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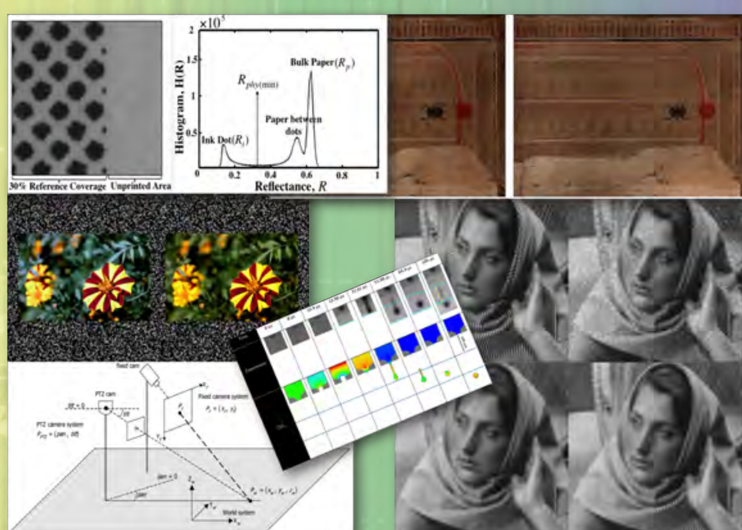

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Correcting for Non-uniform Illumination when Photographing the Mural in the Royal Tomb of Amenophis III (II): Applying Mural Images

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Abstract. *The authors have been attempting to digitize murals at the royal tomb of Amenophis III. When photographing the murals, two strobe lights, each of which had an umbrella, were used to provide uniform illumination. Nonetheless, the illumination was still somewhat non-uniform. This non-uniform illumination was corrected by applying an illumination model, which was evaluated using images of the simulated mural with and without white patches. The illumination model was then extended to two light sources and applied to images of the actual mural. The corrected images were observed to be more uniformly illuminated. © 2013 Society for Imaging Science and Technology.*
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INTRODUCTION

The royal tomb of Amenophis III, one of the pharaohs of ancient Egypt, is located in the Valley of the Kings in Luxor, Egypt. The burial chamber is 8.2 m wide, 15.4 m long, and 3.1 m (partially 4.7 m) high. The Amduat is painted on the four walls. We have been attempting to create a full-size digital image of this mural, so that the mural can be displayed on a computer display, which can be observed by many researchers in the world without going to the location.[1–3] Ninety-nine images (small-size images) of each position of the mural were taken with a 21 megapixel camera. These 99 small-size images were then stitched to produce a stitched image with approximately 500 megapixels, which is referred to as a middle-size image. From these middle-size images, we are attempting to produce a full-scale large-size image corresponding to the entire area of each of the four walls: north, south, east, and west.[2]

To make the illumination to the murals uniform, we have been photographing the murals using two strobe lights, each of which has an umbrella. The strobes are placed on the right and left sides of the mural. However, due to columns in the room and the low power of the strobe, it is impossible to illuminate the mural from a distance, and therefore it is difficult to achieve uniformity of the illumination.

In a microscopic image, correction of non-uniform illumination has been carried out using a luminance distribution in the conditions photographed under without any objects. Further, a correction has been carried out by approximating the illumination distribution with a polynomial equation.[4] Moreover, for trend removal of a radiological image, a second-order polynomial has been used.[5] The correction of illumination patterning in photomicrograph mosaics introduced by spacial non-uniformity of the capture illumi-

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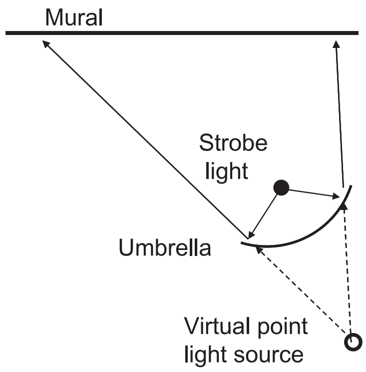

Figure 1. Illumination model in which illumination, provided by light from a strobe and reflected light from an umbrella, is assumed to act as a virtual point light source.

