Measurement and Modeling for the Two Dimensional MTF of Human Eye and Its Application for Digital Color Reproduction

Yoichi Miyake, Tetsuya Ishihara, Keitaro Ohishi and Norimichi Tsumura
Department of Information and Image Sciences, Chiba University
Chiba, Japan

Abstract

MTF (Modulation Transfer Function) is useful to characterize the response of a linear imaging system, namely MTFs of the imaging systems and human eye determine the overall sharpness quality. Therefore various merits used MTF have been proposed and applied for evaluation of image quality. However, almost merit used MTF is not considered anisotropy properties of imaging system and human eye response.

In this paper, dependence of the directivity of contrast sensitivity of human eye in various luminance, RGB color space and opponent color space is measured and analyzed. On the basis of those measured contrast sensitivities, two-dimensional MTF model of human eye is proposed and applied to designing and evaluate digital imaging system such as CCD array and digital color reproduction.

Introduction

In recent years, many kinds of digital imaging devices such as CCD camera, inkjet printer, LCD, Plasma display and have been developed and widely used to record and display of high quality images instead of conventional silver halide photography. Image quality of digital image is dependent on many factors, for example, a number of pixels of CCD camera, spectral sensitivity of filter, CCD array, image processing, digital half-toning algorithm, display and printer characteristics.

Point Spread Function (PSF) of those obtained images or each component of imaging devices, in other words MTF does not have isotropic properties such as photographic image. The merit of image quality is determined by overall characteristics of imaging systems and human eye response. Conventional silver halide photographic system has isotropic properties; therefore it was not necessary to consider the merits as two-dimensional characteristics of imaging systems and human eye.

In this paper, dependence of directivity in spatial frequency characteristics of human eye was measured in the luminance, RGB color space and opponent color space, r/g, b/y and w/k. On the basis of those measured results, the two dimensional mathematical MTF model of human eye was calculated and applied to designing of CCD array of digital camera. It was also applied to evaluate the digital color image quality by using the modified S-CIELAB (Spatial extension to CIELAB).

Measurement of the Contrast Sensitivity of Human Eye

Contrast sensitivity, namely MTF of eye was measured as the response for the stimulus of sinusoidal pattern with different spatial frequencies. The sinusoidal pattern was displayed on to the high quality TFT LCD that can be rotated in arbitrary angles as shown in Fig.1.

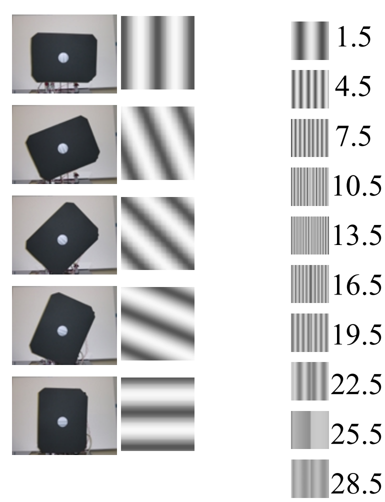


Figure 1 Sinusoidal pattern with different directions and spatial frequencies displayed on to high resolution LCD

In this experiment, contrast sensitivity of human eye was measured in five directions(0°, 22.4°, 45°, 67.5°, 90°), nine spatial frequencies (1.5, 4.5, 7.5, 10.5, 13.5, 16.5, 19.5, 22.5, 28.5 cycles/degree), four luminance levels (67.85, 42.40, 16.95, 7.29 cd/m^2) by eight observers. Measurement of the contrast sensitivity of human eye was done in the dark room at viewing distance, 2.5m and viewing angle, 2°. Figure 2 shows measured result of the contrast sensitivity four different luminance levels.

Figure 3 shows the directivity dependence of contrast sensitivities (average of four luminance), which is ratio to the contrast sensitivity of horizontal direction. It is clear that contrast sensitivity of eye does not have isotropic properties and the contrast sensitivity of vertical and horizontal directions is superior to that of diagonal direction. Similar results were obtained in contrast sensitivity at RGB channels.

