Studies on the application of neural networks for the optimization of holographic endoscopy with a fiber bundle

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Coherent fiber bundles (CFB) are commonly used for endoscopy, allowing pixelated 2D imaging of intensity information. Using holographic image formation at the distal fiber facet enables lensless 3D imaging. We demonstrate an enhanced deep super-resolution network (EDSR), in order to improve the holographic reconstruction quality.

1 Introduction

A current goal in the development of fiber endoscopes is the reduction of the endoscope diameter for minimal invasiveness as well as 3D imaging capability. One promising approach is based on holography. However, imaging fiber bundles scramble the phase information of the light [1]. This problem can be overcome by distal hologram formation [2]. Here, the lens at the distal end of the endoscope is omitted, where no imaging optics are required and the endoscope diameter is only limited by the CFB. However, due to the pixelization of the CFB, the holographic image reconstruction is distorted. Therefore, an optimization of the imaging properties by means of deep learning based signal processing [3] is investigated in this paper.

2 Experimental Setup

The experimental setup used, is shown in Fig. 1. The illumination source consists of a short coherence length laser and a Michelson interferometer, generating two temporally shifted beams. Both beams are propagated through a single, central fiber to the distal end and are (partially) reflected at a semi-reflecting reference mirror and the structure under investigation. By adjusting the temporal delay τ to the object-reflector-distance $z_O = \tau \cdot c$, an interference pattern is formed at the distal fiber facet.

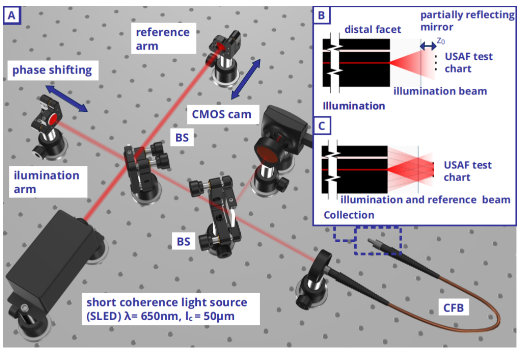

***Fig. 1** Schematic structure of the endoscope*

Thus, the measurement range can be varied at the distal end. In order to enable holographic imaging, phase shifting is applied to one of the two beams using a piezo-driven mirror. The interference pattern is imaged on the entire distal facet of the CFB and propagated to the proximal fiber end (Fig. 1C). At the proximal fiber end, the light is imaged through a lens onto a CMOS camera.

3 Signal processing

To recover the object, four intensity images are captured with phase shifts of $\pi/2$ and the complex wave is calculated. Next the reference wave is subtracted. Finally, the resulting hologram is propagated back to the measurement volume. To test the approach, a fourieroptic simulation is used. Due to the comparative low pixel number of CFBs, low resolution holograms are taken worsening reconstruction (see Fig. 3 B), while the periodic structure of CFBs results in high diffraction orders, which limits the field of view (cf. Fig. 4 B). To overcome these limitations an EDSR is used to recover high resolution intensity images on the distal side from the distorted images on the proximal side before reconstruction [3]. The EDSR uses the mean average error and perceptual losses as loss function (Fig. 2).

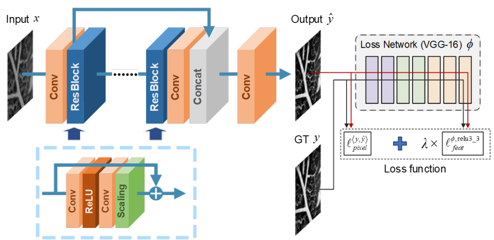

***Fig. 2** Neural network architecture. [3]*

For training the *MNIST* dataset is used. For each object image four phase shifted images are generated. Hence, only the transmitted intensity information is filtered by the network. After filtering, the holographic reconstruction is performed by using angular spectrum propagation.

