Schweickhardt, León ; Tausendfreund, Andreas ; Stöbener, Dirk ; Fischer, Andreas

Speckle pattern modulation for high-resolution displacement measurements

Conference paper as: published version (Version of Record)

DOI of this document*(secondary publication): https://doi.org/10.26092/elib/3654

Publication date of this document: 07/02/2025

* for better findability or for reliable citation

Recommended Citation (primary publication/Version of Record) incl. DOI:

León Schweickhardt, Andreas Tausendfreund, Dirk Stöbener, and Andreas Fischer "Speckle pattern modulation for high-resolution displacement measurements", Proc. SPIE 11782, Optical Measurement Systems for Industrial Inspection XII, 117820D (20 June 2021); https://doi.org/10.1117/12.2591847

Speckle pattern modulation for high-resolution displacement measurements

León Schweickhardt[a,*], Andreas Tausendfreund[a], Dirk Stöbener[a,b], and Andreas Fischer[a,b]

[a]University of Bremen, Bremen Institute for Metrology, Automation and Quality Science, Linzer Str. 13, 28359 Bremen, Germany
[b]University of Bremen, MAPEX Center for Materials and Processes, P.O. 330440, 28334 Bremen, Germany
[*]l.schweickhardt@bimaq.de

ABSTRACT

For digital image speckle correlation (DISC), a novel approach is introduced where an ensemble average over multiple different speckle patterns is calculated. As a result, the measurement uncertainty of the displacement is reduced by an order of magnitude without deteriorating the spatial resolution. This enables precise surface displacement field measurements in the micrometer range with a measurement uncertainty lower than 100 nm at a spatial resolution below 20 µm. By using a digital micromirror device (DMD) for illumination modulation, measuring rates in the range of 25 Hz are possible while each measurement is based on 80 images.

Keywords: digital image speckle correlation, displacement measurement, laser speckles, modulation

1. INTRODUCTION

In manufacturing processes and in materials development, non-invasive and high-resolution measuring methods for displacement fields are required to monitor the mechanical loads and the material behavior. In order to accelerate the development of new construction materials, material properties are now being tested increasingly on micro samples.[1] To measure displacement fields in tensile tests on samples of sub-millimeter size, a spatial resolution in the range of 20 µm and, in addition, a displacement measurement uncertainty below 100 nm is required.[2]

The state of the art for fast and contactless measurement of displacement fields is digital image correlation (DIC).[3] The displacement field is calculated from two sequential images of the sample surface. However, artificial markers must be applied to track the local displacements on most surfaces.[4] In digital image speckle correlation (DISC) laser speckles are used as surface markers.[5] This offers the decisive advantage that the speckle pattern can be instantaneously adapted by modulating the laser illumination.

The theoretical lower bound for the DISC measurement uncertainty is determined by shot noise due to the quantum mechanical properties of light.[6] In practice, the measurement uncertainty budget of DISC consists of temporally varying components such as shot noise and camera noise and spatially varying components such as speckle noise, which is caused by the statistics of the spatially distributed speckle pattern.[7] Speckle noise was found to dominate the uncertainty budget for a sub-pixel displacement.[2] Thus, the dominant uncertainty components of DISC cannot be reduced by temporal averaging, while spatial averaging worsens the spatial resolution. Therefore, the open research question is how the measurement uncertainty of the displacement field in DISC can be sufficiently reduced without deteriorating the spatial resolution and what ultimate lower bound for the uncertainty principle-like relation between the displacement measurement uncertainty and the spatial resolution is achievable?

For this reason, ensemble averaging over different speckle patterns is introduced for DISC in order to beat the current limits of measurability. The measurement principle is detailed in section 2. In section 3 a measurement setup for the respective generation of independent speckle patterns is presented. A digital micromirror device (DMD) is used in combination with a stationary diffuser to achieve fast measurement rates and high reproducibility. The experimental results are shown and discussed in section 4. The final section 5 concludes the article and gives an outlook on the theoretical potential of the measurement setup.

