White Paper

A Pragmatic Speckle Measurement Method

Visteon®

A Pragmatic Speckle Measurement Method

Yanning Zhao*

Visteon Electronics GmbH, Germany

Abstract

Laser projection is a promising technology for automotive displays. Until now, however, this technology did not find its way into mass production due to limited image quality. One of the image-degrading factors is the speckle noise. As speckles in an imaging system are subjective and the observed result highly dependent on the observer, there is no standardized way to measure it. We propose a pragmatic approach to quantify speckles in laser projection systems using commercially-available equipment.

Author Keywords

Laser projection; speckle; measurement; camera; F-number.

1. Introduction

The idea of laser-based projection display has been considered as a promising display technology ever since the first laser was invented by Charles H. Townes and Arthur Leonard Schawlow in 1958. This is due to its advantages of extended color gamut, small étendue and low power consumption of the laser source [1-3]. It is even more interesting for automotive applications e.g. HUD, because of the potential compact module size of laser picture generation units (PGU). However, it was not until recently that it gained extra momentum due to the rapid development in the visible semiconductor laser diode material, especially in the green color [4].

As a relatively young display technology, laser as an illumination source in projection applications still has several technical hurdles to overcome before it can reach an acceptable image quality to be used in mass production. One well-known issue is the so-called phenomenon 'speckle'. Speckle is generated when a coherent (or partially coherent) light source, like a laser beam, is projected onto a random rough surface [5]. The reflected light will then generate an interference pattern. This can be observed as a granular pattern on the projection screen and as such masks the depicted information and degrades the image quality. Thus, it is desirable to reduce or eliminate speckle in this kind of projection display system.

Many methods to reduce speckle have been proposed. Most of them are based on the principle of superimposing partly decorrelated or fully decorrelated, statistically independent speckle patterns. Both instantaneous and time-sequential speckle reduction methods have been proposed. These can be divided into four different categories depending on how the superimposed speckle patterns are mutually decorrelated [6]. These four categories are wavelength decorrelation, spatial decorrelation, angular decorrelation and scrambling techniques.

In order to reduce the speckle, it is essential to know how to quantify this phenomenon in the first place. This is, however, a very complex problem, and there is no state-of-the-art standardized way to measure speckle.

Speckle can be quantified by its speckle contrast value, defined as:

$$C = \sqrt{\langle I^2\rangle - \langle I\rangle^2 / I} \quad (1)$$

Where the numerator is the standard deviation of the intensity fluctuation and the denominator is the mean intensity speckle patterns are often divided into objective and subjective speckle. Speckle patterns are called objective when there is no imaging involved. The speckle distribution can then be measured by, for example, an optical sensor without a lens. When an imaging system is involved in the formation of the speckle pattern, e.g. the speckle pattern on the human retina formed by the eye lens, we speak about subjective speckle. In any information display systems, we are only interested in the 'subjective speckle pattern' - what the human eye would perceive when looking at the projected image. Depending on the eye situation of the observer, everybody would perceive the speckle behavior differently. The speckle contrast result is highly dependent on several critical measurement parameters, such as camera focus, F-number, camera position and camera integration time [7]. This means that in order to compare the speckle behavior of different projectors objectively, there is a need for defining a standardized speckle measurement.

In this paper, we propose a pragmatic approach to reduce the measurement complexity while still enabling reliable and reproducible measurement results. Rather than trying to construct a complex setup that perfectly mimics the human eye [8], our approach chooses the critical parameters fixed at a reasonable value and optimizes the camera integration time to fully resolve the speckle contrast to the maximum value.

2. Methods

2.1 Measurement Setup For the measurements reported in this paper, a projector without an imager was built (see Figure 1):

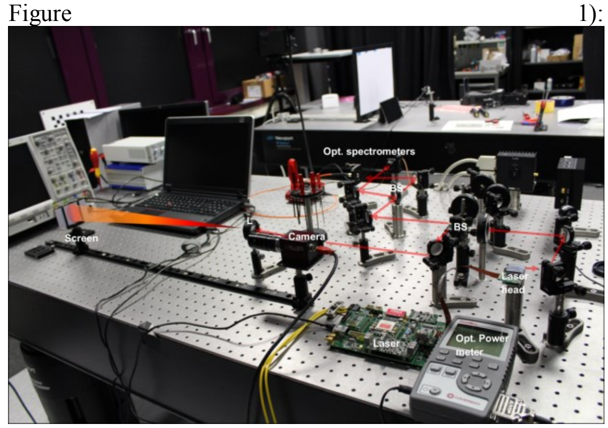

Figure 1 Measurement setup (L: lens; BS: beam splitter)

