9.5: Laser projector speckle measurements

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Abstract

Observed speckle contrasts depend strongly on the setup of the measurement. To compare laser projectors objectively speckle measurements have to be standardized. In this paper some important parameters that need to be fixed in order to come to a measurement standard are discussed.

1. Introduction

Traditionally a projector uses a short-arc lamp as a light source. The short lifetime of these lamps is one of the main reasons why projector makers would like to switch to a solid state light sources like LED or laser. Another advantage is the extended color gamut that can be achieved using lasers or LEDs. While the output brightness of an LED-based projector is limited due to the large étendue of the LEDs, lasers could be well-suited for high-brightness projectors (>5000 lm). Laser projectors are not common (yet) due to the high cost of the lasers and laser speckle, which deteriorates the quality of the projected images [1].

There have been reported several values for the detection threshold of speckle ranging from 2% [2] to 8% [3]. Lee et. al. [4] pointed out that the appearance of speckle depends on several parameters like the luminance, the illumination of the room, etc. The reported values are overall hard to interpret and compare, as the measured speckle contrasts strongly depend on the setup of the measurement as will be shown in this paper.

Measurement standards exist in order to determine the performance of a projector: there is e.g. the ICDM Display Measurement Standard [5], which defines proper ways to measure uniformity, output brightness, contrast ratio, etc. However, there is no standard to evaluate speckle contrasts, yet. The idea behind a laser projector speckle measurement is simple: using a camera a picture of a uniformly illuminated screen is taken for each of the primaries of the projector; then the low-frequency fluctuations in the picture are filtered away and the contrast of the filtered image is calculated [6]. The high-pass filter is necessary to remove global intensity variations, which are not caused by speckle, but e.g. the efficiency of the projection lens.

However, the result will still not be very useful. If the same measurement on the same projector would be repeated with a different camera, the result could be completely different! This is caused by the large amount of parameters, which influence the recorded speckle pattern. All this can be understood from an extensive mathematical treatment of the speckle phenomenon (see reference [7] for these calculations).

This means that there is a need for a standardized speckle measurement, which would allow comparing the speckle contrast of different projectors objectively, as is done now with the contrast ratio, etc. In this paper we list a few important parameters that need to be fixed in order to standardize laser projector speckle measurements. We propose to choose these parameters such that the sensitivity of the measurement to speckle is maximized, rather than to build a setup that mimics the human eye, because this would make the setup too complicated.

2. Measurement setup

For the measurements reported in this paper, a projector without an imager was built: the exit of a light tunnel was directly projected onto a screen. In case a light modulator is used in the test system, pixels are visible on the screen and these pixels might be detected by the camera and add additional contrast to the image. The projection lens had an iris to enable it to change the f-number of the projected light distribution between F/2.5 and F/8. For our measurements we used a black and white camera with a CCD-sensor of 1024 x 768 pixels, a diagonal of 6.0 mm and a pixel size of 4.65 x 4.65 μm^2. A 50 mm camera lens with variable F-number in the range from F/2.8 to F/22 was mounted on the camera and focused on the screen. The screen is made out of (printing quality) paper.

The projector was despeckled by breaking the coherence of the beam by means of a rotating diffuser. The laser source for these measurements was a green frequency-doubled laser. The central wavelength of the laser is 532 nm and the FWHM of the spectrum is below 0.1 nm. 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.

3. Results

3.1. Camera

The behavior of the speckle contrast as a function of the f-number of the camera lens is shown in Figure 1. The measurement was repeated for different f-numbers of the projection lens. In all cases, we found that the speckle contrast goes through a maximum for a camera f-number around F/11. This maximum is independent of the f-number of the projection lens, but might be different for another camera and lens combination.

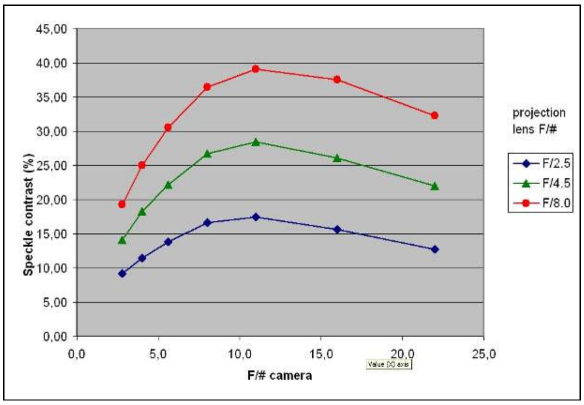

Figure 1: Speckle contrasts as a function of the f-number of the camera.

