Speckle analysis in laser scanning display system

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The theory of speckle formation in laser scanning display system is established based on the averaging effect of eye response as laser beam scanning through an eye resolution spot. It is analyzed that speckle reduction can be obtained by averaging states of speckle during scanning. The theoretical results show that a smaller correlation length of screen surface and the narrowing of laser beam in scanning direction can reduce speckle contrast for this system.

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A laser scanning display system with red-green-blue (RGB) laser sources provides a wide color gamut which is not achievable by conventional light sources and can present more realistic nature color on screen. But there is a major problem in this system for high coherence of laser beam, which is a phenomena called speckle. Speckle arises when coherent light is scattered from a rough surface of a screen and then detected by a detector such as observer's eye[1]. It reduces the contrast and resolution of images seriously. Many methods have been proposed to resolve this problem[2−5] and there is also analysis about the speckle reduction in laser scanning display system[4,6], in which the one-dimensional (1D) pixel array in a reflected laser beam is projected on the screen by optical system and scanned by electrically driven mirror. In this letter, we investigate the speckle image formation in a laser display system by scanning single spot with three color (RGB) laser beams onto the screen. In this display, different pixels are written at different time, so there is no possibility of interference between pixels. This is an advantage and simplification over displays in which laser illuminates a one- or two-dimensional (2D) spatial light modulator [SLM, such as digital light processing (DLP) or liquid crystal on silicon (LCOS)], leading to pixel-to-pixel interference effects[7]. A difficulty of beam scanning is that each pixel is illuminated for a very short time when the entire image is being written. Typical values are that each pixel is illuminated for 16 ns once every 16 ms. Thus any speckle reduction by temporal averaging must be based on a mechanism that has a coherence time of picosecond level. It is necessary to study the affections of parameters from the system on speckle contrast for finding appropriate parameters to suppress speckle vision. We analyze the human eye response in the scanning course and its averaging effect, and give some results about the affections of some parameters from the system on speckle contrast. We find that narrowing laser beam in the scanning direction and using screen with smaller correlation length can reduce speckle contrast in the laser scanning display system.

In a laser scanning display system, the laser beam is modulated according to the original pattern and projected to the screen point by point. The color is constructed according to original RGB ratio. Figure 1 shows a schematic diagram of a scanning projection device[8], in which a polygonal mirror M(P) is rotated for fast scanning in horizontal direction and a slow galvo mirror M(G) is used for vertical displacement of subsequent lines. The laser spot scans across the screen displaying the whole image within the response time of eyes. The speckle patterns seen by observer are generated in the screen pixel by pixel. There is no interference of light from different pixels. So we just need to analyze the mechanism of speckle's generation for one pixel.

In the path from lasers to screen, there are no physical reasons to generate speckle in principle. The modulators and mirrors are manufactured precisely by optical polishing and coating. They do not give random phases to laser beam passing through them ideally. In the path from screen to observer (human eyes here), the roughness of screen surface is the main physical reason for obvious speckle arising. The waves scattered from the surface with different phases caused by the roughness of screen interfere with each other and produce speckle in eye. It is the main speckle effect in laser scanning projection display.

For simplicity, we assume that the size of human eye resolution spot on screen is about the same as that of the scanning laser spot on screen. Figure 2 is the simplified optical diagram of image formation for one pixel. When the observer is looking at an eye resolution spot, the laser

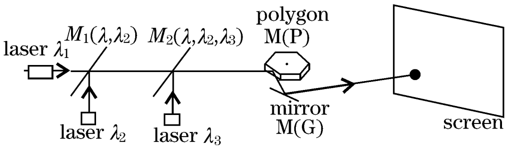

Fig. 1. Diagram of a scanning projection device.

