# Speckle based Extended Depth-of-Field for Macroscopic Imaging: First results

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**Abstract:** Optical imagers experience a fundamental trade-off between spatial resolution and depth-of-field (DoF). This work discusses the possibility of speckle projection to achieve super-resolution within a large DoF. Preliminary results for planar objects are presented. 

**OCIS codes:** (100.1830) Deconvolution; (100.6640) Superresolution; (110.6150) Speckle imaging

## 1. Introduction

Conventional imaging systems are subject to the fundamental trade-off between resolution and depth-of-field due to diffraction. A large aperture resolves high-resolution (HR) features, but results in a small DoF. On the other hand, stopping down the aperture increases the DoF, but diffraction hits in and limits the optical resolving power.

While this trade-off is an ubiquitous problem in microscopy where high magnifications are required, diffraction is not as apparent in daily life photography with moderate magnification numbers. Yet, there are macroscopic applications, such as in surveillance or biometrics, that require both high resolution and a large DoF.

Extending the DoF is an active field of research for the last decades. Most approaches sacrifice bandwidth in complementary modalities, such as time, illumination, system complexity or computational decoding to meet the desired requirements. Among others, these techniques encompass wavefront coding, Scheimpflug imaging, focal stack and sweep imaging, plenoptic imaging or aperture coding (see [1] for a thorough review). For microscopy it was shown that a series of projected random speckle patterns allows superresolution (SR) within an extended DoF as long as the patterns' features are smaller than the respective diffraction disk size [2].

The knowledge of the underlying speckle pattern simplifies the reconstruction, but requires a complex calibration process. To avoid this problem, other SR approaches in literature estimate the projected patterns. However, achieving a similar degree of resolving power as in the calibrated case is challenging [3,4].

On the contrary, for macroscopic imaging - to the best of our knowledge - there is no work that aims to extend the DoF using external illumination (EI) encoding. We propose to use an imager with a large DoF by stopping-down the aperture, hence sacrificing optical resolution. If one were able to apply super-resolution techniques - e.g. by capturing an image sequence with a time-varying EI - one would effectively end-up with a extended DoF by trading temporal resolution.

SR for macroscopic imaging is a challenging problem. It can be achieved by projecting high-frequent fringes that demodulate the object's high-spatial frequencies to low frequencies that can be captured by the optical system [5]. However, since the projection optics follow the same laws as the imaging optics, the required HR-fringes can only be projected with-in a small DoF, or in case of interferometric projection with a small Field-of-View. Thus fringe projection will not solve our problem of extended DoF.

## 2. Speckle-based Superresolution with Large Depth-of-Field

The problem of pattern projection with small enough features being sharp over the whole depth-of-field can theoretically be solved by projection of a coherent speckle pattern produced by an optical diffuser onto the object. The 3D-speckle field consists of small cigar-shaped intensity peaks. These speckle are sharp throughout the whole desired measurement since it is a coherent interference phenomenon and their size and DoF depend on the illumination aperture size at the diffuser. This idea brings us back to the speckle-based SR-techniques mentioned above.

The intersection of the speckle field with the object can be interpreted as a point-wise multiplication of a random 2D-pattern with the object. If the object or the diffuser is moved, the object experiences a projection of a different speckle pattern. We believe that acquiring an image sequence containing different speckle pattern realizations, should carry enough information to reconstruct the HR-image. As the SR-techniques mentioned above, reconstruction requires either knowledge or estimation of the projected pattern. Former implies pre-calibration and storing the 3D-speckle field, while latter becomes a SR problem with unknown speckle-illumination which is computationally much harder to solve.

