Image Resolution Enhancement based on Curvelet Transform

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Abstract: We present an image resolution enhancement method based on Curvelet transform. This transform is used to decompose the input image into different subbands. After this decomposition, a nonlinear function is applied to the Curvelet coefficients in order to enhance the content of the different frequency subbands. These enhanced frequency subbands are then interpolated. We increase the enhancement results by a fusion of the obtained data and the interpolated input image. An image database is used for experiments. The visual results are showing the superiority of the proposed technique compared to two state-of-art image resolution enhancement techniques. These results have been confirmed by quantitative image quality metrics.

1 INTRODUCTION

Image resolution enhancement is an active field of research. The main goal of this research is to remedy the problems related to the image acquisition device (Suganya et al., 2013), to the limited size of digital image sensor or to the poor conditions of image acquisition. Furthermore, the increasing ever more important of screen sizes makes this problematic more current.

The resolution is an important aspect of image. Many techniques are proposed in order to enhance the image resolution and are specifically dedicated to super resolution. These techniques affect many fields and different kinds of images. This is the case of satellite images where the resolution enhancement permits to extract more information of these images (Suganya et al., 2013), (Abirami et al., 2013), (Harikrishna et al., 2012). The same applies to medical images where the goal is to facilitate the radiologist diagnosis and interpretation (Muna et al., 2011), (Hanan et al., 2011).

One of the most classical methods of image resolution enhancement is the image interpolation. This commonly technique permits to increase the number of pixels in an image using known data values to estimate unknown data values. Therefore, it has been widely used in various imaging applications such as facial reconstruction (Muna et al., 2011), description coding (Hanan et al., 2011), and image resolution enhancement (Carey et al., 1999), (Demiral et al., 2010), (Xie et al., 2003).

The principal image interpolation techniques are nearest neighbor interpolation, bilinear interpolation, and bi-cubic interpolation. However, these well-known techniques present some visual drawbacks which are mainly due to the loss on the high image frequency components corresponding to the edges. In fact, we observe a smoothing in the interpolated image. The principal goal of the actual researches is to ameliorate the image quality of super resolution by preserving the edge information. In this purpose, different works involving frequency domain instead of spatial domain have been proposed. Consequently, the image is first converted to frequency domain, treated and then converted back to spatial domain. Fourier domain which is the basic frequency domain is more appropriate for spectral filtering by removing particular image frequencies. Wavelet domain which is a time frequency domain separates the image components into separated images representing both spatial and frequency information.

The wavelet transform has been used successfully in image resolution enhancement and various approaches resulting therefrom (Birare et al., 2010). Many approaches such as that of G. Anbarjafari and H. Demirel use a combination of the Discrete Wavelet Transform (DWT) and interpolation. These techniques reduce some

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drawbacks. However, it introduces an aliasing caused by the used interpolation in high frequency wavelet sub-bands (Bagawade et al., 2012), (Venkata et al., 2014). Other approaches combine DWT and Stationary Wavelet Transform (SWT) in order to preserve more the edges of image (Hasan et al., 2011), (Battula et al., 2012). Note however that the wavelet transform and other classical multi-resolutions decompositions like Laplace pyramid, form actually a restricted and limited category of multidimensional signal representation. Indeed, other more recent works have shown that it is possible to define larger multiscale representations establishing new transforms more suitable for the representation of geometric structures and edges (Tripathi et al., 2014). These multiscale decompositions operate according to many frequency directions. The proposed super resolution approach is based precisely on a transform of this new transform generation, the Curvelet transform. This transform, in addition to its multiscale character uses much directional information, which allows for upon decomposition, images containing more details. All these features make this transform the one that best represents the curves and contours in an image. Given the importance of edges and detail information in image resolution enhancement, we opt for the use of this transform for the super resolution problematic.

This paper is organized as follows; in section 2 Curvelet transform is briefly introduced. Section 3 is dedicated to the image resolution enhancement approaches. The proposed Curvelet based image resolution enhancement is introduced in section 4. Section 5 shows experimental results with comparison and analysis. Finally, section 6 is devoted to conclusion and perspectives.

