Laser speckle reduction using micro-structured screens

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We report on a novel speckle reduction scheme using microlens-arrays as screen material for application in laser-based projection systems. The speckle is reduced when the laser's spatial coherence area on the microlens-array screen is smaller than the microlens footprint. Resultantly, the fields emitted by the different microlenses cannot interfere in the observer plane and thus no speckle is created. We experimentally test this scheme, demonstrating that microlens arrays with a regular and irregular surface structure show promising results. The experimental results correspond well with a model we constructed, giving us more insight into the different effects influencing the speckle contrast.

Introduction

Laser technology provides a plausible response to the demand for high image brightness in 3D cinema [1]. The only drawback of using laserlight is the formation of speckle in the projected image, consisting of random intensity fluctuations superposed on the projected images. The speckle pattern forms when coherent light is reflected off (or transmitted through) a surface which is rough on the scale of the optical wavelength [2, 3]. Speckle can be reduced to acceptable levels [4, 5] by overlapping multiple uncorrelated speckle patterns within the spatiotemporal resolution of the observer [6, 7, 8, 9, 10, 11]. The most common ways to create uncorrelated speckle patterns are through polarization diversity, wavelength diversity and angular diversity. Present day laser-based projection systems often combine multiple speckle reduction schemes in order to sufficiently reduce the amount of speckle in the projected images. This leads to complex and costly laser projectors.

We combine the concept of reduced spatial coherence as discussed in Ref. [2] with a specialized microstructure of the screen material. When the screen is an array of microlenses, the interference between the fields emitted by different lenses in the array (the cause for speckle) can be inhibited by reducing the on-screen spatial coherence area to below the microlens footprint. In this approach we also have to ensure that this footprint

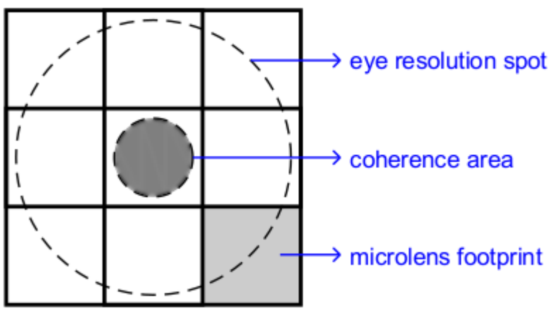

Figure 1: Schematic of MLA-screen based speckle reduction scheme.

is smaller than the observer's resolution spot on the screen. Otherwise, we risk resolving the individual lenses of the array in the observed image, thereby reducing image quality. These two criteria are visualized in Fig.1. If successful, this approach for the prevention of speckle formation eliminates the need to use any other speckle reduction schemes. This might lead to simpler and cheaper laser projectors and can pave the way towards small-scale laser projectors.

We investigated two distinct types of microlens arrays (MLAs): an irregular MLA (type EDS-20-05584 Engineered Diffuser from RPC Photonics) with varying lens sizes, 120 µm wide on average, and a regular MLA (type MLA-S100-f4 Microlens Array from RPC Photonics) with regular, rectangular grid and fixed lens size, 100 µm wide. For comparison we performed the same experiments on a screen consisting of a sheet of printing paper (i.e. without specialized microstructure).

Speckle contrast measurements

The screens were mounted in a small-scale laser projection setup with the human audience replaced by a CCD sensor. A rotating diffuser reduces the spatial coherence area of the laser beam incident on the MLA screen [2]. By changing the beam size at the rotating diffuser, we control the size of the coherence area [12]. By moving the sensor or changing the settings of the imaging lens mounted on the sensor, we control the observer resolution spot on the MLA screen. We measured the speckle contrast on different screens for decreasing spatial coherence of the incident beam, and the results are shown in Fig.2a. The goal is to obtain low speckle contrast. When the width of the on-screen coherence area L_{coh} is large compared to that of the resolution spot L_{res} and the microlens footprints L_{fp} all screens show maximal speckle contrast, limited only by polarization and wavelength diversity. The results on the regular MLA are meaningless when the coherence is large. Due to the regular surface structure, the light propagating through this screen creates a diffraction pattern in the observed image and our speckle contrast extraction process is not suited for dealing with this. The presence of a structured diffraction pattern is undesirable in an imaging setup. When the coherence is reduced, the speckle contrast on all screens decreases due to spatial averaging. The steepest decrease in speckle contrast occurs when the on-screen coherence area and the resolution spot are approximately of the same size. Up to this point the MLAs show higher speckle contrast than the paper screen because they don't scramble the incident linear polarization. When the coherence area is reduced further, to below the microlens footprints, the proposed speckle reduction scheme leads to a decreased speckle contrast for the MLAs. For the irregular MLA, the speckle contrast drops to values lower than those of the paper screen, as the fields emitted by different microlenses can no longer interfere to form speckle. For the regular MLA, the diffraction pattern disappear. When using an MLA as screen the observer's resolution spot on the screen needs to be sufficiently large to avoid resolving the individual lenses of the array in the observed image. Especially for the irregular MLA this condition is very strict. If only a few microlenses fit within the observer resolution spot, substantial intensity fluctuations will be visible due to the varying lens sizes. When the coherence area is much smaller than the microlens footprints and the resolution spot on the screen, only irregularities on the scale of the observer resolution can explain the remaining intensity fluctuations (non-zero speckle contrast measured) as observed for all types of screens.

