Image Super Resolution Based on Interpolation of Wavelet Domain High Frequency Subbands and the Spatial Domain Input Image

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In this paper, we propose a new super-resolution technique based on interpolation of the high-frequency subband images obtained by discrete wavelet transform (DWT) and the input image. The proposed technique uses DWT to decompose an image into different subband images. Then the high-frequency subband images and the input low-resolution image have been interpolated, followed by combining all these images to generate a new super-resolved image by using inverse DWT. The proposed technique has been tested on Lena, Elaine, Pepper, and Baboon. The quantitative peak signal-to-noise ratio (PSNR) and visual results show the superiority of the proposed technique over the conventional and state-of-art image resolution enhancement techniques. For Lena's image, the PSNR is 7.93 dB higher than the bicubic interpolation.

Keywords: Static image super resolution, discrete wavelet transform.

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I. Introduction

Interpolation in image processing is a method to increase the number of pixels in a digital image. Interpolation has been widely used in many image processing applications such as facial reconstruction [1], multiple description coding [2], and super resolution [3], [4].

Interpolation-based super resolution has been used for a long time, and many interpolation techniques have been developed to increase the quality of this task. There are three well-known interpolation techniques; namely, nearest neighbor interpolation, bilinear interpolation, and bicubic interpolation. Bicubic interpolation is more sophisticated than the other two techniques but produces smoother edges than bilinear interpolation.

Image resolution enhancement in the wavelet domain is a relatively new research addition, and recently, many new algorithms have been proposed [4], [5]. Carey and others have estimated the unknown details of wavelet coefficients in an effort to improve the sharpness of the reconstructed images [5]. Their estimation was carried out by investigating the evolution of wavelet transform extrema among the same type of subbands. Edges identified by an edge detection algorithm in lower frequency subbands were used to prepare a model for estimating edges in higher-frequency subbands, and only the coefficients with significant values were estimated as the evolution of the wavelet coefficients. These significant coefficients correspond to salient image discontinuities, and consequently, only the portrayal of those can be targeted with this approach.

In this work, we have proposed a new technique which generates sharper super resolved images. The proposed Demirel-Anbarjafari Super Resolution (DASR) technique uses discrete wavelet transform (DWT) to decompose a low-resolution image into different subband images. Then the high-frequency subband images are interpolated using bicubic interpolation. In parallel, the input image is also interpolated separately. Finally, the interpolated high-frequency subband images and interpolated input image are combined by using inverse DWT (IDWT) to achieve a high-resolution output image. The DASR technique has been compared with conventional and state-of-art image resolution enhancement techniques.

The conventional techniques used are:

- Interpolation techniques; namely, nearest interpolation, bilinear interpolation, and bicubic interpolation,
- Wavelet zero padding (WZP).

The state-of-art techniques used for comparison purposes are:

- Regularity-preserving image interpolation [5],
- New edge-directed interpolation (NEDI) [6],
- Hidden Markov model (HMM) [7],
- HMT-based image super resolution (HMT SR) [8],
- WZP and cycle-spinning (CS) [9],
- WZP, CS, and edge rectification (ER) [10].

Some of the aforementioned state-of-art techniques [5], [7]-[10], use DWT for image super resolution. According to the results, the DASR technique outperforms the aforementioned state-of-art and conventional techniques for image resolution enhancement. For example, in the case of Lena's image, the peak signal-to-noise ratio (PSNR) of the DASR technique is 5.43 dB higher than the WZP, CS, and ER image resolution enhancement techniques.

II. Proposed Image Resolution Enhancement Technique

The main loss of an image after being super-resolved by applying interpolation is on its high-frequency components, that is, the edges. This loss is due to the smoothing caused by interpolation.

Hence, in order to increase the quality of the super-resolved image, preserving the edges is essential. In this work, DWT [11] has been employed in order to preserve the high-frequency components of the image.

DWT decomposes an image into different subband images; namely, low-low (LL), low-high (LH), high-low (HL), and high-high (HH).

