Speckle contrast reduction in laser projection displays

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ABSTRACT

Speckle arises when coherent light scattered from a rough surface is detected by an intensity detector that has a finite aperture, such as an observer. In a laser projection display, the presence of speckle tends to mask the image information and therefore its reduction is highly desirable. Speckle contrast reduction is based on averaging a number of speckle configurations within the spatio-temporal resolution of the detector through diversification of the light parameters – angle, polarization, and wavelength. The maximum speckle contrast reduction for a given system will be derived, and two novel approaches to achieve the maximum reduction will be introduced. Application to the Grating Light Valve™ (GLV™) laser projection system using the Hadamard diffuser has resulted in a suppression to 8% residual speckle contrast.

Keywords: laser projection displays, speckle

1. INTRODUCTION

The use of lasers in a projection display enables the creation of vibrant images with extensive color coverage that is unachievable by conventional sources. One major obstacle – well-known since the invention of visible laser – is a phenomena called speckle. Speckle arises when coherent light scattered from a rough surface, such as a screen, is detected by a square-law (intensity) detector that has a finite aperture, such as an observer's eye. The image on the screen appears to be quantized into little areas with sizes equal to the detector resolution spot. The detected spot intensity varies randomly from darkest, if contributions of the scattering points inside the spot interfere destructively, to brightest if they interfere constructively. This spot-to-spot intensity fluctuation is referred as speckle. The characteristic granular size of the speckle is therefore the same as the size of the detector resolution spot. This situation is illustrated in Fig. 1.

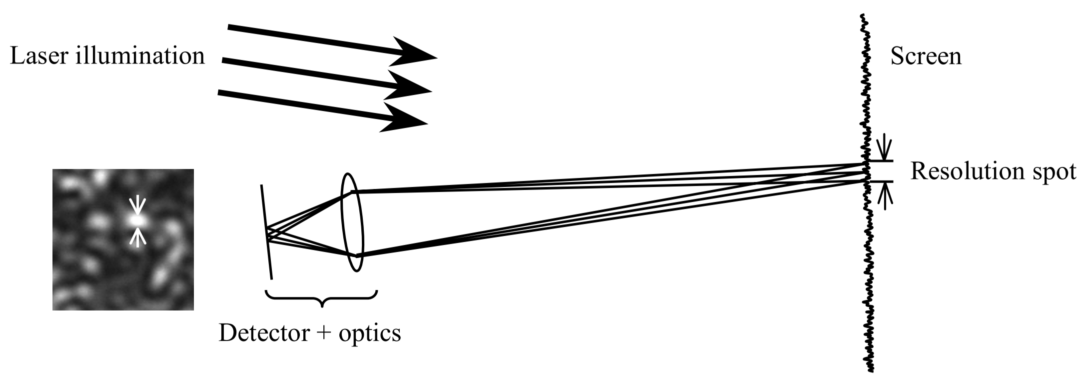

Fig. 1: Speckle formation

In a laser projection display, the presence of speckle tends to mask the image information and therefore its reduction is highly desirable. This paper describes the principle and methods of speckle reduction that allow practical and efficient implementations for use in commercial laser projection displays.

2. PRINCIPLE OF SPECKLE REDUCTION

Speckle reduction is based on averaging N independent speckle configurations within the spatial and temporal resolution of the detector. The term independent means that the speckle configurations are (i) uncorrelated, *and* (ii) non-interfering. Usually, the second condition is satisfied when the configurations are either generated by sources which are not coherently related or, for a pair of configurations, are orthogonally polarized. Following Goodman[1,2], we will use speckle contrast as a measure of speckle. Speckle contrast is defined as the ratio of the standard deviation of the intensity fluctuation and the mean intensity, and its value lies between 0 to 1. Goodman[1,2] has proven that, under the most favorable condition, where all the N independent speckle configurations have equal mean intensities, the contrast is reduced from 1 to $1/\sqrt{N}$. In what follows, we define $R = \sqrt{N}$ as the reduction factor. If not done properly, however, reduction degeneracy may happen. Degeneracy occurs when the implementation of several reduction methods are not independent, i.e. $R_1, R_2, \ldots, R_N$ produces a total reduction $R < R_1 R_2 \cdots R_N$. For example, illumination from two different angles with two different wavelengths does not automatically imply $N = 4$. Only when each wavelength is angle diversified will we get $N = 4$. Therefore it is important to keep the reduction book-keeping properly.