2. MEASUREMENT PRINCIPLE

Ensemble averaging reduces noise by averaging multiple measured displacement fields obtained from different speckle patterns. Different speckle patterns are generated through the modulation of the laser illumination. Measuring multiple speckle patterns decreases the temporal resolution, but not the spatial resolution, which is related to the evaluation window size. Fig. 1 illustrates the DISC measurement principle enhanced by the ensemble averaging technique. Multiple speckle patterns are imaged from modulated illumination patterns first

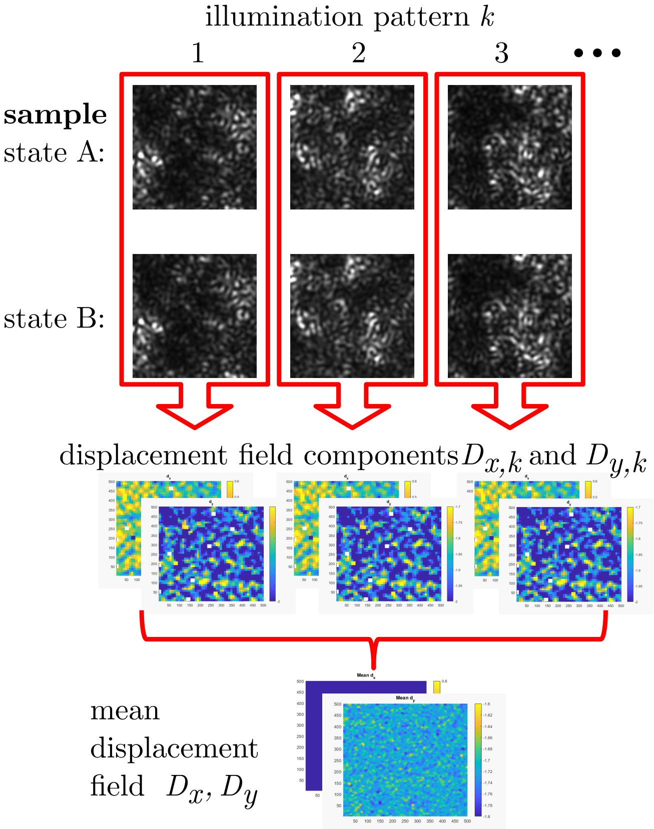


Figure 1. Measurement principle of DISC with ensemble averaging. Displacement fields $D_{x,k}$ and $D_{y,k}$ are calculated from speckle patterns at sample states A and B. The ensemble average D_x, D_y is the weighted average of the individual displacement fields.

at sample state A and then the same illumination patterns are reproduced on the sample in state B, i. e. after the sample's deformation or displacement. For each illumination pattern k, the displacement field components $D_{x,k}$ and $D_{y,k}$ are calculated by the two-dimensional cross-correlation of the speckle patterns from sample states A and B. Sub-pixel displacement is then interpolated with a two-dimensional Gaussian function according to.[8] Subsequently, the ensemble average

$$D(i,j) = \frac{\sum_{k=1}^{n} D_k(i,j) w_k}{\sum_{k=1}^{n} w_k}, \tag{1}$$

is calculated from the weighted arithmetic mean of the n individual displacement fields D_k, $k = 1, \ldots, n$, with the weightings w_k.

Note that the weighted arithmetic mean is a least squares solution. When the inverse covariance matrix is used as the weighting matrix in a least squares solution, the Gauss–Markov theorem states that the least squares estimator minimizes the estimator variance.[9] The covariance matrix is made up of the variances of the individual displacement measurements on the principal diagonal and the respective covariance terms form the remaining

matrix entries. However, the covariance terms are zero if the individual displacement measurements are uncorrelated. Therefore, the covariance terms are not considered in Eq. (1). The estimation optimality is thus achieved when the weightings w_k are directly proportional to the reciprocal of the corresponding variances σ_k^2, i. e. $w_k \sim \sigma_k^{-2}$.
When applying the ensemble average, the variance of the measured displacement reads

$$\mathrm{var}\,(D) = \sigma^2 = \sum_{k=1}^{n} \left(\frac{\partial D}{\partial D_k} \sigma_k \right)^2 \tag{2}$$

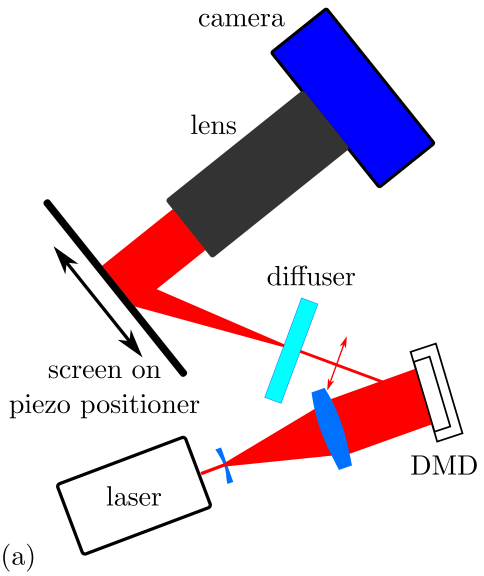
for uncorrelated displacement measurements D_k. When the optimal weighting factors are applied, Eq. (1) together with Eq. (2) yield the minimal achievable measurement uncertainty for uncorrelated speckle patterns:

$$\sigma \geq \left(\sum_{k=1}^{n} \frac{1}{\sigma_k^2} \right)^{-1/2} . \tag{3}$$

