Measuring Spectral MTF of Color Display Using Trichromatic CCD Camera

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Abstract

A method is proposed for measuring the spectral modulation transfer function (MTF) of color displays. The spectral MTF is defined as the absolute value of Fourier transform of the spectral line spread function (LSF) on displays. In order to obtain the spectral LSF, we measure the spectral radiance distribution of a displayed single line of various colors. The measurement system is constructed with a charge coupled device (CCD) and three band-pass filters. Three-bands CCD values can be transformed to 81-bands spectral radiance using the transformation matrix generated by multiple linear regression analysis. Using our proposed method, we measured the spectral MTFs of a color liquid crystal display (LCD). The MTF characteristics of the LCD were measured as device-independent value.

1. Introduction

Flat panel displays (FPDs) such as liquid crystal displays (LCDs) and plasma display panels (PDPs) have been widely used for TV displays in place of conventional cathode ray tube (CRT). The FPDs with higher image quality have been developed year by year. The display performance can be compared by image quality. Spatial modulation transfer function (MTF) is one of the famous criteria to evaluate the still image quality of displays[1,2,3]. In the medical field, the MTF of monochrome displays for diagnosing of X-ray images is measured by a lot of researchers[4,5,6]. In case of color displays, it is difficult to define MTF because the MTF changes with the color of displayed lines. Then, Song et al. propose that the MTF of color displays should be measured for each color[7,8]. However, in Song's method, the measured MTFs are depends on the spectral sensitivity of the camera system.

In this paper, the MTF of a color display is measured with device-independent value. We propose a measurement method of spectral MTF with a spectral radiance standardized as physical value using a CCD camera. The spectral MTF is calculated for each visible wavelength.

2. Modulation Transfer Function

2.1 MTF of Monochrome Display

Modulation Transfer Function (MTF) is commonly used to evaluate sharpness of imaging systems. The MTF of monochrome displays is defined as,

$$M(f) = \left| \int_{-\infty}^{+\infty} l(x) \exp(-i2\pi f x) \mathrm{d}x \right|, \quad (1)$$

$$\mathrm{MTF}(f) = M(f)/M(0), \quad (2)$$

where f is spatial frequency on the displays and $l(x)$ is the line spread function (LSF) obtained by integrating the luminance distribution of a displayed single pixel line over the y-direction.

2.2 MTF of Color Display

Differently from monochrome displays, color displays are generally constituted with three individual sub-pixels, red (R), green (G), and blue (B). Because various colors are displayed by combinations of 3 sub-pixels, the line spread changes depending on the color. To evaluate the image quality of color displays, Song et al. propose a method that LSFs of various colors are measured with a monochrome camera, and

MTF is calculated for each color[7,8]. The MTF of color displays is defined as,

$$M_{r,g,b}(f) = \left| \int_{-\infty}^{+\infty} l_{r,g,b}(x) \exp(-i2\pi fx) \mathrm{d}x \right|, \quad (3)$$

$$\mathrm{MTF}_{r,g,b}(f) = M_{r,g,b}(f) / M_{r,g,b}(0), \quad (4)$$

where r, g and b are input pixel values of R, G and B from 0 to 255, respectively, $l_{r,g,b}(x)$ and $\mathrm{MTF}_{r,g,b}(f)$ are the LSF and the MTF for each color.

However, this method has a problem that the measured LSF (MTF) depends on the spectral sensitivity of the camera used for the measurement.

2.3 Proposed Spectral MTF

To measure MTFs of color displays as device-independent value, we propose spectral MTF measured with spectral radiance. The spectral MTF is defined as

$$M_{r,g,b}(f,\lambda) = \left| \int_{-\infty}^{+\infty} l_{r,g,b}(x,\lambda) \exp(-i2\pi fx) \mathrm{d}x \right|, \quad (5)$$

$$\mathrm{MTF}_{r,g,b}(f,\lambda) = M_{r,g,b}(f,\lambda) / M_{r,g,b}(0,\lambda), \quad (6)$$

where λ is visible wavelength, $l_{r,g,b}(x,\lambda)$ and $\mathrm{MTF}_{r,g,b}(f,\lambda)$ are spectral LSF and spectral MTF for each color, respectively. In order to obtain the spectral LSF, we measure the spectral radiance distributions of a displayed single line of various colors. However, it is impossible to take directly spectral radiance images by standard RGB cameras. In this paper, the spectral radiance distributions are estimated from camera images based on multiple linear regression analysis.

