Speckled Image Resolution Measured in Nine Regions on Screen using Raster-scan RGB Laser Mobile Projector

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ABSTRACT

Image resolution affected by color speckle is measured for the nine projected regions on the screen using a raster-scan mobile projector. The modified contrast modulation method is used for analyzing speckle noise effects. The nonuniformity of the image resolution among the nine regions is compared and analyzed.

1 INTRODUCTION

The "human-observed" image resolution of laser projectors is affected by color speckle noise. The color speckle has been studied since the first work by Kuroda et.al [1]. The color speckle noise pattern does not exist on a projection screen but does on human retina as an interference pattern of laser light, which is a "human-observed" pattern specific to laser projectors. Therefore, the standardized color speckle measurement method [2] must be also applied for measuring the "human-observed" image resolution.

The authors have already published some works on the image resolution affected by color speckle for raster-scan mobile laser projectors [3, 4]. However, the contrast modulation method formulated for measuring the image resolution affected by color speckle was modified [5]. In our previous works [3, 4], the contrast modulation, C_{M} affected by speckle was simply formulated using the averages of speckle along the grille pattern. In the modified method, the contrast modulation $C_{\mathrm{M\text{-}speckle}}$ was redefined based on the eye diagram for distinguishing whether white or black [5].

The other point to be modified was a grille pattern with multiple line-pairs of which width is varying [3, 4]. The nonuniformity of the image resolution among the nine regions could not be measured successfully. The narrowest line-pair was not reproducibly displayed on the screen [4].

In this work, the nonuniformity of image resolution affected by color speckle is measured at nine regions using a raster-scan mobile projector. The modified contrast modulation $C_{\mathrm{M(speckle)}}$ redefined based on the eye diagram and the grille patterns with multiple equi-width line-pairs were used. The measured nonuniformity data are presented and discussed here.

* Contributed before his recent career change.

2 MEASUREMENT PREPARATION

2.1 Measurement Setup

The setup for directly measuring the nonuniformity of the R, G, B wavelengths and R, G, B powers of projected solid window patterns is shown in Fig.1. A raster-scan RGB mobile laser projector, Celluon PicoBit was set just in front of the virtual screen at the exact position of the real standard diffusive reflectance screen for measuring speckle and contrast modulation C_{M} in Fig.2. The RGB laser meter, TM6102 provided by HIOKI E. E. CORPORATION [6] was set behind normal to the nine regions on the virtual screen. The layout of the projected image pattern with nine solid regions shown in Fig.3. The measurements are repeated by moving the RGB laser meter to another solid window region in turn.

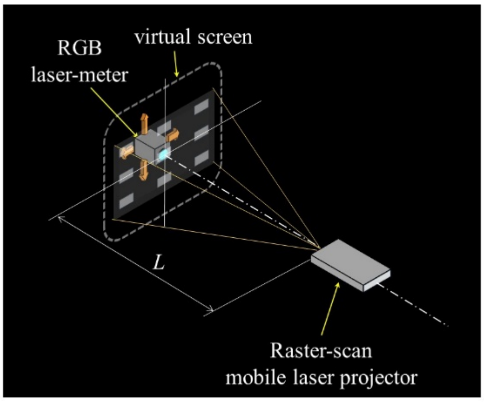

Fig. 1 Setup for directly measuring R, G, B wavelengths and optical powers

The setup for measuring the nonuniformity of the monochromatic / color speckle and the image resolution affected by color speckle is shown in Fig.2. The solid pattern in Fig.3 for measuring speckle nonuniformity or grille patterns of multiple equi-width line-pairs for measuring the resolution were projected on the real standard diffusive screen, SRT-99-120 (Labsphere). Three grille patterns of vertical line pairs with widths corresponding to 3.77, 1.88, and 1.0 pixels were prepared. The specified virtual pixel dimensions of the laser mobile projector under test is 1280×720 (for input signal) with an aspect ratio of 16:9. The layout of the grille patterns at the nine regions is shown in Fig.4 for the width of 3.77 pixels, for example. The 2D data (350×300 sensor pixels) of the speckled grille patterns were captured by the speckle measuring device, SM01VS11 provided by Oxide Corporation [7, 8]. The speckle measuring device should be set normal to the screen. However, the projector set in front of the screen might obstruct the measurement, or the speckle measuring device might obstruct the image projection. To avoid this situation, the direction of the optical axis of the measuring device is shifted by angle $\Delta\theta$ from the projector axis. The shift angle $\Delta\theta$ was kept constant by moving the measuring device parallel during the nonuniformity measurement. The dimensions are L=390mm, D=710mm, and $\Delta\theta$=20.6º.

