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Errata and Replacement

This manuscript was replaced on February 22, 2024, with a newer version. The previous version stated:

However, no studies have been conducted on improving the wavelength dependence of spatial resolution characteristics by correcting the MTFs of different channels.

on page 163-1. It now states:

The authors have studied the impact of MTF color dependence on display measurement [8], but not enough study has been conducted on improving the wavelength dependence of spatial resolution characteristics by correcting the MTFs of different channels.

A new Ref 8 has been added to correspond with the correction. Previous Refs 8-11 are now Refs 9-12.

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Experimental Study on Reducing Wavelength Dependency of Spatial Resolution Characteristics of a Digital Camera by MTF Correction

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Abstract

In digital cameras, the wavelength dependency of images captured through lenses and filters affects the spatial resolution characteristics of the images, which adversely impacts image quality. Previously, lens design and image processing techniques have been considered to address the aforementioned problem. Although aberrations could be improved, it was difficult to completely analyze the wavelength dependency of resolution characteristics. This study aims to reduce the wavelength dependency of the spatial resolution of digital cameras. Edge-based modulation transfer function (MTF) measurements using a 2D spectroradiometer were used to obtain wavelength-specific MTFs and quantitively reveal the wavelength dependency of the spatial resolution characteristics. Moreover, we experimentally confirmed that adjusting the MTFs of the CIEXYZ images obtained by combining spectral images to be closer reduces the difference in spatial resolution among color images while minimizing the color change before and after the adjustment.

Introduction

In digital cameras, the wavelength dependency of images captured using a lens may induce chromatic aberration. In addition, the characteristics of the color filters used to acquire the color information may exhibit a wavelength-dependent spatial resolution. These factors affect the spatial resolution characteristics of the captured digital images and image quality, leading to blurring and artifacts. For this reason, chromatic aberrations have been conventionally corrected by improving aberration in lens design [1, 2]; however, improvements in commercial digital cameras have not been widely considered owing to the cost and size of the cameras. Moreover, aberrations can be improved using software-based image-processing techniques [3]. Although artifacts, such as purple fringes, occurring in the contours of objects in digital images can be improved, the wavelength dependency of spatial resolution characteristics has not been fully analyzed.

Recent technological advancements in spectral cameras and the introduction of commercial two-dimensional (2D) spectroradiometers have helped digital cameras capture images at different wavelengths, which are used for display characterization and various applications. Compared to widely used one-dimensional (1D) spectroradiometer and three-channel RGB color cameras, a 2D spectroradiometer can acquire more essential color information. However, wavelength dependency on spatial resolution characteristics remains a concern for 2D spectroradiometers, which needs to be resolved to obtain more accurate real-world color information.

The modulation transfer function (MTF) is a useful indicator for evaluating the performance of cameras and optical systems. It indicates the spatial resolution characteristics of a camera or optical system at each spatial frequency, and varies depending on the characteristics of the lens and filters. In other words, the MTF helps comprehensively evaluate the resolution characteristics of the entire optical system, along with the number of pixels in the imaging device. In MTF research, the focus is on improving image quality via MTF enhancement [4, 5] and enhancing measurement methods [6, 7]. The authors have studied the impact of MTF color dependence on display measurement [8], but not enough study has been conducted on improving the wavelength dependence of spatial resolution characteristics by correcting the MTFs of different channels.

This study aims to reduce the wavelength dependency of spatial resolution by considering the wavelength-dependent MTF characteristics of a 2D spectroradiometer and correcting the MTF using an image-processing technique to make it color-independent.

Method

We propose a method for correcting a source MTF that is closer to the target MTF via image processing for multiple channels with different resolution characteristics.

Overall procedure

Figure 1 shows the flowchart of the proposed method. The input image is first divided into multiple channels. Then, MTF correction is performed between the source and target MTF within the channel images, and each channel image after correction is combined to generate a colored image. As the proposed method uses frequency modulation in the spatial frequency space, a 2D discrete Fourier transform (DFT) is performed before MTF correction, and a 2D inverse DFT (IDFT) is performed after MTF correction.

During the MTF correction process, the source MTF is modulated in the frequency space so that it can approach the target MTF. Herein, the target MTF is selected from all channels that exhibited the highest integrated MTF values up to the Nyquist frequency, and the MTFs in the other channels become the source MTFs. All MTFs are calculated using conventional measurement methods [9, 10].

