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Research Paper

An Efficient Edge Preserving Interpolation Method for Underwater Acoustic Image Resolution Enhancement

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Underwater acoustic images are acquired using sonar instrument that uses sound propagation to navigate and map the sea floor. The sonar devices are effectively used to create images of large area of the seabed. However, the visual perception of the object in the acoustic image depends on refraction, which is a function of changes in the speed of sound in successive layers of water. And refraction depends mainly on temperature, slightly on salinity and hydrostatic pressure. The quality and resolution of sonar imaging of the bottom depends on many other factors such as pitch, yaw and heave of the side scan sonar, the presence of volume scatterers in the water body, the distance of the sonar from the bottom and orientation of the object. Generally, the objects in an acoustic image would be of small size compared to their normal size as the distance between the sonar and object is larger. To detect and recognize the objects in the images, the resolution should be enhanced. In this paper, we propose an efficient edge preserving interpolation method for underwater acoustic image resolution enhancement which preserves the edge sharpness. The method handles the diagonal pixels in the first pass, in turn fills the horizontal and vertical pixels in the second pass. The results obtained are compared with the state-of-the-art interpolation techniques and the performance measures such as Peak Signal to Noise Ratio (PSNR) and Structural Similarity Index Measurement (SSIM) shows an improved result.

Keywords: acoustic images; edge preserving interpolation; resolution enhancement; sonar; underwater.

1. Introduction

Sonar imaging system generates acoustic images and maps the sea floor during the movement of the ship. Among the sonar systems, a side scan sonar is one of the readily available devices which is used for applications such as object detection and classification of mines. The side scan sonar uses the sideway scanning principle which occurs along track and across track (GIACHETTI *et al.*, 2011). The information gathered along the track depends upon the tow fish speed and across the track depends on the attenuation of sound in water. Across the track, the intensities received depends upon the target such as rock or soft sediments. The acoustic images are displayed as grey scale images with dark and bright intensities. The images acquired by the side scan sonar are normally lower resolution images where the objects are very difficult to identify. Hence, the best way to detect the objects is by enhancing the Lower Resolution (LR) image to Higher Resolution (HR) image. The HR image can offer more details and a better view compared to its LR image. The process of converting the LR to HR image is referred as image interpolation or scaling. Interpolation is done by constructing approximating function which agrees perfectly with the unknown original function at the given measurement points (MEIJERING, 2002). The concept of interpolation is used in different applications in variety of ways. Image interpolation refers to filling in of missing pixel values using known data. The pixel-based interpolation techniques such as nearest neighbour, bilinear, bicubic and Lanczos (Zhou *et al.*, 2012) tend to improve the resolution of the image but the details such as edges and corners get affected. The nearest neighbour interpolation technique fills the missing pixels with the nearest intensity value, in turn bilinear and bicubic interpolation techniques use average of four neighbours and sixteen neighbours' intensity values respectively. The Lanczos interpolation utilizes thirty-six neighbourhood intensity values for estimating the new pixel value. The characteristics of acoustic images are extremely different from the digital images. They have the sea floor and sediments that form textures. The state-of-the-art interpolation methods introduce many artifacts while converting the lower resolution to higher resolution image. The important artifact identified is blurring of edges. The proposed method handles the pixels in two phases to preserve the edge features to improve the quality of the acoustic images during interpolation.

2. Related work

While enhancing the acoustic images in wavelet domain, the low frequency components are reduced to half of the size of the original image. The enhancement is done on the LL component and the high frequency components already downsampled will be again upsampled and added with the enhanced LL components. During the interpolation process, there may be loss in the data which may affect the visual quality of the image (Meijering, 2002; Lehmann *et al.*, 1999). In order to avoid that, an edge dominated interpolation is proposed where the edges are preserved while interpolation. There are few research works carried out with the same goal where the neighbourhood of each missing sample is partitioned into two oriented subsets in orthogonal directions (Zhang, Wu, 2006). The pixel is finally interpolated by combining the two directional estimates in the principle of Linear Minimum Mean Square Error (LMMSE). The pixels can also be differentiated into edges and homogenous pixels (Chen *et al.*, 2005). The homogenous areas in an image can be interpolated by bilinear methods and the edge pixels are interpolated using adaptive methods. The basic idea of New Edge Directed Interpolation (NEDI) (Li, Orchard, 2000) algorithm is to estimate the local covariance coefficients from LR image and then use these covariance estimates to adapt the interpolation at a higher resolution based on the geometric duality between the low-resolution covariance and the high-resolution covariance. The NEDI algorithm was improved by using different training window (Mai *et al.*, 2011) to mitigate the interpolation error propagation problem. The high computational cost of NEDI was resolved by an improved statistical optimized interpolation method that considers multiple training windows and modified training window structure. The modified edge-directed interpolation (Tam *et al.*, 2010) mitigates the covariance mismatch problem and eliminates the prediction error accumulation problem. Multiresolution based techniques have been used to enhance the quality of the acoustic images. The Discrete Wavelet Transform (DWT) along with Karhunen-Loeve Transform (KLT) (Priyadharsini *et al.*, 2015) was used to enhance the images and while reconstruction, all the frequency components are first up-sampled using the bicubic interpolation technique. During the enhancement of acoustic image using multiresolution based technique (Priyadharsini *et al.*, 2017b), Gaussian pyramid is constructed by downsampling, and Laplacian pyramid is obtained by upsampling the images in different resolution. The downsampling and upsampling of the images were done using the bicubic interpolation. In these methods, the edge features were not preserved. Thus, an edge preserving interpolation method is much needed for multiresolution based techniques.