In the proposed DASR technique, DWT is used to decompose an input image into subband images. LH, HL, and HH subband images contain the high-frequency components of the input image. In the DASR technique, the interpolation is applied to high-frequency subband images. In the wavelet domain, the low-resolution image, LL, is obtained by lowpass filtering of the high-resolution image, Ξ [12]. In other words, the LL subband image is the low-resolution of the original image, Ξ.

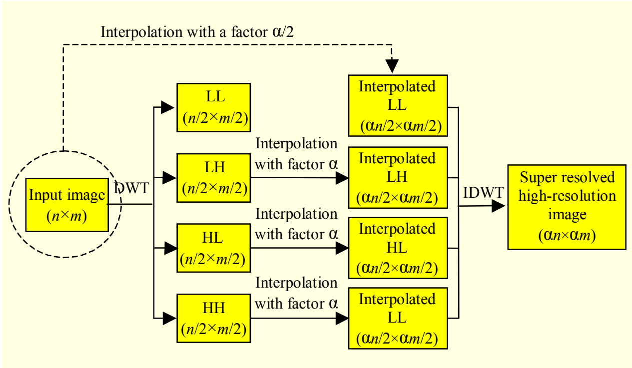

Fig. 1. Block diagram of the proposed super resolution algorithm.

Therefore, instead of using LL, which contains less information than Ξ, we are using the Ξ for interpolation. Hence, using Ξ instead of the LL subband image increases the quality of the super-resolved image. Note that Ξ is interpolated with half of the interpolation factor, α, used to interpolate the high-frequency subbands, as illustrated in Fig. 1.

By interpolating Ξ by α/2, and interpolating HH, HL, and LH by α, and then applying inverse IDWT, the output image will contain sharper edges than the interpolated image obtained by interpolation of the image Ξ directly. This is because the interpolation of isolated high-frequency components in HH, HL, and LH will preserve more high-frequency components after the interpolation of the respective subbands separately than interpolating Ξ directly.

In summary, the proposed technique interpolates the input image as well as the high-frequency subband images obtained through the DWT process. The final high-resolution output image is generated by using the IDWT of the interpolated subband images and the input image. In the DASR technique, the employed interpolation method is the same for all subband and the input images. The interpolation technique and the wavelet function are two important factors in determining the quality of the super-resolved images. The visual and PSNR results in the proceeding section show that the DASR with bicubic interpolation and db.9/7 wavelet function out performs conventional and state-of-art techniques included as references in this paper.

III. Results and Discussions

Figures 2(a) and (b) show the error image between the

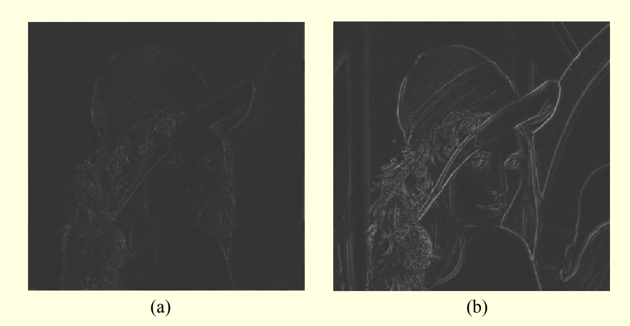

Fig. 2. (a) Amplified error image between the original high-resolution Lena image and DASR based super-resolved image, and (b) the bicubic interpolated image.

