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Wavelet Domain Image Super-Resolution Reconstruction Based on Image Pyramid and Cycle-Spinning

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Abstract. On the base of the analysis of single image super-resolution reconstruction, wavelet domain super-resolution reconstruction based on image Pyramid and cycle-spinning is proposed in the paper. The algorithm consists of the following parts: the predictive high-resolution image are obtained by a LR image based on laplacian pyramid method; the discrete wavelet transform is used for predictive high-resolution image to obtain the high-frequency wavelet coefficients; a high-resolution image is obtained by the inverse wavelet transform; Finally the cycle-spinning method is used to reduce ringing. The proposed algorithm avoids the application of iterative method, reduces the complexity of calculation and applies to large dimension low-resolution images. The results show the proposed approach has succeeded in obtaining a high-resolution image with a high peak signal-to-noise ratio and good visual quality.

1. Introduction

Super-resolution(SR) image reconstruction produces a high-resolution(HR) image from a single low-resolution(LR) image or a set of shifted, blurred, and decimated versions. Many SR algorithms have been proposed including the projection onto convex sets (POCS)[1] method, the regularized[2] method, the iterative backward projection(IBP)[3], and the maximum a posteriori (MAP) [4] method and so on. The above methods need to know the degraded model of image and the SR reconstruction problem is an ill-posed inverse problem having matrix of very large dimension. So, many methods of SR reconstruction have to solve a large ill-condition equation group by approximately finding the inverse of a large sparse matrix or perform some iteration to approach the solution. The Wavelets and multiresolution analysis are especially well-suited for image processing. Many investigators have considered the use of wavelet representations for image denoising, deblurring, and image reconstruction [5]. A common feature of these is the assumption that the LR image to be enhanced is the lowpass filtered subbands of a decimated-wavelet-transformed HR image. The high frequency wavelet coefficients are estimated by LR image and the HR image is obtained by applying the inverse wavelet transform (IWT).

In order to avoid the iterative operation and reduce the time-consuming, we present a SR image reconstruction method of single image based on image Laplacian Pyramid(LP), wavelet transform and cycle-spinning, in this paper. The proposed method avoid the a number of iterative operations and make the SR reconstruction possible of large dimension image.
The organization of the rest of the paper is as follows. In sec. 2 the problem formulation is explained. The steps of the suggested SR algorithm are summarized in sec. 3. Section 4 describes LP to estimate HR images. The wavelet transform and cycle-spinning method is described in sec. 5. In sec. 6 some experimental results are given. Finally, some conclusions are given in sec. 7.

2. Problem formulations

In SR image reconstruction algorithms, the mathematical model that relates the LR observation to the required HR image is given\[6\]

\[ g = Hf + n \]  

(1)

Where g is an N×1 vector representing the \( m \times n \) (N=\( m \times n \)) pixel LR image in lexicographic order. If l is the resolution enhancement factor in both directions, then f is an \( l^2 N \times 1 \) vector representing an \( l \times l \) (\( m \times n \)) HR image in lexicographic order. H is the \( N \times l^2 N \) matrix representing the weight of HR pixels to the LR pixels called degrading matrix. The value of H refer to the system PSF (Point Spread Function), in most application, this PSF is modeled as a spatial averaging operator. n is the N×1 noise vector.

There is a problem in the implementation of (1). The matrix inversion process cannot be performed directly. There is because \( l \) is very large of matrix. Thus, regularization is the main method of solving this kind of problems, of which the critical ingredient is to introduce the prior knowledge about the HR image. A large number of iterations are required to get an estimate of the required HR image. The computational complexity of SR image reconstruction is very high. In the paper, the method based on LP, wavelet transform and cycle-spinning is proposed to reduce the computational complexity.

Using regularization theory to solve (1) gives\[7\]

\[ \hat{f} = (H^T H + \lambda C^T C)^{-1} H^T g \]  

(2)

Where, C is the regularization operator, which is preferably the 3-D laplacian operator process, to capture the between-channel information in the reconstruction process. The parameter \( \lambda \) is a global regularization parameter.

3. Suggested algorithm

Recently, the Wavelets are widely used to the SR reconstruction. A common feature of Wavelets SR reconstruction(WSRR) is the assumption without loss of generality that the LR images to be enhanced are the corresponding lowpass filtered subbands of decimated-wavelet-transformed(DWT) for HR images. So, all kinds of WSRR methods estimate mostly the highpass filtered subbands of a DWT for HR images, then, to reconstruction the HR image by IWT. An simple approach to the HR image to be reconstruction is used by setting all elements of these highpass subbands to zeros\[8\]. The approach is called wavelet-domain zero padding(WZP). The process is showed in figure 1.

In this section, we propose a new WSRR method that estimates highpass filtered subbands coefficients instead of zeros by LP. In order to obtain the more information from LR image, cycle-spinning\[8\] method is used to reduce ringing in reconstructed image. The suggested SR algorithm is consisted of the following steps. the predictive high-resolution image(PHRI) are obtained by a LR image based on LP method. The high-frequency wavelet coefficients obtained by DWT for the predictive high-resolution image are substituted by LR image, then, the HR image is obtained by IWT. Making the cycle-spinning to suppress the ringing in the neighborhood of discontinuities.

