PSF Estimation with Speckle Illumination

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Motivation

- The Point Spread Function (**PSF**) characterizes how light from a point source (i.e. laser) is altered by an optical system, influencing how light is distributed in an image.
- Optical systems often suffer from performance challenges due to **non-ideal PSF**, **impacting resolution** and **image quality**.
- Speckle Illumination harnesses, random, granular patterns (**speckles**) resulting from the interference of light waves
- **Speckles** serve as a reference pattern for precise **PSF estimation** and **enhancing** optical system **quality**.

Goal: Develop a computational technique with speckle-pattern illumination for aberration correction at varying distances, aiming to enhance optical system quality without adaptive optical elements.

Related Work

PEPSI Technique [1]:
- Using speckles counter aberrations for a local PSF estimation without calibration through a single-speckle projection

Sub-Image Speckle Illumination [2]:
- Utilize sub-image speckle illumination, creating uncorrelated images to extract the PSF

Blind PSF Recovery [3]:
- Independent of prior optical system knowledge, utilize speckle illumination, gradient descent, and estimated shift positions to estimate the PSF

Imaging through Turbulent Media [4]:
- Using short-exposure images, recover the Fourier power spectrum, which provides crucial Fourier phase information for PSF estimation through coherent averaging

Future Work

Validate speckle size effect
- Experiment with different speckle sizes by modifying optical setup

Optimize speckle detection
- The recovered PSF is dependent on the average of the detected speckles.

References

[1] Meitav, N., Ribak, E. N., & Shoham, S "Point spread function estimation from projected speckle illumination", *Light: Science & Applications*, 2016
[2] Hwang, B., Piestun, R., & Irsch, K, "Non-Isoplanatic PSF and Image Estimation Using Speckle Illumination", 2023
[3] Premillieu, E., Labouesse, S., Irsch, K., & Piestun, R. "Blind speckle illumination for aberration correction", *Frontiers in Optics* 2021
[4] Hwang, B., Woo, T., Ahn, C., & Park, J-H. "Imaging through Random Media Using Coherent Averaging", *Laser & Photonics Reviews*, 2023

New Technique

PSF recovery of an imaging system by projecting a speckle pattern onto a non florescent imaging target.

Steps:
- Simulate PSF of the optical system for varying focal distances
- Average extracted speckles for experimental and simulated data.
- Using averaged speckles from the simulation and experimental data estimate the PSF.