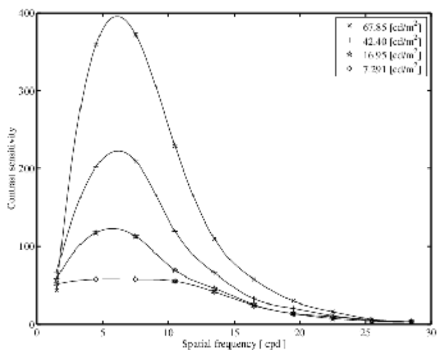


Figure 2 Contrast sensitivities as a function of spatial frequency at four luminance levels

We also measured contrast sensitivities of eye at opponent color space, r/g, b/y and w/k in two directions (0, 45 degree), nine special frequencies (1.5, 4.5, 7.5, 10.5, 13.5, 16.5, 19.5, 22.5, 28.5 cycles/degree) and five luminance levels by five observers. Transform to opponent color space r/g, y/b, w/k from XYZ was calculated by Eq.1.

$$\begin{bmatrix} w/k \\ r/g \\ b/y \end{bmatrix} = \begin{bmatrix} 0.279 & 0.72 & -1.107 \\ -0.499 & 0.29 & -0.077 \\ 0.086 & -0.59 & 0.501 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (1)$$

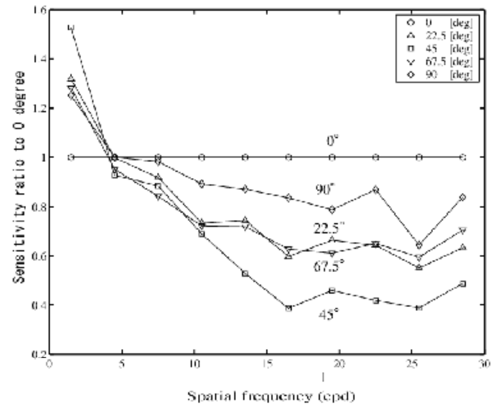


Figure 3 Contrast sensitivity ratio four angles to horizontal direction levels

Hering proposed the concept of opponent color in 1878. This theory was accepted as the most likely description of color processes in the optic nerve and cortex.[2] Therefore, measurement of the contrast sensitivity in the opponent color space is significant to apply the evaluation of image quality. Figures 4 and 5 show the contrast sensitivity of r/g, b/y at two directions (0, 45 degree), five luminance levels (15.00, 7.901, 5.00, 4.748, 2.452 cd/m^2).