2 CURVELET TRANSFORM

Wavelet transform is adapted to the discontinuities description of mono dimensional signals, but this property is not true if the dimension increase. In image processing, wavelets are used in separable manner on the horizontal and vertical axes, which generates a partial decorrelation of the image giving many high energy coefficients along contours or edges. To overcome this problem, several works was continued in order to find which transform can filter directly along the image contours. Thus many transform have been proposed (Tripathi et al., 2014). There are two major types of approaches, adaptive and non-adaptive approaches. The first is based on fixed and directional banks of filter which permit image analysis at fixed positions, scales and orientations. The second is based on an adaptive approach from a geometric model providing local analysis direction.

The Curvelet transform belong to the non-adaptive approaches. This transform is derived from Ridgelet transform.

Ridgelet coefficients (Land et al., 1986) are obtained by applying 1D wavelet transform to all image projections corresponding to Radon transform. In Summary, Ridgelet transform is a 1D wavelet analysis on slices of Radon transform where the angle q is fixed. Continuous Ridgelets are defined by the following formula.

$$Rf(a,\theta,b) = \iint f(x_1,x_2)\Psi_{a,\theta,b}(x_1,x_2)\,dx_1dx_2 \quad (1)$$

When

$$\Psi_{a,\theta,b} = a^{-1/2}\Psi\left(\left(x_1 * \cos(\theta) + x_2 * \sin(\theta) - b\right)/a\right)$$

is 1D wavelet constructed along a line oriented and defined by the fallowing equation :

$$x_1 * \cos(\theta) + x_2 * \sin(\theta) = b \quad (2)$$

Their link with Radon transform is represented by the following equation:

$$Rf(a,\theta,b) = \int Rf(r,\theta)\, a^{-1/2}\Psi\left((t-b)/a\right) dt \quad (3)$$

When Rf is the Radon transform defined by :

$$Rf(t,\theta) = \int f(x_1,x_2)\ \delta(x_1\sin\theta + x_2\cos\theta - t)\ dx_1dx_2 \quad (4)$$

Ridgelet transform has been established to analyze the objects that have discontinuities in straight lines. The basic idea of Curvelet transform is that a curve (contour) can be represented by several segments of straight line. So, an image may contain locally rectilinear contours. Ridgelet Analysis being a multiscale analysis in each radial direction, the Curvelet principle is to develop a multiscale analysis using normalized and transported Ridgelets with various scales.

We define a Curvelet as a function :

$$x = f(x_1,x_2) \quad (5)$$

of scale 2^{-j}, and orientation θ_l, and position:

$$x_k^{(j,l)} = R_{\theta,l}^{-1}\left(k_1 2^{-j}, k_2 2^{-j/2}\right) \quad (6)$$

with R_θ the rotation by θ and R_θ^{-1}its transpose, by:

$$\varphi_{j,l,k}(x) = \varphi_j\left(R_{\theta_l}\left(x - x_k^{(j,l)}\right)\right) \quad (7)$$

Cuvelet transform coefficients are defined by Candes & Dohono:

$$c(j,l,k)=\langle f,\varphi_{i,l,k}\rangle=\int_{\mathbb{R}^2} f(x)\,\varphi_{i,l,k}(x)\,dx \qquad (8)$$

The various steps of the first implementation of Curvelet transform are:

1) Decomposition into different J sub-bands
2) Partitioning
3) Ridgelet analysis (Radon transform + 1D wavelet transform).

So, the block size B can change from a subband k to another according to the following algorithm:

Initialize the block size *B1 = Bmin*.