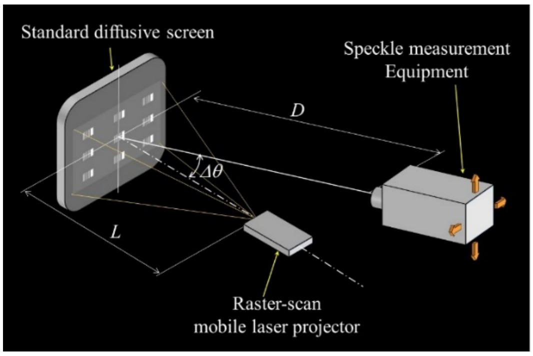

Fig. 2 Setup for measuring the nonuniformity of the image resolution affected by color speckle

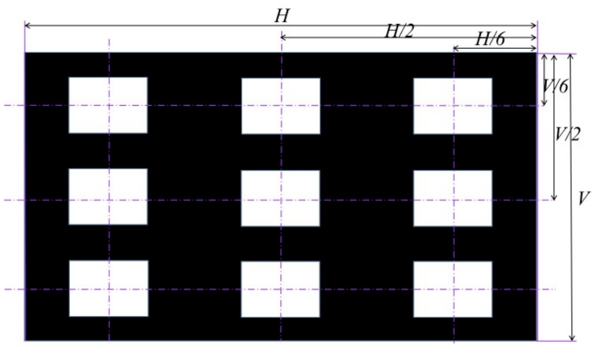

Fig. 3 Nine solid patterns for nonuniformity measurements

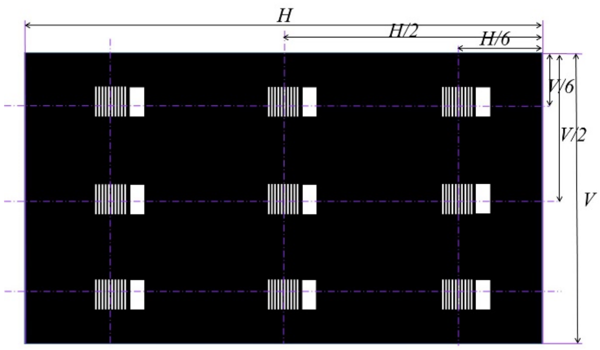

Fig. 4 Nine grille patterns for nonuniformity measurements

2.2 Formulation and measurement method

Due to a narrow spectral linewidth of laser diodes, the tristimulus values are calculated using a single wavelength value and the corresponding single value of CIE colour matching functions, $\bar{x}(\lambda_Q)$, $\bar{y}(\lambda_Q)$, $\bar{z}(\lambda_Q)$, (Q=R, G, B). The tristimulus values X, Y, Z can be calculated by the following equations.

$$X = \bar{x}(\lambda_R)E_{e-R} + \bar{x}(\lambda_G)E_{e-G} + \bar{x}(\lambda_R)E_{e-B}$$
$$Y = \bar{y}(\lambda_R)E_{e-R} + \bar{y}(\lambda_G)E_{e-G} + \bar{y}(\lambda_R)E_{e-B}$$
$$Z = \bar{z}(\lambda_R)E_{e-R} + \bar{z}(\lambda_G)E_{e-G} + \bar{z}(\lambda_R)E_{e-B} \quad (1)$$

where, $E_{e\text{-}Q}$ is irradiance of each color. The measured optical powers can be converted into irradiance.

CIE 1931 chromaticity (x, y) are given as follows.

$$x = \frac{X}{X+Y+Z}, \qquad y = \frac{Y}{X+Y+Z} \quad (2)$$

Illuminance E_v is obtained by,

$$E_v = 683 \times Y \quad (3)$$

The 2D speckle data for uniformly projected areas can be obtained using the setup in Fig.2, and the nine solid window patterns in Fig.3 or the large white areas in Fig.4. The 2D distribution of illuminance and chromaticity of color speckle can be also calculated by the above formulation.