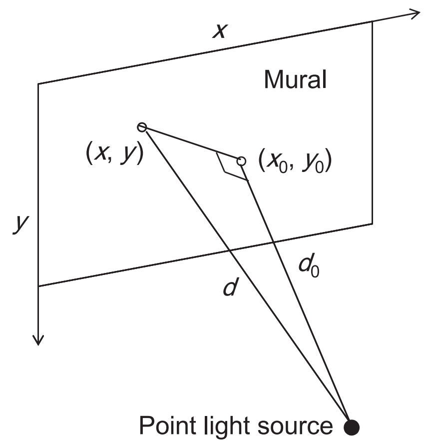

Figure 2. Geometric arrangement of the light source and the mural.

nation in each tile is described in Reference 6. We assumed illumination from the strobe and umbrella as a point light source, and newly devised an illumination model based on the assumption.[1] We showed that non-uniform illumination could be corrected using the model, and further attempted a method for correcting non-uniform illumination only with a photographed image.

ILLUMINATION MODEL

The two-dimensional second-order polynomial expressed by Eq. (1) is often used for illumination correction of a microscope image, etc.[4,5]

$$E = ax^2 + bxy + cy^2 + dx + ey + f, \tag{1}$$

where x and y are coordinate of a point, and a, b, c, d, e, f are constants.

The above model is referred to as the second-order polynomial (SOP) model. We can expand on the SOP model by arguing that it represents the first few terms of a Taylor expansion of the illumination of any light source. Under some circumstances it is an inferior model because higher order terms and more fitting coefficients are needed and it is inadequate for multiple light sources.

We assume illumination using a strobe with an umbrella as illumination from a point light source located at a longer distance, as is shown in Figure 1. Since for illuminance from a point light source an inverse square law holds, the illuminance E at any point (x, y) on the mural is given by the following equation:

$$E = \frac{p}{d^2} = \frac{p}{(x - x_0)^2 + (y - y_0)^2 + d_0^2}, \tag{2}$$

where p is the luminous intensity of the virtual point light source, and, as is shown in Figure 2, d is the distance between the point light source and a point (x, y); x_0 and y_0 are the coordinates of the foot of a perpendicular of the point light source to the wall, and d_0 is the distance between the point light source and the mural. We named this illumination model the point light source (PLS) model.

It is difficult to directly measure the illuminance on the mural. The luminance from a point having a certain reflectance is proportional to the illuminance to the point. The digital values of an image taken by a digital camera are recorded as converted values from a tristimulus value Y which is proportional to the luminance. Therefore, the tristimulus value Y obtained from the digital values of a photographed pixel of a point having a certain reflectance is proportional to the illuminance. The illuminance used in this study is not necessarily an absolute value, and the relative value is enough. Therefore, the tristimulus value Y, which was obtained from digital values R, G, and B of a photographed image of a point having a certain reflectance, is used as the illuminance. As a coordinate (x, y), a position coordinate of a pixel in a digital image is used.

CORRECTION OF NON-UNIFORM ILLUMINATION

Correction of non-uniform illumination is carried out by recording on a color that is different when illumination is not uniform, even if it is the same color. For example, the same color areas are white patches attached to a simulated mural and, later, the background of the mural. To correct the non-uniform illumination, the illuminance at each point is made to agree with the standard illuminance using a model equation, Eq. (2). It is necessary to determine values of the four constants, p, x_0, y_0, and d_0, from the measured values. These values are determined by non-linear optimization using measured values of illuminance E_i at a plurality of points (x_i, y_i), where $i = 1$ to n; n is the number of points. Namely, the four constants are determined so as to minimize the sum of squares of the differences between the measured values and calculated values using the model equation of illuminance. In this calculation, the tristimulus value Y, which was calculated using equations defined in the sRGB standard[7] from digital values R, G, and B recorded in an image, is used as the illuminance.

