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SURVEY ARTICLE

A Survey on Wavelet Domain Techniques for Image Super Resolution

Saranya P[1], Fatimakani K[2], Kanchanadevi P[3], Venkatesan S[4], Govindaraju S[5]

[1234]PG Scholars, Department of Electronics & Communication, Kumaraguru College of Technology, Coimbatore, India

[5]Professor, Department of Electronics & Communication, Kumaraguru College of Technology, Coimbatore, India

[1] saranya.amrita@gmail.com

Abstract— The main objective of super-resolution (SR) imaging is to reconstruct a high-resolution (HR) image of a scene from one or more low-resolution images of the scene. In resolution enhancement of images, the main loss is on the high frequency components (edges) of the image. This is due to the smoothing caused by interpolation. Hence in order to enhance the quality of the super resolved image, preserving the edges is essential. In this paper we are studying various image resolution enhancement techniques that utilize Wavelet Transform (WT) techniques. This paper compares various image resolution enhancement methods that employs discrete wavelet transform (DWT), stationary wavelet transform (SWT), dual tree complex wavelet transform (DT-CWT), wavelet zero padding (WZP), cycle spinning (CS). To enhance the contrast of the image singular value decomposition (SVD) is employed with wavelet transform, in which singular value matrix gives the illumination content. By modifying that value the contrast of the given image is increased. Simulation experiments have been performed on a variety of images using Matlab, and results were compared using peak signal to noise ratio (PSNR).

Keywords— Discrete wavelet transform (DWT), Dual tree complex wavelet transform (DT CWT), Peak signal to noise ratio (PSNR), Stationary wavelet transform (SWT), Singular value decomposition (SVD), Super resolution (SR)

I. INTRODUCTION

Resolution is one of the most important features of an image. Images of low resolution are processed to obtain more enhanced resolution. The most commonly used techniques for image resolution enhancement is Interpolation. Interpolation techniques has been used widely in many image processing applications such as facial reconstruction [1], multiple description coding [2], and super resolution [3][4]. Interpolation increases the number of pixels in the digital image the three well known image interpolation techniques are bicubic interpolation, nearest neighbor interpolation, and bilinear interpolation. Nearest neighbor result in significant jaggy edge distortion. The Bilinear interpolation results in smoother edges but somewhat blurred appearance. Bicubic interpolation results in smooth edges and much less blurring than the bilinear interpolation.

Resolution enhancement of images using wavelet domain is a relatively new research topic and recently new algorithms have been proposed [5][6]. Discrete wavelets transform (DWT) and stationary wavelet transform (SWT) are two wavelet transforms used in image processing. DWT decomposes an image into different subband images, namely low-low (LL), low-high (LH), high-low (HL), and high-high (HH). SWT is similar to DWT but there is no down sampling operation performed in SWT. So in SWT the sub bands will have the same size as the input image. Contrast enhancement of images is done using singular value decomposition (SVD) on low frequency sub-band of both input and histogram equalised images.

The conventional and state-of-art techniques used for resolution enhancement of images are the following:

- Interpolation techniques: nearest neighbor, bilinear interpolation and bicubic interpolation
- Wavelet zero padding (WZP)
- WZP and cycle-spinning (WZP CS)
- SWT based super resolution (SWT SR)
- DWT based super resolution (DWT SR)
- Dual tree complex wavelet transform based super resolution (DT CWT SR)
- SWT DWT based super resolution (SWT DWT SR)
- SWT DWT with SVD

II. INTERPOLATION BASED TECHNIQUES

In numerical analysis, interpolation is a method of constructing new data points within the range of a discrete set of known data points. It is the process of estimating the value of a function for a non-given point in space when given the value of that function in points around that point.