In literature, different edge preserving methods were proposed and applied for generic images. An edge directed cubic convolution interpolation scheme (Zhou *et al.*, 2012) along with estimation method of the strong edge for a missing pixel location was proposed for preserving the sharp edges. Many spatially adaptive image enhancement techniques have been proposed which uses specific super resolution algorithm (Su *et al.*, 2012) for each block of an image. A non-local iterative back projection algorithm (Dong *et al.*, 2009) was proposed for image enlargement to solve the ringing artefacts caused by conventional iterative back projection algorithm. Many works for image super resolution have been carried out using sparse representation for Bistatic Inverse Synthetic Aperture Radar (Bi-ISAR) images (Bae *et al.*, 2016) and for generic images (Yang *et al.*, 2010).

3. Interpolation techniques

The objective of the interpolation techniques includes reconstruction of the Higher Resolution (HR) image from its Lower Resolution (LR) counterpart by preserving the edges and by reducing blur and checkerboard effects. Few state-of-the-art techniques used for interpolating the images in the spatial domain are explained below.

Nearest Neighbour Interpolation (NNI) is proximity-based interpolation technique which fills in the unknown pixels with the neighbourhood pixel values. The horizontal, vertical, and diagonal unknown pixels are filled with the nearest known pixel value. As all three unknown pixels are filled with the same pixel value, the upsampled image will have edge halo, blurring and distortion. Bilinear interpolation is a resampling method that uses the distance weighted average of the four nearest pixel values to estimate a new pixel value. The method gives better results when the surface is continuous, and the neighbouring points are related. The name "bilinear" indicates the linearity of the pixels in two directions (horizontal and vertical). Bicubic interpolation uses weighted average of sixteen neighbouring pixels of the original image. When compared to NN and bilinear interpolation, bicubic reconstructs the image in a better way but the time taken for upsampling the image is too high.

Kriging, also known as Wiener-Kolmogorov prediction is a regression method which uses Gaussian process with prior covariances for image interpolation. The quality of the Kriging's interpolated image depends upon the assumptions of the prior. A weighted average using Variogram is used to compute the unknown value at a pixel location using the Eq. (1):

$$\widehat{I}(x_0) = \sum_{i=1}^{N} \lambda_i I(x_i), \tag{1}$$

where the $\widehat{I}$ is the interpolated value of the pixel which is equal to the sum of the value of each sampled point (x_i) times that point's unique weight λ_i.

Another linear interpolation method using triangulation is also generally used for resizing the image. In triangulation method, the barycentric coordinates of the point are used to take a weighted average of the three observation values of the triangle. It has a drawback of smoothing the image which leads to loss of edges.

4. Proposed edge dominated interpolation

The edge dominated interpolation method categorizes the unknown pixel values into three types namely diagonal, horizontal, and vertical pixels. Figure 1 shows the proposed edge dominated interpolation method, in which the LR image $f(x, y)$ is smoothed using Wiener filtering to reduce speckle noise. The smoothed image is given as input to the two-pass edge preserving interpolation technique where the diagonal pixels are filled in the first pass and the horizontal and vertical pixels in the second pass. The upsampled output image $I'(x, y)$ is compared with the original image $I(x, y)$.

Figure 2 shows the overall process of the interpolation method where Fig. 2a represents the original image grid (4 × 4) with known pixels, and Fig. 2b represents the interpolated image grid (7 × 7) with unfilled unknown pixels. The unknown diagonal pixels are filled in the first pass. Figure 2c shows the interpolated image grid with filled diagonal pixels. In the second pass both horizontal and vertical pixels are filled. Figure 2d shows the edge preserved interpolated image grid with filled in diagonal, horizontal and vertical pixels.