4. Estimating wavelet coefficients based on Laplacian Pyramid

Pyramid date structure is widely used in image processing\[9\]. The process of image decomposition and reconstruction based on LP is shown in Figure 2.
As shown in Figure 2(a), $g_0$ is an image, and $g_i$ is the result image of applying an appropriate low-pass filter and downsampling to $g_{i-1}$. The prediction error $L_i$ is then given by $L_i = g_i - upsampling(g_{i-1})$. $g_i$ is itself low-pass filtered and downsampling to yield $g_{i-1}$ and a second error image is obtained $L_i = g_i - upsampling(g_{i-1})$. By repeating these steps several times, we obtain $L_n$ by $L_n = g_n - upsampling(g_{n-1})$, $0 \leq k < n$. So, we obtain a sequence of two-dimensional arrays $g_0, g_1, \ldots, g_n$ and $L_0, L_1, \ldots, L_n$. In our implementation, each is smaller than its predecessor by a scale factor of 1/2 due to reduced sample density. If we now imagine these arrays stacked one above another, the result is a tapering pyramid data structure. Thus, the image representation is called the Laplacian Pyramid (LP). Those low-pass filtered images $g_0, g_1, \ldots, g_n$ from a Gaussian Pyramid (GP). The two Pyramids are shown in Figure 2.

Since there is no image $g_{i-1}$ to serve as the prediction image for $g_i$, we say $L_i = g_i$. The process of Pyramid reconstruction is shown in figure 2(b). The original image can be recovered exactly by $L_0, L_1, \ldots, L_n$. A more efficient procedure is to upsample $L_0$ once and add it to $L_1$, then upsampling this image once and add it to $L_2$, and so on until level 0 is reached and $g_0$ is recovered. This procedure simply reverses the steps in Laplacian pyramid generation. We obtain $L_i = g_i - upsampling(g_0)$. Our aim want to estimate the higher level resolution image than $g_0$. Suppose the predictive high-resolution image is $g_0$, based on the principle of Laplacian pyramid, $g_0 = L_0 + upsampling(g_0)$. We adopt the interpolation method to obtain the low frequency of HR image $g_0$. We have several methods to deal with the prediction error $L_0$. 1) Supposing the pixel value of $L_0$ is zero. The obtained HR image is the result of interpolation for LR image. 2) We suppose $L_0 = upsampling(L_0)$. So, we gained $g_0 = upsampling(L_0 + g_0)$. We call this method as upsampling predictive SR (UPSR). 3) To predict $L_0$ by residual Pyramid. We call this method as LP predictive SR (LPPSR). The process is shown in figure 3.

If we look on the $L_0, L_1, \ldots, L_n$ as a new image Pyramid, we may obtain a residual Pyramid $L_0, L_1, \ldots, L_n$, by using the same method of obtaining $L_0, L_1, \ldots, L_n$. Via the process of Pyramid reconstruction, the $L_0$ is obtained by $L_0 = L_0 + upsampling(L_0)$. $L_i$ is obtained by the following process: upsampling $L_{i-1}$ and add it to $L_i$, upsampling the new image and add it to $L_{i+1}$, by repeating these steps, finally, we obtain the $L_n$.

5. Wavelet transform using cycle-spinning

WSRR method is the assumption the LR images to be enhanced are the corresponding lowpass filtered subbands of DWT for HR images. So, all kinds of WSRR methods estimate mostly highpass filtered subbands of a decimated-wavelet-transformed for HR images, then, to reconstruction the HR image by IWT. The suggested method is showed by figure 4. First, the high resolution image is obtained by LPPSR, the discrete wavelet transforms of the PHRI are computed. The wavelet transform contains the low-high bands (LL), the high-low bands (LH and HL) and the high-high bands (HH) of the images at different scales. For a single image, we may make the LR image replace the LL part and IWT to reconstruct the HR image. We called this method as single image wavelet Laplacian Pyramid SR (WLPSR). Cycle-spinning [9] is used to reduce the ring. Cycle-spinning method is explained in figure 5. A number of LR images are generated by spatial shifting and down-sampling from a HR.
image obtained by WLPSR method. The LR images are reconstructed to obtain some HR images by WLPSR method again. Registrated HR images are fused to a final HR image by average method.

Figure 3. The diagram of obtaining the high frequency $L_1$. 

Figure 4. WLPSR method

Figure 5. Cycle-spinning method.

6. Experimentations
Here we present many experiments to demonstrate the effectiveness of our algorithm. The peak signal-to-noise ratio (PSNR) is adopted as the error metric. Figure 6 is the result of Simulations of Lena image. Table 1 is the comparison between the suggested method and other methods. Simulations demonstrate the superior performance of the algorithm in PNSR and visual quality.

(a) A typical LR image  (b) Bilinear interpolation  (c) WLPSR algorithm  (d) Suggested algorithm

Figure 6. Reconstruction Lena image.
### Table 1. PNSR(dB) results for 2×2 enlarged images (from 128×128 to 256×256).

| Images/methods | Bilinear interpolation | WLPSR algorithm | the suggested algorithm |
|----------------|------------------------|------------------|------------------------|
| Lena           | 27.2489                | 28.1847          | 28.7828                |
| Couple         | 30.1683                | 30.6901          | 31.7046                |
| Blood          | 29.1352                | 31.2218          | 32.2520                |
| Woman          | 30.5016                | 31.0548          | 31.7046                |

7. **Conclusion**

This paper presents a SR image reconstruction algorithm based on Laplacian Pyramid, wavelet transform and cycle-spinning. The suggested method avoids a large number of iterations operations to obtain the HR image. Simulations demonstrate the superior performance of the algorithm in PNSR and visual quality.

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