A specific correction method for illuminance is shown in Figure 3. In Fig. 3, the illuminance, which is primarily on a curved surface in two dimensions, is simply expressed as the illuminance at a distance x in one dimension, for

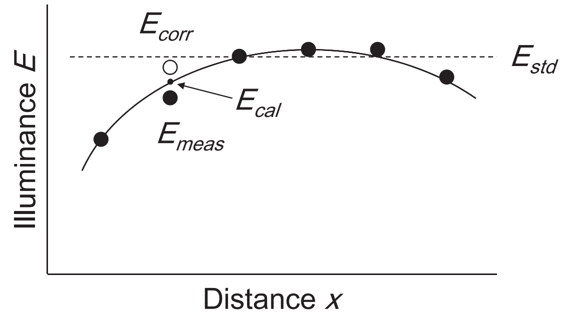

Figure 3. Correction method for illuminance.

explanation. The data shown in Fig. 3 are illustrations used to demonstrate the correction method. First, the four constants, p, x_0, y_0, and d_0 of the model equation are determined by optimization from measured values E_{meas} of illumination, which are shown by black points. Namely, the relative luminous intensity p and the position (x_0, y_0, d_0) of the virtual point light source are determined. The solid line in Fig. 3 is a line expressed by this model equation, and not only fits the measured values but also is smooth. It is the correction of the non-uniform illumination to convert the above curved line into a broken line that expresses the standard illuminance E_{std}. The correction coefficient k which converts illuminance at each point into standard illuminance E_{std} is determined from the illuminance E_{cal} that was calculated from the model equation,

$$k = E_{std}/E_{cal}. \quad (3)$$

Then, a corrected value E_{corr} of the illuminance is determined from Eq. (4).

$$E_{corr} = kE_{meas}. \quad (4)$$

In the example of Fig. 3, since the measured illuminance E_{meas} is slightly smaller than the calculated illuminance E_{cal}, the corrected E_{corr} is slightly smaller than the standard illuminance E_{std}.

Since the illuminance, that is, the tristimulus value Y, was multiplied by k by Eq. (4), the other tristimulus values X and Z are also multiplied by k to conform to the above. In this way, the digital values R, G, and B of the corrected image are determined from the tristimulus values X, Y, and Z, in which the illuminance was corrected; these values are then recorded in a file.

VERIFICATION OF THE ILLUMINATION MODEL USING WHITE PATCH IMAGES

The proposed model was applied to a simulated mural (2.4 m wide $\times$1.6 m high), a print of an image photographed in a preliminary survey. As is shown in Figure 4, which will be described below, thirty-five white patches were attached to the simulated mural, and photography was carried out with illumination only from the right side. The camera and lens used for the photography were a Sony Alpha 900 and an AF 50 mm 1:1.7, respectively. In photographing the murals, a strobe was used, and a white umbrella was also used with the emphasis on diffuseness.

On the supposition that the digital values of each pixel on the original image conform to the sRGB standard, the tristimulus value Y was determined from the digital values R, G, and B of the white patch on the image. The value Y is a relative value of illuminance E. Based on each of the position coordinates (x, y) and tristimulus values Y at 35 positions of the white patches, the constant values used by each of the illumination models expressed by Eq. (2) were determined by the non-linear optimization. Namely, the constant values were determined so as to minimize the sum of squares of the difference between the calculated and measured values of the tristimulus value. Color correction of each pixel was carried out in such a way that, based on the sRGB standard, the digital values R, G, and B of each pixel of the original image were converted into tristimulus values X, Y, and Z, which were then corrected depending on Y, a relative value of illuminance at the pixel, and further the corrected X, Y, and Z were inversely converted into R, G, and B. The original image and the corrected original image based on the PLS model, the proposed model, are shown in Fig. 4(a) and (b), respectively. The contrast of all images is slightly enhanced for clarity. The white patches of corrected image (b) look almost identical to each other. This result can also be understood from bar chart (e). However, in the background, the area on the right side is slightly brighter than the left side. This is because the area on the right side of the original simulated mural itself is slightly brighter than the left side. Namely, this is because when the original image of the simulated mural was photographed, the area on the right side was illuminated slightly more brightly compared to the left side. In addition, the results corrected by the above-described SOP model are also shown in Fig. 4(c) and (f).