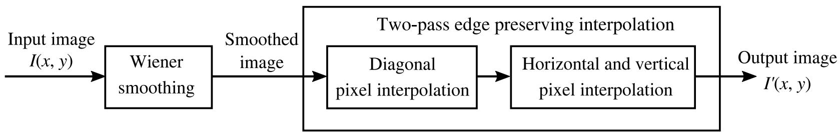

Fig. 1. Proposed system architecture – edge dominated interpolation.

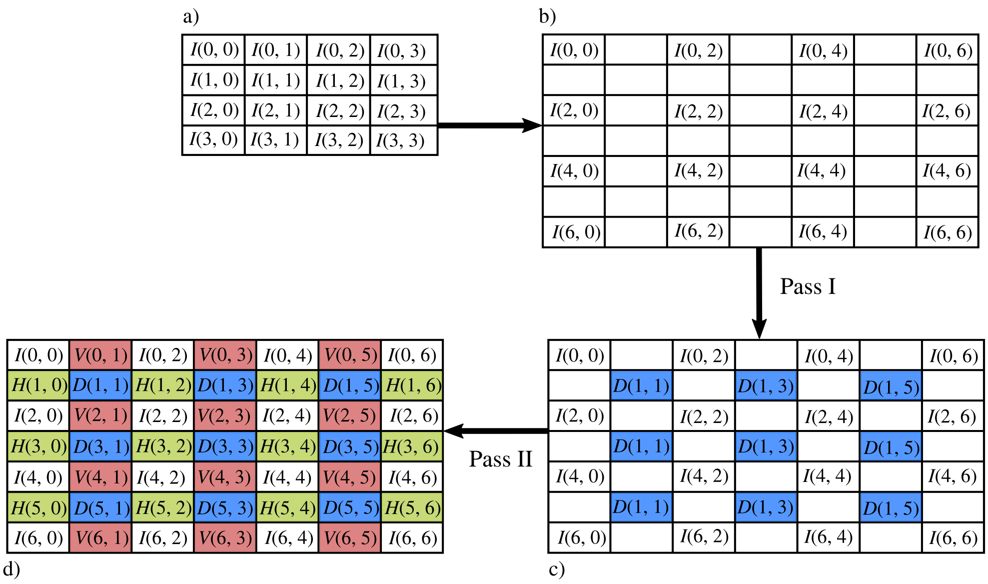

Fig. 2. Overall interpolation process: a) image with known pixels, b) interpolated image gird with unfilled unknown pixels, c) interpolated image gird with filled in diagonal pixels, d) interpolated image gird with filled in diagonal, horizontal, and vertical pixels.

4.1. Algorithm for two-pass edge preserving interpolation

The acoustic images normally consist of speckle noise. The speckle noise being multiplicative in nature is smoothed using Wiener filter. $I[m,n]$ is the lower resolution input image of size $m \times n$. An image grid $I'[i_m, i_n]$ is formed with size of $i_m \times i_n$, where $i_m = 2 \times m$, $i_n = 2 \times n$. The known pixels of the input image I are filled in the interpolated image I'. The gradient G_d along with diagonal directions is calculated in the first pass, and the gradient G_{hv} along with horizontal and vertical directions is calculated in the second pass. The edge weight of a pixel G is calculated by adding the gradients G_d and G_{hv}. The higher resolution image, $I'[i_m, i_n]$ is obtained by adding the gradient G with the interpolated image grid. The algorithm for the proposed two pass edge preserving interpolation is given in Algorithm 1 (Appendix).

4.2. Pass I to find the gradient along with diagonal directions

The function *pass I_diagonal_gradient* (I') (Appendix) calculates the gradient G_1 along with 45° diagonal pixels direction and gradient G_2 along with 135° diagonal pixels direction. The image neighbourhood 7×7 is taken and edges *e1*, *e2*, *e3*, *e4*, and *e5* are obtained by finding the first order gradient along the diagonal directions. In pass I, importance is given to the diagonal pixels as the edge orientation may be in that direction. The interpolated image grid is filled with diagonal pixels gradient after the first pass.

4.3. Pass II to find the gradient along horizontal and vertical directions

The function *pass II_hori_vert_gradient* (I') (Appendix) calculates the gradient G_h along with horizontal pixels direction and gradient G_v along with vertical pixels direction. The image neighborhood 5×5 is taken and the edges e_1, e_2, and e_3 are obtained by finding the first order gradient along with the horizontal and vertical directions. After pass II, the interpolated image grid will fill horizontal and vertical pixel gradients.

5. Experimental results and discussion

The proposed edge preserving interpolation method is compared with the existing image interpolation techniques. In Subsec. 5.1, the details about the dataset taken for the experiment are discussed. In Subsec. 5.2, experimental results are demonstrated, and Subsec. 5.3 discusses the performance measures in terms of Mean Squared Error (MSE), Peak Signal to Noise Ratio (PSNR) and Structural Similarity Index (SSIM).