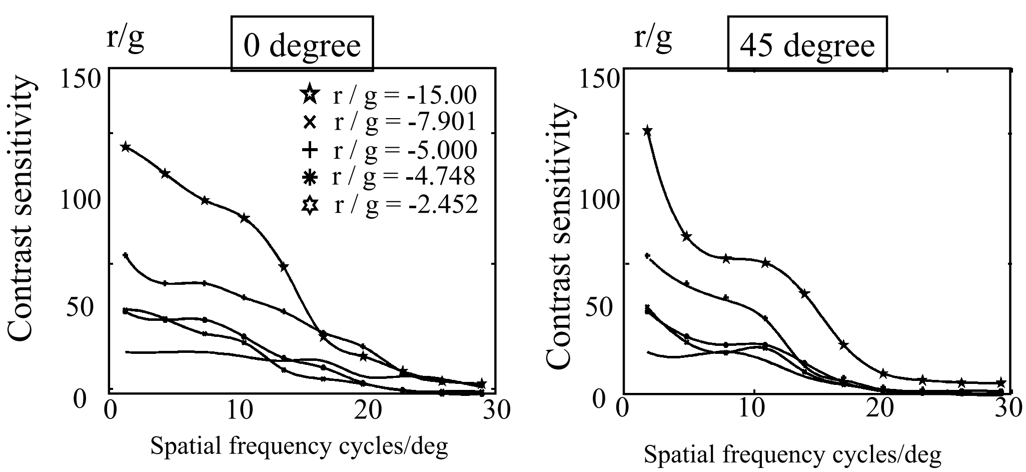


Figure 4 Contrast sensitivities at r/g color space

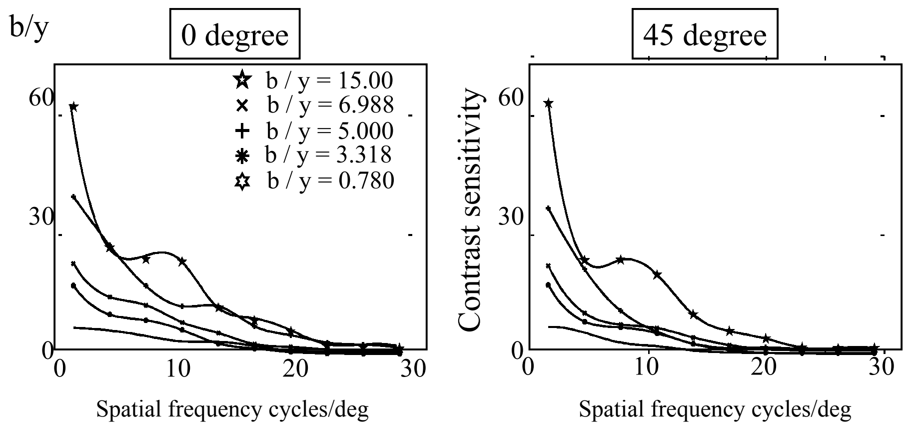


Figure 5 Contrast sensitivities at b/y color space

From those measurements, it became clear that the contrast sensitivity of eye has characteristics of band-pass filter for luminance w/k, and low-pass filter characteristics for chromaticity r/g and b/y.

Modeling of Two-Dimensional MTF of Human Eye

We calculated the two dimensional model of MTF of human eye in the opponent color space by Eq.(2) based on the contrast sensitivity measurement.

$$MTFv(u,v) = M_0(w)[1-\{1-\gamma(w)\}|\sin^b 2\phi|$$
$$w = \sqrt{u^2+v^2} \qquad (2)$$
$$\phi = \arctan(u/v)$$

where *u, v* is the spatial frequency in cycles/degree, $M_0(u)$ is MTF of horizontal direction as shown in Eq. (3), $\gamma(u)$ is relationship between spatial frequency at horizontal direction and the ratio of contrast sensitivity at 45 degree to horizontal direction. *b* is an arbitrary coefficient.

$$M_0(u) = \beta(\bar{o})M(u, m_p, \sigma_p)$$
$$-\varepsilon\{\beta(\bar{o})M(m_c, m_p, \sigma_p) - bias\}M(u, m_c, \sigma_c) \qquad (3)$$

In Eq.(3), $\beta(\sigma)$ is relation between maximum contrast sensitivity and average luminance ε is coefficient and $M(u,m,\sigma)$ is Gaussian function given by Eq. 4, which is based on the Barten's model.

$$M(u,m,\sigma)\ \exp\{-2\pi^2\sigma^2(u,m)^2\} \qquad (4)$$

In the modeling of the MTF at opponent color space, ε was determined as 0 in r/g, 1/4 in b/y and 1 in w/k respectively. The model agreed well with the measured result. The proposed mathematical model also agreed well with the measurements of the contrast sensitivity in luminance and RGB. Figure 6 shows one of the examples of two-dimensional MTF for r/g.

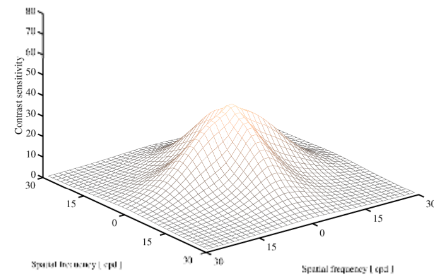


Figure 6 Example of the two-dimensional MTF for r/g.

Applications of Two-Dimensional Human Visual MTF to Image Evaluation

From our experiment, it became clear that the MTF of diagonal direction is less than that of the horizontal and vertical directions. The result was applied to analyze the CCD structure, color filter array and evaluation of digital image quality.

