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Modulo Wavelets for Interferometric Phase Data

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Abstract: A newly proposed modulo wavelet transform incorporated in a JPEG 2000 architecture allows for efficient compression of interferometric phase maps. Coding gains of over 0.5 bpp are reported over the state-of-the-art.
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1. Introduction

Interferometry is widely used today for a multitude of applications. With the advent of modern computing and imaging technologies, the digital acquisition of interferograms has become widespread, steadily increasing both the quantity as well as the resolution of these recordings.

The signal properties of interferometric image recordings differ significantly from regular imagery (such as e.g. photography); therefore, standard compression codecs will not be able to efficiently cope with this type of data and will typically result in poor compression performances.

One such example is microscopic holography. In [1,2], we have shown that these recordings (recorded in an off-axis configuration) can be represented more efficiently by using wavelet packet decompositions and directional transforms [3]. This indicates the potential to find better sparse representations for interferometric imagery in general.

In this paper, we focus particularly on phase information. For many interferometric applications, we are primarily interested in the recorded phase distribution of two interfering wavefronts. These distributions often arise in applications using fringe pattern analysis, such as phase-shifting interferometry (e.g. for holography [4]). Phase distributions also arise in other application such as Interferometric Synthetic Aperture Radar (InSAR) and Magnetic Resonance Imaging (MRI).

In order to compress imagery in general, we have to apply a sparsifying transformation on the image to exploit the present redundancies. Current state-of-the-art image compression codecs such as JPEG 2000 [5] use the wavelet transform. Unfortunately, regular wavelets do not perform optimally on phase distributions: the phase jumps due to transitions from π to $-\pi$ will be considered as sudden drops in magnitude even though the local phase change will be small; these transitions will correspond to sharp borders resulting in many elevated high-frequency coefficients in the wavelet domain, reducing the image compressibility.

One might consider using phase unwrapping on the data prior to the wavelet transform. However, this approach has several limitations in the context of image coding, because of the following reasons:

- Phase unwrapping can dramatically increase the dynamic range of the image, requiring many more bits per pixel, severely worsening the coding performance. Moreover, in the case of lossy compression, the codecs will be inclined to keep the most significant bits; in many cases, one is precisely interested in the least significant bits, e.g. for controlling a phase-only spatial light modulator.
- Unwrapping algorithms assume essentially that the data is representing a height map - modulo 2π. However, this is not the case in general and does not account for phenomena such as optical vortices [6].
- These unwrapping algorithms are not perfect: they are highly sensitive to noise and may introduce sudden jumps in inappropriate locations.

Instead, we propose a different approach, and devised a variant on the regular wavelet transform, named "Modulo Wavelets".

2. Modulo Wavelets

Phase images represent fundamentally different information compared to intensity images. Yet, they have similarities too: generally, the phase changes gradually over space. Nonetheless, one cannot speak of frequencies present in the phase image in the regular sense. Rather, the required sampling rate will depend on the maximal gradient of the phase distribution: assuming the underlying phase function $\phi(x)$ is continuous and differentiable, the gradient should fulfill the following relation in order to fulfill the "Nyquist sampling criterion": $\left|\frac{d\phi(x)}{dx}\right| < \pi$.

Therefore, we can describe lowpass filters as being "averagers", discarding quick phase changes; while highpass filters will only preserve strong local phase changes.

A noticeable property of phase data is their lack of ordinality. We will therefore represent phase values as circular values: one may consider phase values as vectors on the unit circle, with the phase being equal to the formed angle with the x-axis. The possible vector values will have to be discretized; consequently, the phase values will be quantized to b bit-per-pixel (bpp). We will represent them as signed integers, going from -2^{b-1} to $2^{b-1} - 1$.

We will define two operations on phase values:

- Difference $\ominus$: the difference $a \ominus b$ between two phase values is defined as being the length of the shorter of the two arcs between the corresponding unit vectors $\vec{a}$ and $\vec{b}$ on the unit circle. This difference is positive when going from a to b counter-clockwise, and negative when going clockwise.
- Average $\oplus$: we define the average operation $a \oplus b$ as taking the vector going through the midpoint of the smallest arc corresponding to the one used for the difference operation $a \ominus b$.

Given these operations, we can now define the "Modulo Haar Wavelet" (MHW). We respectively define the lowpass and highpass filters:

$$L(n) = X(2n) \oplus X(2n+1) \qquad and \qquad H(n) = X(2n) \ominus X(2n+1) \tag{1}$$

This wavelet operation is losslessly reversible, similarly to the Haar wavelet.