3. METHODS OF SPECKLE REDUCTION

Speckle depends on essentially three light parameters: angle, polarization, and wavelength of the illuminating laser beam. Therefore independent speckle configurations can be generated through the diversification of these three light parameters.

3.1 Angle diversity

Let Ω_{proj} and Ω_{det} denote the solid-angles subtended by the projection system and the detector to the screen, respectively. Assuming $\Omega_{proj} > \Omega_{det}$, the projection optics is capable of illuminating any one of the $N = \Omega_{proj}/\Omega_{det}$ uncorrelated sub-resolution areas within a single detector resolution spot on the screen. Of course there will be no reduction if this *potential* of generating N independent speckle configurations is left unexploited. In principle, the projection optics can be made to sequentially illuminate the N sub-resolution areas inside the detector resolution spot, within the detector integration time (~50 ms for human eye), i.e. within the spatial and temporal resolution of the detector. The speckle contrast will be reduced by a factor $R_\Omega = (\Omega_{proj}/\Omega_{det})^{1/2}$. One common approach to accomplished the same effect is by employing a time-varying diffuser[3,4]. The construction of a novel diffuser that achieves this reduction in minimum steps will be given in section 4.

3.2 Polarization diversity

A polarized laser beam incident on a depolarizing surface will experience depolarization due to multiple scattering. Many commercial screens with unity-gain (or even a sheet of a copier paper) are good depolarizing surfaces. The resulting speckle pattern can always be decomposed into the two orthogonal polarization states, denoted by σ_1 and σ_2. The two orthogonally polarized speckle patterns are independent and an automatic $\sqrt{2}$ reduction will result[1,2]. Further inspection, however, reveals that the σ_i speckles generated by the σ_j illuminations ($i, j = 1,2$) are all uncorrelated. If the two σ_1 speckles as well as the two σ_2 speckles are made incoherent (as produced from two different lasers, or from a single laser with an optical path delay which is longer than the laser coherence length), the four resulting speckle patterns become independent. Therefore full polarization diversity will give $R_\sigma = 2$, instead of just $\sqrt{2}$. We have verified this extra $\sqrt{2}$ reduction factor experimentally, and, to the best of our knowledge, it has not been recognized previously.

3.3 Wavelength diversity

Like all interference phenomena, a speckle pattern depends on the wavelength of the illuminating light. The speckle patterns from two beams with different wavelengths become uncorrelated if the average relative phase-shift created by the surface is ~2π or more. If the average surface profile height variation is y, then the required wavelength difference is $\delta\lambda = \lambda^2/2y$. Several cases commonly occur. The first case is multiple lasers, each with a wavelength that differs by at least $\delta\lambda$ from the others. If there are N_λ lasers (with indistinguishable perceived colors) satisfying this condition, the reduction factor is simply $R_\lambda = \sqrt{N_\lambda}$. The second case is a broadband laser. If the spectral width is $\Delta\lambda$, then the reduction factor is $R_\lambda = (\Delta\lambda/\delta\lambda)^{1/2}$. The third case is a pulsed laser. The reduction is also expressed as $R_\lambda = (\Delta\lambda/\delta\lambda)^{1/2}$, where

$\Delta\lambda = \lambda^2/c\Delta\tau$, c is the speed of light and $\Delta\tau$ the pulse width.

3.4 Maximum speckle reduction

The angle, polarization, and wavelength diversities are independent. Therefore, assuming a depolarizing screen is used, the maximum speckle reduction for a given system is

$$R = R_\Omega \cdot R_\sigma \cdot R_\lambda = 2 R_\lambda \sqrt{\frac{\Omega_{proj}}{\Omega_{det}}} \quad . \tag{1}$$

For a single narrowband laser, there is no wavelength diversity and $R_\lambda = 1$.

4. OPTIMUM DIFFUSER

A common approach to obtain the angle diversity reduction is by employing a time-varying diffuser. The amplitude image is superimposed with the pure phase pattern of the diffuser, normally placed at an intermediate image plane. Since the square-law detector is only sensitive to intensity, this spatial phase modulation will not affect the detected image, provided that the beam does not overfill the projection optics aperture. The role of the diffuser is to partition each detector resolution spot into N smaller phase-cells, and to assign a phase ϕ_i , $i = 1, 2, \ldots, N$ to each cell. Time-varying the phase pattern will effectively destroy the spatial coherence among the phase-cells in the resolution spot, and thereby reducing speckle contrast.