In the grille pattern analysis for obtaining contrast modulation $C_{M(speckle)}$, the distribution of R, G, B monochromatic speckle and color speckle must be processed along a line parallel to the grille direction as a group of the same input signal level. For example, the average of the speckled illuminance distribution is expressed as $\bar{E}_v$. Contrast modulation C_M for average illuminance can be obtained as follows.

$$C_M = \frac{\bar{E}_{vH} - \bar{E}_{vL}}{\bar{E}_{vH} + \bar{E}_{vL}} \quad (4)$$

where, $\bar{E}_{vH,L}$ is the local maximum and the local minimum of the average of the illuminance distribution along the horizontal direction.

The 2D illuminance data distribute statistically. Most of the data exist within $\bar{E}_v(1 \pm C_{ps})$ because photometric contrast C_{ps} implies standard deviation. Considering the eye-diagram shown in Fig.5, speckle-affected contrast modulation $C_{M(speckle)}$ is expressed as follows.

$$C_{M(speckle)} = \frac{\bar{E}_{vH}(1-C_{ps}) - \bar{E}_{vL}(1+C_{ps})}{\bar{E}_{vH}(1-C_{ps}) + \bar{E}_{vH}(1+C_{ps})} = \frac{C_M - C_{ps}}{1 - C_M C_{ps}} \quad (5)$$

In the above equation, $C_{M(speckle)}$ =0 when C_M =C_{ps}, which means the eye-closing condition.

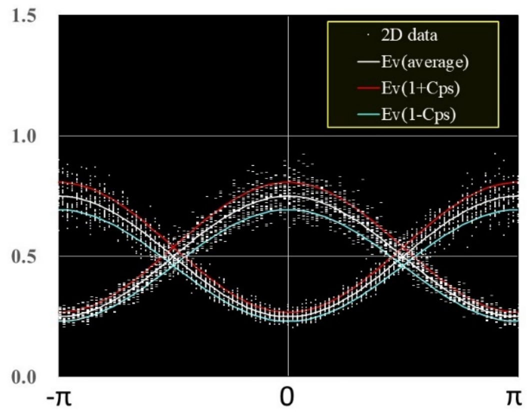

Fig. 5 Eye-diagram of the simulated 2D illuminance distribution

3 MEASUREMENT RESULTS

3.1 Solid pattern measurements

The measured R, G, B wavelength, CIE 1931 chromaticity, RGB power ratio, and R, G, B speckle contrast values, and photometric contrast C_{ps} at the center solid window are shown in Table 1.

Table 1 wavelengths, chromaticity, power ratio, speckle contrast at the center region

	R	G	B	W
wavelength, chromaticity	643.6nm	518.9nm	446.4nm	x=0.3059, y=0.2064
power ratio	0.1946	0.2787	0.5267	-
C_s, C_{ps}	0.0642	0.0415	0.0925	0.0376

The bar chart of the nonuniformity of illuminance and that of the nonuniformity of photometric speckle contrast C_{ps} are shown in Fig.6 and Fig.7, respectively. Both illuminance and C_{ps} are larger at the left and right regions than the center regions.

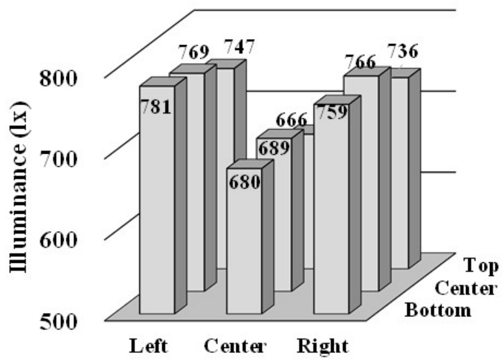

Fig. 6 Nonuniformity of illuminance

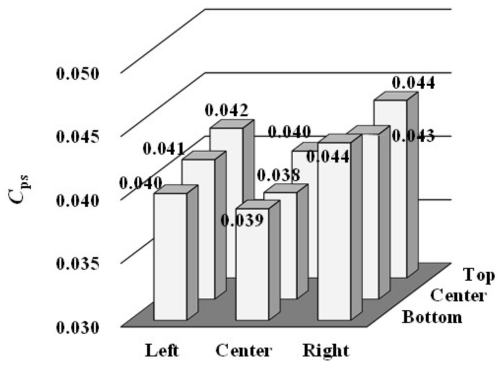

Fig. 7 Nonuniformity of photometric speckle contrast C_{ps}

3.2 Speckle-affected image resolution

The 2D color speckle data (350×300 sensor pixels) captured by the speckle measuring device is shown in Fig.8. The R, G, B monochromatic and the W (white) data are lined in a row, and the data for the grille widths of 3.77, 1.88 and 1.0 pixels are lined in a column. They are captured in the center region, for example.