For *j=1 ,…J,* for each high frequency image: Partition subbands Wj into blocks Bj. Apply locally the Ridgelet transform on each block:

- If *j mod 2 = 1 , Bj+1 = 2Bj* ,
- Otherwise*, Bj+1 = Bj*

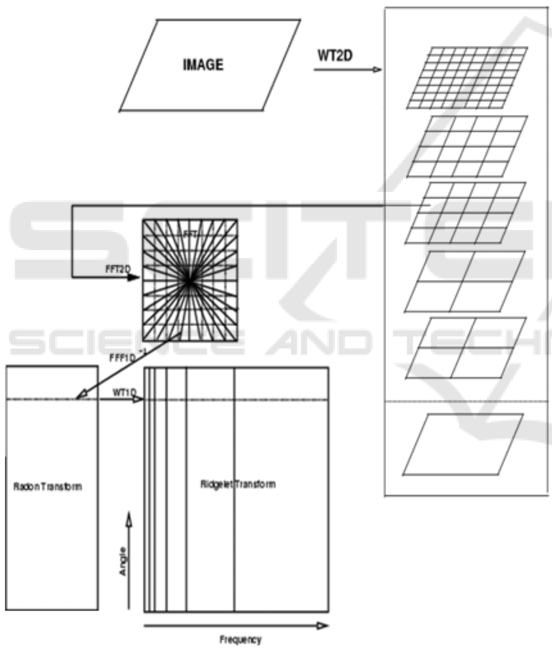

Figure 1: Curvelet transform.

The implementation of the second generation Curvelet transform consists of three steps:

Apply 2D FFT to obtain the Fourier samples $\hat{f}[i_1, i_2]$

For each scale *j* and angle *l*, compute the windowed frequency component and wrap it around the origin $\hat{f}[i_1,i_2]\hat{u}_{j,l}[i_1,i_2]$;

- Compute the inverse 2D FFT in order to obtain discrete Curvelet transform coefficients.

The windowing function $\hat{u}_{j,l}[i_1,i_2]$ gives rise to the frequency tiling as shown in Figure 2.

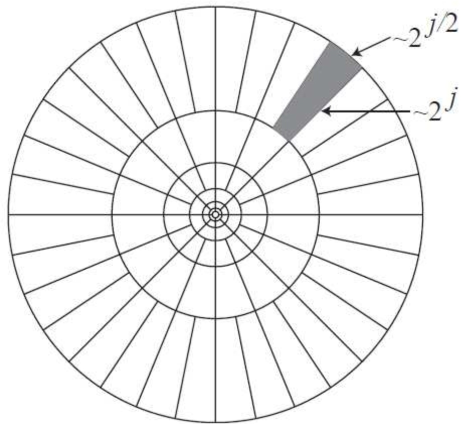

Figure 2: Curvelet transform partitionning.

3 IMAGE ENHANCEMENT APPROACHES

We take a care to apply this function just on the high frequency subbands and no on the low frequency subband.

The image enhancement is a great area of research. In (Land et al., 1986), Land creates a model for human color constancy named the retinex concept. There are SSR (Single Scale Retinal) methods and MSR (Multiscale Retinex) methods which combine several SSR outputs in order to obtain a single output image which presents a good dynamic range compression and also color constancy and good tonal rendition. The Multiscale Retinex presents the multiresolution concept applying to the contrast enhancement. It accomplishes dynamic range compression and is used for different image processing domains. The corresponding approach is detailed in (Barnard et al., 1999). Otherwise, Velde in (Velde et al., 1999) Velde proposes to use the wavelet transform for enhancing the faintest edges and keeping untouched the strongest. This method consists of decomposing the image using the dyadic wavelet transform. The gradient *Gj,k* at each scale j and at each pixel location k is calculated from the wavelet coefficient relative to the horizontal and vertical wavelet bands.

Then the two wavelet coefficients at scale j and at pixel position k are multiplied by:

y (Gj,k)

where y is defined by

$$y(x) = (m/c)p \quad \text{if} \quad |x| < c$$
$$y(x) = (m/|x|)p \quad \text{if} \quad c \le |x| < m \qquad (9)$$
$$y(x) = 1 \quad \text{if} \quad |x| \ge m$$

p determines the degree of nonlinearity in the nonlinear rescaling of the luminance, and must be in [0, 1].