Standard deviation is used for evaluating the variation of illumination on the white patches. Although the standard deviation of the tristimulus value Y of 35 white patches of the original image was 0.143, the standard deviation of this corrected by the PLS model became very small, namely 0.007. On the other hand, the result for an image corrected by the SOP model became only 0.055. As is observed in Fig. 4(c) and (f), one white patch located on the upper left corner is brighter than the others. This is due to the difference between the inverse square equation and the second-order polynomial, as is shown in Figure 5. Namely, in the range where x is small, both models well fit to the experimental values (not illustrated in Fig. 5), but, as x becomes larger, y rapidly decreases in the second-order polynomial, in contrast to the inverse square equation, where y slowly decreases. When the calculated value E_{cal} becomes smaller, the correction coefficient k becomes larger, and thereby the correction value E_{corr} becomes larger. For the above reason, the white patch located on the upper left corner, which is the result corrected by the SOP model, became brighter. Another reason is that the PLS model is physically accurate.

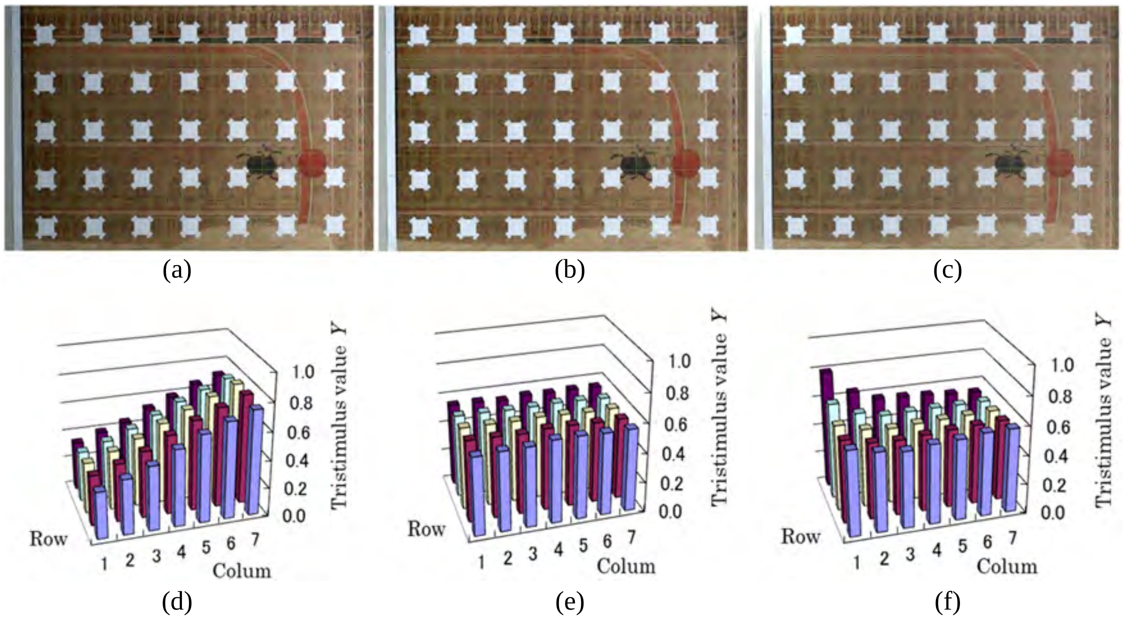

Figure 4. Original image illuminated solely from the right-hand side (a), and images corrected by using the proposed model (PLS model) (b), and the two-dimensional second-order polynomial model (SOP model) (c). The lower figures (d), (e), and (f) show the tristimulus values Y of white patches of the above images (a), (b), and (c), respectively. The standard deviations σ are 0.143, 0.007, and 0.055, respectively.

