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Compressing Macroscopic Near-field Digital Holograms With Wave Atoms

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Abstract: Pushing digital holography into mainstream markets requires efficient compression algorithms. Using a recent technique based on wave atoms, we explore its compression performance for macroscopic near-field holograms as a function of the Fresnel number.

OCIS codes: (090.1995) Digital Holography; (100.2000) Digital image processing

1. Introduction

Holography is the only imaging technology which allows for continuous depth and angular perception as it records both intensity and phase of the incident light wavefield. Static high-quality digital holograms require resolutions of ≥ 100 Mpixels for the display of 10 cm objects and large field of view of up to $\pm 36^\circ$ still pushing the data bandwidth in high-end systems to its limits. Conventional image compression standards, based on thresholding or quantizing coefficients in Fourier or wavelet domain, fail on holograms because their spectral amplitude distribution exhibits a decay that is fundamentally different from that of natural images, the latter depicting a decay of $\sim 1/f^2$ with spatial frequency f . For macroscopic holograms, an almost homogeneous probability distribution of frequencies is typical because the higher frequencies contain information on large viewing angles.

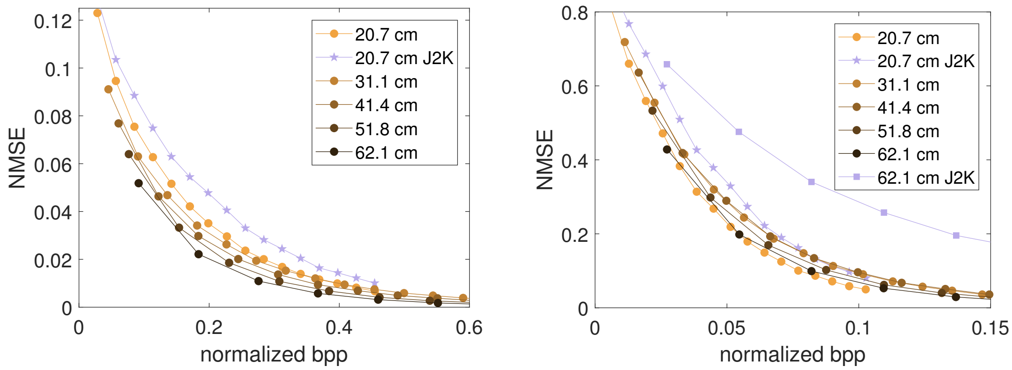
Hence, the development of visually lossless, but quantitatively lossy compression techniques [1] is a necessity. Leveraging yet unused transforms, we explore the feasibility of a wave atom transform [2, 3] for computer-generated holograms as a function of the Fresnel number F_N in the macroscopic near-field regime ($\mathrm{F}_N \geq 1$). F_N is defined as $\mathrm{F}_N := (pN)^2(4\lambda z)^{-1}$, with pixel pitch p, aperture size $N \times N$ pixel, wavelength λ and reconstruction distance z. For the study, all parameters, except for z are kept fix. Due to the exploratory nature of this work we limited ourselves to holograms generated from images both with constant and with random phase. While for constant phase solely the impact of shearing in the space-frequency domain upon propagation can be studied, with random phase also initial data statistics match that of a proper diffuse surface. In Section 2, we provide a short summary of the key properties of the wave atom transform in the present scenario and subsequently state our results in Section 3.

2. Wave atoms

Wave atoms [2,3] are non-standard Villemoes [4] packets of wavelets that are in part multiscale and in part directional. These basis functions are finite supported and simultaneously well localized in the spatial and frequency domains. Albeit having an isotropic support, directionality is achieved through directional oscillations. The wavelength of those oscillations is scaled with the square root of the diameter of the essential support. This condition, called parabolic scaling, enforces the uncertainty principle to hold strictly.

The transform may be defined in any number of dimensions because of its separability. However, it always exhibit an isotropic tiling of space and frequency domain, respectively. In this work, we are using the 2D orthobasis variant as it is the native dimension of the holographic data and non-redundant, hence optimal for compression. Each element of this variant consists of 4 bumps in a cross like arrangement in frequency domain and therefore oscillates in 2 distinct directions at once [3]. That is the price to pay for the good space-frequency localization and lack of redundancy. Curvelets, which also satisfy the parabolic scaling condition, have been already shown to be advantageous handling edge-like content such as geometric image features. Since wave atoms, unlike Curvelets, can oscillate more than once within their support, data containing a dense set of edges can be sparsified more efficiently. Examples are fingerprints [3] or interference fringes. Of practical relevance is also that the wave atom transform (and its inverse) can be implemented efficiently for 2D complex-valued signals with complexity $\mathcal{O}(N^2 log(N))$ with N samples per dimension.

In theory, wave atoms are guaranteed to yield asymptotically optimal sparse representations of certain Fourier integral operators (see chapter 2.1 in [2]), such as those used by Lax [5] for approximating wave equation solutions in the



(a) Constant phase (b) Random phase

Fig. 1: Compression performance JPEG 2000 vs waveatom compression in NMSE over normalized bpp as a function of reconstruction distance z.

high frequency/ray optics limit. In the current context, these operators most importantly are required to be homogeneous of order 1 with respect to the Fourier variable. Because, any approximate scalar diffraction integral kernel other than the far-field specific Frauenhofer kernel (Fourier transform with pre-factor) involves at least a squaring of the Fourier variable, wave atoms are by theory only optimal in the far-field limit, that is $F_N \ll 1$. In the following section, we analyze whether wave atoms are also suited for holographic signals in a range of reconstruction distances well within the near-field.

3. Experiments

Holograms of size 2048×2048 and pixel pitch $8\mu m$ were generated from an image of same size, once with constant and once with random phase, using ray-tracing. The F_N is decreased from $N/4 = 512$ (optimal reconstruction distance) down to 171, by tripling z. For compression we combine the wave atom transform with the JPEG 2000 entropy coder disregarding any special multi level encoding. The performance is then measured as normalized mean square error (NMSE) over a normalized bit-per-pixel (bpp) rate. Normalization is done with respect to the signal support in time-frequency domain detectable by our hologram. Thereby the signal support is estimated in 4D STFT domain via blockwise hard-thresholding wrt. amplitude at 90%. The results, Fig. 1, show slight supremacy of the proposed model over JPEG 2000. Note, for constant phase JPEG 2000 failed almost completely to compress the signal and NMSE was $\geq 74\%$ and had therefore to be omitted from the plot. On contrast, we see using wave atoms even a minimal increase ≤ 0.06 n. bpp for objects placed at three times the optimal distance. Our random phase experiments suggest that for realistic holograms the variance in compression performance of the wave atom method due to shearing seems to be irrelevant, ≤ 0.01 n. bpp, throughout the considered range. For JPEG 2000 a notable decline in efficiency is observed.

4. Conclusion

Wave atoms provide us with a multi-scale, orientable orthobasis suited for oscillatory patterns with fast transforms and compact, Heisenberg optimal supports in the space and frequency domain. We have provided first numerical evidence that in the near-field out-of-focus components do not significantly impact compression performance, well in opposition to the reference method JPEG 2000 where severe performance impacts could be observed. This first minor study suggest wave atoms could be very beneficial in a more general codec, at least for near-field holograms.

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