research on computerized image analysis is supported by ARO Grant No. W911NF-06-1-0359-P00001.

[1] The term "reflectography" was introduced in the 1960s to distinguish between the process of capturing images of paintings using raster-scanned vidicon tubes with sensitivity to wavelengths longer than 900 nm, and capturing "photographs" on film emulsions with sensitivity limited to wavelengths shorter than 900 nm. However, since it is the content of the final images that is of interest, advances in technology have made this distinction artificial and increasingly anachronous.
[2] J. R. J. van Asperen de Boer, Appl. Opt. **7**, 1711 (1968).
[3] *Art in the Making: Underdrawings in Renaissance Paintings*, edited by D. Bomford (National Gallery, London, 2002).
[4] M. Faries, in *Scientific Examination of Art: Modern Techniques in Conservation and Analysis*, edited by B. Berrie, E. Rene de la Rie, R. Hoffman, J. Tomlinson, T. Wiesel, and J. Winter (National Academy of Sciences - National Research Council, Washington, DC, 2002), pp. 87–104.
[5] G. Chiari and C. Scientist, personal communication (2008).
[6] Citing declining demand, in 2007 Kodak discontinued production of their High Speed Infrared HIE film, which had sensitivity to wavelengths up to 900 nm. At the time of this writing the only IR film available with sensitivity beyond 800 nm is Efke IR820.
[7] Kodak Infrared Films, N-17 (Eastman Kodak, 1976).
[8] M. Gargano, N. Ludwig, and G. Poldi, Infrared Phys. Technol. **49**, 249 (2007).
[9] Osiris, Opus Instruments, Ltd., 50 High Street, Bassingbourn, Royston, Herts SG8 5IE, UK.
[10] At the time of this writing a Canon 30D camera body retails for less than \$1000, a Canon 35 mm $f/2$ lens for under \$250, and the cost of conversion \$450 or less, for a total system price of under \$2000.
[11] S. Youn, Y. Kim, J. Lee, and D. Har, *Proceedings of the IASTED International Conference on Internet and Multimedia System and Applications to Visual Communications* (IASTED, Calgary, 2008), p. 128.
[12] Most lenses suitable for this work lack distance markings between 3 m and ∞, requiring the operator to estimate where to position the lens for a desired focus distance, and rely on depth of field to compensate for the inevitable inaccuracy of the setting.
[13] Canon, Inc., 30-2, Shimomaruko 3-chome, Ohta-ku, Tokyo 146-8501, Japan.
[14] A more recent model, the 40D, uses the same CMOS technology, but with 11% greater linear resolution. However, since operation in the IR depends on light being transmitted by the dyes used for the blue, green, and red filters, similar tests to those described in this paper would have to be conducted with this camera to be certain it actually would function for this purpose.
[15] Coastal Optical Systems makes a 60 mm focal length, $f/4$ lens that is apochromatic over the wavelength range of 315–1100 nm. However, aside from its \$4500 cost, the relatively long focal length requires positioning the camera a distance from objects that can be prohibitively far in some museum environments.
[16] My camera was modified by Life Pixel, http://www.lifepixel.com. The modification consisted of replacing the manufacturer's low pass filter on the sensor with an 830 nm high-pass filter (Schott RG 830 equivalent), and offsetting the electronic autofocus system to compensate for the different focal plane of the IR.
[17] Because of the wide range of IR wavelengths captured, it is impossible even with this offset to produce a perfectly sharp image using a lens

designed for high performance in the visible. However, determining the degree of image degradation due to this factor is outside the scope of this paper. Absent the availability of a lens designed specifically to bring this range of IR wavelengths to a common focus, the image degradation due to this factor becomes intrinsic to the measured overall performance of this imaging system.

[18] At the closest focus distance of 0.25 m for this lens, and at the maximum aperture of $f/2$, the measured depth of field extends approximately 4 mm on either side of the point of best focus.

[19] It is important to note that the amount of electronic focus offset is specific to a given lens. It happens that the same fixed offset works for both the Canon 35 mm $f/2$ and the Canon 50 mm $f/1.8$. However, at closest distance, the focus error for a Canon 100 mm $f/2.8$ macro is 2 mm, resulting in visible degradation of the IR image at maximum aperture for this lens.

[20] The poster for this test was a multicolor print from a museum shop, made using ink on paper.

[21] Although the sensors in these cameras are of different size and pixel density, these factors are not important here since we are only concerned with determining the total exposure time when they are set at the same sensitivity (ISO).

[22] H. Angus Macleod, *Thin Film Optical Filters*, 3rd ed. (Taylor & Francis, London, 2001).

[23] The low-spatial-frequency target consisted of 2 cm black bars spaced by 2 cm, consisting of photocopier toner fused on white photocopier paper, in turn placed on matte aluminum foil, and illuminated by direct sunlight. Measured with a Konica Minolta LS-110 $\frac{1}{3}$-degree luminance meter, within experimental uncertainty the brightness range of this target in the visible was exactly 9 stops for one set of experiments described in the text and $7\frac{1}{3}$ for the other.