A. Nearest Neighbor

Nearest-neighbor interpolation (also known as proximal interpolation) is a simple method of multivariate interpolation in one or more dimensions. It selects the value of the nearest point and does not consider the values of neighboring points at all; yielding a piecewise-constant interpolant. The Nearest neighbor interpolation is the fastest and simplest option. It simply takes the color of a pixel and assigns it to the new pixels that are created from that pixel. This simple approach leads to jaggy effect. So nearest neighbor interpolation is considered to be incapable of producing best quality images. Nearest neighbor does not have subpixel accuracy and generates strong discontinuities, especially when arbitrary rotations and scale changes are involved. The interesting property of this method is that it preserves the original noise distribution in the transformed image, which is useful in some image analysis applications. This is used in-camera when reviewing and enlarging images to view details. It simply makes the pixels bigger, and the color of a new pixel is the same as the nearest original pixel.

B. Bilinear Interpolation

Bilinear interpolation utilizes the information from four nearest pixels which are located in diagonal directions from a given pixel in order to find the appropriate color intensity values of that pixel. Bilinear uses simple, linear calculations. It considers the closest 2x2 neighborhood of known pixel values surrounding the unknown pixel's computed location. Then a weighted average of these 4 pixels is taken to arrive at the final interpolated value. The weight on each of the 4 pixel values is based on the computed pixel's distance (in 2D space) from each of the known points. The bilinear interpolation is not considered good enough to obtain best quality images. It produces fairly smooth results, but the images can become blurry.

C. Bicubic Interpolation

Bicubic interpolation uses the information from an original pixel and sixteen of the surrounding pixels to determine the color of the new pixels that are created from the original pixel. Bicubic interpolation is an improvement over the nearest neighbour interpolation and bilinear interpolation methods for two reasons: (1) Bicubic interpolation uses data from a larger number of pixels and (2) it uses a bicubic calculation that is more sophisticated than the calculations of the previous interpolation methods. The interpolated surface is much smoother than corresponding surfaces obtained by bilinear or nearest neighbor interpolation. Bicubic interpolation is capable of producing better quality results and is one of the most commonly used methods.

III. WAVELET BASED TECHNIQUES FOR RESOLUTION ENHANCEMENT

A. Wavelet zero padding (WZP)

Wavelet zero padding is one of the simplest method for resolution enhancement which is shown in Fig. 1. Here the wavelet transform of a LR image is taken first, after which zero matrices are embedded into the transformed image by neglecting the high frequency sub bands through the inverse wavelet transform and thus the high resolution image is obtained.

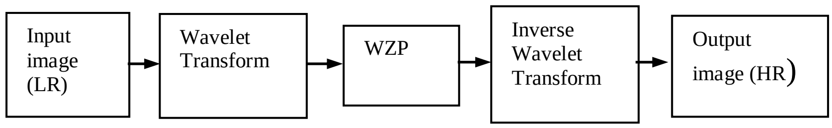

Fig. 1 WZP SR method

B. WZP Cycle Spinning (CS)

As stated in [7], this approach constructs a HR image by adopting the following steps which is illustrated in Fig. 2.

a. First an intermediate HR image is obtained through WZP method.
b. After that N numbers of images are obtained through spatial shifting, wavelet transforming and discarding the high frequency component.
c. Then WZP process is applied to all LR images to obtain a number of HR images.
d. These HR images are realigned and averaged to obtain a final HR image.

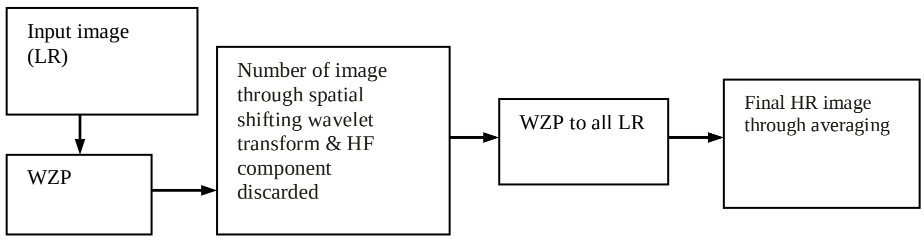

Fig. 2 Cycle spinning

C. Stationary Wavelet Transform(SWT)

SWT is a wavelet transform technique which does not use decimation after the decomposition of images into different frequency sub bands. First WZP is applied to obtain an estimate of HR image. Then SWT is implemented on the estimated HR image. So the image is decomposed into two bands called estimated details and approximation coefficients. The approximation coefficients are replaced by initially estimated HR image and inverse SWT is taken to obtain the final HR image which is shown in Fig. 3