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4 Results

In order to estimate the achievable improvement, a comparison between reconstructions from non-filtered (NF), neural network filtered (NNF) and linear low pass filtered (LPF) images is shown in this section.
As an example a USAF 1951 test chart is used. The NNF reconstruction in Fig. 3 C shows qualitatively more detail and a higher contrast compared to the LPF reconstruction, (cf. Fig. 3 D). The SSIM could be improved by 68% and the correlation coefficient by 50%. Thus structures up to 280 µm can be reconstructed. In addition, the results show that the network does not overfit, since the test chart differs significantly to the training samples.

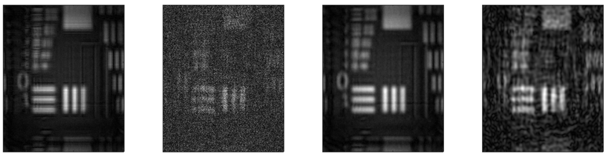

Fig. 3 *A: Ground truth, Reconstructions from B: non-filtered (NF), C: Neural Network-filtered (NNF) and D: low pass filtered (LPF) images.*

The suppression of higher diffraction orders is highlighted in Fig. 4 which shows the Fourier transform of the reconstructions in Fig. 3.

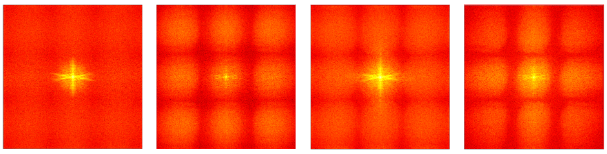

Fig. 4 *Fourier transformed USAF test chart. Ground truth, Reconstruction with CFB, with NN and with LP (LTR)*

To verify the results, the NN was also applied to real measured data (Fig. 5).

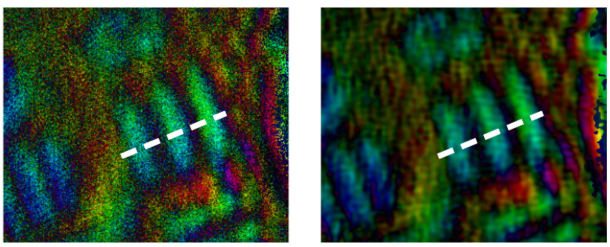

Fig. 5 *USAF test chart from real measurement. (False color representation)*

The realized measurement system corresponding to Fig. 1, employed a Fujikura CFB, with 10000 cores and a total diameter of 450 µm. As a reference mirror the backside of the test chart was used. The measurement object is Group 4 of a USAF test chart at a distance of 1.5 mm

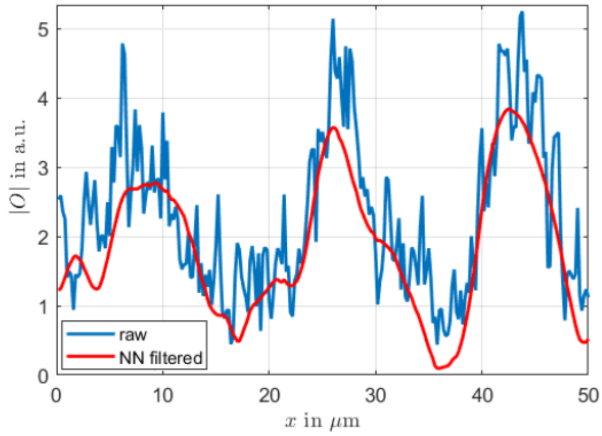

Fig. 6 *Comparison of the amplitudes.*

Fig. 6 shows the amplitude of the three test strips (marking in the picture). The NN can successfully filter the real measured values without re-training. Thus, the NN is also robust against unknown disturbances.

5 Conclusion

Holographic imaging through imaging fibers is possible. However, coherent fiber bundles distort the intensity images required for calculating phase shifting holograms. This results in a reduced pixel number and higher diffraction orders, reducing reconstruction quality. We have investigated the use of non-linear filtering using neural networks, on the acquired images. Simulations show a significant improvement regarding contrast, SSIM and field of view for NN filtered images compared to unfiltered or linearly filtered images, as does a first validation experiment. The results may pave the way towards minimally invasive 3D imaging.

6 Acknowledgements

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7 Bibliography

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