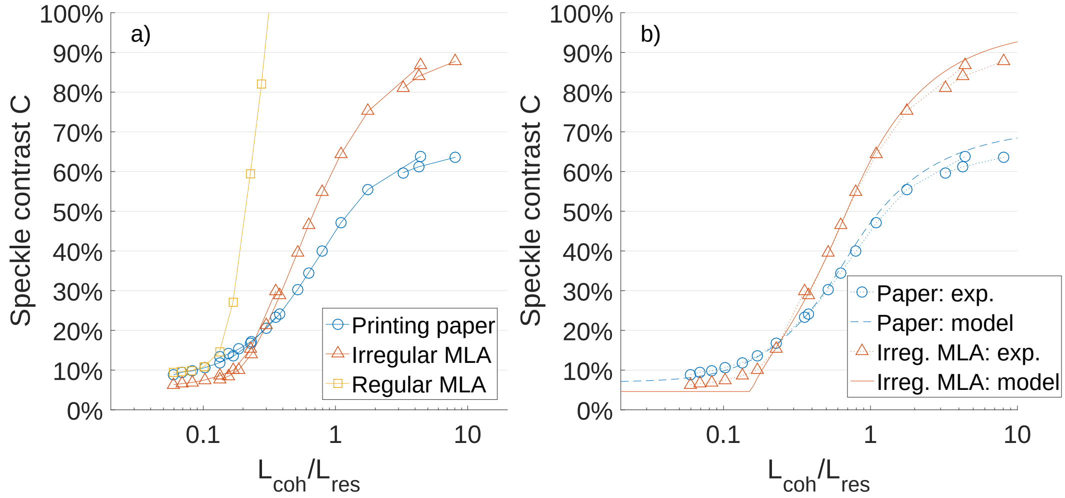

Figure 2: **a)** Comparison of the speckle contrast measurements for different screens, imaged with $L_{res} = 650\mu m$. **b)** Comparison of these speckle contrast measurements (markers) with the speckle contrast model (full and dashed lines) according to Eq.(1).

Modelling

To explain the speckle contrast measurement results we constructed a model that combines the speckle reduction factors due to polarization diversity R_{pol}, wavelength diversity R_λ, spatial averaging R_N and the screen's microstructure R_μ with the measured screen irregularities C_{nu}. We assume the mentioned speckle reduction schemes to be independent. Also, we assume the speckle-induced and irregularity-induced intensity variations to have uncorrelated Gaussian distributions, allowing us to sum up their variances. This leads to the following model to explain the measured speckle contrast C:

$$C^2 = \left(\frac{1}{\prod_i R_i}\right)^2 + C_{nu}^2 \qquad (i = pol, \lambda, N, \mu) \tag{1}$$

The main challenge lies in finding appropriate expressions for the different reduction factors. We found useful suggestions in literature [6, 7, 8, 9, 10, 11], but we formulated a new expression for the reduction factor due to spatial averaging R_N to improve the accuracy of the model. This expression, constructed through simple geometrical arguments, eliminates the need to model partial coherence in a mathematically rigorous fashion. The model can be compared with the measurement results in Fig.2b. The results of the regular MLA were not modelled due to the presence of structured diffraction patterns in the recorded images when the coherence area exceeds the microlens footprint.

Conclusion

Our experimental work validates the proposed speckle reduction scheme based on the use of microlens arrays as screen material. If the microlenses are small enough compared to the observer's spatial resolution and the spatial coherence of the optical source is sufficiently reduced, these screens exhibit less speckle than normal screens. This allows laser-based projection systems, e.g. for 3D cinema, to benefit from the proposed scheme. Through our modelling efforts we were able to quantify the contributions of the different speckle reduction mechanisms that affected our speckle contrast measurements on the different types of screens. The model we constructed can now be used as a design-tool to optimize the screen's surface structure as to achieve even lower speckle contrasts.

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