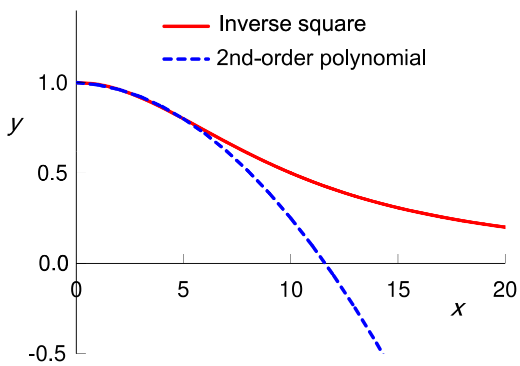

Figure 5. Curves of an inverse square equation and a second-order polynomial.

As was shown in Fig. 4, the tristimulus values Y of the white patches were made almost identical by the correction using the PLS model. This verifies that the illumination model developed by this study is effective.

VERIFICATION OF THE ILLUMINATION MODEL BY USING BACKGROUND

It is not permitted to attach the white patches used in the test of the illumination model to the mural at the royal tomb, which is a precious monument. Therefore, instead of the white patches, background regions having nearly the same color were used. UNESCO removed the bat feces and urine etc. on the mural and cleaned up the mural. The background of the mural was recovered as the original and almost uniform color.[8,9] As is shown in green in Figure 6, 45 rectangular background portions having nearly the same color, which were photographed without a white patch, were extracted manually. The digital values, R, G, and B of these rectangular portions were corrected in a similar way to the image with white patches. The original image photographed under illumination only from the right side and the image corrected using the PLS model are shown in Figure 7(a) and (b), respectively. The corrected image looks like one photographed under uniform illumination. As was described above, the right side of the simulated mural itself looks slightly brighter than other areas, but the non-uniform luminance is not observed in the corrected image, and the non-uniform illumination on the simulated mural itself is also corrected.

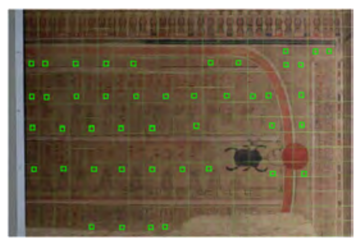

Figure 6. Extraction of backgrounds having nearly the same color.

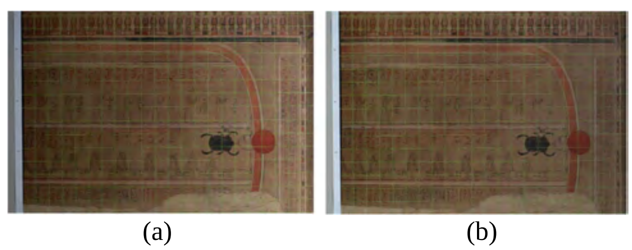

Figure 7. The original image of the model mural illuminated from a light on the right side (a) and an image corrected by using the point light source (PLS) model (b).

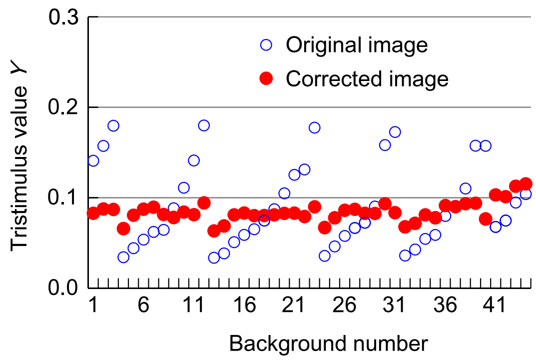

Figure 8. Tristimulus values Y of backgrounds in the original and corrected images shown in Fig. 7. The standard deviations σ are 0.046 and 0.011, respectively.