[24] The lens used for this test consists of three elements in three groups and has a focal length and aperture I measured to be 120 mm $f/2.4$. Although it has no markings other than the manufacturer's name, James W. Queen & Company, Philadelphia, its age and appearance makes me believe it was intended for a 19th century magic lantern projector.

[25] Pigments vary in reflectivity from $\sim$4% for a deep black to $\sim$90% for a bright white. This range of less than 5f-stops for all paintings is far less than that of a scene containing an actual light source and shadows, where the brightness range can exceed 15f-stops.

[26] The International Standards Association (ISO) has standards for specifying the sensitivity of photographic film to light, based on the measured density of an exposed negative above the density of the unexposed film. This numerical system was carried over to digital cameras in analogy to the behavior of film. For film, small grains of silver are less sensitive to light, but result in higher quality images, whereas for digital sensors lower electronic gain results in less noise in the image. "ISO 100" is the lowest gain, highest quality setting for the Canon 30D.

[27] Canon places an antialiasing filter is above the sensor to reduce Moire fringes from subjects with fine detail. This filter degrades the resolution to slightly worse than the 1 pixel that otherwise would be possible.

[28] A common 40 W light bulb with a blackbody temperature of 2800 K has peak intensity at approximately 1000 nm, and a 100 W, 3200 K tungsten-halogen bulb at approximately 850 nm.

[29] When "custom function" setting 02 on this camera is enabled, for exposures of 1 s or longer a second exposure from the sensor is automatically acquired with the shutter closed. The camera's processor then does a pixel-by-pixel subtraction of this "dark noise" from the image, thereby reducing the noise from this source. Although this process doubles the time required to acquire an image, even if for some reason a 30 s exposure were required, it would not represent a significant restriction for this application to IR reflectography.

[30] Edmund Optics 1000 nm long pass filter, part number NT32-770, with threaded filter holder NT59-445. The 52 mm thread on the holder attaches directly to the Canon 35 mm, $f/2$ lens and is large enough not to cause vignetting of the image.

[31] If the camera's autofocus system has focused on a painting at a measured distance of 2.00 m from the plane of the sensor, the lens must be manually offset to 1.60 ± 0.05 m to bring the object into focus with the 1000 nm filter. This is accomplished by rotating the focusing collar by 5° in the direction of closer distances (i.e., to 1.6 m), which can be repeatedly done to an accuracy of approximately 1° using the serrations on the focusing collar (the lens used for this study has 144 serrations on its circumference or 2.5°/serration). Although the measured distances for correct focus in the IR differ somewhat from the scale on the lens, it happens that this 5° offset is appropriate for the 1000 nm filter everywhere within the distance range of 1–3 m as indicated by the scale. For all indicated distances less than 1 m, an offset of 7.5° brings the image into focus within the depth of field of the lens at $f/4$.

[32] "The Man of Sorrows with Saints and Donors," unknown French artist, c1525 (oil on oak panel, 47×55 cm^2). The Samuel H. Kress Collection at the University of Arizona Museum of Art.

[33] With the focus offset as described in Ref. 31, the measured resolution with the 1000 nm filter was $\frac{3}{4}$ mm at ISO 100 for the same medium contrast target located 2 m from the image plane as was used for the other tests in this paper.

[34] PAL has 625 vertical lines and NTSC has 525. If a 1 m diagonal television set is viewed from a distance of 3 m, these correspond to angular resolutions of 0.018° and 0.022°, respectively. For comparison, when held at a viewing distance of 30 cm the pixel spacing of the LCD screen of the Canon 30D corresponds to an angular resolution of 0.016°.

[35] It is not necessary to use the same model camera and lens for this purpose, or to take the visible and IR images from the identical location, but it does make the later process of accurately overlapping the images in an editing program somewhat easier.

[36] D. Hockney, *Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters* (Viking, New York, 2001).

[37] See, for example, D. Hockney and C. M. Falco, in *Human Vision and Electronic Imaging X*, edited by B. E. Rogowitz, Proceedings of the IS&T-SPIE Electronic Imaging (SPIE, Bellingham, WA, 2005), p. 326, and references therein.

[38] This 96×116 cm^2 oil on canvas painting, also referred to as "Husband and Wife" in a number of sources is in the collection of the State Hermitage Museum in St. Petersburg, Russia.

[39] D. Hockney and C. M. Falco (unpublished).

[40] After focusing in the visible, the microscope stage is lowered by an appropriate amount to bring the IR into focus on the focal plane of the camera. The necessary offset distance need only be determined once for each objective on a given microscope by making a series of exposures at different distances.

[41] By using an ISO of 1600 I was able to capture IR reflectograms of approximately 50 paintings in Tokyo's National Museum of Western Art in under an hour without use of a tripod. Although the noise due to the high ISO reduced the resolution to $\sim$1 mm, the longest exposure was 1/30 s, resulting in minimal additional loss in resolution due to camera motion.