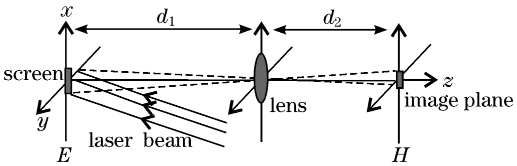

Fig. 2. Optical diagram of image formation for one pixel.

spot is scanning through the eye resolution spot from left to right, as shown in Fig. 3. At the time instant t, the shadow region ($ABCD$) in eye resolution spot O_{E} is illuminated by the laser spot. The scattering light rays from $ABCD$ region meet and interfere with each other at the eye's place. The light field into eye can be written as

$$U(\xi,\eta,t)=\iint\limits_{s(t)} U_{\mathrm{loc}}(x,y)\exp[-\mathrm{i}kh(x,y)] \cdot F(\xi,\eta;x,y)\mathrm{d}s, \tag{1}$$

where U_{loc} is the complex amplitude of light field reflected immediately from the screen surface, $S(t)$ is the illuminated region $ABCD$ at the time instant t, $h(x,y)$ is the screen surface height function in z-direction, (x,y) is the coordinates of point in the object plane, (ξ,η) is the coordinates of point in the image plane (here it is the retinal plane H). The impulse response function $F(\xi,\eta;x,y)$ in Eq. (1) can be written as

$$\begin{aligned} F(\xi,\eta;x,y) &= K\cdot\frac{\exp\left[\mathrm{i}\dfrac{\pi}{\lambda d_1}(x^2+y^2)\right]}{\lambda d_1} \cdot \frac{\exp\left[\mathrm{i}\dfrac{\pi}{\lambda d_2}(\xi^2+\eta^2)\right]}{\lambda d_2}, \\ K &= \frac{J_1(2\pi\rho)}{\rho}, \\ \rho &= \frac{\phi}{2}\sqrt{\left(\frac{Mx+\xi}{\lambda d_1}\right)^2+\left(\frac{My+\eta}{\lambda d_1}\right)^2}, \end{aligned} \tag{2}$$

where d_1 is the object distance, d_2 is the image distance, λ is the wavelength of light source, $J_1(x)$ is the Bessel function of the first kind, ϕ is the diameter of the lens (or pupil), and $M=d_2/d_1$ is the magnification factor of the system. For the projection display system, U_{loc} can be approximately written as

$$U_{\mathrm{loc}}\approx U_{\mathrm{in}}\exp[-\mathrm{i}kh(x,y)], \tag{3}$$

where U_{in} is the complex amplitude of light field incident immediately to the screen surface from laser source. Substituting Eqs. (2) and (3) into Eq. (1), we can get $U(\xi,\eta,t)$. Then the light intensity of the pixel (ξ,η) can be written as

$$I(\xi,\eta)=\frac{1}{T}\int_0^T I(\xi,\eta,t)\mathrm{d}t=\frac{1}{T}\int_0^T |U(\xi,\eta,t)|^2\mathrm{d}t, \tag{4}$$

where T is the scanning time over one pixel.

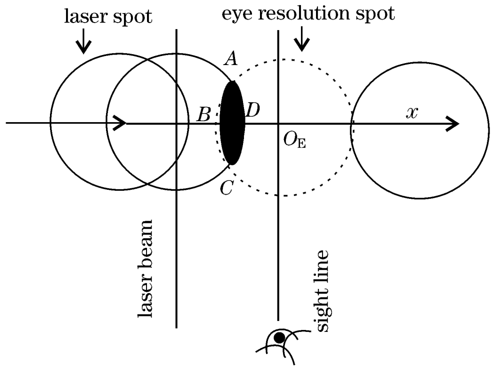

Fig. 3. Diagram of laser spot scanning through an eye resolution spot.

As shown in Fig. 3, the laser spot scans through the eye resolution spot from left to right. The illuminated region gets bigger at first; when the laser spot just overlaps the eye resolution spot, it gets the biggest; then it decreases. The change of light intensity into eye should also accord with this tendency during scanning. But since scattering elements of the screen surface bring random phases to the light rays, the scattering elements in the illuminated area $ABCD$ change partly as laser beam scanning, then the interference intensity caught by eye changes randomly.

Figure 4 shows the change of light intensity caught by eye as laser beam scanning through an eye resolution spot. Here the surface correlation length l_{corr} is set as 20 μm, the standard deviation of surface height σ_{h}=10 μm, where the definitions of l_{corr} and σ_{h} will be given later. The total time for scanning through a pixel is 16 ns. We adopt 200 time instants for calculation during scanning in Fig. 4. When the laser spot scans through an eye resolution spot, the speckle experiences many states of interference, so there is strenuous fluctuation of light intensity during scanning. The light intensity caught by eye is that of the averaging effect of these states. So to suppress speckle, it should experience more states during scanning. If it is supposed that the speckle changing is an ergodic process, by averaging effect there is no speckle vision.

