Image Resolution Enhancement using Inter-Subband Correlation in Wavelet Domain

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ABSTRACT

Wavelet-based resolution enhancement methods improve the image resolution by estimating the high-frequency band information. In this paper, we propose a new resolution enhancement method using inter-subband correlation in which the sampling phase in DWT is considered. Interpolation filters are designed by analyzing correlations between subbands having different sampling phases in the lower level, and applied to the correlated subbands in the higher level. The filters are estimated under the assumption that correlations between two subbands in the higher level are similar to that in the lower level in DWT. The experimental results show that our proposed method outperforms the conventional interpolation methods including the other wavelet-based methods with respect to peak signal-to-noise-ratio (PSNR) as well as the subjective quality.

Index Terms— Wavelet transforms, Image resolution, Image enhancement

1. INTRODUCTION

Conventional image resolution enhancement methods, such as bilinear and bicubic interpolation methods, may generate false information and blurred images because they do not utilize any information relevant to edges in the original image. Wavelet-based methods [1]-[8] enhanced the image resolution by estimating the preserved high frequency information from the given images. They were based on the assumption that the image to be enhanced was the low-frequency subband among wavelet-transformed subbands of the original one and the target is to estimate the high frequency subbands of wavelet transform, so that a resolution-enhanced image can be obtained. Because the analysis filter bank used in the wavelet transform has a poor frequency characteristic such as wide transition region, some information of high-frequency band is remained in the low-frequency band.

The resolution enhancement methods in wavelet domain are very significant not only for enlarging the image size but also for in-band scalable video coder. In in-band scalable video coding [10]-[13], because the motion estimation is performed in wavelet domain, over-complete form [9][10][12] of reference bands is usually used to solve the shift-variance problem in wavelet domain. However, it brings serious drifting errors in decoder since the high-frequency bands are not available to construct the over-complete form of reference band and the drifting error propagates along the lifting structure of temporal filtering. If the unavailable high-frequency bands are estimated from the only available low-frequency band in the decoder, the drifting error will be reduced dramatically. Therefore, wavelet-based resolution enhancement technique becomes more and more important.

In [1] and [2], the coefficients of high-frequency bands are estimated by exploiting the regularity of edges across scales. In these methods, only coefficients having significant magnitude can be estimated whereas it is difficult to estimate the other small coefficients. In [3] and [4], the statistical relationship between coefficients at lower level is modeled by using a hidden Markov model [5] to predict coefficients at high level. A set of parameters should be obtained from the training images, where the information from the training images may not match effectively with the input image. Cycle-spinning based resolution enhancement methods were also proposed recently in [6] and [7], where the ringing artifacts caused by decimation were eliminated by averaging out the translated zero-padded reconstruction images, and by using the local edge orientation to influence cycle spinning parameters. In [8], the unknown wavelet coefficients are estimated by utilizing existing correlation between neighbouring coefficients. However, the correlation of the undecimated subbands is not similar to the correlation of the decimated subbands. All of the above methods predict the high-frequency bands directly from the available low-frequency band. In this paper, a new algorithm based on inter-subband correlation is proposed.

This paper is organized as follows. Section 2 explains characteristics of the phase-shifting matrix [14] and correlations between subbands in DWT. Our proposed resolution enhancement method is described in detail in section 3. Experimental results are presented in section 4 to be followed by conclusions of the paper in section 5.

2. INTER-SUBBAND CORRELATION

Phase-shifting matrix was first derived by Xin Li [14] for saving the computational complexity of LBS [9] method. It showed that two subbands of a two-channel perfect reconstruction filter bank in Fig.1 were linked by a unique phase-shifting matrix.