MTF Correction

The source MTF is corrected by deriving a coefficient array of the same size as the number of vertical and horizontal pixels of the source image and multiplying it by the spectrum of the source image in the spatial frequency space. Herein, the MTF spectrum frequency is expressed in cycles per pixel (cpp). Thus, the Nyquist frequency in cpp of the image is 0.5 cpp. As it become difficult to obtain all the values of the coefficient array individually, the spatial frequency space between 0 and 0.5 cpp is quantized to 21 points, the correction coefficients are obtained, and the coefficient array is created for the number of pixels by interpolating the correction coefficients. Since a camera pixel processes a rectangular aperture and the MTF of a general camera is approximated by a sinc function [11, 12], the quantization points are determined to follow the differential value in the sinc function. Herein, a coefficient array is developed to make the source MTF closer to the target MTF by manually adjusting the correction coefficients of the quantization points.

Figure 2 shows the correspondence between 2D spatial frequency space and coefficient array. The coefficient array is 0.5 cpp from the center to the four corners, which corresponds to the Euclidean distance in the spatial frequency space. Thus, the frequency components located in the concentric circles in the spatial frequency space have the same coefficients. The green circles in Figure 2 represent the concentric circles of the 21 quantization points. The coefficients at frequencies other than the quantization point are obtained via the linear interpolation of the coefficients at the preceding and subsequent quantization points.

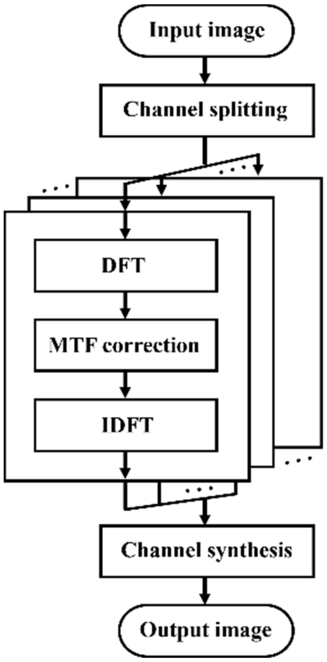
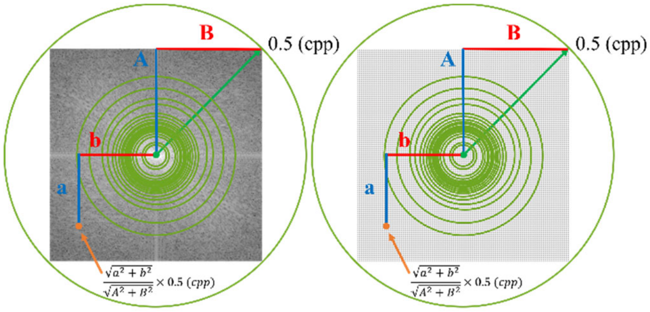


Figure 1. *Flowchart of the proposed method*



Input DFT image

Coefficient array

Figure 2. *Correspondence between 2D spatial frequency space and the coefficient array*

Experiments

To confirm the effectiveness of the proposed method, the MTFs of the channels of a 2D spectroradiometer (SR-5100, Topcon Technohouse Corp., Japan) were measured, and MTF correction was performed. Moreover, to analyze changes in the color and spatial resolution characteristics, real sample images captured under the same focus conditions as the MTF measurements were corrected.

Measurement for Spectral MTFs

A 2D spectroradiometer was used as a spectral camera to acquire 2D spectral information. It can capture spectral images from 380 to 780 nm at intervals of 1 nm in a single measurement. The MTFs of the 2D spectroradiometer were measured by analyzing the response of an edge spectral image illuminated by a white backlight [10].

The measurement environment is shown in Figure 3. The measurements were conducted in a dark room. An LCD monitor (ColorEdge PROMINENCE CG3146, Eizo Corp., Japan) was used as the backlight for the MTF measurement, and a white color was displayed in the center of the display screen. An edge target with a sharp straight blade was placed in front of the backlit display. In other words, in the region of interest (ROI) area acquired by the instrument, the edge target is taken to block a portion of the white backlight on the display. The edge target and the 2D spectroradiometer kept an orthogonal relationship to prevent stray light from shining into the 2D spectroradiometer. The backlit display was positioned at a distance outside the depth of field of the 2D spectroradiometer to eliminate the effect of the pixel structure of the display from the MTF measurement while calculating the MTF based on the images captured by the 2D spectroradiometer.