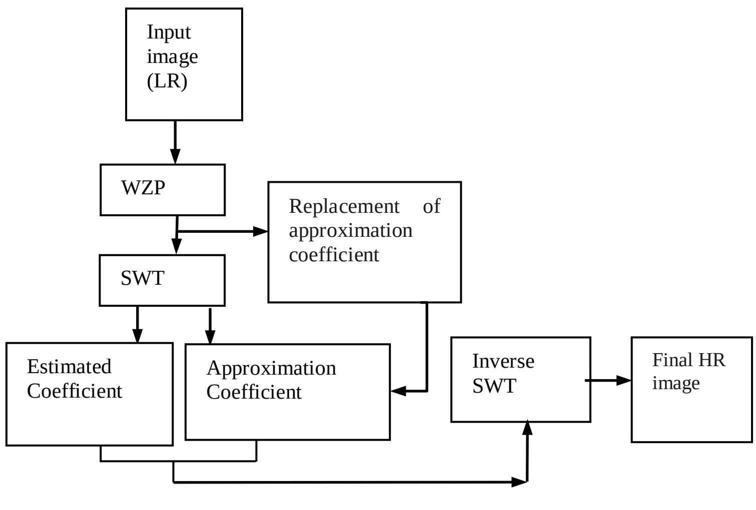

Fig.3 SWT based SR

D. Discrete Wavelet Transform

Discrete wavelet transform based technique [8] is one of the widely used techniques for performing image interpolation. DWT is used to decompose a low resolution input image into 4 subband images namely, LL, LH, HL and HH. LH, HL, and HH subband images contain the high-frequency components of the input image. The high-frequency components of image are then interpolated by bicubic interpolation. The LL subband image is the low-resolution of the original image. So instead of using LL, the input image is used for interpolation as it contains more information than the LL sub band. The input image is interpolated with half of the interpolation factor, α, used to interpolate the high frequency subbands as shown in Fig.4.So it increases the quality of the super-resolved image. The final HR image is generated by using the IDWT of the interpolated subband images and the input image. By interpolating the input image 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 input image directly.