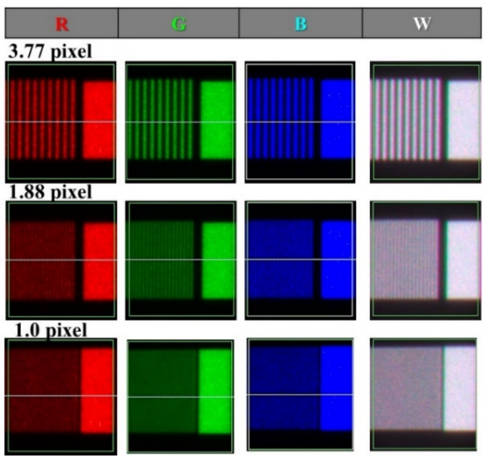

Fig. 8 Captured R, G, B. W speckled data for the grille widths of 3.77, 1.88 and 1.0 pixels

As clearly observed in Fig.8, the grille lines of 1.0 pixel cannot be distinguished. The contrast modulation C_M obtained by the average values of the illuminance distribution along the lines parallel to the grille direction. Then the $C_{M(speckle)}$ values for all the nine regions were calculated using Equation (5). The C_{ps} values for the nine regions shown in Fig.6 were used for calculation.

The bar chart of the nonuniformity of the image resolution (pixels) affected by color speckle judged at $C_{M(speckle)}$ =0.5 is shown in Fig.9. For comparison, the bar chart of the nonuniformity of C_M when eliminating the speckle effects by opening the iris of the speckle measuring device [9] is shown in Fig.10. The image resolution data for each R, G, B color are summarized in Table 2.

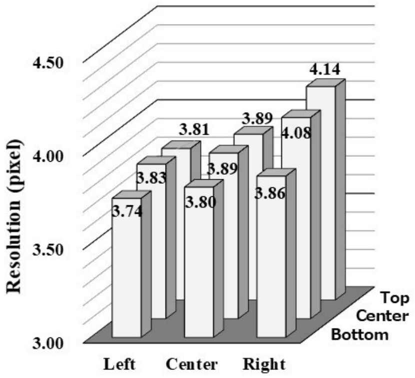

Fig. 9 Nonuniformity of image resolution affected by color speckle

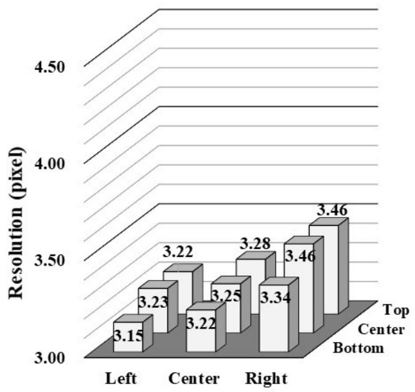

Fig. 10 Nonuniformity of image resolution eliminating the effects of color speckle

Table 2 Image resolution for each R, G, B, W color

Resolution (pixels)	R	G	B	W
w speckle effects	3.86	3.22	3.29	3.89
w/o speckle effects	2.97	3.02	2.78	3.25

4 DISCUSSION

Illuminance and photometric speckle contrast C_{ps} were found to be larger on the left and right regions. The scan speed becomes slower there. Illuminance control on the slower scan regions might not work sufficiently. Speckle contrast tends to be reduced by scanning the laser beam faster. Therefore, the higher C_{ps} values on the left and right regions might be reasonable.

The image resolution affected by color speckle was obviously worse than the image resolution unaffected by speckle. As in Table 2, the effect of R speckle has a dominant effect on making the W image resolution worse because of larger grain size of R speckle than G and B. The speckle size is larger for longer wavelengths.

The image resolution becomes worse in the regions closer to the right-top region. The similar tendency is found both for the speckle-affected and the speckle-free image resolutions in Fig.9 and Fig.10. The nonuniformity of C_{ps} in Fig.7 does not affect the nonuniformity of the resolution because the C_{ps} nonuniformity is not large enough. The resolution nonuniformity might be caused by unoptimized optics or other reasons specific to the projector under test.

5 CONCLUSION

The nonuniformity of speckle contrast and speckle-affected image resolution is measured for the nine projected regions using a raster-scan mobile projector. Color speckle is found to make the image resolution worse. The effect of the larger speckle grain size of R is found to be greater. The nonuniformity of C_{ps} does not affect the nonuniformity of the resolution so much.

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