A slanted edge was used to measure the edge-based MTF of the 2D spectroradiometer. The edge target was tilted 3° with the optical axis of the 2D spectroradiometer as the axis of rotation to allow the edge to have various phases relative to the sampling position of the camera. Each MTF was calculated based on the acquired spectral edge images of the ROI. To prevent saturation in the pixels of the acquired ROI image, images were captured with an exposure time of 150 ms using the saturation detection function of the application that was compliant with the standard of the 2D spectroradiometer. The signal-to-noise ratio was improved by considering the additive average of three captured images to obtain a stable MTF. Printed text strings were pasted on the edge target, and the rough focus was adjusted by visually checking the blurriness of the text strings. The focus was further fine-tuned by moving the 2D spectroradiometer because its focus considerably impacts the MTF measurement. The working distance, i.e., the distance between the lens of the 2D spectroradiometer and the edge target, was varied by 10 mm from 380 to 420 mm, and the edge was photographed. The working distance with the largest MTF was defined as the optimal focus distance. The MTFs were determined by luminance images, which were spectral images (380 nm to 780 nm, 1 nm intervals) weighted and added by CIEXYZ color matching function (CIE1931). The working distance was set to 390 mm by the described method.

Based on the measurement results, the MTFs for five spectral images (450–650nm, at intervals of 50nm) are shown in Figure 4. The MTF of each measured spectral image was different for each wavelength. Moreover, the MTF tended to be lower at wavelengths near the edge of the visible wavelength range. These results quantitatively indicate that the spatial resolution characteristics of a 2D spectroradiometer are wavelength-dependent.

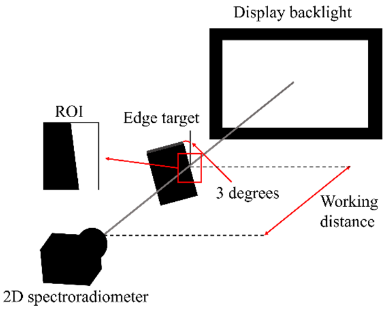


Figure 3. *Measurement environment*

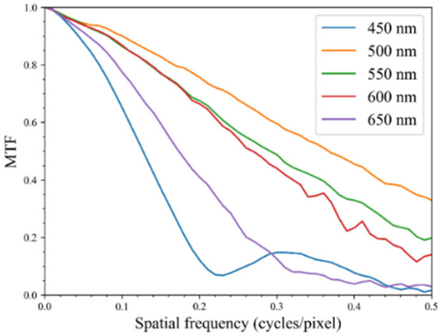


Figure 4. *MTFs of five spectral images*

Acquisition of MTFs for CIEXYZ images

The 2D spectroradiometer measured 401 spectral images from 380 to 780 nm, and it became difficult to correct the MTFs for all the images due to the huge amount of calculations. Therefore, the number of channels was reduced by combining 401 spectral images obtained from a 2D spectroradiometer with CIEXYZ images. Specifically, CIEXYZ images were obtained by weighting and adding the measured spectral images using the CIEXYZ color matching function (CIE1931). In addition, the MTFs were calculated based on the CIEXYZ edge images. The results are shown in Figure 5. From the MTF results of the spectral images, the MTFs of the channels were different, as shown in the figure.

Results of MTF correction

MTF correction was performed on the CIEXYZ images created from the spectral images. The Y image with the maximum integrated value of the MTF up to a Nyquist frequency of 0.5 cpp was set as the target MTF, whereas the other images were set as the source MTFs. In other words, the MTFs of the X and Z images were corrected to approach those of the Y image. The MTF correction results are illustrated in Figure 6. The MTF after correction was calculated from the image after the correction process for each channel before channel synthesis, as shown in Figure 1. Compared to the MTF before correction in Figure 5, the difference in the MTF of each channel was almost negligible, indicating that the correction process was performed with high accuracy. In addition, the MTF of the Z image in Figure 5 is very difference from that of the Y image, and is very close to zero from moderate to high frequency. Therefore, the proposed method can accurately correct MTFs, even for channels with extremely low MTFs.

To further confirm the effect of MTF correction, real samples were captured under the same focusing conditions as the MTF measurements. The X-Rite ColorChecker Passport, resolution chart (ISO 12233 compliant), and colorful lame samples were used as real samples. Each sample was illuminated by two parallel light sources (5000 K) from the left and right sides and captured using a 2D spectroradiometer. The MTF correction technique described in Figure 6 was applied to each channel of the captured real sample image, and a color image was obtained by synthesizing each channel image after correction. The channels were synthesized by converting the corrected CIEXYZ image into an AdobeRGB color space.

The MTF correction results of the edge image, resolution chart and lame sample are shown in Figure 7. Figure 7 (i) shows that the purple fringes around the edges decreased. Figures 7 (ii) and (iii) show that in areas where rapid luminance changes occur, the original images become purple; however, this effect is reduced in the corrected images. By bringing the MTF of the Z image, which exhibited a peak on the low-wavelength side, closer to the MTF of the Y image, the blue spatial resolution characteristics were increased, and purple fringes were suppressed. The results confirm that by bringing the MTFs closer to each other, differences in the resolution characteristics of each channel can be reduced.

