Wavelet domain image resolution enhancement using cycle-spinning

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A wavelet domain image resolution enhancement method is proposed. The method adopts the cycle-spinning methodology adapted for use in the wavelet domain. The perceptual and objective quality of resolution enhanced images compare favourably with recently emerged algorithms in the field.

Introduction: Recently there has been much interest in wavelet-based algorithms for image resolution enhancement tasks and several methods have appeared in the literature. A common feature of these is the assumption that the low-resolution (LR) image to be enhanced is the lowpass filtered subband of a decimated-wavelet-transformed high-resolution (HR) image. A trivial approach might be to approximate the HR image by filling the unknown subbands (containing highpass spatial frequency information) with zeros and applying the inverse wavelet transform (IWT). More sophisticated methods have attempted to estimate these unknown detail wavelet coefficients. In [1] and [2], the estimation was carried out by examining the evolution of wavelet transform extrema in coarser subbands. In [3] a technique was proposed which takes into account the hidden Markov tree (HMT) approach of [4]. The latter was successfully applied to a different class of problems including image denoising and related applications. An extended version of this approach utilising super-resolution-like methods is presented in [5]. The HMT-based method has also been developed so that it does not require any training data set [6]. In [7] and [8] a wavelet-based superresolution method was presented based on the multiresolutional basis fitting reconstruction technique in [9]. Finally, a similar approach was proposed in [10] using a single LR image.

The decimated wavelet transform is not shift-invariant and, as a result, suppression of wavelet coefficients, such as quantisation of coefficients during the compression process or non-exact estimation of high-frequency subband coefficients, introduces cyclostationarity into the image which manifests itself as ringing in the neighbourhood of discontinuities. Cycle-spinning has been shown to be an effective method against ringing when used for denoising purposes in the wavelet domain [7]. Cycle-spinning was also proven effective towards reducing ringing and increasing the perceptual quality of compressed images. In [8] and [9], it was shown that cycle-spinning applied as a post-processing operation after decompression results in significant improvements in the framework of JPEG and JPEG2000 image compression.

In this Letter, we adopt the cycle-spinning methodology and demonstrate that it is a useful tool for image resolution enhancement in the wavelet domain, offering a low-complexity but powerful alternative to competing methods that have appeared recently in the literature.

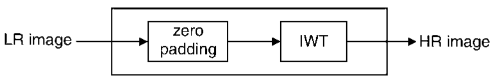

Fig. 1 *Wavelet domain resolution enhancement with zero padding – WZP*

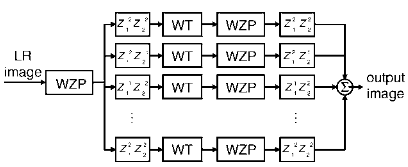

Fig. 2 *Block diagram of proposed method*

Algorithm description: The proposed algorithm consists of the following steps.

– An initial approximation to the unknown HR image is generated using wavelet-domain zero padding (WZP). Using a given LR image $\mathbf{x}$ of size $m \times n$, the unknown HR image $\mathbf{y}$ is reconstructed using zero padding of high-frequency subbands (i.e. setting all elements of these subbands to zeros) followed by inverse wavelet transform:

$$\hat{\mathbf{y}}_0 = W^{-1}\begin{bmatrix} \mathbf{x} & 0_{m,n} \\ 0_{m,n} & 0_{m,n} \end{bmatrix}$$

where $0_{m,n}$ is an all-zero matrix of size $m \times n$ and W^{-1} is the inverse discrete wavelet transform. As already discussed, the underlying assumption is that $\mathbf{x}$ is an approximation of the low-order wavelet coefficients of $\mathbf{y}$. This process is summarised in Fig. 1 and subsequently referred to as WZP.

– Next the cycle-spinning methodology is adapted to operate in the wavelet domain as follows. First, a number of LR images $\hat{\mathbf{x}}_i$ are generated from $\hat{\mathbf{y}}_0$ by (i) spatial shifting, (ii) wavelet transforming and (iii) discarding the high frequency (HF) coefficients: $\hat{\mathbf{x}}_i = DWS_i\hat{\mathbf{y}}_0$ where D represents discarding of HF coefficients, W denotes wavelet transform and S_i is a shift operator applying N horizontal and vertical shifts of $(-k,-k)$, $(-k+1,-k)$, $(-k+1,-k+1), \ldots, (0,0), \ldots, (k-1, k-1)$, $(k-1, k)$, (k, k) for $i \in \{1,2,3,\ldots, N\}$ respectively, where $N = (2k+1)(2k+1)$. Secondly, WZP processing is applied to all $\hat{\mathbf{x}}_i$ yielding N $\hat{\mathbf{y}}_i$ images. Finally, these intermediate HR images are realigned and averaged to give the final HR reconstructed image: $\hat{\mathbf{y}} = 1/N(\sum_{i=1}^{N} S_i^{-1}\hat{\mathbf{y}}_i)$ where S_i^{-1} is the inverse of the shifting operator S_i. A simplified block diagram of the algorithm is shown in Fig. 2 where the notation for spatial shifting is in the z-domain.