3. Spectral Radiance Estimation

3.1 Multiple Linear Regression Analysis

In general color displays, the spectral radiance distribution $\boldsymbol{r}_{x,y}$ can be estimated from the 3-bands image $\boldsymbol{v}_{x,y}$ based on multiple regression analysis as follows,

$$\boldsymbol{r}_{x,y} = \mathrm{G}\boldsymbol{v}_{x,y}, \quad (7)$$

where G is the regression coefficient matrix given by

$$\mathrm{G} = \mathrm{RV}^t (\mathrm{VV}^t)^{-1}, \quad (8)$$

$$\mathrm{R} = [\boldsymbol{r}_1, \boldsymbol{r}_2, \cdots, \boldsymbol{r}_n]^t, \quad (9)$$

$$\mathrm{V} = [\boldsymbol{v}_1, \boldsymbol{v}_2, \boldsymbol{v}_3], \quad (10)$$

where t is matrix transpose, and -1 is inverse matrix, $\boldsymbol{r}_i$ (i = 1, 2, ..., n) is a row vector of spectral radiance for each wavelength, and $\boldsymbol{v}_j$ (j = 1, 2, 3) is a row vector of camera response value for each band.

3.2 Making Multiple Regression Coefficient Matrix

Our system for calculating the multiple regression coefficient matrix G consists of a LCD (SHARP AQUOS(LC-45AE5)), a monochrome 16-bit CCD camera (Lumenera, Infinity 4) with three band-pass filters (Fujifilm Filter Optical), and a spectroradiometer (MINOLTA, CS-1000). High resolution images are measured in close-up mode using a bellows. The matrix is obtained as follows:

1. Spectral radiances of 24 color patches displayed on the LCD are measured with the spectroradiometer. These patches are consisted of 8 red, 8 green and 8 blue patches which have different luminance whose input pixel values are from 0 to 255 at 32 intervals, respectively. The obtained spectral radiances have 81 dimensions (380-780nm, at 5nm intervals).
2. These 24 patches are also measured with the 3-bands CCD camera as shown in Fig. 2.
3. The 81x24 matrix **R** in Eq. (9) is obtained from measured spectral radiances.
4. The 3x24 matrix **V** in Eq. (10) is obtained by meaning 3-bands CCD images.
5. The 81x3 multiple regression coefficient matrix **G** is obtained by Eq. (7).

Figure 1 shows a flowchart to obtain the matrix **G**.

3.3 Estimation Accuracy

Accuracy of estimated spectral radiances by Eq. (7) was evaluated in this section. Ten test color patches were randomly selected, and we calculated RMSEs of test patches between actual measurement values using the spectroradiometer and estimate values using the 3-bands CCD camera with the matrix G. In order to prove that estimated values are not depend on measurement cameras, the same experiments were performed under two camera conditions: one condition uses a set of band-pass filters shown in Fig. 3(a), and the another uses a set shown in Fig. 3(b).