This is due to the fact that two effects play a role: spatial integration of speckle and speckle reduction by angular diversity.

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The first effect was studied by a measurement of speckle without speckle reduction using the single mode laser. This experiment showed that the observed unsuppressed speckle contrast depends on the size of the speckle grains on the CCD relative to the size of the pixels of the CCD. Figure 2 shows unsuppressed speckle contrasts as a function of the f-number of the camera lens.

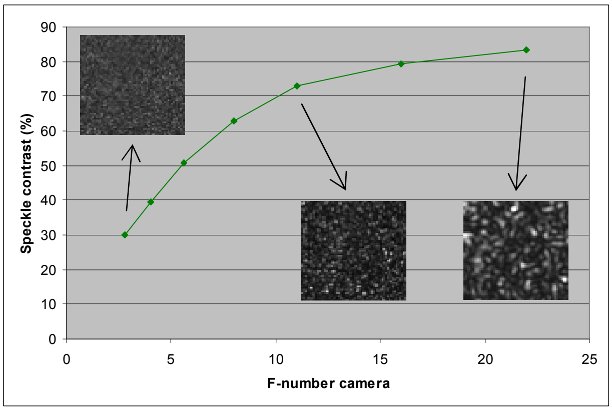

Figure 2: Unsuppressed speckle contrasts for different f-number of the camera lens.

For low f-numbers, the aperture of the camera is widely open, and the grain size of the speckle pattern is smaller than the size of a pixel. Speckle is integrated over the area of one pixel and the output of the pixel is the average brightness of all speckle grains inside that pixel. For high F-numbers, the grain size becomes larger than the pixel size and there is no spatial integration of the pattern; the speckle contrast tends to saturate towards 100%, which is the maximum speckle contrast of a single-mode laser [7].

The size of the speckles in an imaging system can be calculated via the autocorrelation function of the speckle pattern. The area of a speckle grain is given by $(\lambda z)^2/A$, where λ is the wavelength of the laser light. z and A are the focal length and the surface of the aperture of the camera lens, respectively [7]. For the speckle patterns shown in Figure 2 the speckle size varies from 1/10th of a pixel for F/2.5 to 6 pixels for F/22.0.

We found that unsuppressed speckle contrasts do not depend on geometric factors like the viewing distance, the f-number of the projection lens, the distance from camera to the screen, etc. Even if the camera is defocused, the speckle contrast remains the same.

From theory it is expected that once the coherence of the laser is broken by means of the rotating diffuser, the speckle contrast is reduced via angular diversity by a factor $\sqrt{(\Omega_c/\Omega_p)}$, where Ω_c and Ω_p are the solid angle of the aperture of the camera and the projection lens respectively (e.g. [3]). These solid angles are proportional to the area of the aperture of the camera and the projection lens. Thus, speckle suppression will be better the smaller the diameter of the camera. More precisely, the speckle reduction factor is expected to be proportional to the diameter of the aperture of the camera, or in other words, inverse proportional to the f-number of the camera lens. The combination of increased speckle reduction with increasing f-number and the spatial integration illustrated in Figure 2, results in the behavior shown in Figure 1.

This discussion points out that, in order to perform accurate and repeatable speckle measurements, the pixel size of the camera, and the properties of the camera lens have to be fixed. Normally the point-spread function of the camera lens and the pixel size of the CCD match: in normal imaging applications it makes no sense to have smaller pixels than the point-spread function of the lens. For accurate speckle measurements, however, it is desirable to have a CCD pixel size, which is smaller than the resolution of the camera lens, as this would allow oversampling the speckle pattern at the position of the CCD. In this way the sensitivity of the measurement is increased.

3.2. Polarization

It is well-known that speckle can be reduced via polarization diversity, where a speckle reduction by √2 is expected in case a screen, that destroys the polarization, is used in combination with a polarized projector. The screen we used in these experiments has this property, because it has a white diffusing surface. In order to test this theoretical prediction, we measured the speckle contrast with a polarizer in front of the camera lens and we compared the results with the measurements without polarizer. We did this test for different f-numbers of the projection lens. The results are shown in Figure 3.