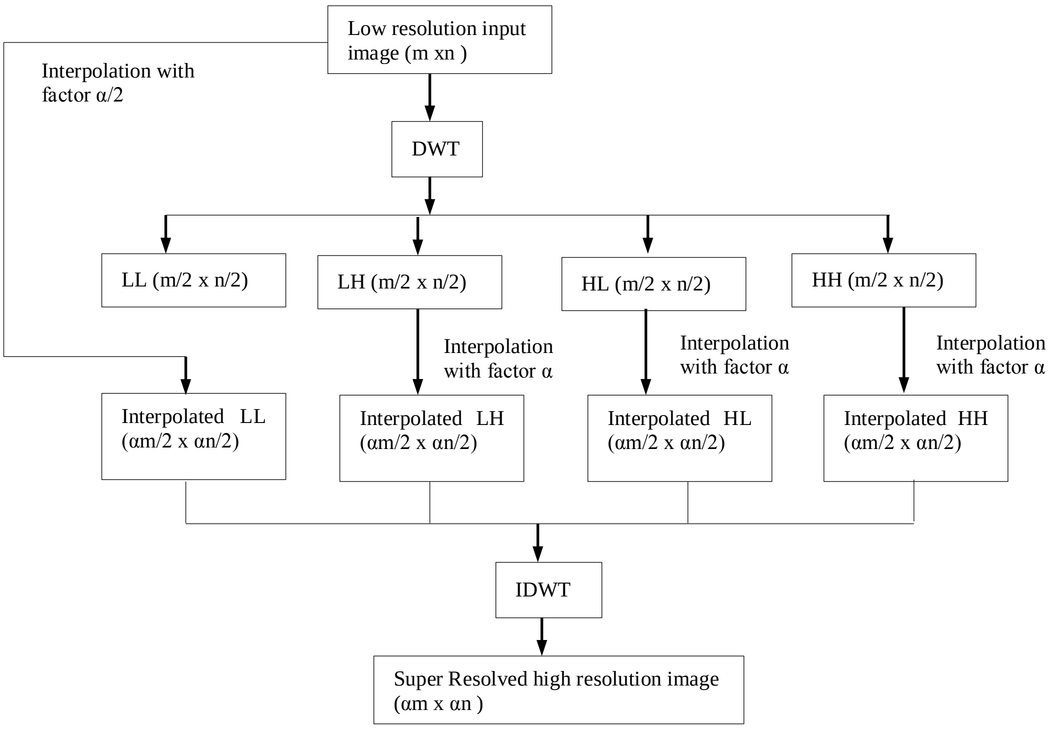

Fig.4. DWT based SR

E. Dual tree complex wavelet transform(DT CWT)

The DT-CWT has good directional selectivity and has the advantage over discrete wavelet transform (DWT). It also has limited redundancy [9]. The DT-CWT is approximately shift invariant, unlike the critically Sampled DWT. The redundancy and shift invariance of the DT-CWT mean that DT-CWT coefficients are inherently interpolable [10]. DT-CWT is used to decompose an input image into different subband images. Six complex-valued high-frequency subband images contain the high-frequency components of the input image. Then, the high-frequency subband images and the input image are interpolated, followed by combining all these images to generate a new high-resolution image by using inverse DT-CWT. The resolution enhancement is achieved by using directional selectivity provided by the CWT, where the high-frequency subbands in six different directions contribute to the sharpness of the high-frequency details, such as edges. Fig. 5 shows details of this technique, where the enlargement factor through the resolution enhancement is α.

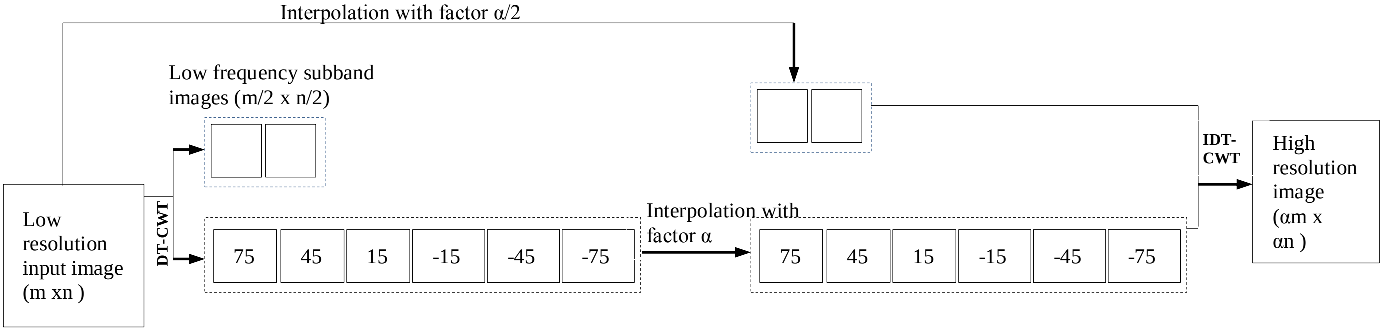

Fig.5. Dual tree CWT based SR

F. *SWT DWT SR*

The main loss in image resolution enhancement by using interpolation is on its edges which are the high frequency components, which is due to the smoothing caused by interpolation. Edges plays very important role in image. To increase the quality of the super resolved image, it is essential to preserve all the edges in image. In [11] work, DWT has been employed in order to preserve the edges. The redundancy and shift invariance of the DWT mean that DWT coefficients are inherently interpolable. One level DWT is used to decompose an input image into different subband images. As stated earlier, three high frequency subbands (LH, HL, and HH) contain the edges. In this technique, bicubic interpolation with enlargement factor of 2 is applied to high frequency subband images. Information loss occurs due to down sampling in each of the DWT subbands caused in the respective subbands. So SWT is used to minimize this loss.