As a first step to solve the extended DoF problem for arbitrarily shaped objects we present a framework to perform SR of planar objects. A series of HR speckle-patterns are captured with a large aperture during a calibration step. For the 2D-case and under the assumption of incoherent scattering at the object surface, the observed image $I_L(\mathbf{x})$ at location $\mathbf{x}$ is modeled, see Eq. 1 for continuous and Eqs. 2 and 3 for discrete implementation, by a convolution of the object $s(\mathbf{x})$ multiplied by speckle-pattern $p_l$ with the system's PSF $h(\mathbf{x})$:

$$I_l(\mathbf{x}) = \Big[s(\mathbf{x}) \cdot p_l(\mathbf{x})\Big] * h(\mathbf{x}) \qquad (1)$$

$$I_l = C D_l s \qquad (2)$$

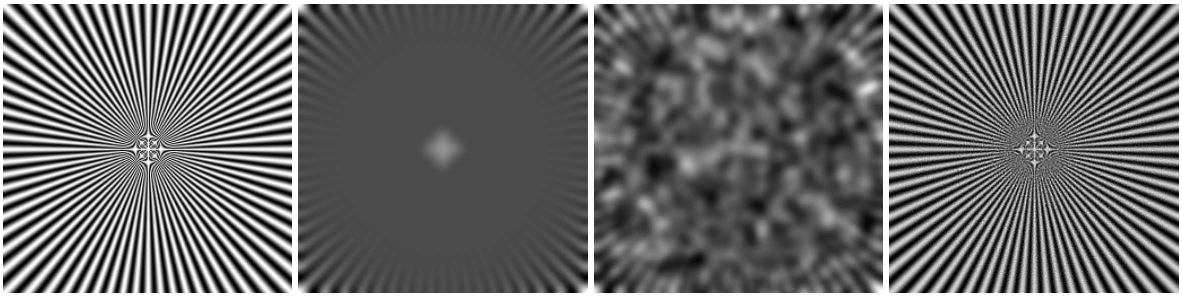
$$\overbrace{\begin{bmatrix} I_1^l \\ \vdots \\ I_N^l \end{bmatrix}}^{I_l} = \overbrace{\begin{bmatrix} c_1 & c_N & \cdots & c_2 \\ \vdots & \vdots & \ddots & \vdots \\ c_N & c_{N-1} & \cdots & c_1 \end{bmatrix}}^{C} \overbrace{\begin{bmatrix} p_1^l & & \\ & \ddots & \\ & & p_N^l \end{bmatrix}}^{D_l} \overbrace{\begin{bmatrix} s_1 \\ \vdots \\ s_N \end{bmatrix}}^{S} \qquad (3)$$

where $N = N_x \cdot N_y$ denotes the number of pixels. The matrix $C$ is circulant and implements the convolution as a matrix operation, $D_l$ is a diagonal matrix and describes a point-wise multiplication of the object with the speckles.

This gives rise to a least-square minimization problem which can be solved in closed form by solving for the zeros of its gradient.

$$s^* = \arg\min_s \sum_l^L \|I_l - C D_l s\|^2 = \Big[\sum_l D_l^\intercal C^\intercal C D_l\Big]^{-1} \cdot \sum_l D_l^\intercal C^\intercal I_l \qquad (4)$$

Figure 1 shows results of a simulation experiment with 50 different speckle patterns. The imaging system is modeled by convolution with an incoherent PSF approximated as a Gaussian. Hence, the HR-features, see Fig. 1a, cannot pass through the aperture, see Fig. 1b. The speckles demodulate the signal and allow part of the high-frequency information to pass through, see Fig. 1c. The pixel resolution is $256 \times 256$, the Gaussian PSF was estimated with a standard deviation of 5 pixel units and the simulated speckle have an average diameter of about 4 pixel. Since storage and inversion of the convolution matrix's $C$ is infeasible, Eq. 4 is solved iteratively using gradient descent which was stopped after 100 iterations. The proposed framework is able to restore the HR-features, see Fig. 1d.



(a) Ground-truth HR image. (b) LR image without speckle. (c) LR image with speckles. (d) Reconstruction result.

Figure 1: Simulation results for the proposed extended-DoF-setup for a planar object. A HR reconstruction from LR image is possible.

## 3. Summary and Outlook

In this paper we present a novel idea for an HR-resolution imaging system with a large DoF using a sequence of time-varying speckle patterns. First simulation experiments for the simplified case of incoherently scattering, planar objects and calibrated speckle patterns are presented. Experimental verification of the simulations as well as development of a mathematical framework for the more challenging case of 3D objects are currently underway.

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