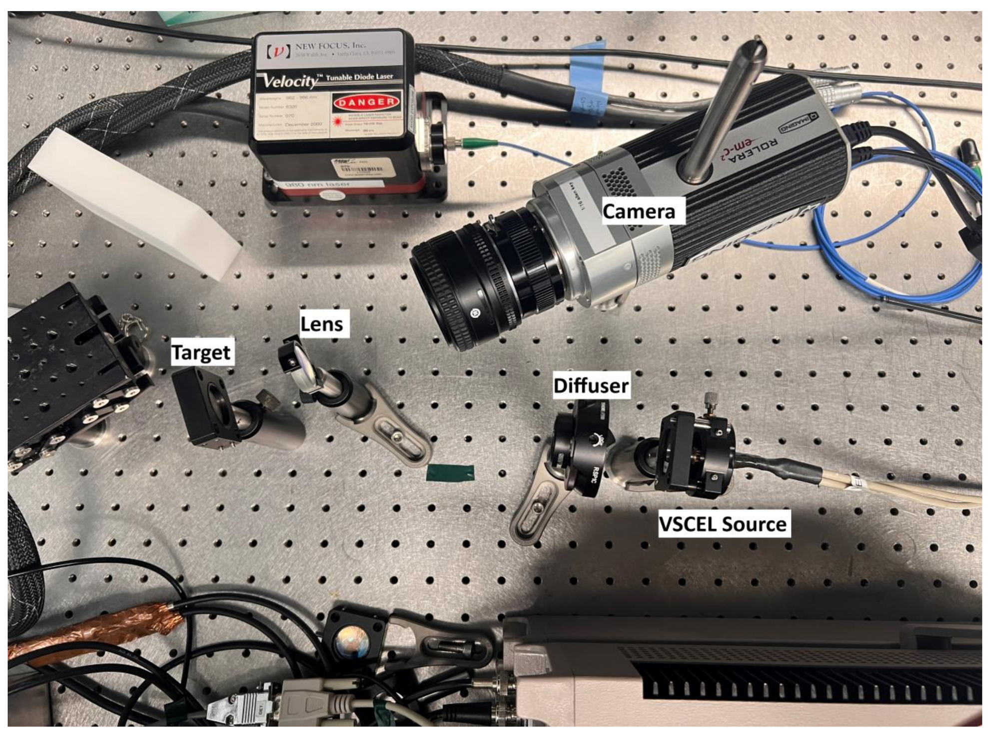


Figure 1: Optical Setup

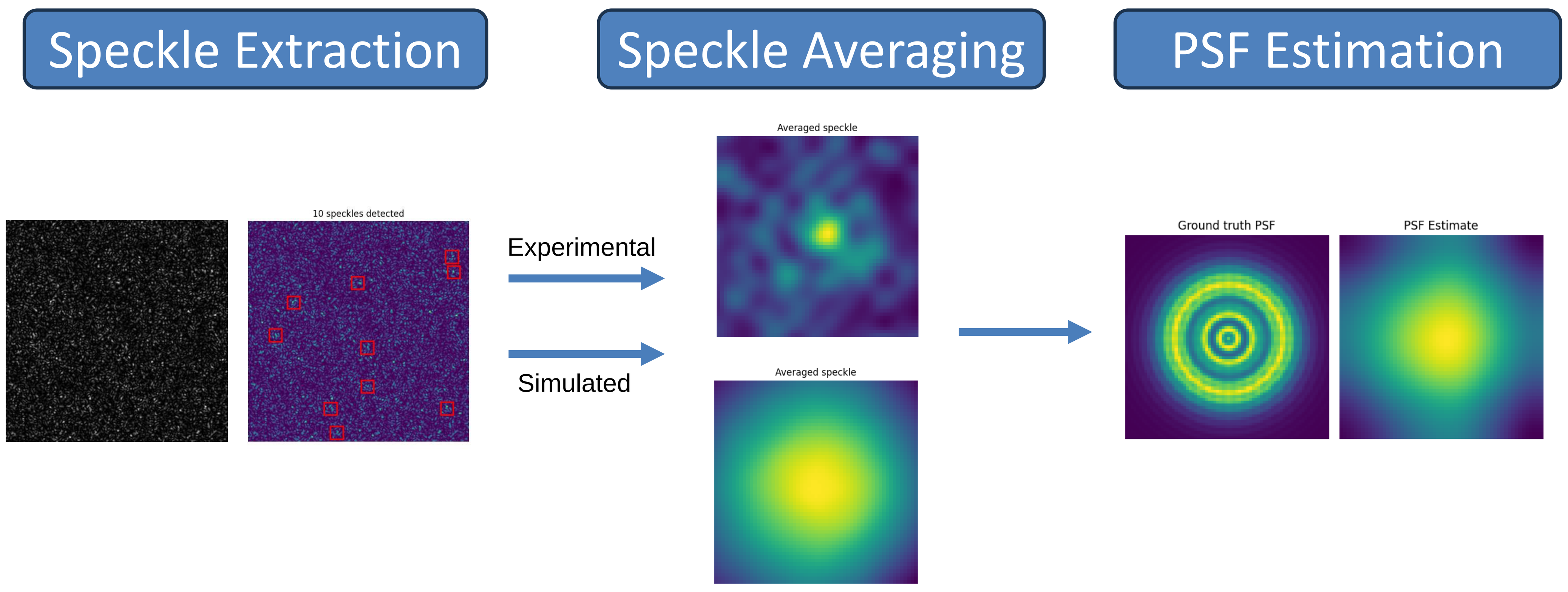


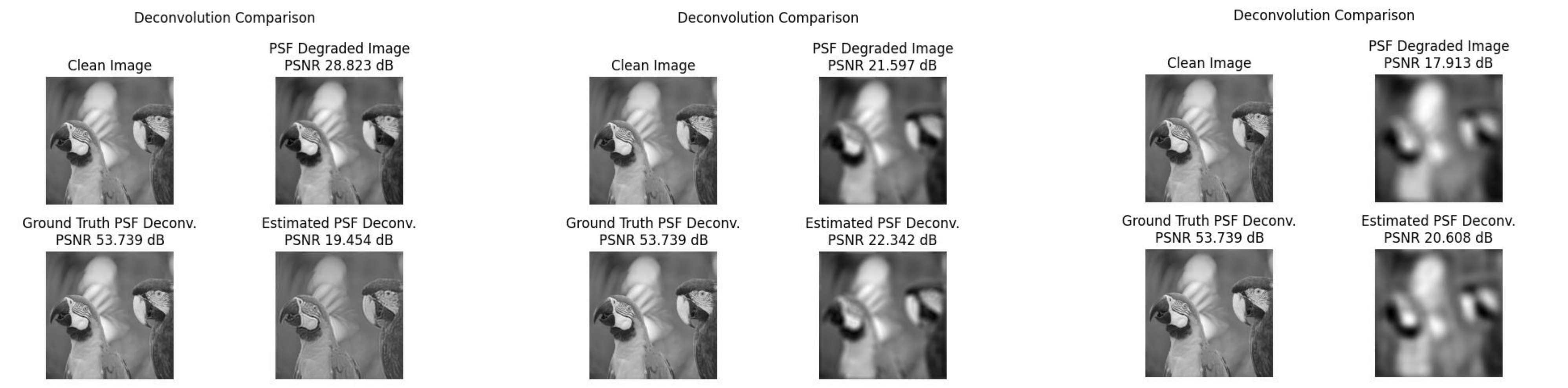
Figure 2: Processing Pipeline

Experimental Results

To identify the capabilities of the given algorithm, 2 tests were performed. A deconvolution comparison between the simulated (theoretical) PSF and the estimated PSF for varying focal distances and fixed noise. A deconvolution comparison between the simulated (theoretical) PSF and the estimated PSF for varying noises and fixed focal distance.

PSF recovery performance is influenced by the performance of the speckled detection. The speckle detection is influenced by the size of the speckles and how distinguishable they are from each other.

Note these are for simulated data that describe the experimental optical setup.



Best focus, object distance 50mm | *Slightly worse focus, object distance 50.5mm* | *Out of focus, object distance 51mm*

Figure 3: PSNR of deconvolved images with recovered PSFs for varying focal distances at fixed noise (50 dB)

SNR after adding noise	50 dB	20 dB	10 dB	6.69 dB
PSNR after deconv. with recovered PSF	25.696 dB	25.964 dB	25.691 dB	25.691 dB

Table 1: PSNR of deconvolved images with recovered PSFs for varying noise levels at best focus (50mm)