The SWT is an inherently redundant scheme as the output of each level of SWT contains the same number of samples as the input, so for a decomposition of N levels there is a redundancy of N in the wavelet coefficients. The interpolated high frequency subbands and the SWT high frequency subbands have the same size so they can be added with each other. The new corrected high frequency subbands can be interpolated further for higher enlargement. Low pass filtering of the high resolution image produce the low resolution image. Hence, low frequency subband is the low resolution of the original image. Therefore, instead of using low frequency subband, which contains less information than the original high resolution image, Hasan Demirel and Gholamreza Anbarjafari [11] used the input image for the interpolation of low frequency subband image. The quality of the super resolved image increases using input image instead of low frequency subband. Fig. 6 illustrates the block diagram of the used image resolution enhancement technique.

By interpolating input image by α/2, and high frequency subbands by 2 and α in the intermediate and final interpolation stages respectively, and then by applying IDWT, the output image contains sharper edges than the interpolated image obtained by interpolation of the input image directly.

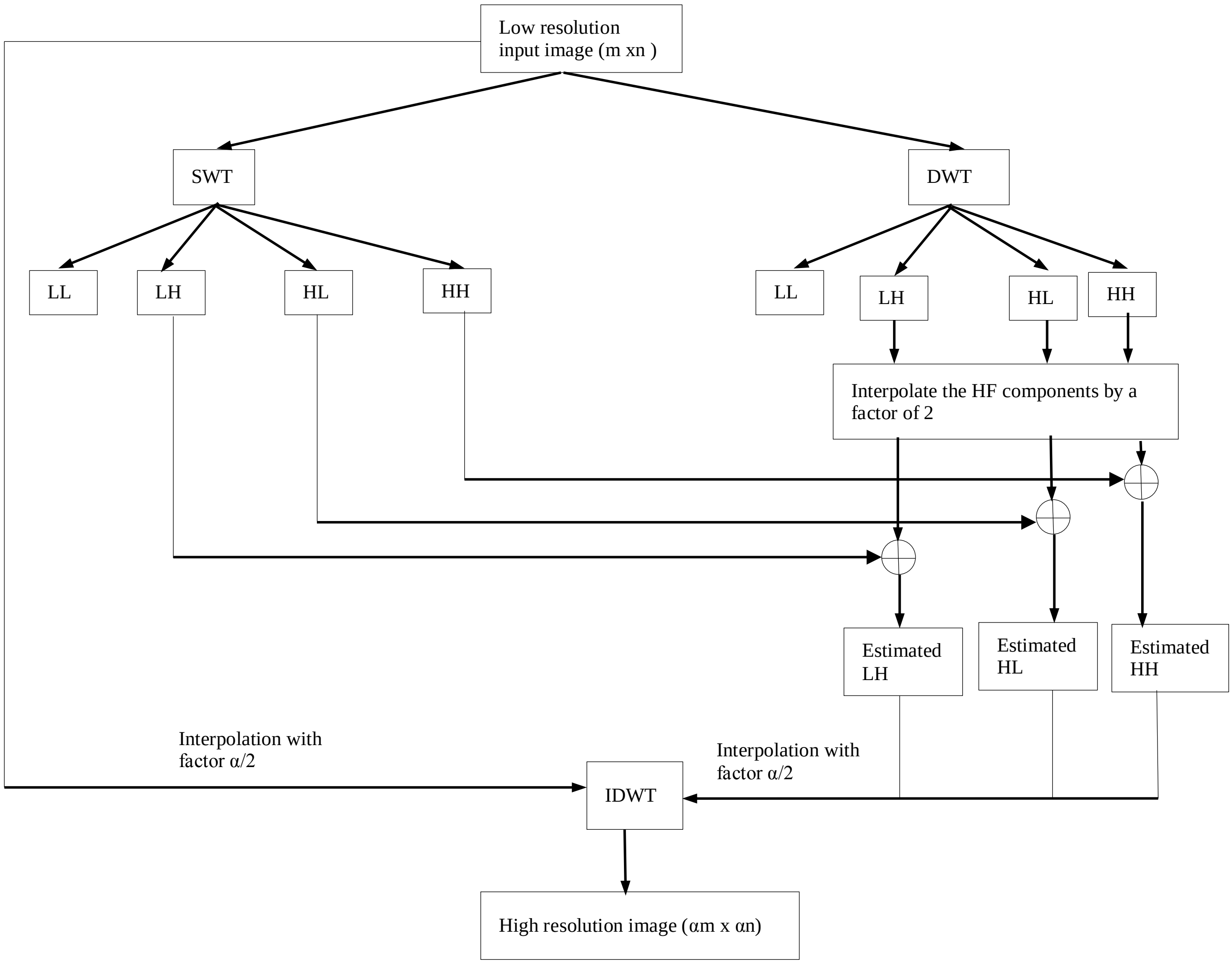

Fig.6 SWT DWT SR

G. *SWT DWT SR with SVD*

The result obtained from the SWT DWT SR is subject to singular value decomposition for brightness and contrast enhancement. The block diagram of this method is shown in Fig. 7.

Singular value decomposition (SVD) [11] of an image, which can be interpreted as a matrix, which is written as follows

