Abstract - A novel method that evaluates the color uniformity grade of electronic displays using a mura (non-uniform region) index $E$ is presented. The visual perceptual filter is defined by using the color contrast sensitivity function as the extension of CIELAB color system at high spatial frequencies. The non-uniform images captured by a color camera are converted into CIELAB images. The images are transformed into frequency domains, and filtered by the newly defined visual perceptual filter. The experimental results showed strong relations between human sensory evaluation scores and the mura index $E$ values. The experimental results of luminance variation samples are also reported.

I. INTRODUCTION

In these days, there are many kinds of electronic displays, but all the displays have mura (non-uniform regions of luminance and/or chromaticity) on display screens. It is still difficult to quantitatively evaluate the mura because it occurs in a variety of shapes, sizes, edge gradients, and contrasts on screens. As a wide variety of different panel sizes are in currently in production, the difficulty of the uniform evaluation has been increasing. Although measurement standards for Flat Panel Displays are proposed [1,2], the mura grade measurement standard which can be used in production line has not been developed.

The first study related to mura quantitative evaluation considered cathode-ray tube displays (CRTs) [3]. Liquid Crystal Displays (LCDs) have strong luminance mura, which are rarely observed in CRT displays. Although a number of studies have examined the quantitative evaluation of luminance mura of LCDs [4]-[7], the development of a quantitative evaluation method of chromaticity mura is necessary in order to improve image quality. In previous studies, the parameters of the evaluation model had to be changed according to the hue, and the effects of human contrast sensitivity were not discussed [3]. On the other hand, S-CIELAB is proposed for color image reproduction[8]. In the system, original images are converted into opponent color images, and filtered by spatial sensitivity filters.

In the present paper, a method by which to automatically evaluate the mura grade of electronic displays using the color CSF is presented. Problems related to the hue of mura variations are resolved by using CIELAB color coordinates and visual perceptual filter. Numerous sample images having various saturations, sizes, and edge gradients are tested and the results obtained using the visual perceptual filter and the human sensory evaluation results are compared. The correlation between quantitative evaluation and human sensory evaluation is examined, and the validity of the proposed method is shown.

II. QUANTITATIVE EVALUATION METHOD

A. Color contrast sensitivity function

The human eye contains three types of cone receptors, which respond to light of short (S), medium (M), and long (L) wave-length. These outputs are calculated in the retina cells. These signals are transmitted to the brain by one luminance channel and two chromaticity channels. Luminance and chromaticity are processed separately.

The color CSF is obtained by measuring the contrast threshold of sinusoidal patterns at each spatial frequency. Fig. 1 shows the sinusoidal patterns of the component color system and the color CSF measured by one of the authors using an instrument (ViSaGe, Cambridge Research Systems Ltd.). The luminance is 20cd/m$^2$. The contrast sensitivity is defined as the reciprocal of the contrast threshold.

![Color Contrast sensitivity function (CSF).](image_url)
B. Visual perceptual filter and Mura Index

The CIELAB color system established in chromatics is useful for the study of mura evaluation in the present paper. Equation (1) shows the definition of the CIELAB color system. Here, \(X, Y, Z\) are tristimulus values in the XYZ color system, and \(X_n, Y_n, Z_n\) are tristimulus values of a standard white image.

\[
L^* = 116 \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16 \\
a^* = 500 \left( \frac{X}{X_n} \right)^{\frac{1}{3}} - \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} \\
b^* = 200 \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left( \frac{Z}{Z_n} \right)^{\frac{1}{3}} \tag{1}
\]

The CIELAB color system has no idea about the size of color area. It is clear that the color sensitivity depends on the spatial frequency from Fig.1. The CIELAB color system can be considered as defined for large color area. The large color area means the low spatial frequency. It is necessary to take the spatial frequency of the color area into consideration. Fig. 2 shows the sensitivity gain to the spatial frequency. The spatial frequency of the color area means the low spatial frequency. It is necessary to take the spatial frequency from Fig.1. The CIELAB color system can be applied using the following equations:

\[
L_i^* = S_L(f) \cdot L^*(f) \\
a_i^* = S_a(f) \cdot a^*(f) \\
b_i^* = S_b(f) \cdot b^*(f)
\]

where \(S_L(f), S_a(f),\) and \(S_b(f)\) are the visual perceptual gain functions of luminance, the red-green component, and the blue-yellow component, respectively. Fig. 3 shows images of the filtering procedure by the visual perceptual sensitivity functions.