The tristimulus values Y of the background portions in the images before and after correction by using the PLS model are shown in Figure 8. The background numbers are given in the order from the upper row to the lower row, and from the left to the right in each row. It is found that the variation of the tristimulus values of the corrected image, that is, the standard deviation, is reduced to about 1/4 of that of the original image, that is from 0.046 to 0.011. It is assumed that the reason why the standard deviation of the corrected image is slightly larger than that of the corrected image with white patches is that the background portions do not have as uniform values as the white patches.

In this way, it was confirmed that non-uniform illumination can be corrected using the illumination model even from an image without white patches. Verification of illumination from both sides is described in Reference 1.

APPLICATION TO THE MURAL IMAGE

Since the photography was actually carried out using two strobes, each of which had an umbrella, from the right and left sides, the proposed illumination model (PLS model) was extended to the following equation for two light sources:

$$E = \frac{p_1}{(x-x_1)^2 + (y-y_1)^2 + d_1^2} + \frac{p_2}{(x-x_2)^2 + (y-y_2)^2 + d_2^2} + a, \qquad (5)$$

where the subscripts 1 and 2 denote the light source number. On the supposition that a constant amount of light enters from the surrounding area, a constant a is introduced in Eq. (5) to represent ambient light. On the other hand, in the second-order polynomial (SOP) model, even if the equation is extended to two light sources, the form of the equation is the same, and the number of constants remains six.

$$\begin{aligned} E &= a_1x^2 + b_1xy + c_1y^2 + d_1x + e_1y + f_1 \\ &\quad + a_2x^2 + b_2xy + c_2y^2 + d_2x + e_2y + f_2 \\ &= ax^2 + bxy + cy^2 + dx + ey + f. \end{aligned} \qquad (6)$$

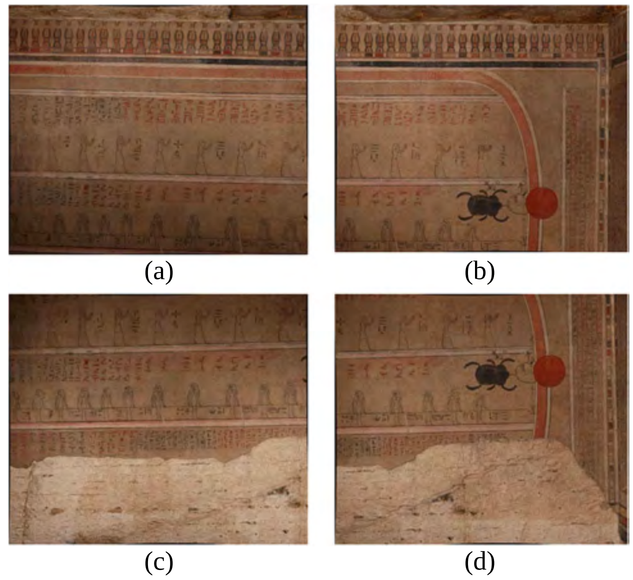

Figure 9. Four original images of the east wall.

Figure 10. An example of extracted background which is assumed to have the same color: (a) is identical to the image of Fig. 9(a), and (b) shows extracted uniform backgrounds.

Although the SOP model did not give a good result in the application to the simulated mural, an application to an actual image was tried in consideration of the case of multiple light sources in the future, since the equation of the model has the same form for multiple light sources, which is convenient for use.