$$I = U_I \Sigma_I V_I^T \qquad (1)$$

where U_I and V_I are orthogonal square matrices known as hanger and aligner, respectively, and the Σ_I matrix contains the intensity information of the given image.

Therefore changing the singular value will directly affect the illumination of the image. The LL sub band image contains all illumination information. So manipulating the LL sub band gives the enhancement in contrast. In parallel, the high resolution image is processed using general histogram equalization (GHE) to generate an image Î. The histogram equalized image is further decomposed into four sub band images $LL_{\hat{I}}$, $LH_{\hat{I}}$, $HL_{\hat{I}}$ and $HH_{\hat{I}}$ using DWT. Then, singular value decomposition is applied on both of the images LL_I and $LL_{\hat{I}}$ to get two matrices, $LL_I = U_{LLI}\, \Sigma_{LLI} V_{LLI}^T$ and $LL_{\hat{I}} = U_{LL\hat{I}}\, \Sigma_{LL\hat{I}} V_{LL\hat{I}}^T$.

The correction coefficient matrix of the singular value matrix is calculated by using the equation,

$$£ = \frac{\max(\Sigma LLI)}{\max(\Sigma LL\hat{I})} \qquad (2)$$

where Σ_{LLI} is the LL singular value matrix of the input image and $\Sigma_{LL\hat{I}}$ is the LL singular value matrix of the output of GHE. A new LL image, Σ'_{LL}, has been constructed by,

$$\Sigma'_{LLI} = £\ \Sigma_{LLI} \qquad (3)$$

where Σ'_{LLI} is referred as the singular value matrix of the equalized image. Using Σ'_{LLI} a new equalized LL sub image matrix is formed. The new equalized LL sub image LL'_I is given by the equation,

$$LL'_I = U_{LLI}\, \Sigma'_{LLI} V^T_{LLI} \qquad (4)$$

Now the equalized image is reconstructed by applying inverse wavelet transform on the sub bands (LL'_I, LH_I, HL_I, HH_I).