In simulations, the rough surface of screen itself is modeled as a surface height function in z-direction $h(x,y)$ over the smooth reference plane x-y. $h(x,y)$ is assumed to be a Gaussian random process with zero mean and standard deviation σ_{h} described by the probability function:

$$p[h(x,y)]=\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{h(x,y)^2}{2\sigma_{\mathrm{h}}^2}\right). \tag{5}$$

The theory of wave scattering from a rough surface often assumes a Gaussian shape of autocorrelation function, where the average size of surface details is described by the correlation length l_{corr} given by the distance over which the value of the correlation function decreases by

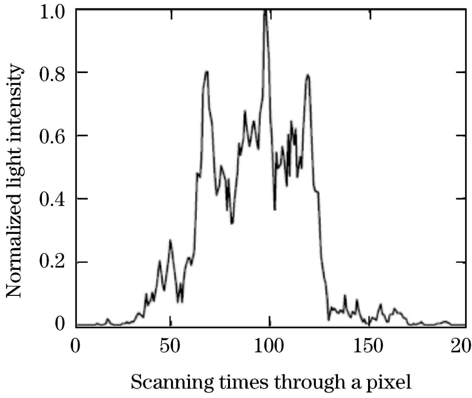

Fig. 4. Light intensity caught by eye as laser scanning through a pixel.

1/e. A standard procedure to generate a sequence of correlating Gaussian variables $h(x,y)$ in Eqs. (1) and (3) is adopted following Ref. [9]. In calculation the important physical parameters are as below. A collimated laser beam with wavelength λ=632 nm scans at nearly normal incidence to the surface, and its diameter D=200 μm. The screen surface is with the deviation of surface height σ_{h} and correlation length l_{corr}. The observation distance is d_1=1000 mm and the pupil diameter ϕ=2 mm, then the diameter of eye resolution pixel is about 0.3 mm. The focal length of eye is set as 20 mm, and the image distance d_2 is about 20.2 mm. For every pixel, the light intensity of its center point is calculated to represent that of this pixel in the image plane, and in simulation the step length for sampling the field on the screen is 0.1 μm.

Figure 5 shows the simulated speckle pattern in a laser projection display system with l_{corr}=20 μm, σ_{h}=10 μm. For Fig. 5(a) the laser beam is projected to the screen dot by dot (pixel) but without continuous scanning for a pixel, while for Fig. 5(b) it is that with continuous scanning. The contrast of speckle in Fig. 5(a) is about 1, while that in Fig. 5(b) is 0.7627. This result confirms that the scanning course itself gives an averaging effect to suppress speckle. Here speckle contrast is defined as the ratio of standard deviation to the mean value of light intensity following Goodman[10,11]. Their histograms are depicted in Figs. 5(c) and (d). Figure 5(c) is close to a negative exponential probability density function, fitting pretty with the theoretical result[1]. For integral speckle, Goodman established a suitable approximation of probability density function, which is the Gamma distribution[1] :

$$P_I(I)=\left(\frac{m}{\langle I\rangle}\right)^m\frac{I^{m-1}}{\Gamma(m)}\exp\left(-m\frac{I}{\langle I\rangle}\right), \tag{6}$$

where $\Gamma(m)$ is the gamma function, and $\langle I\rangle$ the mean intensity. Our histograms are normalized to the mean intensity on the abscissa and to 1 on the ordinate.

Table 1 shows the simulation results of the speckle contrasts with different surface parameters. It has been found that the speckle contrast is not sensitive to σ_{h}, but to l_{corr}. When l_{corr} becomes smaller, there are more independent scattering elements in an eye resolution spot, so the speckle experiences more states as laser beam scanning through this spot. The correlation of light intensity of speckle as time t is reduced and then eye catches an averaging effect of the intensity which suppresses speckle vision more clearly. Since $\sigma_{\text{h}} > \lambda$, when σ_{h} changes, the phase distribution changes slightly, then it affects the speckle contrast slightly.