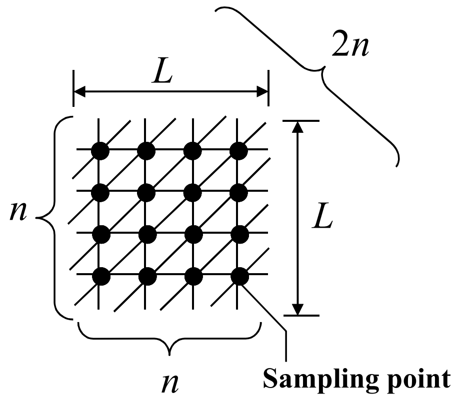
Image quality of CCD camera has been evaluated by a number of pixels. However, image quality of CCD camera is dependent on many factors such as structure and array of CCD, interpolation method, image processing and printer or display characteristics and so on. Image quality of two kinds of CCD camera with interlines and honeycomb structure and array was analyzed and compared with computer simulation.[3]

Figure 7 shows CCD array with interline and honeycomb structure.

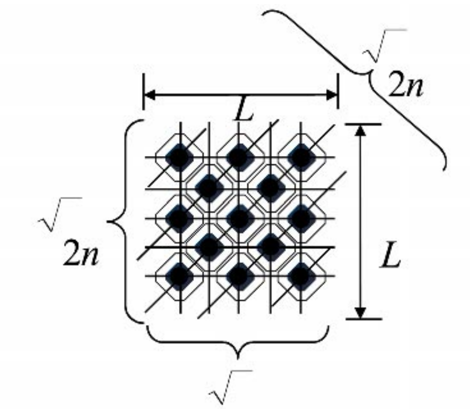
As shown in Fig.7(a), Nyquist frequency f_0 and f_{90} of horizontal and vertical directions in CCD with interline structure is as follow

$$f_0 = f_{90} = n/2L \qquad (5)$$

On the other hand, nyquist frequency f_{45} *for* diagonal direction is represented as shown in Eq. 6.



(a) Interline structure



(b) Honeycomb structure

Figure 7 Interline and honeycomb structure of CCD

$$f_{45} = \frac{n}{\sqrt{2}L} \tag{6}$$

where n × n is a total pixel number, L is horizontal and vertical length of CCD. It is clear that the nyquist frequency f_{45} *is* larger than f_0 and f_{90}. On the other hand, nyquist frequencies of horizontal vertical and diagonal directions in honeycomb structure CCD are presented as follows.

$$f_0 = f_{90} = \frac{n}{\sqrt{2}L} \tag{7}$$

$$f_{45} = n/2L \tag{8}$$

Equations (7) and (8) show that horizontal and vertical nyquist frequencies are larger than that of diagonal direction in honeycomb structure CCD. MTF of human visual system does not have isotropic properties and the MTF of vertical and horizontal directions is superior to the MTF of diagonal direction as shown in Figs. 2 to 5. Therefore we concluded that the honeycomb structure of CCD is better than the interline CCD to improve the sharpness. The observer rating experiment to the image calculated by the computer simulation confirmed it.

Two-dimensional MTF model for opponent color was also applied to evaluate the image quality based on S-CIELAB. Figure 8 shows the schematic diagram of the quality evaluation used modified S-CIELAB.