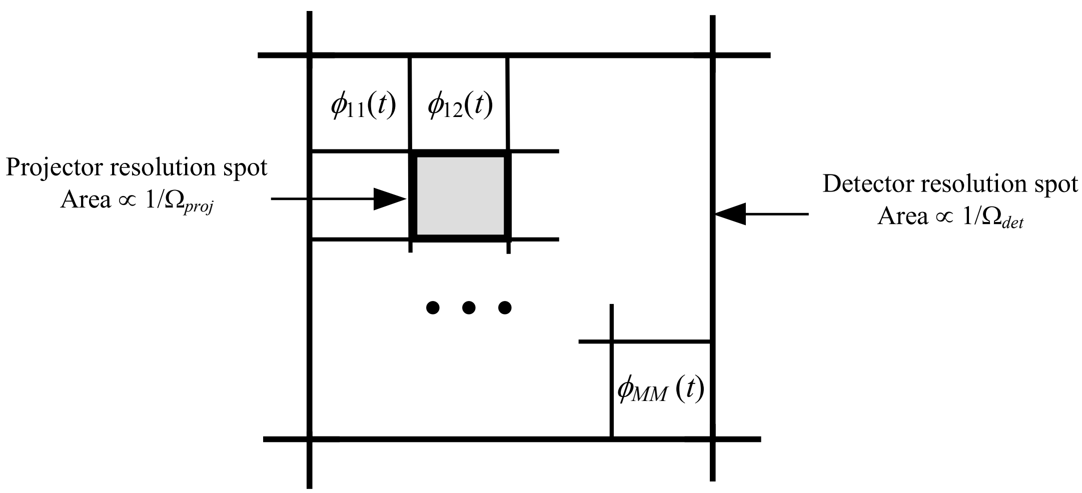

Fig. 2: Partitioning a "square" resolution spot into N equal square phase-cells by a diffuser.

Let's partition a "square" (for mathematical simplicity) resolution spot into $N = M \times M$ equal square cells with $M = (\Omega_{proj}/\Omega_{det})^{1/2}$, as illustrated in Fig. 2. Without the diffuser, all ϕ's are identically zero. If the detected optical field from the ij^{th} cell on the screen is E_{ij}, the speckle intensity of the resolution spot is

$$S_0 = \left| \sum_{i=1}^{M} \sum_{j=1}^{M} E_{ij} \right|^2 \quad . \tag{2}$$

The fields add together on an *amplitude* basis and, as shown by Goodman[1,2], no speckle reduction will result.

Suppose a diffuser that imprints $N = M\times M$ cells with relative phase ϕ^a_{ij} in each resolution spot is superimposed with the original image. Suppose further that A different patterns are sequentially presented with equal duration during the detector integration time, then the speckle intensity becomes

$$S = \frac{1}{A}\sum_{a=1}^{A}\left|\sum_{i=1}^{M}\sum_{j=1}^{M} H^a_{ij} E_{ij}\right|^2 \quad , \qquad H^a_{ij} = \exp\left(i\phi^a_{ij}\right) . \tag{3}$$

If the summation of H^a_{ij} over all the A phase patterns satisfies the decorrelation condition

$$\sum_{a=1}^{A} H^{a*}_{ij} H^a_{kl} = A\delta_{ik}\delta_{jl} \quad , \tag{4}$$

then

$$\begin{aligned} S &= \frac{1}{A}\sum_{a}\left|\sum_{i}\sum_{j} H^a_{ij} E_{ij}\right|^2 = \\ &= \frac{1}{A}\sum_{a}\sum_{i}\sum_{j}\sum_{k}\sum_{l}\left(H^{a*}_{ij} E^*_{ij}\right)\left(H^a_{kl} E_{kl}\right) = \\ &= \frac{1}{A}\sum_{i}\sum_{j}\sum_{k}\sum_{l} A\delta_{ik}\delta_{jl} E^*_{ij} E_{kl} = \\ &= \sum_{i}\sum_{j}\left|E_{ij}\right|^2 \quad . \end{aligned} \tag{5}$$