As a light source we used the OSRAM laser Picasso laser module consisting of the combination of direct red, green and blue laser diodes, individual controllable. The outputs of red, green and blue individual laser beams are directly projected onto a normal (printing quality) paper as a screen. Laser diode power and center frequency was measured by an optical spectrum analyzer (Thorlabs SA201 Spectrum Analyzer Controller) and an optical power meter (Coherent OP-2 VIS together with Coherent FieldMax II). The result of the center frequencies and optical powers are listed as follows:

Table 1 Center frequencies and optical powers of the RGB light source

Color	Wavelength (nm)	Optical power (mW)
Red	639.81	3.77
Green	514.30	4.21
Blue	451.09	2.15

For our measurements we used the AVT OSCAR F-810C color CCD camera with 3288 (H) x 2470 (V) pixels, a diagonal of 11.07 mm and a pixel size of 2.7 µm x 2.7 µm. A camera lens (Pentax TV Lens 75mm C7528-M) with variable F-number in the range from F/2.8 to F/32 was mounted on the camera and focused on the screen. The screen is made out of (printing quality) paper. As speckle depends on the wavelength of the light and the laser technology, it will be important to measure the individual speckle contrasts of each of the primaries (blue, green and red lasers only) of the projector.

The output of the laser diode is split into two parts by the beam splitter: the first part is projected directly onto the diffuser screen. The illuminated image on the screen is then acquired and the signal processed by the camera for speckle contrast calculation.

Simultaneously, the other half of the optical power is travelling to the optical spectrometer (Thorlabs CCS100). The optical spectrometer records the frequency spectrum and the bandwidth of the laser light during the whole process.

2.2 Critical Parameter Several parameters are relevant to the measured speckle contrast, and need to be taken special care of.

Focus: It is usually thought that speckle level does not depend on focus adjustment. In other words, speckle would not vary if the screen is appropriately focused on the CCD through the pair of lenses. In reality, it can be shown that this statement is only valid if the illumination source is spatially coherent. When introducing speckle reduction features such as diffusers, vibrating membranes, etc., spatial coherence is partly destroyed and this statement is no longer valid. As a consequence, when making measurements, it is crucial to verify that the screen is correctly projected on the CCD [9].

F-Number: In a diffraction limited imaging system as a camera-lens system, the speckle size in the image is determined by the diffraction limit: $D = 1.22 \cdot \lambda \cdot (f/\#)$[10][11][12]

This is a wavelength-dependent value. In order to guarantee that the speckle is fully recognized by the CCD sensor, we chose to make D>5P, where P is the sensor pixel size. After some calculation according to the equation, we can obtain the minimum F-number required for the individual colors: $(f/\#)_{red}$= 9, $(f/\#)_{green}$= 11 and $(f/\#)_{blue}$= 13 respectively. In our system, we chose the maximum F-number possible for our camera objective f/(#)=32, which is definitely sufficient for the measurement.

Image Content: In general people are less sensitive to motion pictures than they are with stationary images. Studies [13] show that an observer is more perceptive of speckle in stationary images than they are in motion pictures. This can be explained by the fact that the movement of the images creates different speckle patterns that balance out over time (see speckle overview report). To position ourselves in the 'worst case scenario', the studied images in the following work will be stationary.

Camera's Position: In many papers, it was also noticed that the position of a detector in the setup is extremely relevant in terms of CR evaluation. This is true for the distance between the camera and the projection screen but also for the angle. For this reason, it is crucial to measure speckle contrast in a consistent manner such that the speckle contrast can be precisely and reproducibly determined. This means, amongst other things, that the camera's position should be fixed and never moved during a measurement.

2.3 Measurement Procedure The measurement procedure is described as the flowchart below (see Figure 2):

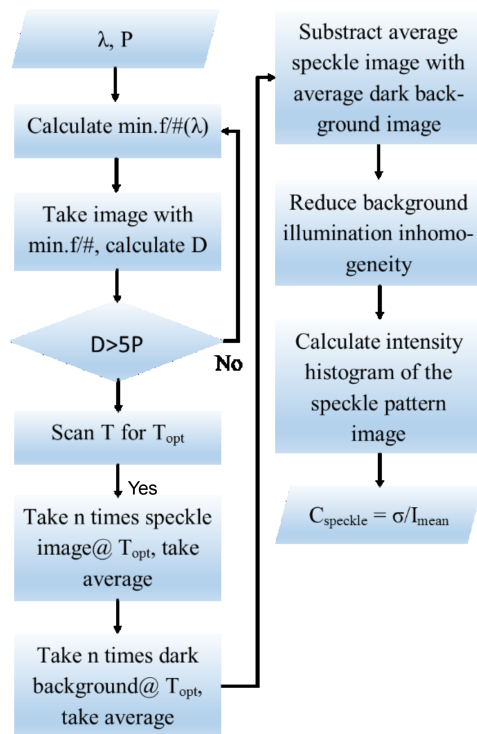

Figure 2 Measurement procedure. f/# is the camera objective F-number; P is the camera pixel size; D is the speckle size; T is the Integration time; T_{opt} stands for the optimized integration time