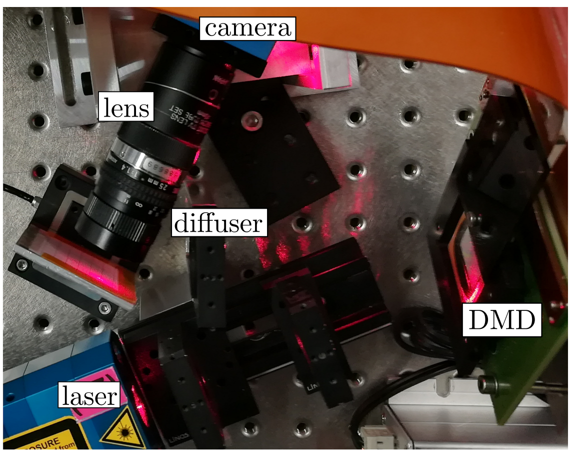
The weighted average is used so that outliers with a high measurement uncertainty σ have no significant impact on the result of the ensemble average. When the standard deviations σ_k of the individual measurements are similar, the resulting measurement uncertainty is approximately proportional to $1/\sqrt{n}$. Thus, the measurement uncertainty can be reduced without deteriorating the spatial resolution by applying an ensemble average.

3. EXPERIMENTAL SETUP

Fig. 2 shows the measuring setup. A laser beam is expanded, spatially modulated by a DMD and scattered onto a paper screen with a ground glass diffuser. The screen is imaged by a monochrome CMOS camera with 5 megapixels (*The Imaging Source DMK 37BUX264*) through an $f/1.4$ lens with a focal length of 25 mm. Using a 60 mm extension tube the magnification of the optical system is increased to 1.4. The screen is moved parallel to the camera sensor by means of a piezo linear actuator (*Physik Instrumente P-622.1CD*). A DMD is a spatial



(a)



(b)

Figure 2. Scheme (a) and image (b) of the measuring setup.

light modulator that consists of a semiconductor-based array of micromirrors which can be individually switched on and off by tilting them by +12° or −12° from the neutral position.[10] The amplitude of the incident laser beam can thus be spatially modulated by removing parts of the wavefront in specified areas. The DMD type *DLP9500* and the controller *DLPC410* from Texas Instruments are used together as parts of the *V-9501* module (*ViALUX GmbH*). The DMD comprises 1920×1080 micromirrors and has a switching rate of 17.9 kHz for 1 bit binary images. Two lenses are used to expand the laser beam to cover the DMD's entire active area. The incidence angle on the DMD is adjusted to 12° to achieve the highest light efficiency.[11] The DMD is used to direct the laser at different positions of the diffuser. For this purpose, during measurements a square of 70×70 on-state mirrors (about $0.76\,\text{mm} \times 0.76\,\text{mm}$) is moved over the illuminated area of the DMD while the remaining micromirrors are in off-state. The beam expansion and subsequent spatial modulation reduces the light efficiency. However, with this setup speckle patterns can be generated in principle with 17.9 kHz.

4. RESULTS

Fig. 3 shows exemplary results of the DISC displacement measurement uncertainty σ for the temporal, spatial, and ensemble average over the normalized effective evaluation area. In the double-logarithmic scales the square