The middle-size image formed by stitching photographed images was a 16 bit TIFF image of about 500 megapixels.[3] OpenCV 1.0, which we were using at that time, was not able to handle the above TIFF image. Therefore, an image of 20 megapixels formed by stitching JPEG images, which were produced rather than RAW images when pictures were taken, was used for the correction. Twelve images of the East wall were corrected using both PLS and SOP models. As an example, four middle-size images of the east wall are shown in Figure 9. Images (a), (b), (c) and (d) are the Image numbers e51, e61, e52 and e62 of Figure 11, respectively. Figure 9(a) is the one of the images which was most non-uniformly illuminated.

Uniform background portions were manually extracted. As an example, Figure 10 shows 65 background portions extracted from Fig. 9(a). The constants used in the two illumination models were determined by the non-linear

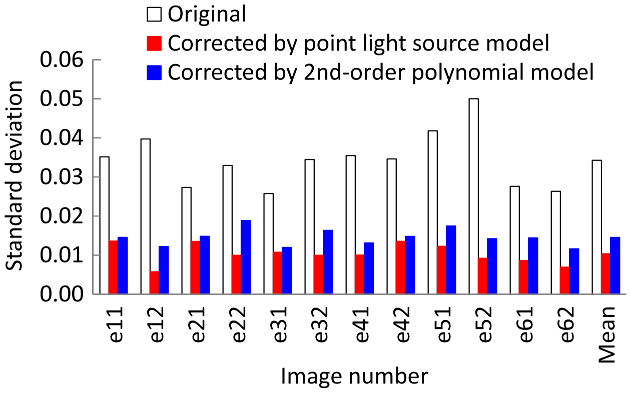

Figure 11. Standard deviations of the tristimulus values Y of backgrounds of twelve original and corrected images.

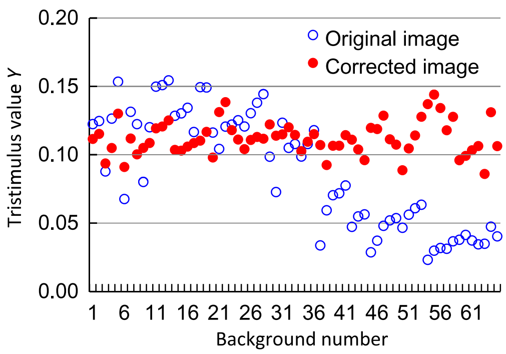

Figure 12. Tristimulus values Y of the backgrounds of Fig. 9(a), the original image, and Fig. 13(a) shown later, the corrected image, which correspond to the white and black bars of image number e51 in Fig. 11, respectively.

optimization as described above. The twelve images of the east wall were corrected using these constants. The standard deviations of the tristimulus values of the twelve images before and after the correction are shown in Fig. 11. The mean of the standard deviation of the twelve images was 0.034 for the original images, but it was decreased to 0.010 and 0.015 for the PLS model and the SOP model, respectively.

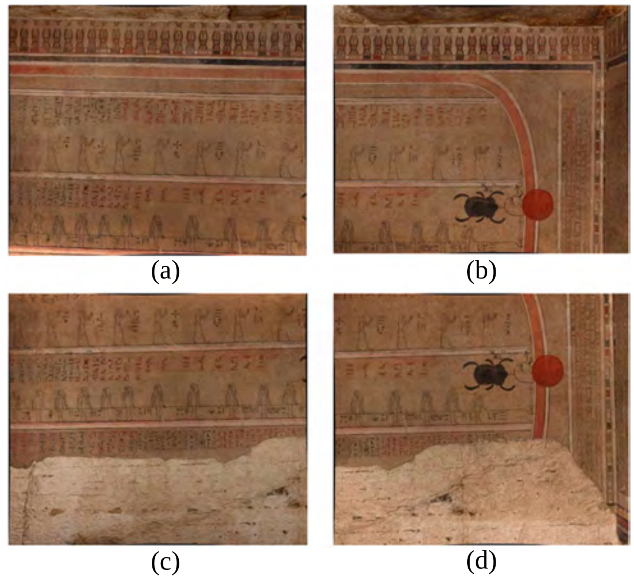

Figure 13. Corrected images of originals.