After filtering, the filtered \(L^*, a^*,\) and \(b^*\) images can be obtained by inverse fast Fourier transform (IFFT). The mura index \(E\), which represents the sensuous strength of mura, is determined by the following equation:

\[
E = \frac{1}{M E_{0}} \sum_{i=1}^{M} \left( (\Delta L_{i}^*)^2 + (\Delta a_{i}^*)^2 + (\Delta b_{i}^*)^2 \right) - \Delta E_{0}
\]

where \(L_{i}^*, a_{i}^*,\) and \(b_{i}^*\) are the \(L^*, a^*,\) and \(b^*\) values of the mura test image, \(L_{i}^{*'}, a_{i}^{*'},\) and \(b_{i}^{*'}\) are the \(L^*, a^*,\) and \(b^*\) values of the standard white image, and \(M\) is the size of the panel. \(\Delta E_{0}\) is the perceivable threshold of color difference.

III. PSEUDO MURA SAMPLES

In the present study, various saturations, sizes, and edge gradients of round mura samples were generated using a software program developed for experimental purposes. It is difficult to collect various mura samples of real displays. Fig. 4 shows the saturation, size, and edge gradient definitions of the mura samples. The pseudo-mura samples include eight saturation variations, 10 size variations, and 10 edge gradient variations. The luminance of the pseudo-mura is the same as background luminance. The hues are red (R), green (G), blue (B), cyan (Cy), magenta (Mg), and yellow (Y). The total number of mura samples is 168 patterns.

Color saturation \(C\) is determined by measuring the xy chromaticity value at the center of the mura area using a colorimeter (BM-7, TOPCON). The measured xy chromaticity values are converted into XYZ and CIELAB color system values. The color saturation \(C\) is obtained as the change \(\Delta E_{ab}\) between the mura region and the background. The mura area \(A\) is defined by an outer circle of diameter \(l\) of the pseudo-mura. The edge gradient \(G\) is defined in terms of

![Fig. 2. Visual perceptual filter.](image-url)
\[ \pi \frac{4}{2} \Delta = \text{abEC} \]

(a) Saturation \( C \)

\[ A = \frac{j^2}{4\pi} \]

(b) Mura area \( A \)

\[ \Delta l \]

(c) Edge gradient \( G \)

Fig. 4. Mura sample parameters.

\[ \Delta E^*_{ab} \]

\[ \Delta l \]

\[ G = \frac{\Delta E^*_{ab}}{\Delta l} \]

Fig. 5. \( a^*b^* \) chromaticity diagram of mura samples with saturation change.

IV. HUMAN SENSORY EVALUATION

The standard mura is displayed at the center of the display for 3 seconds. White raster is then displayed for 5 seconds, followed by the test mura for 3 seconds. The hue of the standard mura is red. The test mura are displayed at random. The diameters of the outer and inner circles of the standard mura are 400 and 275 pixels, respectively, and the saturation of the standard mura is 4.84. The total number of test mura patterns is 168. Evaluations were performed twice by nine people using seven grades evaluation method, ranging from –3 (hardly perceptible) to +3 (very strong). A 32-inch LCD display (UT32-MX800J(B), HITACHI) was used for the evaluation. The average luminance of the display was 100 cd/m². The experiment was performed in a dark room, and the distance between the observers and the display was 1.5 m.

Fig. 6 shows the human evaluation results. Each plotted point is the average of 18 data. Fig. 6(a) shows the results obtained for saturation values ranging from 1.5 to 12.0. The size and edge gradient are the same as those of the standard sample. Fig. 6(b) shows the results obtained for sizes ranging from 1.52% to 16.0% for the entire display area. The saturation and edge gradient are the same as those of the standard sample. Fig. 6(c) shows the results obtained for edge gradients of the inner circle ranging from 100 to 370 pixels. The saturation and size are the same as those of the standard sample. In each case, human sensory evaluation values vary 2 to 5 grades according to the hue variation.

V. QUANTITATIVE EVALUATION

A. Perceivable threshold of the color difference

The perceivable threshold \( \Delta E_0 \) in Equation (3) was determined by an experiment. The samples whose color
differences are from 1.29 to 1.46 were displayed on a LCD display. The mura regions are round shaped and the diameter is 30 mm. The human evaluation was executed 4 times by 5 people if the mura regions could be recognized or not. The viewing distance was set at 1.5m. A TV camera (gamma=1, 1024 x 768 pixels) was used to capture the mura images, and the color differences were calculated. Fig. 7 shows the human evaluation results and the color difference. The vertical axis is the recognition rate. The color difference of 0.5 recognition rate was 1.33. So, the $\Delta E_0$ was determined as 1.33 in the following experiments.