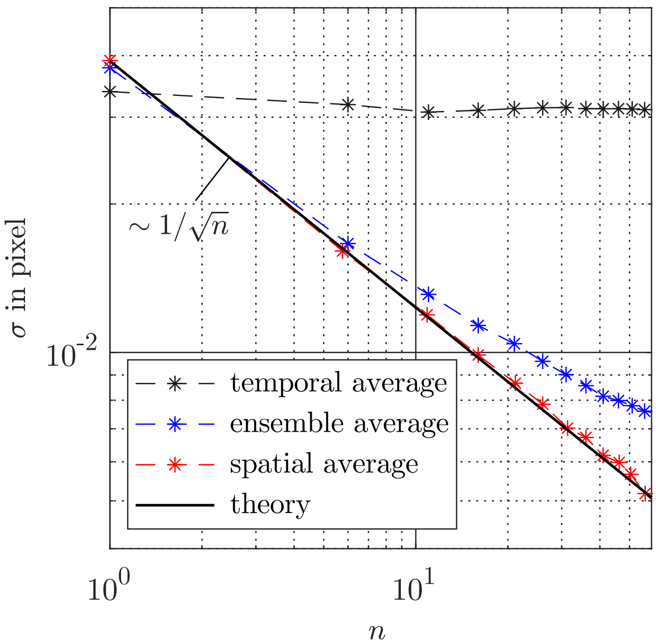


Figure 3. Comparison of temporal, spatial, and ensemble averaging: displacement field standard deviation σ over n, which is the effective evaluation area divided by the original evaluation window area $A_1 = 20 \times 20$ pixel. Note the double-logarithmic scales where the square root function from the theoretic prediction is represented as a straight black solid line.

root function is represented as a straight black solid line with a slope of $-1/2$. The measurement uncertainty σ is calculated as the standard deviation of the displacement field in a field of view of 500×500 pixels. This method is based on the assumption that the sample is displaced parallel to the camera sensor. In that case, the true values of the local displacements are equal across the entire field of view. Thus, the standard deviation of the measured local displacements is a measure of the DISC setup's displacement measurement uncertainty. This procedure offers the advantage that one DISC measurement is sufficient for the empirical determination of its measurement uncertainty. Therefore, disturbances that occur between the measurements are not significant. On the abscissa in Fig. 3 the effective evaluation area A_{E}, which is defined differently depending on the averaging method, divided by A_1 is written. A_1 is the evaluation window area for $n = 1$. The dimensionless factor $n = A_{\mathrm{E}}/A_1$ is used because the evaluation window size behaves differently depending on the averaging method. Note that the different σ at $n = 1$ for the temporal average and the ensemble average is due to being calculated from separate test series. Therefore, the first images in each series are different and have a slightly different measurement uncertainty σ.

The temporal average is calculated from 60 image pairs of the same speckle pattern before and after the defined displacement. Here n corresponds to the number of displacement fields that are averaged. The results show no significant reduction of the displacement measurement uncertainty. To calculate the spatial average, only one speckle image pair is evaluated at different evaluation window areas up to $60 \cdot A_1$. Thereby the spatial resolution is decreased but the measurement uncertainty is reduced inversely proportional to the square root of n. For the spatial average, n is the ratio by which the area of the evaluation window is increased, i. e. $A_n = n \cdot A_1$. The ensemble average is calculated from 60 image pairs of different speckle patterns. These patterns were generated with a diffusor rotating in 6° increments. Here, n again corresponds to the number of displacement fields that are averaged. The results show a substantial reduction of the measurement uncertainty. However, the slope variation from the theoretic curve suggests that not all generated speckle patterns are uncorrelated.

In Fig. 4 the measurement uncertainty results of the ensemble average over a large number of speckle patterns n are shown. The measurement uncertainty results are presented with error bars that show the experimental

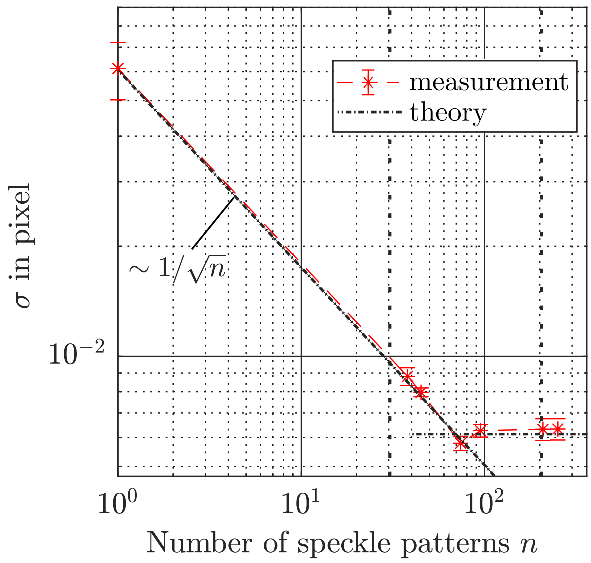


Figure 4. Displacement measurement uncertainty σ when the ensemble average is applied over the number of speckle patterns n. Dotted vertical lines indicate different sections in the behavior of σ. Error bars show the experimental standard deviation of the mean of σ over 10 test series. Note the double-logarithmic scales.