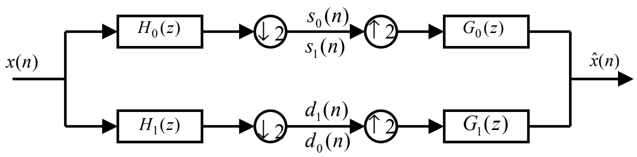


Fig.1. Two channel wavelet filter bank

Since it is customary to put the center of an odd symmetric filter at 0, for odd length biorthogonal filters, the sample positions in the low-frequency band and the high-frequency band are alternative, which means even-phase for low–frequency band and odd-phase for high-frequency band. Therefore the relations between different phase subbands in [4] can be modified as follows:

$$\begin{bmatrix} S_0(z) \\ D_1(z) \end{bmatrix} = T(z) \begin{bmatrix} S_1(z) \\ D_0(z) \end{bmatrix} \tag{1}$$

where S_0 S_1, D_0 and D_1 are the even-phase and odd phase low-pass and high-pass filtered coefficients, and

$$T = \frac{1}{2} \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \tag{2}$$

where

$$T_{11}(z) = -H_0(z^{1/2})H_1(-z^{1/2}) + H_0(-z^{1/2})H_1(z^{1/2})$$
$$T_{12}(z) = -2H_0(z^{1/2})H_0(-z^{1/2})$$
$$T_{21}(z) = -2H_1(z^{1/2})H_1(-z^{1/2})$$
$$T_{22}(z) = -T_{11}(z)$$

From eq. (1), we can derive 1-D inter-subband relationship as follow:

$$D_1(z) = \frac{1}{2}(T_{21}(z)S_1(z) + T_{22}(z)D_0(z)) \tag{3}$$

1-D inter-subband relationship can be easily extended to 2D image. First, four subbands of 2-D wavelet transform can be denoted as $LL00$, $HL10$, $LH01$ and $HH11$ as shown in Fig.2. The postfixes mean horizontally downsampled phase and vertically downsampled phase, respectively, where 0 means even-phase and 1 means odd-phase. Inter-subband relationships in 2D are given as follows:

$$\begin{aligned} HL10(z) &= \frac{1}{2}(T_{21}(z)LL10(z) + T_{22}(z)HL00(z)) \\ LH01(z) &= \frac{1}{2}(T_{21}(z)LL01(z) + T_{22}(z)LH00(z)) \end{aligned} \tag{4}$$

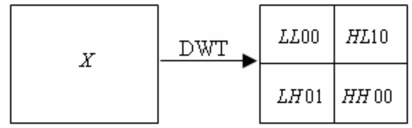


Fig.2. 2D Wavelet Transform

3. PROPOSED RESOLUTION ENHANCEMENT SCHEME

Actually the analysis filter bank has finite filter taps, so the low-pass filtered signal contains some high-frequency information and also the high-pass filtered signal has some low-frequency information. If both low-pass and high-pass filtered signals are downsampled by the same phase, there still remains some correlation between low-frequency band and high-frequency band, however, when downsampled by different phases, there will be low correlation. In other words, $HL00$ has higher correlation with $LL00$ than $HL10$ Therefore, estimating the same phase high-frequency band from low-frequency band is more reasonable than directly estimating different phase high-frequency band. Our proposed algorithm is based on this point.

The proposed resolution enhancement scheme consists of three steps: filter estimation, band estimation and reconstruction.

Filter Estimation:
First we apply overcomplete wavelet transform on the given $LL00$ to achieve all different phase cases of each subband. Overcomplete wavelet transform is showed in Fig.3.

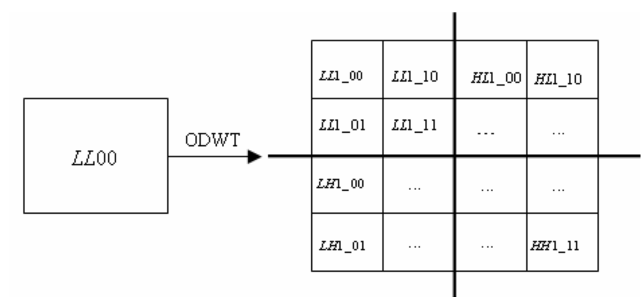


Fig.3. Overcomplete wavelet transform of level 1

In this step, we design four filters, with which $LL1\_10$, $LL1\_01$, $HL1\_00$ and $LH1\_00$ are estimated respectively from $LL1\_00$. The filter estimation approach is based on the linear least-squares regression which was also utilized in [8]. By denoting the coefficients at position (m,n) in $LL1\_10$ as $y_{m,n}$ and coefficients at position (m,n) in $LL1\_00$ as $x_{m,n}$, an estimation of $y_{m,n}$ is described as follow:

$$y_{m,n} = a_{h8}x_{m-3,n} + a_{h7}x_{m-2,n} + a_{h6}x_{m-1,n} + a_{h5}x_{m,n} + a_{h4}x_{m+1,n} + a_{h3}x_{m+2,n} + a_{h2}x_{m+3,n} + a_{h1}x_{m+4,n} \quad (5)$$