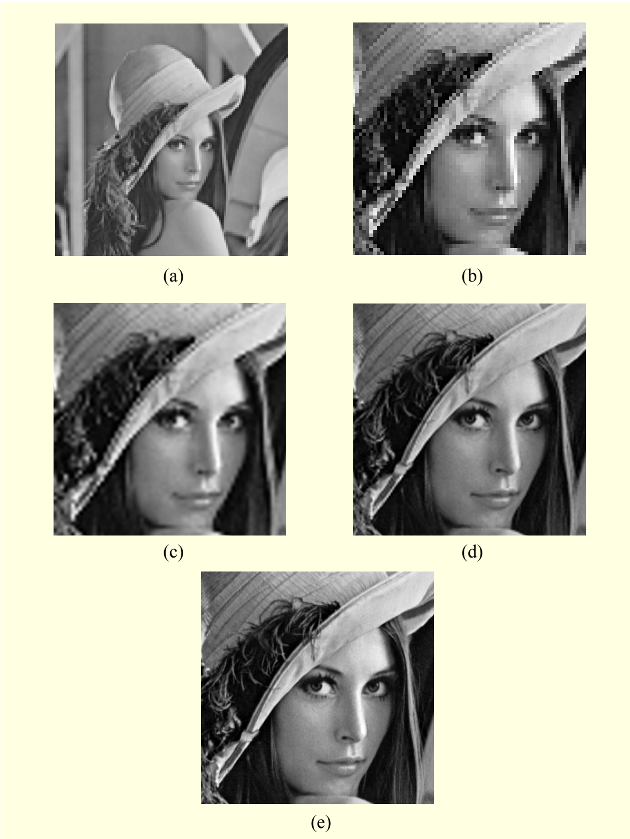

Fig. 3. (a) and (b) original low-resolution image, (c) bicubic interpolated image, (d) super-resolved image using DASR with db.9/7 wavelet function and bicubic interpolation, and (e) original high-resolution image.

original high-resolution Lena image with the DASR super-resolved image, and the error image obtained by using bicubic interpolation directly. The DASR technique preserves the high-frequency details more than the conventional interpolation techniques, where Fig. 2(a) reflects this by including less high-frequency details in the error image.

Figure 3 shows that the Lena image in (d) is much better than the low-resolution image in (b) and the interpolated image

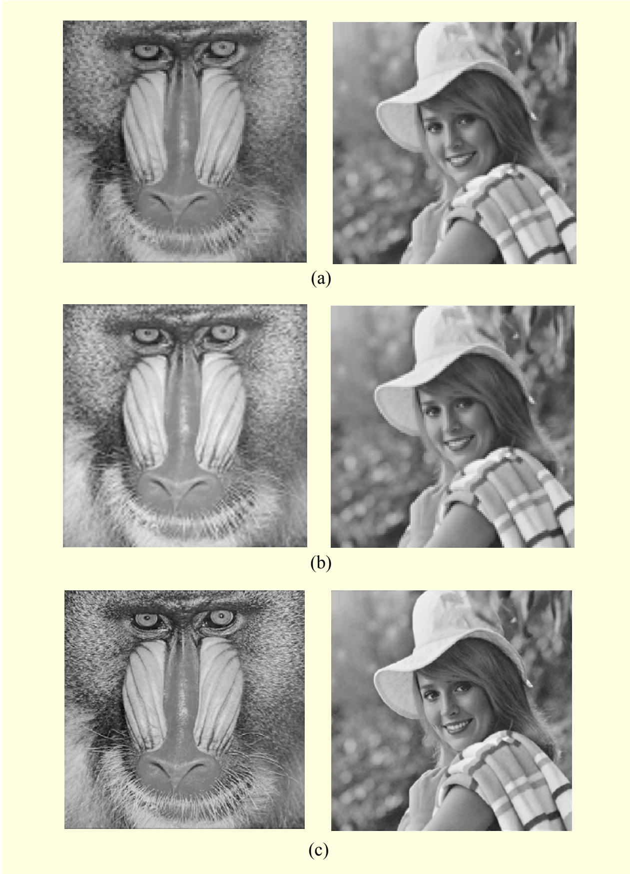

Fig. 4. (a) Original low resolution images, (b) bicubic interpolated images, and (c) super-resolved images using DASR with db.9/7 wavelet function and bicubic interpolation.

in (c). In order to show the effectiveness of the proposed method over the conventional and state-of-art image resolution enhancement techniques, four well-known test images (Lena, Elaine, Baboon, and Peppers) with different features are used for comparison. In this context, for example, Fig. 4 shows the strength of the method by including Baboon for texture and Elaine for edges.

Due to the fact that the high-frequency subbands contain directional frequencies, embedding the interpolated high-frequency components, that is, edges, into the reconstruction process by using IDWT introduces aliasing effects on the super-resolved image as shown in Fig. 5(c). However, the achieved gain on the quality of the image is much higher than the loss caused by distortion, and the super-resolved image is sharper and less blurred.