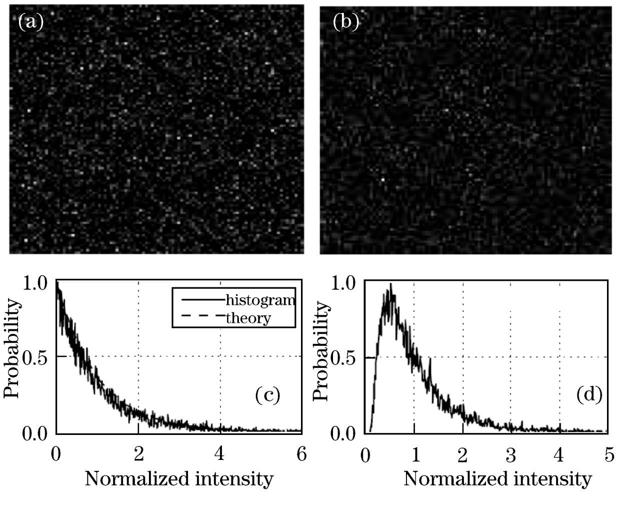

Fig. 5. Simulated speckle patterns and histograms. (a) Speckle pattern without continuous scanning; (b) speckle pattern with continuous scanning; (c) histogram of speckle pattern in (a); (d) histogram of speckle pattern in (b).

Table 1. Speckle Contrasts with Different Surface Parameters of Screen

l_{corr} (μm)	σ_{h} (μm)	Speckle Contrast (%)
50	25	100
50	10	97.40
50	5	99.43
40	20	92.67
40	10	95.19
40	5	91.65
40	2.5	90.18
30	15	80.64
30	10	83.26
30	5	81.73
30	2.5	78.38
20	10	70.96
20	5	72.22
20	2.5	70.96
10	5	68.25
10	2.5	69.47
10	1	68.38
10	0.5	69.15
5	1	69.81
5	0.5	67.59

When the laser spot scans, the illuminated area $ABCD$ changes with time t continuously. Therefore, there are some new scattering elements getting into the area $ABCD$ and some getting out at every time instant as shown in Fig. 3. So the light intensity $I(\xi,\eta,t)$ changes with t too. But there is the correlation of light intensity at two time instants because most surface elements in $ABCD$ are still the same if the interval between the two time instants is very short. To reduce the correlation, we suggest the laser beam be narrowed in the scanning direction.

Figure 6 shows the simulation results of speckle contrast scanning with quadrate laser beam narrowed in the scanning direction compared with that of circular laser spot. In Fig. 6(a), W_{L} is the width of laser beam in scanning direction and the width in another direction is set as 200 μm. In simulation, $l_{\text{corr}} = 2\sigma_{\text{h}}$ for every point in the curves. In Fig. 6(b), the curve 2 is the simulation result with W_{L}=50 μm, the curve 1 is that with $W_{\text{L}} = l_{\text{corr}}$. It can be found that with a narrowed laser beam, the speckle contrast is reduced clearly compared with the result of curve 3 scanning with a circular laser beam with the diameter D=200 μm. When the correlation length of the screen surface is nearly 50 μm,

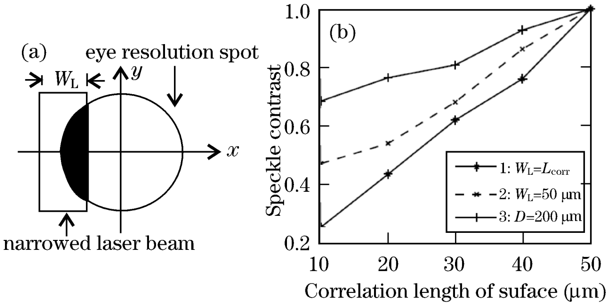

Fig. 6. Scanning with a narrowed laser beam. (a) Diagram of narrowed beam scanning through a pixel; (b) simulation results of speckle contrasts with narrowed laser beam.

there are few independent scattering elements in a pixel, so the averaging effect is not notable.

In conclusion, considering the averaging effect of eye during scanning for a pixel, speckle vision can be suppressed by choosing suitable optical parameters in laser scanning display system. Reducing the correlation of light intensity caught by eye during scanning is the guideline to suppress speckle. By simulation, it is found that with smaller correlation length of screen surface and narrowing the laser beam in the scanning direction, speckle suppression can be obtained.

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