B. Evaluation of pseudo-mura samples

The mura images were captured by a color camera. The RGB values of each pixel of mura images were converted into XYZ values by Equation (4).

$$
\begin{align*}
X & = 0.6067R + 0.1736G + 0.2001B \\
Y & = 0.2998R + 0.5868G + 0.1144B \\
Z & = 0.0000R + 0.0661G + 1.1150B
\end{align*}
$$

(4)

The XYZ values were then converted into CIELAB values using Equation (1). The $L^*$, $a^*$, and $b^*$ images were transformed to the frequency domain by fast Fourier transform (FFT). After FFT, color CSF filtering was performed using Equation (2). The chromaticity mura index $E$ of each mura image was calculated using Equation (3). $\Delta E_0$ is determined as 1.33 by the experiment. The results of quantitative evaluations were compared with the results of human sensory evaluations.

Fig. 8 shows the relationship between the mura index $E$ calculated by the proposed method and the grades obtained by human evaluation. Fig. 8(a), 8(b), and 8(c) show the results for saturation changes, size changes, and edge gradient changes, respectively. The mura index $E$ is found to be proportional to the human evaluation results for the mura grade. The correlation coefficient ($r$) between the quantitative evaluation results and the human sensory evaluation results was 0.89 for all patterns, and the validity of the proposed method was demonstrated.

![Fig. 7. Perceivable threshold of the color difference.](image)

![Fig. 8. Comparison of chromaticity mura index and human evaluation grade (168 patterns).](image)
Fig. 9. Visual sensitivity image of a red mura.

Fig. 10 shows the visual sensitivity image that was obtained by applying the CSF filter. The cyan ring is observed as the opponent color of red.

Fig. 10 shows a* and b* values on the centerline of the original mura image (Red line: no CSF filtering) and the visual sensitivity image (Blue line: with CSF filtering). As shown in Fig. 10(a) and 10(b), however, the chromaticity values of the visual sensitivity images around the edge of the mura are emphasized. When a human see the red mura, he/she perceives a cyan ring around the red mura. The validity of the proposed method can also be confirmed by this experiment.

V I. MURA SAMPLES WITH LUMINANCE VARIATION

In the above experiments, the luminance values of the pseudo samples were the same (100cd/m²). But, real mura samples have both luminance and chromaticity non-uniformity. So, pseudo color mura samples with luminance variations were generated, and the experiments of human evaluation and quantitative evaluation by mura index \( E \) were executed. The background luminance of the six hue samples was changed 7cd/m² pitch from -21 to +21 cd/m², around 100 cd/m². The experiments were executed with two saturation values, low and high. The total of each saturation sample were 42. The area values were the same of the standard mura samples.

Fig. 11 shows the results of low saturation samples and Fig. 12 shows the results of high saturation samples. Fig. 11(a) is the chromaticity diagram of the samples, and Fig. 11(b) shows the human evaluation results. The evaluation scores grow worse according to the decrease of luminance independent of the hue. Fig. 11(b) also shows that even if the luminance of the mura increases (bright mura), the evaluation scores do not go worse sharply compared with the luminance decrease (dark mura). Fig.11(c) is the comparison between human evaluation and mura index \( E \) for dark mura. The correlation coefficient was 0.92.
Fig. 12 shows results for high saturation samples. The bright mura were also evaluated as better grades compared with dark mura in the human evaluation. It is necessary to consider the quantitative evaluation model including the bright mura. Fig. 13 shows results for both low and high saturation dark mura samples. The correlation coefficient was 0.85.

V II. CONCLUSION

In the present paper, we proposed a novel method by which to evaluate the mura grade of electronic displays using the color CSF. We showed that good correlations existed between the novel mura index and the results of human evaluations for samples with no luminance variations. The correlation coefficient between the quantitative evaluation results and the human sensory evaluation results was 0.89, and the validity of the proposed method was demonstrated. Problems related to hue variations of the mura were also resolved by using CIELAB color coordinates and the visual perceptual filtering. We also extended this method to the samples with luminance variations, and concluded that the proposed method is adaptable for dark mura samples.

In the future, we plan to use S-CIELAB color system and develop more accurate method for the mura associated with color and luminance change.

REFERENCES