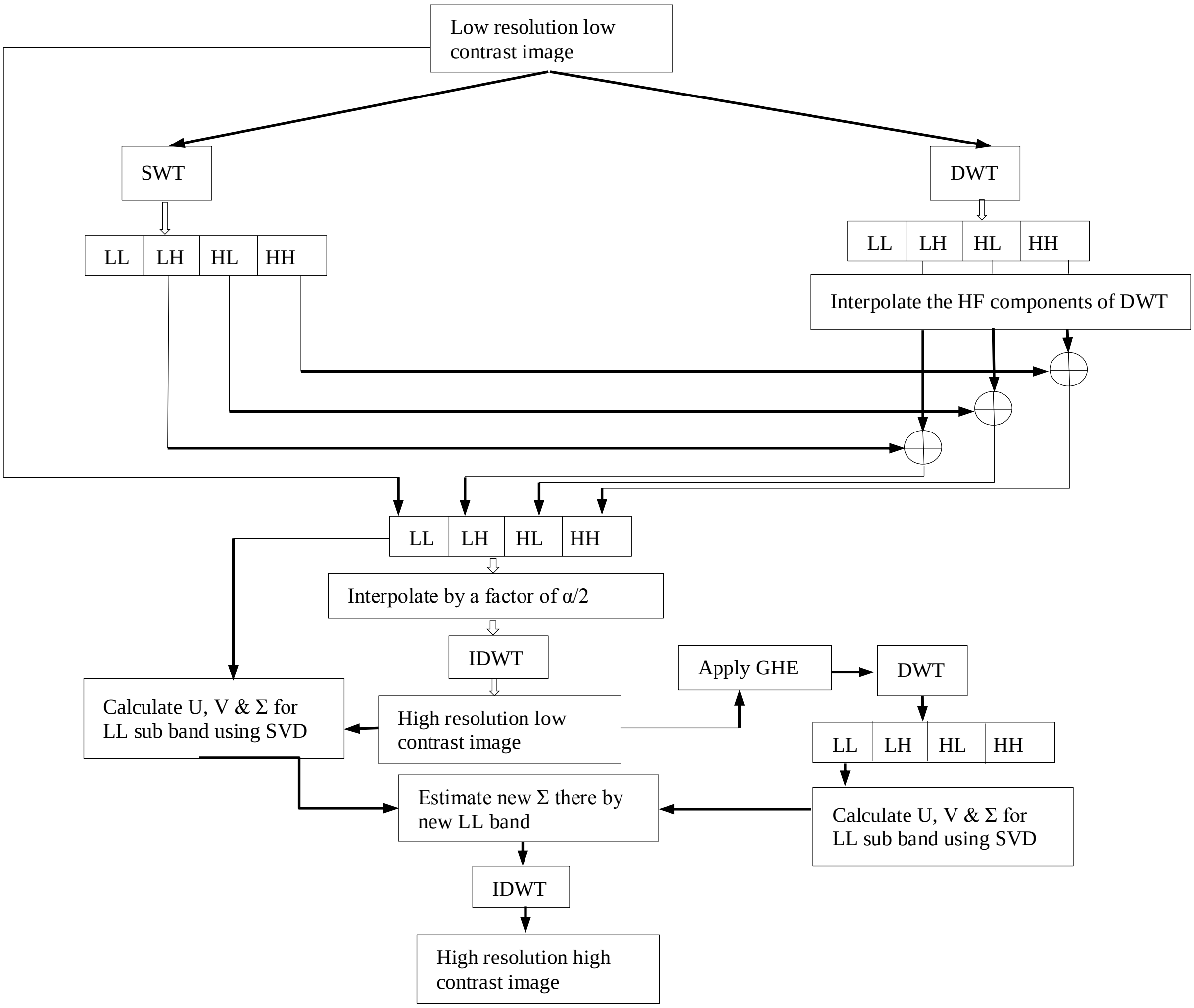

Fig.7 Resolution Enhancement using SWT DWT and SVD

The algorithm can be described by the following steps:

a. A low resolution input image is decomposed at one level into four sub bands (LL, LH, HL & HH) with both DWT and SWT respectively.
b. The resultant higher sub band images of DWT are interpolated by a factor of two.
c. The interpolated high frequency subbands of DWT and the SWT high frequency subbands are added to produce the new estimated LH, HL, and HH.
d. The new corrected high frequency subbands and the low resolution input image can be interpolated further for higher enlargement. The resultant four bands are combined using inverse DWT to recover the high resolution image.
e. The high resolution image is passed through a combination of DWT and SVD algorithm. First DWT is applied on the input image and its contrast is enhanced using GHE.
f. Take DWT of the histogram equalised image.

g. Calculate the hanger (U), aligner (V) and singular value matrix (SVM) for the LL sub-bands obtained above.
h. Find the maximum element in both the SVMs and take their ratio (£).
i. Calculate the new SVM and estimate the new LL sub-band. The estimated LL sub- band and the HF components of actual input image are used to re-produce the contrast enhanced image.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, we present the efficiency of the various methods to recover the super-resolved image from a number of test images. The simulation experiments were carried out using Matlab on Windows 7 OS with 2 GB RAM and 2.30 GHz Intel processor. The methods are evaluated using peak signal to noise ratio (PSNR).

PSNR is the quality measurement between the original image and the reconstructed image which is calculated through the Mean Square Error (MSE). The MSE represents the cumulative squared error between the reconstructed and the original image.

$$\text{PSNR} = 10.\log_{10}\frac{MAX_I^2}{MSE} \tag{6}$$

where MAX_I is the maximum possible pixel value of the image. The higher the PSNR value, the better will be the reconstruction of the image.

$$\text{MSE} = \frac{1}{mn}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j)-K(i,j)]^2 \tag{7}$$

where i and j are the rows and columns of the image.

The image resolution enhancement techniques namely, nearest neighbor, bilinear, bicubic, WZP, WZP CS, DWT SR, SWT SR, DT CWT SR, DWT SWT SR, SWT DWT SVD SR are compared. Table I compares the PSNR performance of the various techniques. The results in Table I indicate that combination of SWT, DWT and SVD outperforms other image resolution enhancement techniques. Fig. 8 shows that super resolved Lena image using SWT DWT & SVD in (h) is much better than the super resolved image by using bicubic interpolation (c), WZP CS (e) and DWT SWT SR (g). So among all techniques, SWT DWT with SVD provides higher PSNR values and better visual quality.

TABLE I

PSNR (dB) FOR RESOLUTION ENHANCEMENT FROM 128X128 TO 512X512

Technique	Image	
	Lena	***Pepper***
Nearest Neighbor	23.81	24.02
Bilinear	24.26	24.98
Bicubic	26.86	27.01
WZP	28.87	29.43
WZP CS	29.07	29.94
SWT	31.21	32.02
DT CWT	32.76	33.92
DWT	33.16	34.09
DWT SWT	34.73	35.26
SWT DWT SVD	35.17	36.84

(a) (b) (c) (d)

(e) (f) (g) (h)

Fig.8. Comparison of super resolution results for Lena image (with magnification factor 4) using various SR methods: (a) Nearest neighbor (PSNR:23.81) (b) Bilinear (PSNR:24.26) (c) Bicubic (PSNR: 26.86) (d)WZP(PSNR:28.87) (e) WZP CS (PSNR: 29.07) (f) DWT SR (PSNR: 33.16) (g) DWT SWT SR (PSNR: 34.73) (h) SWT DWT SVD (PSNR: 35.17)

V. CONCLUSION

In this paper, we have made a survey on various techniques used for obtaining a super resolved image from a low resolution image. Image resolution enhancement using SWT DWT and SVD is giving better result than other techniques. From the PSNR values and visual quality comparison it is observed that using SVD along with SWT & DWT for image super resolution is superior and scope full.

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