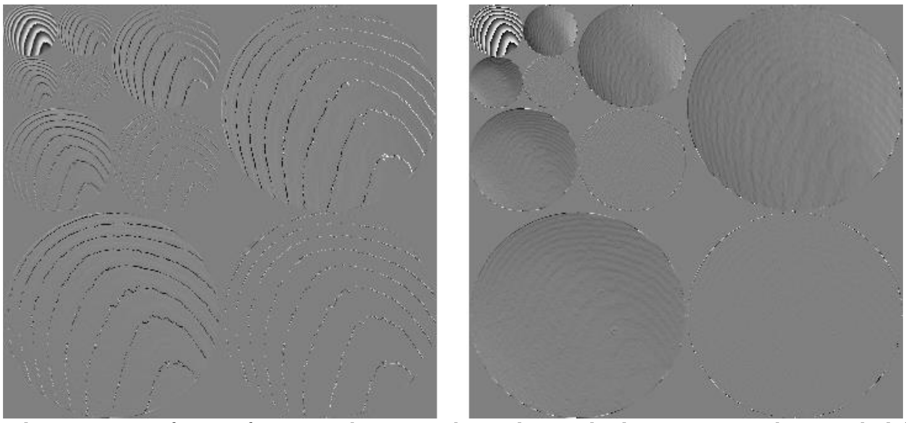

Fig. 1. Wavelet decompositions of an interferometric phase map. The regular wavelet decomposition is shown on the left, the Modulo wavelet decomposition on the right. Phase values are represented in grayscale values: $-\pi$ (black) to π (white).

Note that the Modulo decomposition (Figure 1, on the right) has more desirable properties: (1) the highpass values are more regular, unlike the regular wavelet decomposition where the borders are present; this regularity will reduce the entropy, thereby improving compressibility. (2) the Modulo wavelets are a true multiresolution representation: the lowpass values are circular averages of the local phase values. Regular wavelets will typically return lowpass values that are not representative of the global phase distribution (e.g. $-\pi$ and π will average out to 0).

3. JPEG 2000

JPEG 2000 is a state-of-the-art image compression codec allowing both for lossless as well as lossy compression. It has a modular architecture consisting out of the multiple core modules: image tiling, a wavelet transform, embedded encoding of code-blocks and finally a rate-distortion optimization mechanism [5]. The tiling component is only used when the image is too large because of memory constraints, which is not an issue for the presented research. Then, the samples are wavelet transformed, resulting in a wavelet domain representation of the image, decomposed into multiple frequency subbands. These subbands are further divided into smaller chunks named "code-blocks"; each of these code-blocks is separately entropy encoded: JPEG 2000 employs fractional bit-plane scanning and context-based adaptive arithmetic coding to generate independent embedded bit-streams per code-block. In the lossy compression case, a rate-distortion optimizer combines these bit-streams such that based on the requested functionality and rate vs. quality requirements, optimal rate-distortion coding performance is delivered for the produced JPEG 2000 code-stream.

Thanks to the modularity of JPEG 2000, we are able to separately modify individual modules. This enabled us to replace the regular wavelet transform with the newly designed Modulo wavelets, leaving the remaining modules intact. As such, we modified the coding architecture into a codec suited for dealing with phase distributions.

4. Results

Five different interferometric recordings have been tested; all phase maps were quantized using 8 bpp. We compared the performances of the Modulo wavelets configuration with the two standard lossless wavelet transforms: the Haar and the Biorthogonal Cohen-Daubechies-Feauveau 5/3 wavelets.

Table 1: Lossless bitrates are expressed in average bit-per-pixel (bpp). The gain is determined as the bitrate difference between the best performing regular wavelet transform (Haar or 5/3) and the Modulo Haar wavelet.

Image	Resolution	DWT: Haar	DWT: 5/3	Modulo Haar	Gain
Knife	512x512	7.50	7.54	**6.95**	0.55
L1_60_3rms	544x528	4.01	3.75	**3.60**	0.15
Doublet	416x400	3.76	3.79	**3.45**	0.31
u2_w3	352x336	3.81	3.63	**3.35**	0.28
testHO_50x_lens3	368x352	4.47	4.42	**3.85**	0.58

The recordings have all been compressed using the same settings: a Mallat decomposition structure with four levels, using 32x32 sized codeblocks on a standard compliant JPEG 2000 architecture.

These results show that Modulo wavelets can be a useful tool for compressing phase distributions. We expect that even further gains could be achieved after modifying the entropy coder to suit phase maps as well.

5. Conclusions

In this work, we have shown that phase-only data can be represented more efficiently using a new transform called “modulo wavelets”. We demonstrated as well that this transform can be directly incorporated in the JPEG 2000 architecture, resulting in significant improvements in coding performance of over 0.5 bpp for lossless coding.

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