Speckle Size Calculation With input parameters λ and P, the correct f/# is determined. To ensure a reliable result during the image acquisition, the actual speckle size is calculated from the acquired image. In order to calculate the actual speckle size in the camera taken image, the image's auto-covariance matrix is calculated:

The speckle size is determined by the FWHM or $1/e^2$ (beam waist) values of Gaussian fits to the sums of the normalized auto-covariance. This calculated speckle size value should be larger than five times the pixel size in order to assure a reliable measurement.

A warning message will be sent informing that the f/# number needs to be increased in case of a D smaller than five times the size of the sensor pixel pitch P.

Camera Integration Time Optimization In order to fully resolve the speckle contrast, the camera integration time will then be scanned. During this process, we can see that the speckle contrast is evolving with the increasing camera integration time (see Figure 3). At short integration time, the dark current is the dominating noise factor and covering up the real speckle noise. As the integration time increases, the speckle noise is increasingly resolved along with better signal to noise ratio of the image signal. At the edge where the camera sensor approaches saturation and the maximum intensity curve turns flat (indicated by the red line), we can achieve the maximum speckle contrast. After this, the speckle contrast stays relatively flat for a period of time and starts to gradually decline as the saturation of the camera increasingly eats up the speckle noise. Therefore, we should choose the integration time length accordingly to enable a maximum speckle contrast value measurement result.

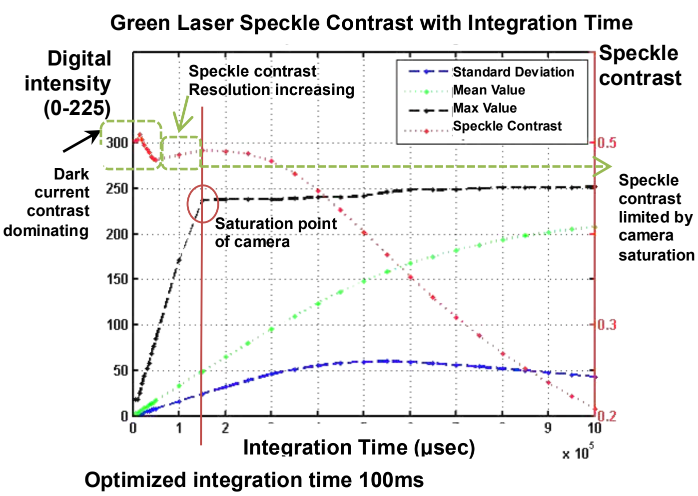

Figure 3 Camera integration time optimization

Image Acquisition After we have set the optimized camera integration time, we can start with the actual speckle contrast measurement. For a reliable result, a homogeneously illuminated area of the projected image should be chosen to avoid errors in data processing. During our program, 10 images are taken for each individual color at the correct integration time with a correct f/# number, as a data base for the averaging in the data process. Then, without any illumination,10 dark current background images are taken at the correct integration time for each color. This will be averaged and subtracted from the original image, to reduce the camera noise.

3. Results

In order to reduce the background inhomogeneity, a Gaussian smoothing of the image illumination is calculated and then subtracted from the averaged camera image. The intensity histogram of the speckle pattern is then calculated according to Equation 1.

The calculated speckle contrast for the whole image and local areas are listed in the table below:

Table 2 Center frequencies and optical powers of the RGB light source

Color	Without homogenizing background	With homogenized background
Red	97.5%	48%
Green	50.2%	29.2%
Blue	61.3%	45.5%

Figure 4 shows a typical speckle contrast calculation result. The averaged dark background is subtracted from the averaged original image. The speckle contrast is then calculated over the n×n image area.

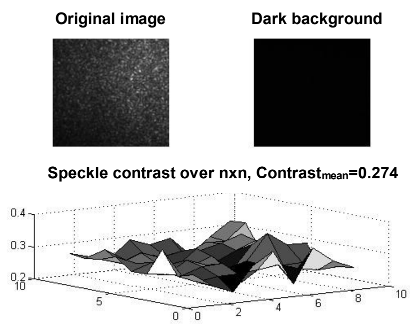

Figure 4 Typical result of a speckle contrast

4. Discussion

The theoretical speckle contrast C for broadband illumination onto the paper screen is given by

$$C_\lambda = \left(1 + 2\pi^2 n^2 * \left(\frac{\delta\lambda}{\bar{\lambda}}\right)^2 * \left(\frac{c\sigma_t}{\bar{\lambda}}\right)^2\right)^{-1/4} \quad (2)$$