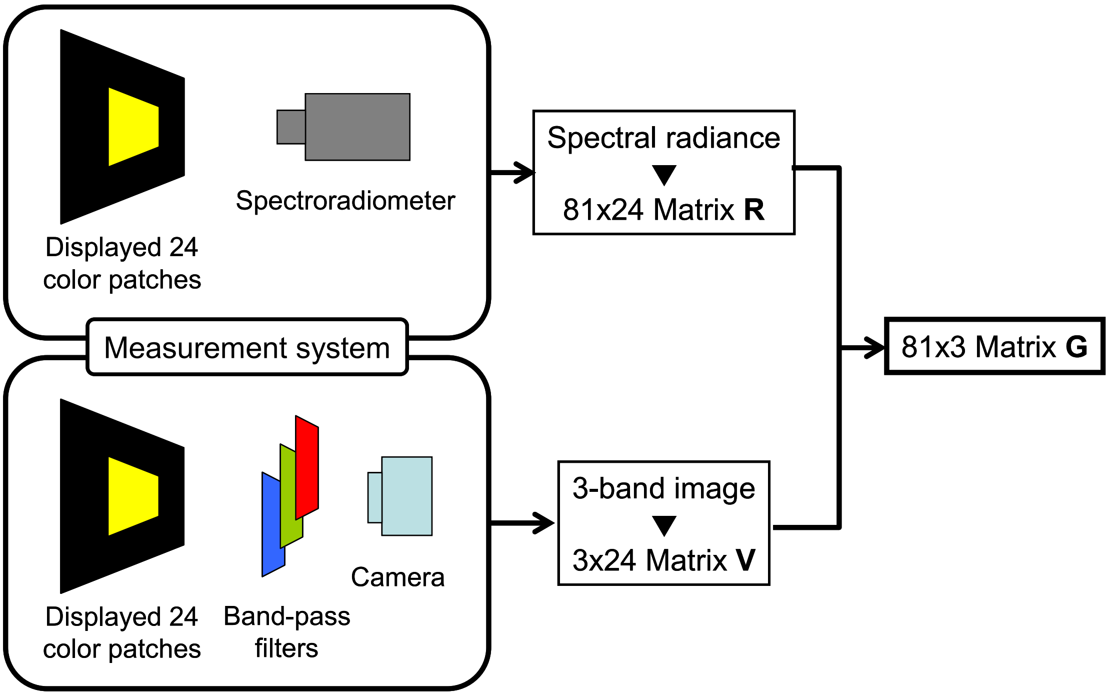

Figure 1Fflowchart for obtain matrix G

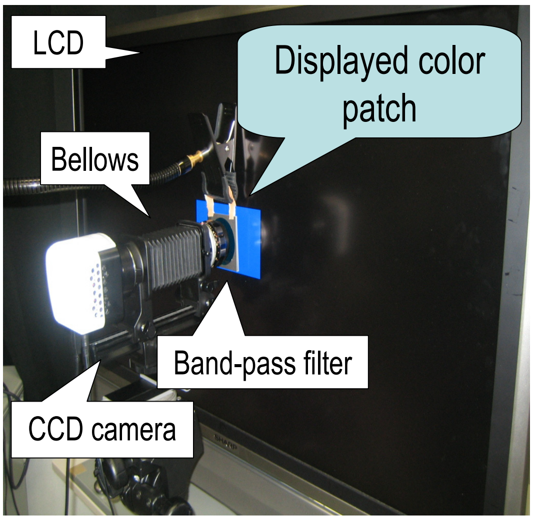

Figure 2 A measurement system of LCD using CCD camera and band-pass filter

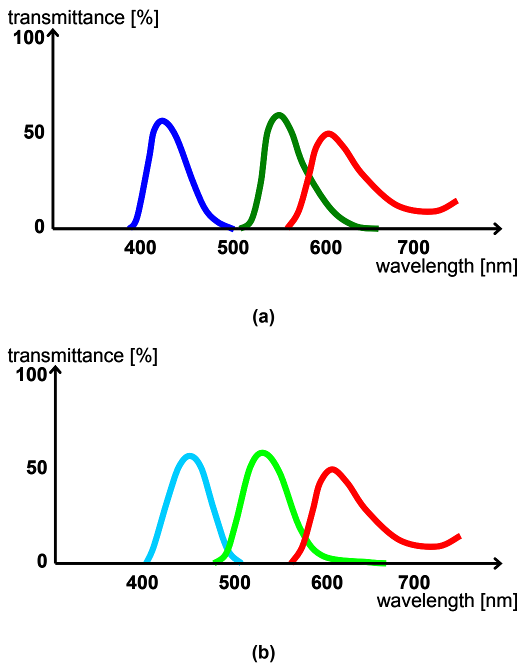

Figure 3 Spectral transmittances of two sets of band-pass filters: Peak wavelength of (a) are 420, 530 and 600 [nm], and of (b) are 450, 500 and 600 [nm].

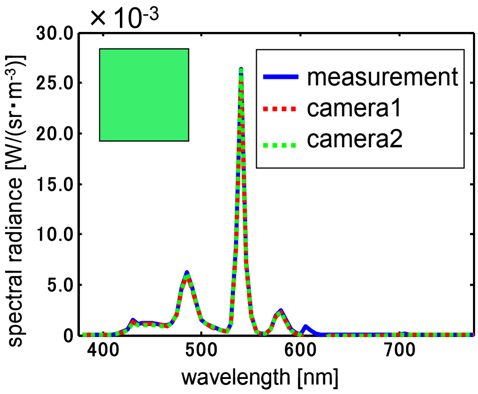

Figure 4 An example of result of estimated spectral radiance: (R, G, B) = (59, 238, 108) is input.