Coefficients larger than m are conserved. The c parameter corresponds to the noise level. Figure 3 shows the modified wavelet coefficients versus the original wavelet coefficients for a given set of parameters (*m =30, c = 3, and p = 0,5*). Finally, by applying the inverse wavelet transform from the modified wavelet coefficients, we obtain the enhanced image. This work represents one of the first to introduce the application of non-linear function in order to enhance the image quality by using a multiscale domain. Furthermore, other works use the same idea in order to enhance the image quality. For example, Stark et al in (Starck et al., 2003) proposes a gray and color contrast enhancement by using the cruvelet transform. Similarly, Cherifi et al in (Cherifi et al., 2010) works on a color contrast enhancement method based on steerable filters. The basic idea of the proposed approach is to use tools that have proven their efficiency for image enhancement (the use of nonlinear function) in order to use it for another purpose which is the image resolution enhancement.

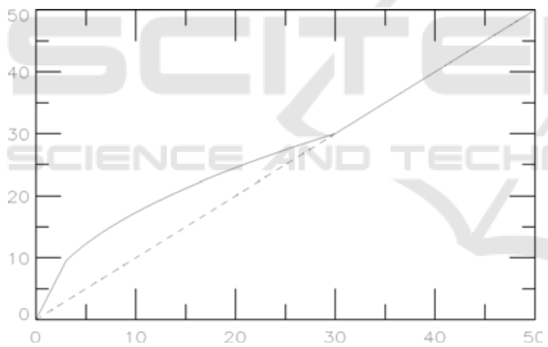

Figure 3: Enhanced coefficients versus original coefficients. Parameters are m =30, c = 3, and p = 0,5.

4 THE PROPOSED APPROACHE

One of the major problems in image resolution enhancement techniques concerns the edge quality in an image. In fact, the most of these techniques don't preserve the sharpness of edges. In order to increase the quality of the image of super resolution, using a tool that enhances the edges is essential.

Curvelet transform is a multiscale and multidirectional transform. As indicated by its name, it is the transform which best represents the curves and the contours in an image. The Curvelet decomposition generates different images, one image corresponding to low frequency band and set of images corresponding to high frequency bands with different orientations. Edges which correspond to high frequencies are represented with very rich information in Curvelet decomposition. For this reason, we choose to use this transform in the proposed image resolution enhancement method.

The proposed image resolution enhancement approach firstly consists in decomposing the image by Curvelet transform into different frequency subbands resulting to different scales and different orientations. Then, we enhance edges present in the different high frequency images of the Curvelet decomposition by using a nonlinear function defining by the following formula:

$$R(i,j) = \begin{cases} G\,x(i,j)\left(1 - \dfrac{|x(i,j)|}{M}\right)^{p} + x(i,j) & x \le M \\ x & otherwise \end{cases} \quad (10)$$

Where:
$x(i,j)$ is the input image;
M the upper limit of nonlinear enhancement;
G the gain factor;
p defining the rate of attenuation towards M.
Figure 4 represents the enhancement function.

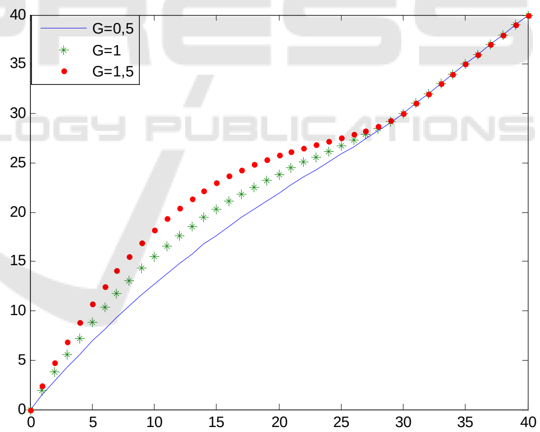

Figure 4: Enhancement function for *M=30*, *p=1,5* and different values of *G*.

We take a care to apply this function just on the high frequency subbands and no on the low frequency subband.

The translated information by Curvelet coefficients says how they are aligned in the real image. Indeed, more accurately a Curvelet is aligned with a given curve in an image; higher is its coefficient value. By applying the proposed function, we increase moderately the coefficients in order to enhance the edges. After enhance the edges images, the interpolation of image resulting of the Curvelet decomposition is done by applying bicubic interpolation of factor α. These steps are represented by the dotted group in figure 5. We can stop here and use the resulting image. However, we propose a second approach which consists to fusion the obtained image with the interpolated original image by taking the maximum value component (global scheme of figure 5).