Table 1 shows the resulting PSNR values of the DASR technique compared with interpolation techniques based on using bicubic, bilinear, and nearest interpolation.

The original high-resolution images have been used as the ground truth to calculate the PSNR values. The input low-resolution images (128×128) have been generated by two

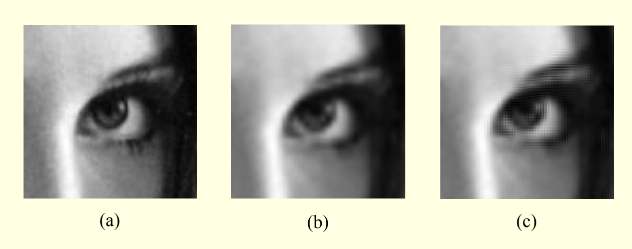

Fig. 5. Lena image with 400% zooming of right eye region of: (a) original high-resolution image, (b) the respective region after bicubic interpolation, and (c) the respective super-resolved region achieved by the proposed technique.

Table 1. PSNR results for resolution enhancement from 128 × 128 to 512 × 512.

(dB)

Technique / Image	Nearest neighbor		Bilinear		Bicubic	
	Spatial	DASR	Spatial	DASR	Spatial	DASR
Lena	25.23	34.38	26.34	34.55	26.86	34.79
Elaine	26.64	31.14	27.96	32.64	28.16	32.75
Baboon	20.28	23.40	20.51	23.25	20.61	23.29
Peppers	24.39	32.05	25.16	32.14	25.66	32.19

Table 2. PSNR results for resolution enhancement from 128 × 128 to 512 × 512 of the proposed DASR technique compared with the conventional and state-of-art image resolution enhancement techniques.

(dB)

Images / Technique	Lena	Elaine	Baboon	Peppers
Bilinear	26.34	25.38	20.51	25.16
Bicubic	26.86	28.93	20.61	25.66
WZP (db.9/7)	28.84	30.44	21.47	29.57
WZP (Haar)	26.67	28.06	18.02	23.80
Carey and others [5]	28.81	30.42	21.47	29.57
NEDI [6]	28.81	29.97	21.18	28.52
HMM [7]	28.86	30.46	21.47	29.58
HMT SR [8]	28.88	30.51	21.49	29.60
WZP-CS [9]	29.27	30.78	21.54	29.87
WZP-CS-ER [10]	29.36	30.89	21.56	30.05
DASR (Haar + bicubic)	27.07	27.94	18.06	23.84
DASR (db.9/7 + bicubic)	34.79	32.73	23.29	32.19

consecutive downsamplings of the original high-resolution images (512 × 512) using DWT. The visual results of the DASR technique in Figs. 3 and 4 support the quantitative results in Table 1. The quantitative results in Table 1 show the superiority of the DASR technique over the conventional interpolation techniques. Furthermore, the performance of the DASR technique increases as more sophisticated interpolation techniques are used in the implementation process.

Table 2 compares the PSNR performance of the DASR technique (using Daubechies (db.9/7) and Haar wavelet functions with bicubic interpolation) with conventional and state-of-art resolution enhancement techniques: bilinear, bicubic, WZP, NEDI, HMM, HMT SR, WZP-CS, WZP-CS-ER, and regularity-preserving image interpolation. For example, in the Lena image, the PSNR of DASR using the db.9/7 wavelet function is 5.43 dB higher than the PSNR obtained by using WZP-CS-ER. Table 2 indicates that the proposed DASR technique outperforms the aforementioned conventional and state-of-art image resolution enhancement techniques.

IV. Conclusion

This paper proposes a new super-resolution technique based on the interpolation of the high-frequency subband images obtained by DWT and the input image. The DASR technique uses DWT to decompose an image into different subband images. The high-frequency subband images are interpolated. An original image is interpolated with half of the interpolation factor used for interpolating the high-frequency subband images. Afterwards all these images are combined using IDWT to generate a super-resolved image. The DASR technique has been tested on well-known benchmark images, where their PSNR and visual results show the superiority of the DASR technique over conventional and state-of-art image resolution enhancement techniques.

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