standard deviation of the mean of σ over 10 test series. The plot is divided into three sections by two dashed vertical lines: In the first section of about 1–30 speckle patterns, the curves are in accordance with the $1/\sqrt{n}$ proportionality. From 30–200 images, the negative slope decreases, but the measurement uncertainty is still significantly reduced. In the third section for more than 200 images a lower limit of the measurement uncertainty is reached. More speckle patterns no longer significantly reduce the measurement uncertainty. The results suggest that the measuring setup is only able to generate a limited number of uncorrelated speckle patterns, thus limiting the ensemble average's lower bound of the measurement uncertainty.

However, the ensemble average's lower bound of the measurement uncertainty not only depends on the number of speckle patterns but also on the spatial resolution. Small evaluation windows complicate the detection of the cross-correlation's peak.[12,13] In addition, small evaluation windows only allow small local displacements to be measured before decorrelation interferes with the analysis. Fig. 5 shows the measurement uncertainty over the spatial resolution before and after the ensemble averaging of 180 speckle patterns. The area shaded in green indicates the possible measurement parameters limited by the measurement requirements for the electrohydraulic extrusion of micro samples. For this application a spatial resolution in the range of 20 µm and a measurement uncertainty of less than 100 nm is required.[2] Furthermore, the average number of speckles per evaluation window

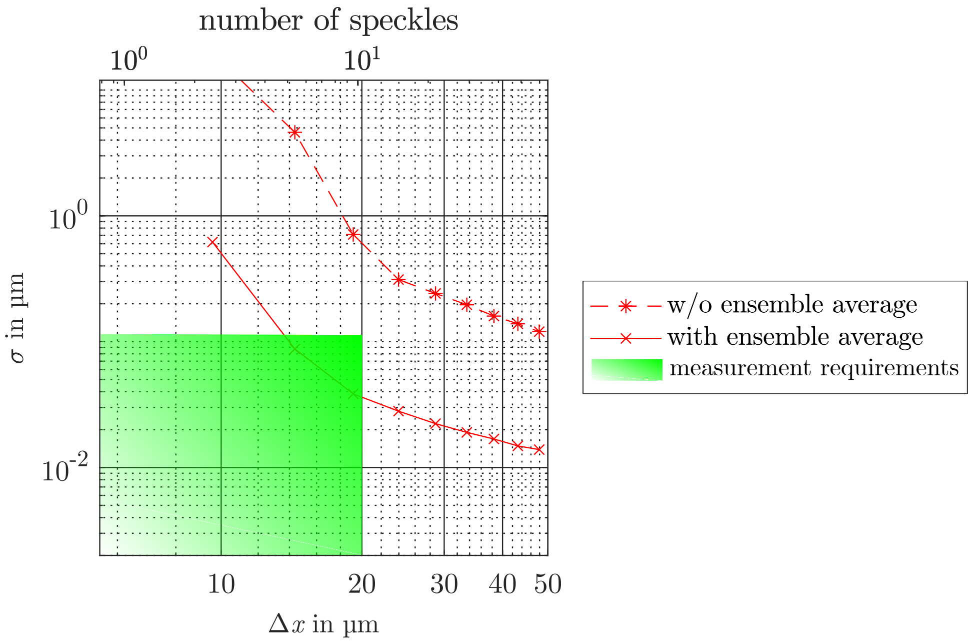


Figure 5. Measurement uncertainty σ over spatial resolution Δx. Green area indicates the possible measurement parameters limited by the measurement requirements for the electrohydraulic extrusion of micro samples.

is displayed on a second abscissa at the top. Note that the average number of speckles is calculated by dividing the evaluation window area W_{eval}^2 by the squared speckle size[5] s_{speckle}^2.
The results show that ensemble averaging decreases the measurement uncertainty for the entire relevant spatial resolution range. The measurement requirements (green) can be met only through ensemble averaging. The optical magnification of the setup is 1.44 and the pixel pitch 3.45 µm. Therefore, an evaluation window of 6 by 6 pixels contains around 5 speckles on average and results in a $\Delta x = 6 \cdot 3.45\,\mu\text{m}/1.44 = 14.4\,\mu\text{m}$ and a measurement uncertainty σ of 0.087 µm. Through ensemble averaging the displacement measurement uncertainty is reduced by one order of magnitude in the entire relevant spatial resolution range.