The choice of bicubic interpolation method instead of bilinear interpolation or nearest neighbor is done because images resampled with this interpolation are smoother and have fewer interpolation artefacts, especially when speed is not an issue.

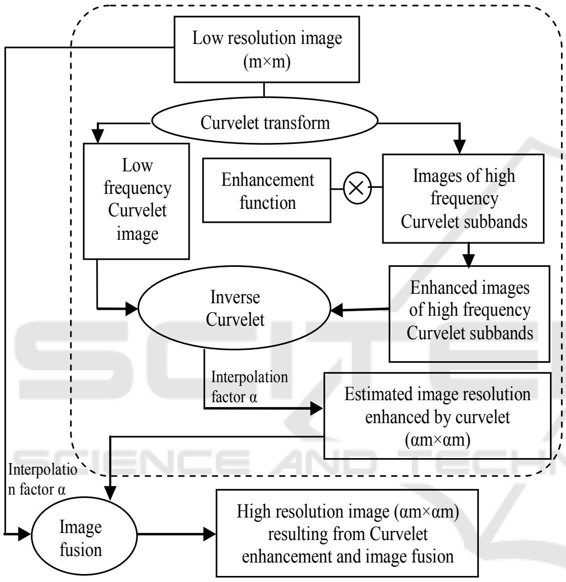

Figure 5: The proposed approach.

5 EXPERIMENTAL RESULTS

For experiment, we use a database of twelve images. These images are classical and well known in image processing validation process. All the images are gray scale and have 512*512 pixels. In order to estimate the image quality, we use two image quality measures: the classical PSNR and the structural similarity index SSIM. In order to compare the proposed approaches to other performant approaches, we recall succinctly the image resolution enhancement based on DWT and SWT transform.

5.1 Image Resolution Enhancement based on DWT and SWT

The input low resolution image is decomposed through the DWT and SWT into four subbands represented by LL (low-low), LH (low-high), HL (high-low) and HH (high-high) each.

We summarize in the diagram of figure 6 and that of figure 7, the principle steps of two approaches based on DWT and SWT transform (Tripathi et al., 2014).

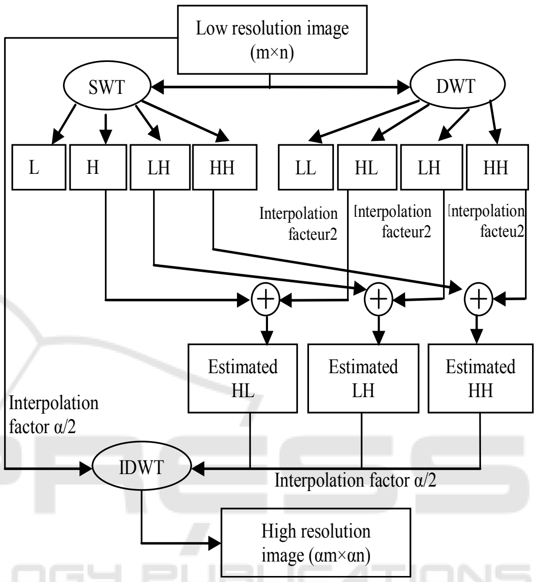

Figure 6: Image resolution enhancement based on DWT and SWT.

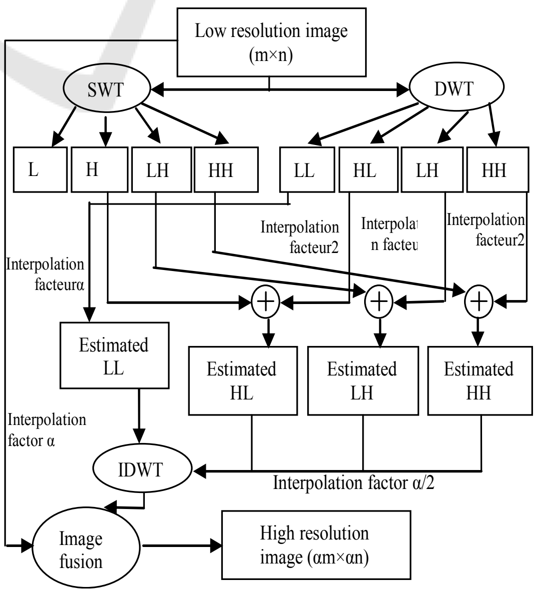

Figure 7: Image resolution enhancement based on DWT and SWT and image fusion.