Then, the filter $f_{Ah} = \{a_{h1}, a_{h2}, a_{h3}, a_{h4}, a_{h5}, a_{h6}, a_{h7}, a_{h8}\}$ can be obtained by solving the over-determined problem using linear least-squares regression [8]. Because $LL1\_01$ and $LL1\_00$ bands are downsampled by different phases only along vertical direction, filter f_{Av} can be designed along columns with the similar process to eq.(5). In the similar way, two filters f_{Bh} and f_{Bv} are designed considering correlations between $LL1\_00$ and $HL1\_00$, and between $LL1\_00$ and $LH1\_00$, respectively.

Band Estimation:

In this step, the filters estimated in the lower level (level 1) are utilized to estimate the corresponding bands in the higher level (level 2).

Using filters f_{Ah}, f_{Av}, f_{Bh} and f_{Bv} estimated in the lower level, we obtain $LL10$, $LL01$, $HL00$ and $LH00$ of high level from $LL00$ as follows:

$$\begin{aligned} LL10(z) &= (F_{Ah}(z) \cdot LL00(z))_{row} \\ LL01(z) &= (F_{Av}(z) \cdot LL00(z))_{col} \\ HL00(z) &= (F_{Bh}(z) \cdot LL00(z))_{row} \\ LH00(z) &= (F_{Bv}(z) \cdot LL00(z))_{col} \end{aligned} \quad (6)$$

where $F_{Ah}(z)$, $F_{Av}(z)$, $F_{Bh}(z)$ and $F_{Bv}(z)$ represent filters f_{Ah}, f_{Av}, f_{Bh} and f_{Bv} in z-domain, respectively, and the subscript *row* and *col* denote filtering along rows and columns, respectively. Using the inter-subband relationship in eq.(4) we can achieve final $HL10$ and $LH01$ from the estimated four bands $LL10$, $LL01$, $HL00$ and $LH00$.

Reconstruction:

Inverse wavelet transform is performed with $LL00$ and the estimated $HL10$ and $LH01$ to reconstruct original image or in other words to enhance the resolution of input image. Here, the diagonal band of $HH11$ is supposed to be zero, because $HH11$ not only belongs to different subband from $LL00$ but also has different sampling phases.

4. EXPERIMENTAL RESULTS

Four well-known test images of 'Lena', 'Peppers', 'Baboon' and 'Crowd' are used in our experiments. We first perform low-pass filtering on the original images and decimate to obtain $LL00$ of the original ones which will be used as the given images to be enhanced in the following experiments. The original images are used as the ground truth and we evaluate the enhancement results with respect to the peak signal-to-noise ratio (PSNR).

Table 1 shows the PSNR comparison of various resolution enhancement methods for two-fold enlarging the resolution. As shown in table 1, our proposed method outperforms the competing methods as much as 0.36 dB.

If we compare the difference images in Fig. 4, which are from subtracting the reconstructed images from the original ones, our proposed method presents less residual signal compared to the other methods. Table 2 shows rates of the correctly estimated sign of band $HL00$ and $LH00$. Almost 70% of coefficients' signs are estimated correctly in our proposed method.