The averaging forces the cross-terms to vanish. The M^2 cells decorrelate from each other and their contributions become independent. Unlike (2), the fields now add together on an *intensity* basis. Following Goodman[1,2], the speckle contrast is reduced by a factor of $R_\Omega = M$. This reduction is maximum for the $M\times M$ case, because the upper limit of independent configurations that can be generated is M^2. It is also clear that the number of phase patterns to produce M^2 independent speckles cannot be less than $A_{min} = M^2$. For example, the traditional random diffuser needs a large number (theoretically infinite) of phase patterns to reach the $M\times$ reduction[4]. If the maximum reduction is achieved with the minimum number of phase patterns, the reduction is *optimum*. The set of phase patterns that satisfies the optimum decorrelation condition

$$\sum_{a=1}^{M^2} H^{a*}_{ij} H^a_{kl} = M^2\delta_{ik}\delta_{jl} \tag{6}$$

will be referred as the optimum decorrelation set. A priori, it is not obvious that such a set exists. However, we have identified the set of certain Hadamard matrices[5] that satisfies the condition (6). The construction of the optimum decorrelation set, based on Hadamard matrices of order $M = 2^{\text{integer}}$, will be reported elsewhere[6].

5. APPLICATION TO GLV LASER PROJECTION SYSTEM

The Grating Light Valve™ (GLV™) array is a unique MEMS based, 1-D spatial light modulator that modulates light by diffraction[7,8]. The fundamental advantages of the GLV technology are high efficiency, large dynamic range, precise analog attenuation, fast switching speed, high reliability, high yield, and the ability to integrate thousands of pixels into a single device. The GLV device is an array of reflective ribbons, where the static ribbons are interlaced with the electrostatically deflectable ribbons. One or more ribbon-pairs form a pixel and is independently addressable (e.g. 1080 pixels for HDTV). The amount of diffraction can be accurately controlled to impart an 8-bit or better gray-level intensity gradation. In a projection display, the GLV array is illuminated with a laser beam (a laser is required to illuminate the 1-D GLV array efficiently) and imaged to a screen through a galvo mirror. A 2-D image is formed by modulating the

GLV array with consecutive columns information (1920 columns for HDTV) as the galvo mirror scans the 1-D image across the screen. This rapid modulation is enabled by the fast GLV switching time (~ 1μsec). The diffuser used for speckle mitigation is placed in an intermediate image plane. The projector-detector geometry is shown in Fig. 3.

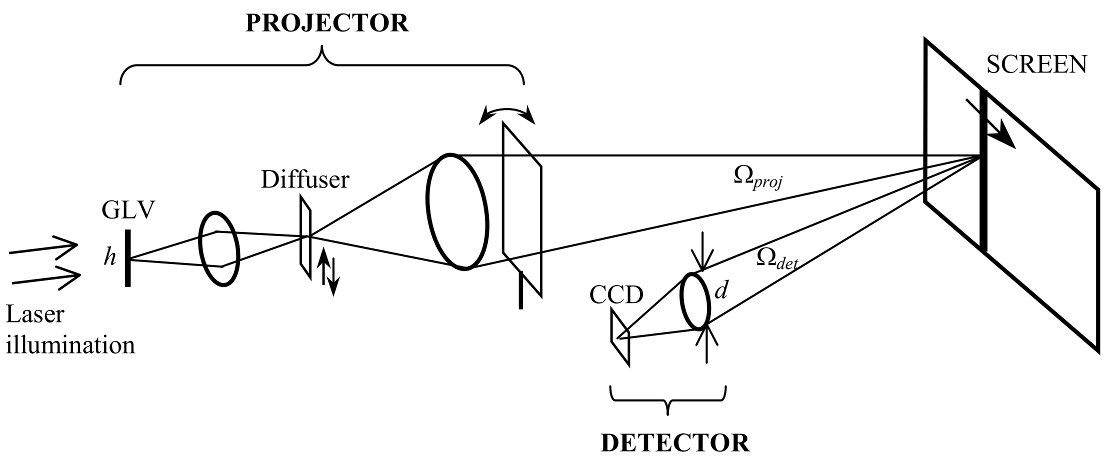

Fig. 3: Basic projector-detector geometry.