The same MTF correction technique was applied to the ColorCheker image to verify the change in color before and after correction. To analyze the color change, the color difference was calculated for all 24 color patches of the ColorCheker image before and after correction. The CIE 1976 color-difference formulae was used to calculate the color difference. First, the CIEXYZ images before and after correction were converted into the CIELab color space (D50). The color difference was then calculated by averaging the central area (20 × 20) of each color patch and calculating the Euclidean distance before and after correction of CIELab value. The color difference among all the patches was less than 0.06. Thus, it was confirmed that the color did not change before and after correction in flat areas, with little change in luminance.

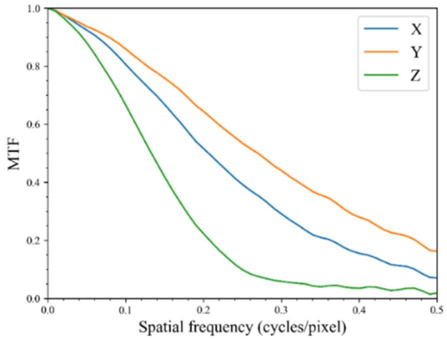


Figure 5*. MTFs of the CIEXYZ images*

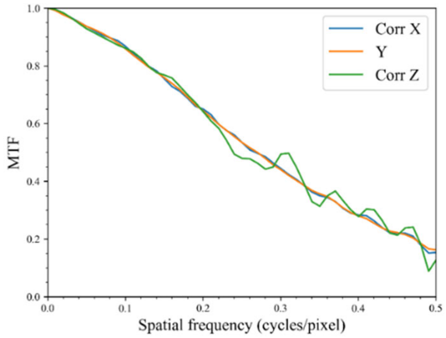


Figure 6. *MTFs of the CIEXYZ images after MTF Correction (Corr X and Corr Z represent the corrected MTFs, and Y denotes the MTF of the target image.)*

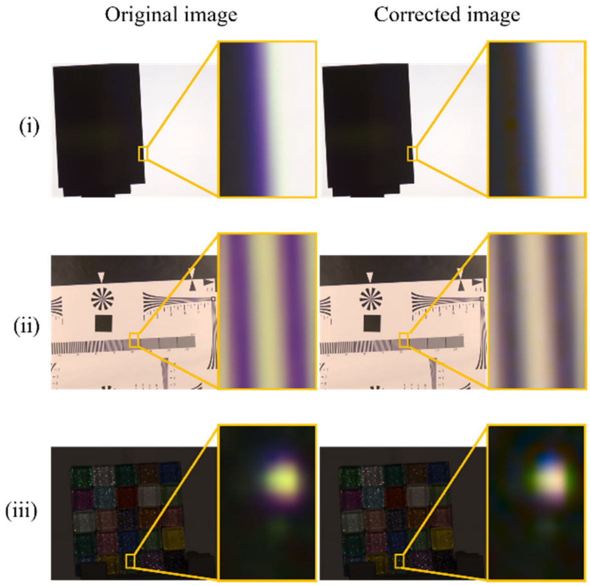


Figure 7. *MTF correction results of real sample images (the left-hand and right-hand sides show the original and corrected images, respectively). (i) Edge image used for the MTF measurement, (ii) resolution chart image, and (iii) lame sample image.)*

These results confirm that the proposed method can reduce the wavelength dependence of resolution characteristics without changing the color. Two issues must be addressed in future studies. First, artefacts that occur in corrected color images need to be reduced. As shown in Figure 7 (i), colored line artefacts slightly exist in the black areas inside the edges. These artefacts are assumed to be caused by color transformation during channel synthesis. Second, the coefficient array creation needs to be automated. Herein, the correction coefficients were manually obtained and the MTF correction was subjectively adjusted. In the future, automation will be necessary to quantitively perform corrections.

Conclusions

We proposed an MTF correction method using frequency modulation to reduce the wavelength of the spatial resolution characteristics of digital cameras. The effectiveness of this method was verified by applying the correction technique to real sample images captured by a 2D spectroradiometer. The results indicated that the difference in the spatial resolution characteristics of each channel can be reduced and the purple fringing effect can be suppressed. Moreover, X-Rite ColorChecker verified that the color difference before and after MTF correction did not change considerably and the color information was maintained.

Future studies will focus on eliminating artefacts that occur during channel synthesis. Moreover, an automated algorithm needs to be developed to determine coefficient arrays used for MTF correction, allowing for reproducible and objective corrections.

Acknowledgement

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Author Biography

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