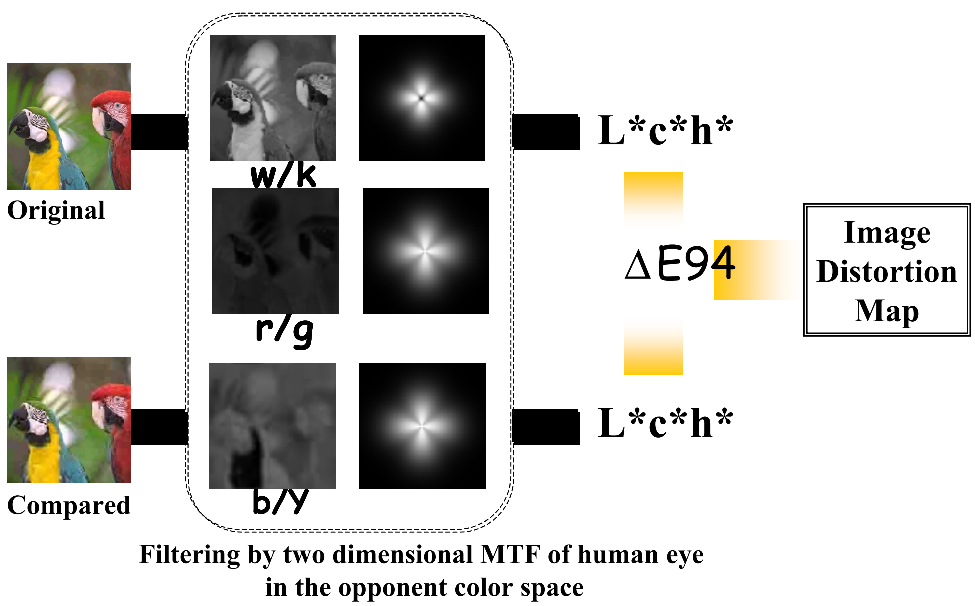


Figure 8. Schematic diagram of image evaluation based on modified S-CIELAB

Figure 9. Example of distortion map, (a) original image, (b) compressed image, (c) distortion map

In this process, first, original image and to be compared image are transformed to opponent color space, namely r/g, b/y and w/k. Secondly, Fourier transform of those images are convolved to the two dimensional MTF of human eye MTFv(u,v) modeling by Eq.(2). The convolved image is processed by inverse Fourier transforms and the color difference ΔE94 of each pixel between two images are calculated and then the distortion map is calculated. Figure 9 shows one of the example of distortion map between original image and image by JPEG compression. Original image is oil paint that is taken by five bands camera and is recorded the reflectance spectra of each pixel of oil paint. From the distortion map, we can analyze precisely the relationship between color difference and spatial frequency characteristics of eye. Namely, in this distortion map, white region shows that the color difference is larger than 3.0, which is determined by human visual characteristics.

Conclusion

We have measured contrast sensitivity of human eye in different directions at various luminance, RGB color space and opponent color spaces. On the basis of those measured results, mathematical model for the two dimensional MTF of eye was proposed and the model was applied to evaluate effect of CCD array and image quality by modified S-CIELAB. We consider that two-dimensional MTF model of human eye is a very significant to designing and evaluating of digital imaging systems.

Acknowledgment

The authors would like to thank Mr. Yoshida, LCD System Device Development Center, SHARP Corporation for providing the rotary LCD system.

References

1. P.G.J. Barten: Contrast sensitivity of the Human Eye and Its Effect on Image Quality (SPIE Press, 1999)
2. B.A. Wandell: Foundations of Vision (Sinauer, 1995)
3. M. Baba, T. Ishihara, M. Tamaru, M. Inuiya, H. Haneishi and Y. Miyake: Evaluation of Image Quality for CCD Camera with Honeycomb Structure by Computer Simulation, J. Photographic Science and Technology of Japan, 63(4) 204-209(2000)
4. X. Zhang, E. Setiawan and B. Wandell:Image Distortion Map, Proc. Fifth IS&T/SID Color Imaging Conference, 1220-125 (Scottsdale, 1997)

Biography

Professor Yoichi Miyake has been professor in the Department of Information and Image Sciences, Chiba University since 1989. He received Ph.D. from Tokyo Institute of Technology in 1978. During 1978 and 1979, he was post doctoral fellow of Swiss Federal Institute of Technology (ETHZ). In 1997, he was a guest professor of University of Rochester. He received Charles E. Ives Award from IS&T in 1991. He became a fellow of IS&T in 1995. He also received Electronic Imaging Honoree of the year in 2000 from SPIE and IS&T. He published many books and original papers on the image processing, color science and image evaluations. He is currently served as a president of SPSTJ and vice president of IS&T. etsuya ISHIHAR. He received his BS and ME in information and image science from Chiba University in 2000 and 2001 respectively. He jointed to the Patent agency of Japan in 2001.

Keitaro Ohishi is a graduate course student of Department of Information and Image Sciences.

Norimichi Tsumura received his BE, ME and Ph.D. in Applied Physics from Osaka University in 1990, 1992, 1995 respectively. He jointed Department of Information and Image Sciences, Chiba University as assistant professor in 1995. He was a visiting scientist of University of Rochester from 1999 to 2000. He received Optics prize and applied physics prize for young scientist from OSJ and SAPJ in 1995 and 2000. He is interested in the color image processing, computer vision and biomedical optics.