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Speckle Denoising of Computer-Generated Macroscopic Holograms

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Abstract: An investigation of subjective quality of 16 numerical speckle denoising filter techniques for computer-generated holograms of macroscopic objects with diffuse surfaces is undertaken. Promising candidates with respect to computational complexity and quality are emphasized.

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1. Introduction

The quality of reconstructions from coherent imaging techniques such as digital holography (DH) suffer from prominent speckles: a multiplicative noise stemming from coherent illumination on diffusely refracting or reflecting surfaces [1]. Speckles are visible in either optical or numerical reconstructions as extremely bright grains, whose intensity depends on the underlying signal. When DH content is consumed by means of 2D or light-field displays (stationary [2] or head-mounted [3]) speckles can only be suppressed numerically.

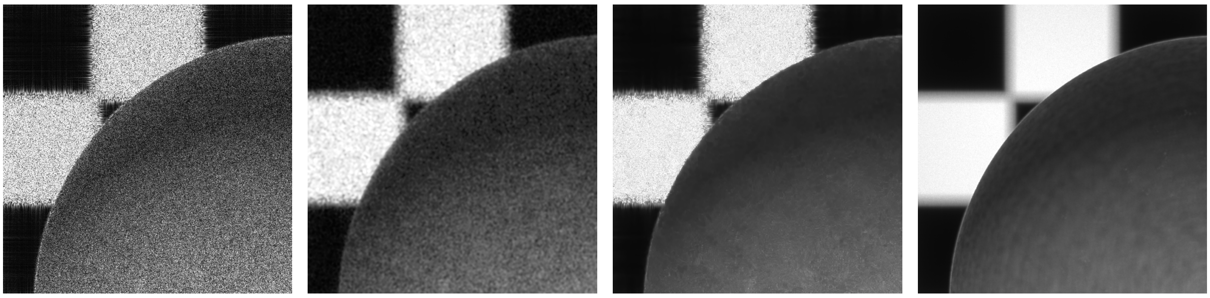
Current literature lacks a comparative analysis of numerical speckle denoising filters for amplitude images that require solely single-shot holograms, applicable for any of the aforementioned scenarios, which all come with two distinct requirements. First, is low computational complexity, which is required due to the large number high-resolution views ($\geq$ 8K) that are potentially needed for the exploration of a single hologram and which are obtained by means of numerical backpropagation. Even without aiming for real-time reconstructions and having a powerful rendering cluster in place, the additional time required for denoising should be small. Second is, of course a good perceptual quality, which will express itself by: retaining sharp edges in areas set in focus upon backpropagation while homogenizing initially solid and diffuse surfaces.

We will restrict our discussion to monochromatic, in-line computer-generated holograms (CGH) with diffuse scattering surfaces. Because speckles are dependent on local signal intensity, denoising for color holograms is done best per color channel. In CGH there is no need for compensation of additive incoherent measurement noise, which is a separate denoising problem. And only diffuse surfaces will be strongly visible under non-paraxial viewing conditions providing the impression of a solid object. This is because the sub-wavelength depth variations of diffuse surfaces scatter light to large viewing angles, as evidenced by the grating equation, $\lambda/(2p) = \sin(\theta_{max})$ with pixel pitch p, wavelength of the illuminating light λ and the maximal diffraction angle θ_{max}. Therefore it is impossible to generate a single digital hologram containing diffuse surfaces, that when numerically reconstructed, does not possess speckle noise at any given distance and out of necessity all investigated methods work either by averaging reconstructions with different uncorrelated instances of speckle noise, or directly on the reconstructions themselves. We chose an in-line arrangement because its geometry guarantees that the size of speckle grains is ~ 1 pixel.

2. Experiments

We studied 16 methods, ranging from simple local statistics filters over patch-based learning strategies to various sets of aperture masks, yielding uncorrelated speckles through phase-space subsampling. The methods used are: moving average filter, BM3D, BM3D-SH3D, Fourier transform thresholding, Frost filter, multiplicative Lee filter, Wiener filter, moving median filter, adaptive-median filter, non-local means, stationary wavelet thresholding, wavelet subband thresholding, Gabor frame hard thresholding (WFR2), random mask resampling, ring mask resampling, spatial aperture averaging method. A noise-free reference for our tests was obtained by arithmetic averaging of reconstructions from 1026 CGHs with independent noise realizations.

For computational reasons, experiments were performed on a modest size CGH (2048 × 2048 pixel), generated with [4]. The used holograms were modeled after the red color channel of the "Sphere1A" hologram from the Interfere-III dataset publicly available at `http://www.erc-interfere.eu`.



(a) Noisy input (b) Wiener filter (1s) (c) BM3D-SH3D (55s) (d) Reference

Fig. 1: Exemplary denoising of the "Sphere1A" scene with focus distance set to the rim of the sphere.

3. Results and Conclusion

In a double-stimulus subjective test on 6 expert testers, mean opinion scores (MOS $\in [1,5]$) were obtained on a Eizo CG318-4k screen while following the relevant recommendations in Annex B of ISO/EC 29170-2 (AIC-Part 2). Note, that it has been shown already that scores obtained from a few expert subjects can easily replace a test involving many novices [5]. The denoised views of the entire scene presented to the testers, were normalized by exact histogram matching to the reference view, prior to testing.

The scores given below as mean ± standard deviation show that there exist visually pleasing methods, which do not require a manifold of reconstructions, and are reasonably fast. Good quality was achieved with BM3D based methods, such as BM3D-SH3D, or the simpler and much faster Wiener filter. While the majority of classic image denoising filters show above average performance, it is surprising that ring and random mask resampling, which were especially designed for these denoising scenarios, perform at most average.

Method	MOS	Time in s	Method	MOS	Time in s
BM3D-SH3D	4.3 ± 1.0	55	Stat. wavelet thresholding	3.5 ± 1.4	3
Wiener filter	4.2 ± 0.8	1	Ring mask resampling	3.0 ± 1.3	21
BM3D	3.8 ± 0.8	50	Fourier thresholding	2.8 ± 1.1	0.3
Adaptive median filter	3.7 ± 0.5	10	Wavelet subband thresholding	2.8 ± 1.2	2
Median filter	3.7 ± 0.8	0.5	Lee filter	2.6 ± 0.8	0.2
Shifting aperture	3.7 ± 0.8	51	WFR2	2.6 ± 1.4	140
Frost filter	3.7 ± 1.0	14	Random resampling	2.2 ± 1.2	410
Mean filter	3.7 ± 1.0	0.3	Non-local means	2.2 ± 1.6	216

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