5. CONCLUSION

Ensemble averaging over different speckle patterns is introduced for DISC, and a measurement setup for the respective generation of independent speckle patterns is applied: A digital micromirror device (DMD) is used in combination with a stationary diffuser to achieve fast measurement rates and high reproducibility. For a small number of speckle patterns ($n < 30$), the measurement uncertainty of the ensemble average over n speckle patterns is at first reduced by $1/\sqrt{n}$, as is expected for uncorrelated single measurements. About 30 uncorrelated speckle patterns can be generated with the glass diffuser. If more (correlated) patterns are used, the achievable measurement uncertainty converges to a lower bound. As a result, the displacement measurement uncertainty is finally reduced by one order of magnitude without deteriorating the spatial resolution.
Using the ensemble averaging approach, displacement measurements in the micrometer range are demonstrated with a measurement uncertainty of 87 nm and a spatial resolution of 14.4 µm, which meets the measurement requirements for the electrohydraulic extrusion of micro samples. The used DMD setup is able to generate speckle patterns at a rate of 17.9 kHz. Together with a high-speed camera and an optimized triggering, measuring rates in the range of 25 Hz are possible even with 80 images per measurement, therefore enabling high-throughput testing and a continuous measurement.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support by the German Research Foundation (DFG) for subproject C06 “Surface optical measurement of mechanical working material loads” within the Transregional Cooperative Research Center SFB/TRR136. They also thank F. Glandorf for his support in setting up and measuring with the DMD.

REFERENCES

[1] Ellendt, N. and Mädler, L., "High-throughput exploration of evolutionary structural materials," *HTM Journal of Heat Treatment and Materials* **73**(1), 3–12 (2018).

[2] Alexe, G., Tausendfreund, A., Stöbener, D., Langstädtler, L., Herrmann, M., Schenck, C., and Fischer, A., "Uncertainty and resolution of speckle photography on micro samples," *Nanomanufacturing and Metrology* **3**(2), 91–104 (2020).

[3] Pan, B., Qian, K., Xie, H., and Asundi, A., "Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review," *Measurement Science and Technology* **20**(6), 062001 (2009).

[4] Dong, Y. L. and Pan, B., "A review of speckle pattern fabrication and assessment for digital image correlation," *Experimental Mechanics* **57**(8), 1161–1181 (2017).

[5] Goodman, J. W., [*Speckle phenomena in optics: Theory and applications*], Roberts, Englewood, Colo. (2007).

[6] Fischer, A., "Fundamental uncertainty limit for speckle displacement measurements," *Applied optics* **56**(25), 7013–7019 (2017).

[7] Tausendfreund, A., Stöbener, D., and Fischer, A., "Precise in-process strain measurements for the investigation of surface modification mechanisms," *Journal of Manufacturing and Materials Processing* **2**(1), 9 (2018).

[8] Nobach, H. and Honkanen, M., "Two-dimensional Gaussian regression for sub-pixel displacement estimation in particle image velocimetry or particle position estimation in particle tracking velocimetry," *Experiments in Fluids* **38**(4), 511–515 (2005).

[9] Lewis, T. O. and Odell, P. L., "A generalization of the Gauss–Markov theorem," *Journal of the American Statistical Association* **61**(316), 1063–1066 (1966).

[10] Hornbeck, L. J., "Digital light processing for high-brightness high-resolution applications," in [*Projection Displays III*], Ming Hsien Wu, ed., **3013**, 27–40, SPIE (1997).

[11] Scholes, S., Kara, R., Pinnell, J., Rodríguez-Fajardo, V., and Forbes, A., "Structured light with digital micromirror devices: a guide to best practice," *Optical Engineering* **59**(04), 1 (2020).

[12] Wang, Y. Q., Sutton, M. A., Bruck, H. A., and Schreier, H. W., "Quantitative Error Assessment in Pattern Matching: Effects of Intensity Pattern Noise, Interpolation, Strain and Image Contrast on Motion Measurements," *Strain* **45**(2), 160–178 (2009).

[13] Xu, X., Su, Y., and Zhang, Q., "Theoretical estimation of systematic errors in local deformation measurements using digital image correlation," *Optics and Lasers in Engineering* **88**, 265–279 (2017).