To standardize the speckle contrast measurement, we introduce the notion of a standard detector (or observer) located at a distance equal to twice the image height from the screen, and an aperture (or eye's pupil) diameter of $d = 3$ mm. The *potential* reduction can be calculated to be $(\Omega_{proj}/\Omega_{det})^{1/2} = 2h/(d\,F/\#)$, where h is the GLV length and $F/\#$ the speed of the projection optics. In our experiment, the GLV array is 27 mm long (25 μm pixel) and the projection lens speed is $F/2.5$, for which $(\Omega_{proj}/\Omega_{det})^{1/2} = 7.1$. To realize this reduction, we use the set of sixty-four Hadamard matrices of order-8 (i.e. $M = 8$) that offers an up to 8× reduction. These Hadamard phase patterns are imprinted in a piece of fused silica by standard lithography. The binary nature of the Hadamard phase patterns requires only one mask for its fabrication. The unetched cells correspond to 0 relative phase, and the etched cells to π. For $\lambda = 532$ nm, the etch depth is 0.58 μm. All the sixty-four phase patterns must be presented within the detector integration time. With our scan architecture, this is accomplished by the combination of the scanning action itself and moving (vibrating) the diffuser across the non-cyclic arrangement of the phase patterns. In addition to angle diversity, we also employ polarization diversity. The source is a Spectra Physics intra-cavity doubled Nd:YVO_4 laser (532 nm), which has a single transverse mode, but a few hundred longitudinal modes. The latter implies an effectively short coherence length – a few centimeters in this case. The short coherence length offers a simple way to implement polarization diversity, in which a polarizing beam splitter and a few centimeter optical delay are used to create the two incoherent orthogonal polarization states. The screen used in the experiment is Da-Lite's Da-Mat that has a near unity gain and a high degree of depolarization. With both angle and polarization diversities, the reduction factor is 7.1×2 = 14.2, bringing the speckle contrast down from 1 to 0.07.

To measure the speckle contrast, we use a CCD camera that operates in the linear regime and imaging optics that conform to the standard detector geometry. Each speckle image is normalized to eliminate any background contribution. Fig. 4 compares the original and the reduced speckle patterns. The measured contrast of the original speckle in Fig. 4a is 0.70, close to the expected value of $1/\sqrt{2}$ from a single narrow-band laser scattered off a depolarizing screen. The measured reduced speckle contrast in Fig. 4b is 0.08, in good agreement with the calculated result of 1/14.2 from angle and polarization diversities. This level of residual speckle is only marginally perceivable for stationary images, and should be perfectly acceptable for motion pictures.

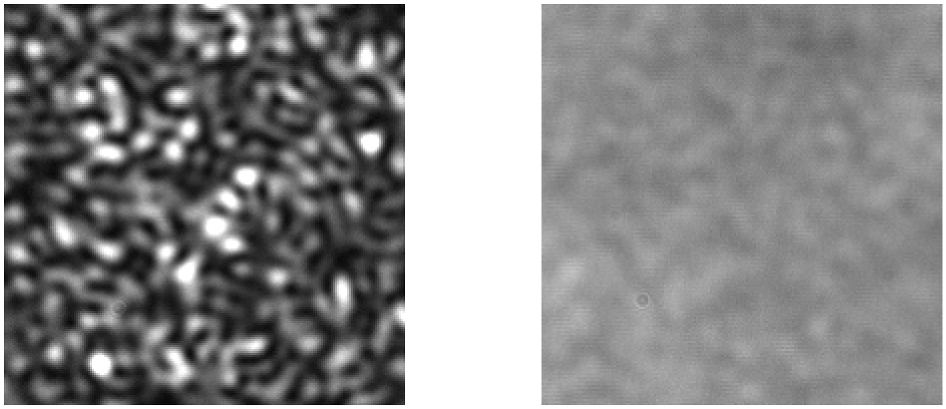

Fig. 4: Images of (a) the original speckle (70% contrast) , and (b) the reduced speckle (8% contrast).

The original image quality of the GLV projection system is preserved by the diffuser. The fraction of light scattered by the diffuser beyond the projection optics aperture constitutes a loss. The measured optical efficiency, taken as the ratio of the light power transmitted to the screen with and without the diffuser, is 85%. The use of a gradual transition between the etched and unetched cells is expected to make the diffuser even more efficient.

6. SUMMARY

Speckle contrast reduction is based on averaging a number of speckle configurations within the spatio-temporal resolution of the detector through diversification of the light parameters – angle, polarization, and wavelength. The maximum reduction for a given system is $2R_\lambda\,(\Omega_{proj}/\Omega_{det})^{1/2}$. Two novel approaches to accomplished the maximum reduction are presented: the use of an optimum diffuser and the extra $\sqrt{2}$ reduction factor in polarization diversity. Application to the GLV laser projection system using the Hadamard diffuser has resulted in a suppression to 8% residual speckle contrast at a single wavelength, in good agreement with the theory. The Hadamard diffuser is efficient and preserves the original image quality.

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