Experimental results: The algorithm was tested on several standard monochrome test images which were regarded as the unknown HR originals. These were lowpass filtered and downsampled to provide the LR images $\mathbf{x}$ available for resolution enhancement. This scheme allows the calculation of peak signal-to-noise ratio (PSNR) values of the reconstructed images using the HR originals as ground truth. The wavelet transform was implemented using the well-known Daubechies 9/7 filters [10].

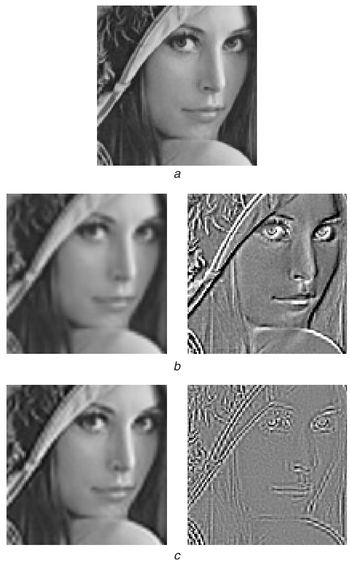

Fig. 3 *Extracts from original and reconstructed Lena images*
a Original image
b Reconstructed and residual images using bilinear interpolation
c Reconstructed and residual images using the proposed method

In Table 1, we tabulate PSNR values against maximum shift k for the Lena test image. It can been seen that the results are highly dependent on the number of shifted images used and $k = 2$ yields the best performance. Using a smaller neighbourhood suffers from not having sufficient data while a larger neighbourhood is liable to crosstalk from spatially uncorrelated image features.

Table 1: PSNR performance against maximum shift for Lena image ($2\times$ resolution enhancement: from 128×128 to 256×256)

Max. shift (k)	PSNR
0	30.99
1	30.76
2	31.37
3	31.04
4	31.31
5	31.11
6	31.28

Enlargement by a factor of 4× was achieved by two alternative methods: either (i) generating the initial image at 4× resolution by iterating WZP twice and then applying cycle-spinning, or (ii) iterating twice the baseline method described in this Letter. Experiments show that the former method gives better results. Both methods can be further iterated in a similar fashion to achieve higher factors of enlargement.

Experimental results for Lena are shown in Fig. 3 together with reconstruction error images. PSNR values for various standard test images are tabulated in Tables 2 and 3 for 2× and 4× enlargement factors, respectively. Our results compare favourably both in subjective and objective terms with standard techniques such as bilinear interpolation as well as recently emerged wavelet-based schemes. In addition, we have included a non-wavelet scheme based on edge-directed interpolation [11] to provide a comparison with a powerful method not operating in the wavelet domain.

Table 2: PSNR results for 2× enlarged images (from 256 × 256 to 512 × 512)

Image/method	Bilinear	NEDI [11]	WZP (Haar)	WZP (Db.9/7)
Lena	30.13	34.10	31.46	34.45
Elaine	30.60	32.89	31.71	33.26
Baboon	22.85	23.87	23.61	24.22
Peppers	30.01	33.54	31.45	33.94
Image/method	Carey *et al.* [2]	HMM [3]	HMM SR [4]	Proposed technique
Lena	34.48	34.52	34.61	34.93
Elaine	33.29	33.31	33.40	33.56
Baboon	24.24	24.24	24.31	24.28
Peppers	34.03	34.04	34.10	34.32

Table 3: PSNR results for 4× enlarged images (from 128 × 128 to 512 × 512)

Image/method	Bilinear	NEDI [11]	WZP (Haar)	WZP (Db.9/7)
Lena	24.06	28.81	26.67	28.84
Elaine	25.38	29.97	28.06	30.44
Baboon	20.43	21.18	21.11	21.47
Peppers	24.37	28.52	26.89	29.57
Image/method	Carey *et al.* [2]	HMM [3]	HMM SR [4]	Proposed technique
Lena	28.81	28.86	28.88	29.27
Elaine	30.42	30.46	30.51	30.78
Baboon	21.47	21.47	21.49	21.54
Peppers	29.57	29.58	29.60	29.87

Conclusion: A method for image resolution enhancement in the wavelet domain is presented. Our approach incorporates elements of the cycle-spinning methodology, already proven successful for other image processing tasks such as denoising. The cycle-spinning principle was adapted for use in the wavelet domain and it was shown to offer a low-complexity yet powerful alternative to competing techniques producing good quality image reconstructions for a useful range of enlargement factors.

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