Of the twelve images, all images showed smaller standard deviation in the PLS model compared to the SOP model.

The image of Fig. 9(a), which is one of the most non-uniformly illuminated images, is designated by e51 in Fig. 11. The tristimulus values Y of 65 background portions in the original image and the image corrected by the PLS model are shown in Figure 12. It is found that the tristimulus values of the original image, which are distributed in the range from 0.02 to 0.15, are decreased to the range from 0.06 to 0.11 in the corrected image. Further, the standard deviation of the tristimulus values of the corrected image is reduced to about 1/5 of that of the original image, that is, from 0.042 to 0.008.

The four original images shown in Fig. 9 were corrected using the PLS model; the corrected images are shown in Figure 13. Although the lower part of Fig. 9(a) is darker than the central area, the lower part of the corrected Fig. 13(a) shows almost the same luminance as that of the central area. However, the left bottom part of Fig. 13(a) is slightly brighter than other areas, which indicates an overcorrection.

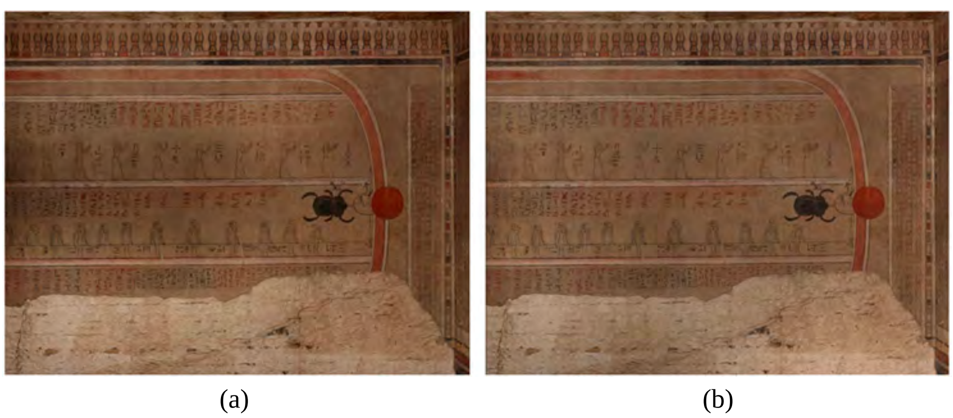

Figure 14. Stitched images from the original images (a) and from images corrected by using the proposed point light source (PLS) model (b).

Since it was impossible to extract uniform backgrounds from the delaminated areas of Fig. 9(c) and (d), it was not possible to reflect the tristimulus values of these areas in the calculation of the constants. Therefore, it seems that the luminances of the delaminated areas of Fig. 13(c) and (d) differ slightly from each other. In the future, it is necessary to incorporate the tristimulus values of the delaminated areas into the calculation of the constants.

Lastly, stitched images made from the original images shown in Fig. 9 and the corrected images shown in Fig. 13 are shown in Figure 14. Since the lower area of Fig. 9(a) and the upper area of Fig. 9(c) of the original images are slightly dark, the left central area of the stitched Fig. 14(a) is slightly dark. However, the corresponding area of the stitched image Fig. 14(b) made from the corrected images shows almost the same luminance as that of the other areas. The overcorrection of the left bottom part of Fig. 13(a) does not appear in the stitched image, because the overcorrected area is replaced by the corresponding overlapped area of Fig. 13(c).

SUMMARY

An illumination model was developed in which illumination with a combination of a strobe and an umbrella is assumed to be illumination from a point light source. The effectiveness of this model was verified with an image illuminated only from one side. Further, by applying the model to an actual mural image, it was shown that an image taken with non-uniform illumination could be corrected into an image which looked like an image taken with uniform illumination.

In future work, we are going to apply the model to 500 megapixels TIFF images and perform the illumination correction.

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