Here, C is the speed of light in vacuum, $\delta\lambda$ is the 1/e-width of the wavelength spectrum of the laser source, $\bar{\lambda}$ is its mean emission wavelength and σ_t is the standard deviation of the scattering path time distribution of the photons on the paper screen. For normal copy paper as screen, we can take $\sigma_t \approx$ 1.681 ps [6]

Table 3 is a comparisons between the typical line width from data sheet and a theoretical calculated line width. Calculated linewidth 1 is the line width calculated based on the speckle contrast without subtracting the Gaussian background, while the calculated line width 2 is the speckle contrast after subtracting the Gaussian background.

From the results listed in the table, it is obvious that background not homogenized original images agree better with the theoretical value. Therefore, Gaussian smoothening diameter for background homogenization has dramatic influences in the calculated speckle value, with the potential risk for error inflow. This suggests that special care need to be taken during the image acquisition process to choose a homogenized illuminated image area as a region of interest in order to avoid errors from the low-frequency background noise.

Table 3 Calculated linewidth of the RGB light source

Color	Calculated linewidth 1 (nm)	Calculated linewidth 2 (nm)	Typical datasheet linewidth (nm)
Red	0.06	0.76	0.04
Green	0.46	1.38	0.50
Blue	0.22	0.43	0.50

5. Conclusion

In this paper we have presented a pragmatic approach to quantify speckle behavior for laser projectors with commercially-available equipment with several easy steps. This method can make the comparison of laser projectors' image quality regarding to speckle fast and convenient, which provides the foundation of future work of laser speckle reduction in projection display applications.

References

[1] K. Chellappan, E. Erden, and H. Urey, "Laser-based displays: a review," Appl. Opt. 49, 79–98 (2010).

[2] J. Hecht, "A short history of laser development," Appl. Opt. 49, F99–F122 (2010).

[3] U. Weichmann, A. Bellancourt, U. Mackens, and H. Moench, "Solid-state lasers for projection," JSID 18, 813–820 (2010).

[4] S. Lutgen, D. Dini, I. Pietzonka, S. Tautz, A. Breidenassel, A. Lell, A. Avramescu, C. Eichler, T. Lermer, J. Müller, G. Bruederl, A. Gomez-Iglesias, U. Strauss, W. G. Scheibenzuber, U. T. Schwarz, B. Pasenow, and S. Koch, "Recent results of blue and green InGaN laser diodes for laser projection," in Novel In-Plane Semiconductor Lasers X, A. A. Belyanin and P. M. Smowton, eds., Proc. SPIE 7953, 79530G (2011).

[5] J. W. Goodman, "Speckle phenomena in optics: theory and applications," Roberts and Company, Englewood, (2007).

[6] F. Riechert, "Speckle reduction in projection systems," Ph.D. thesis, Karlsruhe Institute of Technology (KIT), (2009).

[7] P. Janssens, "Laser projector speckle measurements," in 29th International Display Research Conference. EURODISPLAY 2009, Proc. SID, 5–7 (2009).

[8] R. Stij, "Standardized speckle measurement method matched to human speckle perception in laser projection systems," Optics Express, (2012).

[9] J. Gollier, "Speckle measurement procedure," Corning Tech. Rep., (2010).

[10] Jiłí Keprt, L. Bartonìk, "Measurement of small deformations by laser speckle interferometry," acta univ. palacki. olomuc., fac. rer. nat., physica 38, 115-125, (1999).

[11] E. Archbold, J. M. Burch, A.E. Ennos, "Recording of In-Plane Surface Displacement by Double -Exposure Speckle Photography," Opt. Acta 17, 883-898, (1970).

[12] K. A., Stetson, "A Review of Speckle Photography and Interferometry," Opt. Eng. 14, 482-489, (1975).

[13] Y. M. Lee, D. K. Lee, J. M. Park, S. Y. Park and S. G. Lee "A study of the relationship between human perception and the physical phenomenon of speckle," Volume 39, Issue 1, pages 1347–1350, SID digest, (2008).

About Visteon

Visteon is a global company that designs, engineers and manufactures innovative cockpit electronics products and connected car solutions for most of the world's major vehicle manufacturers. Visteon is a leading provider of driver information and controls, audio and infotainment, and domain controllers; its brands include Lightscape®, OpenAir® and SmartCore™. With corporate offices in Van Buren Township, Michigan, (U.S.); Shanghai, China; and Chelmsford, UK; Visteon has more than 40 facilities in 18 countries. Learn more at www.visteon.com.

Visteon®

Visteon Corporation
One Village Center Dr.
Van Buren Township, MI 48188
1-800-VISTEON
www.visteon.com