5.2 Image Resolution Enhancement Results

Tab1 and tab2 present PSNR and SSIM results of the proposed image resolution enhancement compared to the two approaches presented above. (A) corresponds to DWT and SWT based approach. (B) corresponds to DWT, SWT and image fusion based approach. Our results correspond to (C) and (D). In (C), we have the proposed approach based on Curvelet enhancement and (D) the proposed approach based on Curvelet enhancement and image fusion.

Table 1: PSNR of resolution enhanced images (for α=4).

	I1	*I2*	*I3*	*I4*	*I5*	*I6*
A	14,89	15,87	12,68	13,69	15,63	17,49
B	16,59	18,01	13,68	16,21	17,61	21,33
C	**22,57**	**24,33**	**21,95**	22,37	24,88	22,68
D	20,85	21,69	21,59	**22,57**	**25,49**	**25,05**
	I7	*I8*	*I9*	*I10*	*I11*	*I12*
A	16,80	14,63	14,07	15,79	13,91	13,03
B	19,89	16,05	19,64	17,90	14,62	19,94
C	21,32	**23,81**	20,07	**21,80**	**20,56**	**23,68**
D	**22,22**	23,02	**23,80**	20,82	17,76	23,64

Table 2: SSIM of resolution enhanced images (for α=4).

	I1	*I2*	*I3*	*I4*	*I5*	*I6*
A	0,558	0,673	0,562	0,415	0,493	0,388
B	0,706	0,773	0,649	0,540	0,619	0,503
C	0,768	0,895	0,785	0,686	0,764	0,628
D	**0,826**	**0,903**	**0,794**	**0,704**	**0,780**	**0,647**
	I7	*I8*	*I9*	*I10*	*I11*	*I12*
A	0,295	0,444	0,318	0,275	0,424	0,409
B	0,399	0,572	0,483	0,379	0,529	0,757
C	0,551	0,703	0,571	0,519	0,641	0,806
D	**0,565**	**0,728**	**0,629**	**0,528**	**0,655**	**0,883**

Figure 8 presents two visual examples of the proposed approach compared to DWT and SWT based approaches.

Figure 8: Visually results of high image resolution obtained by DWT and SWT based approaches (left) and the proposed approach (right).

The obtained results demonstrate clearly the superiority of the proposed approaches compared to the others. However, we can notice that PSNR results are shared between (C) and (D), while the SSIM results (metric more sophisticated and more effective than classical PSNR) show clearly that the best approach is (D).

6 CONCLUSIONS

We propose an image resolution enhancement approach based on Curvelet transform. Since the main inconvenient of the majority of the literature approaches concern the edges quality, we propose to use a transform which is especially dedicated to the good representation of image edges. For this, we enhance the Curvelet coefficients of each subband by applying an enhancement function. The obtained results demonstrate also that by applying a fusion between the resulted image by Curvlet enhancement and the interpolated image, we observe better results. We compare these proposed approaches with two other approaches in the literature in term of quality by using PSNR and SSIM. The obtained results show that the proposed method is considerably better than the other techniques.

As perspective, we propose to test the proposed method on other types of images like satellite, medical images. Also, we propose to work on images containing text recognition. In fact, in this type of images, we must generally use the super resolution image in order to extend the text, this is necessary for a good text detection and recognition by OCR. Furthermore, the text in these images (like geographical images) is generally confused with the image contours and the use of the proposed approach could give good results. So, the proposed approach gives a solution to understand the image content in small images in order to achieve the desired objective.

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