Table 1 RMSEs of 10 color patches. Filter set 1 and filter set 2 are set of band-pass filters, respectively.

input value			RMSE [W/(sr·m³)]	
R	G	B	filter set 1	filter set 2
31	112	35	0.179	0.255
115	87	209	0.168	0.260
183	80	110	0.113	0.165
65	151	175	0.123	0.123
59	10	42	0.137	0.139
59	238	108	0.166	0.206
13	41	125	0.229	0.162
163	61	117	0.122	0.132
44	170	105	0.134	0.102
254	3	1	0.327	0.356

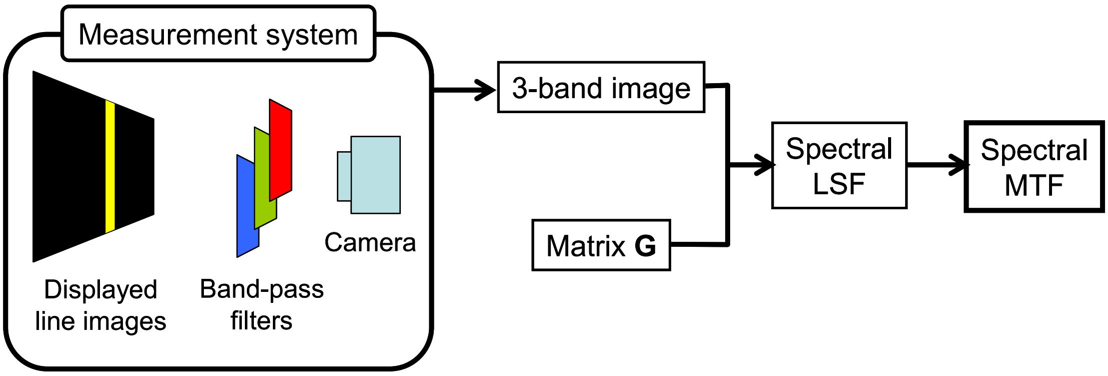

Figure 5 Flowchart for measuring the spectral MTF

Figure 4 shows an example of results when a yellow-green patch was used. Table 1 shows the RMSEs for 10 random color patches. In Table 1, (R, G, B) is input pixel value. The results show that the estimation was performed with a high degree of accuracy regardless of the camera conditions.

4. Experiment for spectral MTF

4.1 Experiment Method

Our system for measuring spectral MTF consists of the LCD, the 3-bands CCD camera with the filter set shown in Fig. 3(a), used in section 3.

The spectral MTF was measured as follows:

1. Sixty-four color line images displayed on the LCD are measured in high resolution and wide
2. sphere with the 3-bands CCD camera. These line images were arranged all combination of each pixel value of RGB for four input value which are 0, 127, 191, 255. A width of line is one pixel.
3. Using Eq. (7), the spectral LSFs are calculated from camera images and the matrix **G** obtained in section 4.
4. The spectral MTF is calculated by Eq. (5), (6).

Figure 5 show a flowchart of the proposed method.

4.2 Results and Discussion

Figure 6 shows a example of a line image on LCD taken by the camera, and Fig. 7 shows a spectral LSF of the white line when (R, G, B)=(255, 255, 255) is input. As examples, spectral MTFs of white, red, green, blue, violet, and yellow-green are shown in Fig. 8. It was found that the MTF curves were dependent on the wavelength, we confirmed that the MTF characteristics of color display was measured using device-independent value.

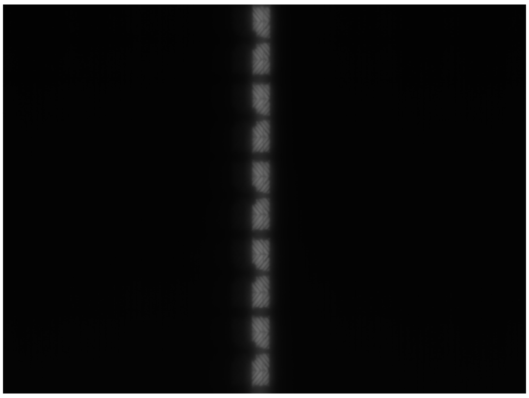

Figure 6 A example of taken line image on LCD

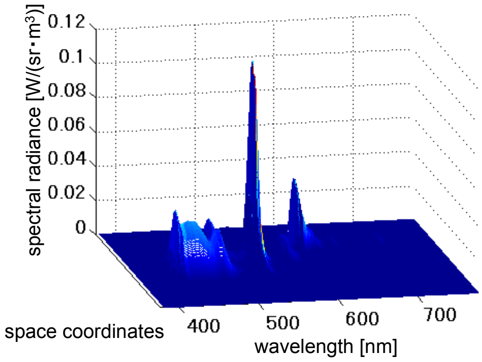

Figure 7 A example of the spectral LSF:

(R, G, B)=(255,255,255) is input.