Table 1. PSNR comparison of various methods

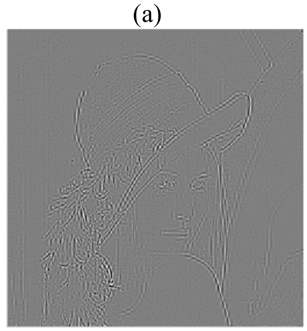
	Lena256	Pepper256	Baboon256	Lena512	Pepper512	Baboon512	Crowd512
Bilinear	28.9426	31.0478	24.5759	31.9421	31.5263	23.0106	31.8801
Bicubic	29.7907	32.2416	24.885	32.9776	32.2973	23.2999	33.2558
Xin[15]	29.6687	31.9915	24.5962	32.4686	32.1847	23.0647	31.7119
CS[7]	29.993	32.5858	24.8383	33.3165	32.4689	23.2664	33.7695
DCS[8]	30.2032	32.8023	25.0299	33.4776	32.5926	23.4509	33.9496
Proposed	30.4374	33.1224	25.0993	33.7277	32.8447	23.4983	34.3084

Table 2. Rate of correctly estimated sign of $LH00$ and $HL00$ from LL [%]

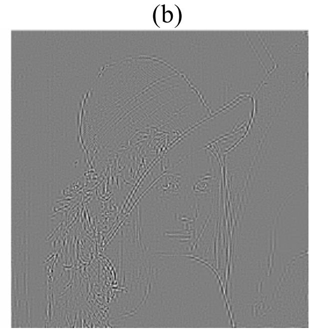
	Lena256	Pepper256	Baboon256	Lena512	Pepper512	Baboon512	Crowd512
HL00_new	70.16	70.28	72.41	68.54	66.60	71.66	74.38
LH00_new	68.72	73	69.27	69.09	66.96	68.73	72.35

(a)

(b)



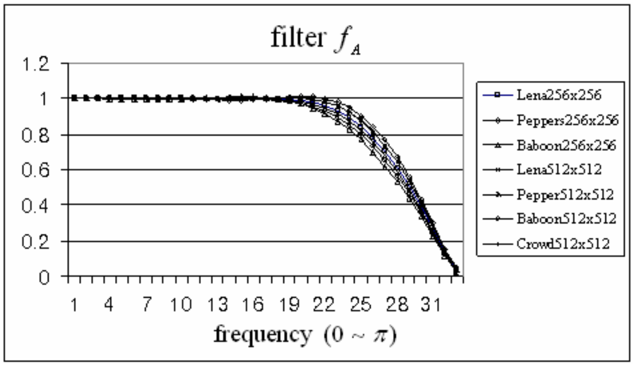
(c)



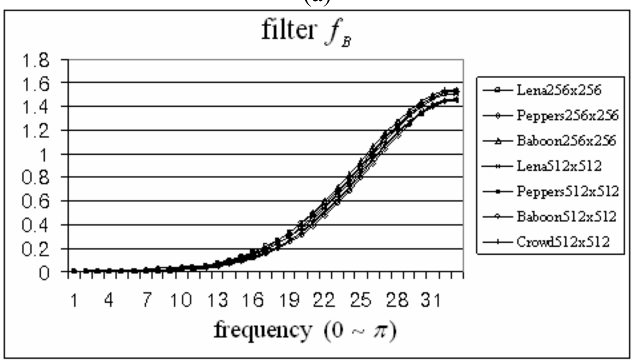
(d)

Fig.4. Difference images magnified by two (a)bicubic (b)Xin (c)DCS (d)Proposed

Moreover, the estimated filters for various test images in Fig.5 show similar characteristics. So if we can design a set of general filters for all images, the filter estimation step can be omitted and the computational complexity will be reduced dramatically when applied to the video sequence.



(a)



(b)

Fig.5. Filter coefficients (a) horizontal filter f_{Ah}
(b) horizontal filter f_{Bh}

5. CONCLUSIONS

In the paper, we proposed a new image resolution enhancement method in wavelet domain using inter-subband correlation. Our proposed method utilized the correlation of subbands with different sampling phases in DWT. The high-frequency bands were estimated with filters designed in the lower level under the assumption that filters connecting two bands are similar in different levels. The experimental results demonstrated that our proposed method outperformed the competing methods by as much as 0.36 dB. Moreover, filters estimated in various test images showed similar characteristics. It motivates us to design a general filter set well adapts to all images, since estimation of filters for each frame is time consuming when applied to video sequence. This will be considered as the further work.

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