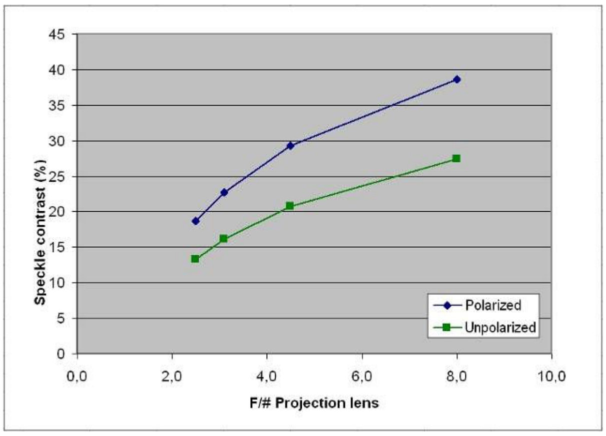

Figure 3: Speckle contrasts recorded with and without polarizer in front of the camera (F/11) as a function of the f-number of the projection lens.

We found a ratio between polarized and unpolarized speckle contrasts of 1.41, which is almost exactly √2 (our results tend to be slightly smaller than √2). Because this factor is very well reproduced, we suggest that all speckle measurements are performed with a polarizer in front of the camera for increased sensitivity to speckle. From this measurement it is trivial to calculate the speckle contrast on a perfectly depolarizing screen.

3.3. Distance between camera and screen

Another important parameter is the distance between the camera and the screen. The further away the camera is positioned from the screen, the lower the recorded speckle contrast will be. This can be understood from the speckle suppression factor $\sqrt{(\Omega_c/\Omega_p)}$, which behaves approximately as $1/D$, with D the distance between the camera and the screen.

Speckle suppression depends also on the size of the projected image. The speckle suppression factor $\sqrt{(\Omega_c/\Omega_p)}$ is inverse proportional to the diameter of the aperture. For a given diagonal of the light modulator, projection distance and f-number of the projector, the diameter of the aperture is inverse proportional to the height H of the image on the screen.

Thus, speckle contrasts are linear to *H*/*D*. This means that the ratio *H/D* has to be fixed in the standard for speckle measurements. At this point we propose to take $H/D = 1$, as this corresponds to the closest viewing position in a theater. In our case, there were no pixels in the image, due to the absence of a light modulator in the setup. In a real situation one has to be careful that the pixels are not resolved by the camera, and in speckle measurements of projectors (including an imager) it might be necessary to use lower values for *H/D*. The optimal situation would be that the resolution of the camera matches the size of the pixels of the projector on the screen.

3.4. Exposure time of the camera

Another parameter that might influence speckle measurements is the exposure time of the camera. In our measurement the integration time was varied between 30 and 240 ms, and we only could find a small influence of the exposure time on the obtained speckle measurements. The speckle contrast tends to decrease slightly for increased exposure times. Between an exposure time of 30 ms and 240 ms, we measured relative differences in the speckle contrasts of the order of 5%: e.g. 38.0 % for 30 ms and 36.5% for 240 ms. Although we did not determine the cause of this effect, we suspect it is due to the high sensitivity of the speckle measurement to vibrations.

We suggest fixing the exposure time to 30 ms, as this roughly corresponds to the temporal response of the eye. Speckle suppression might rely on temporal integration of speckle patterns (as it is the case for this experimental setup by means of a rotating diffuser), so it is important that the temporal response of the eye is taken into account.

Somewhat related to the exposure time of the camera is the image brightness and the noise in the camera. The projector brightness has to be adjusted in such a way that the camera is not saturated, and that the dynamic range of the camera is used as much as possible. This will avoid that camera noise influences the measurement.

3.5. Screen type

Speckle depends also strongly on the screen type. Important parameters are the gain and the surface structure of the screen, whether the screen conserves polarization or not, etc. At this moment we propose no specific screen-type, because further experiments are required to determine the optimal screen type for speckle measurements. The screen should be widely available, and preferentially it should preserve the polarization, as this would be the screen type used for polarization-based 3D stereoscopic projection.

4. Conclusion

In order to be able to compare speckle contrasts of different projectors, there is a need for a standardized procedure for speckle measurements. In this paper, the effect of the f-number of the camera lens, the pixel size of the CCD, the distance between the camera and the screen, and the exposure time of the camera, were discussed. It is clear that, in order to develop a standard, all these properties have to be fixed. Further work is needed to come to a standard for speckle measurements.

5. Acknowledgements

This work has received research funding from the EU 6th Framework Program under contract number IST-33799 Osiris [8]. The views expressed here are those of the authors only. The Commission is not liable for any use that may be made of the information contained therein.

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