5. Conclusion

To evaluate the image quality of color displays, we proposed a method for measuring the spectral MTF that was measured with spectral radiance. The spectral radiance distribution of the color display was obtained from camera images using the transformation matrix generated by multiple linear regression analysis. The same experiments for estimating spectral radiance were performed under two camera conditions with different spectral sensitivity. As a result of the experiments, it was confirmed that the estimated spectral radiance was not depend on the camera conditions. Using multiple regression matrix and 3-band camera images, the spectral MTF was calculated as device-independent value. The MTF curves changes depending on the wavelength.

As the future work, a subjective evaluation will be performed, and we will compare the observer rating value with the measured spectral MTF.

References

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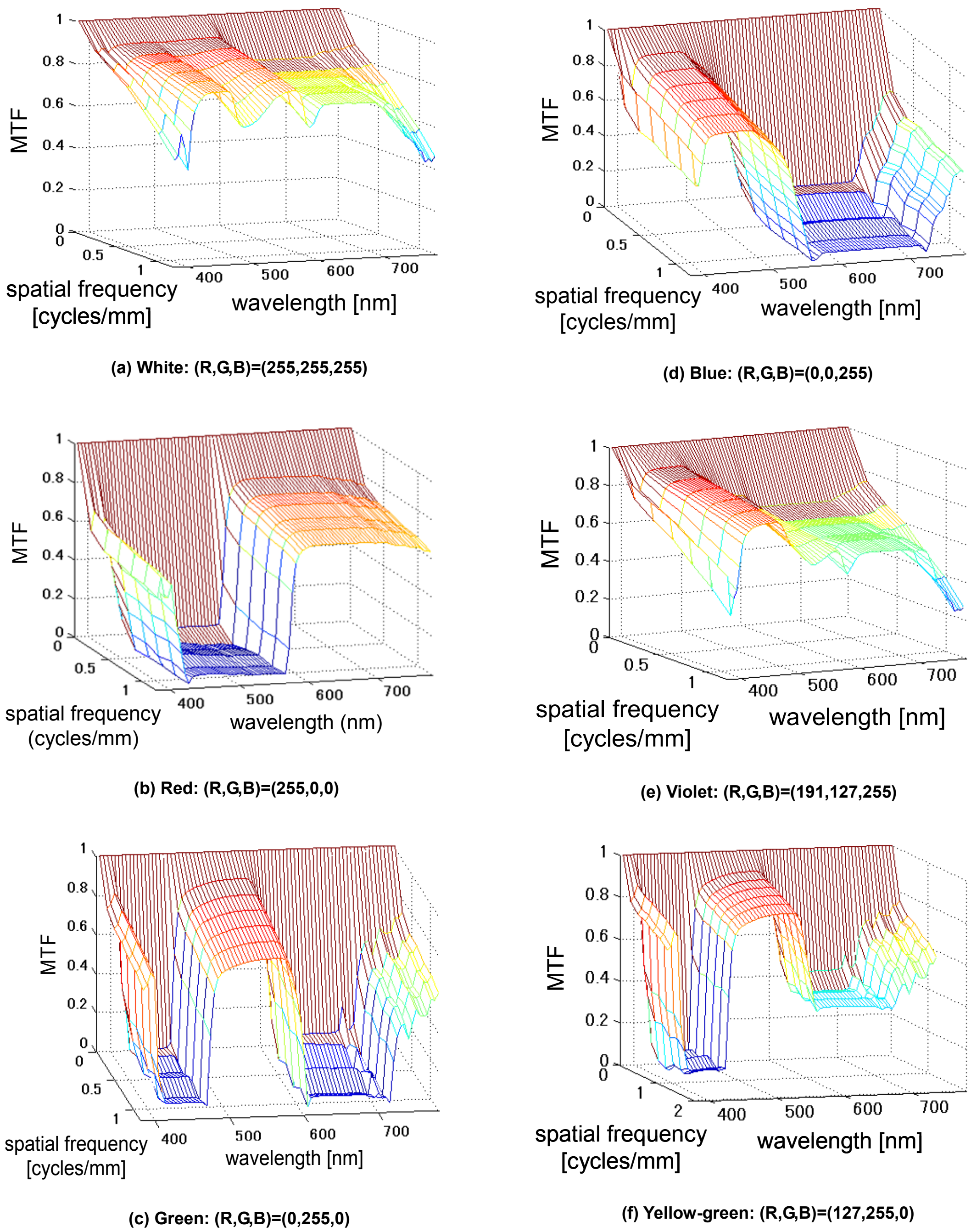

Figure 8 Spectral MTF which calculated by Fourier transforming a spatial spread every each wavelength