5.1. Dataset

The acoustic images are obtained using the Edgetech 4125, ultra-high resolution, light weight side

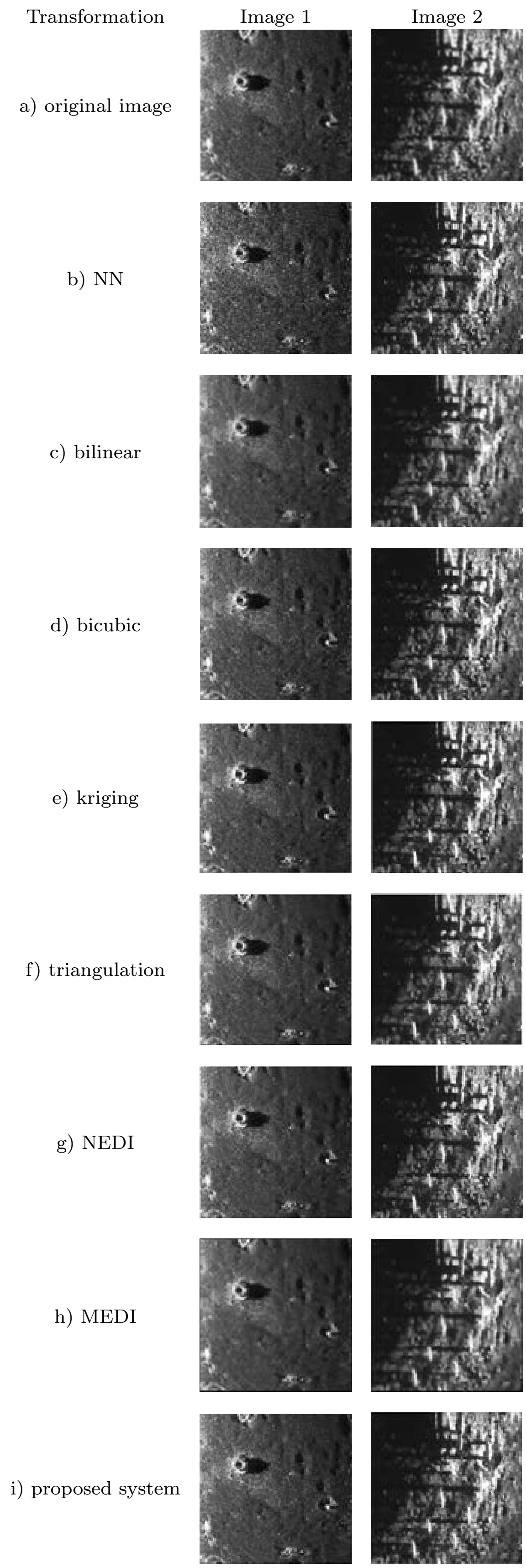

Fig. 3. Results of NN, bilinear, bicubic, kriging, triangulation, NEDI, MEDI, and proposed interpolation methods on acoustic images.

scan sonar. The 4125 series dual-frequency side scan sonar system is composed of a 4125-P portable topside processor, a 4125 tow vehicle (commonly called a Towfish), and a tow cable with 400–600 kHz in frequency. The side scan sonar was immersed in a depth of 20 m in Bay of Bengal. The scene of the sea floor was imaged using *discover* imaging software.

5.2. Experimental results

Figure 3a is the input lower resolution acoustic image of size 256×256 obtained from the side scan sonar. Figures 3b to 3i show the results of nearest neighbour (NN), bilinear, bicubic, kriging, triangulation, NEDI, MEDI and the proposed edge preserving interpolation method, respectively. The output images have a higher resolution of 512×512. The basic idea of interpolation is to convert the lower resolution image into higher resolution image to view the objects in a better way. The small objects may not be visible in the lower resolution images. The traditional methods used for interpolation fill in the missing value by considering only their neighbourhood value. From the results, it is observed that during upsampling, the image tends to blur. The objective of the proposed method is to preserve the edges during interpolation. The result of the proposed method shows that the edges are dominant in the higher resolution output.

5.3. Performance measures

5.3.1. PSNR

For quantitatively evaluating the image quality, a measure based on the Mean Squared Error (MSE) and the Peak Signal-to-Noise Ratio (PSNR) is used (Gonzalez, Woods, 2007). MSE is used to measure the amount of data loss through the pixel value comparison. As the PSNR is derived from MSE, it is used to measure the image quality. The Eq. (2) is used for calculating the PSNR:

$$\mathrm{PSNR} = 10 \log_{10} \frac{255^2}{\mathrm{MSE}}, \tag{2}$$

$$\mathrm{MSE} = \frac{\sum\limits_{M,N} \left[R(x,y) - F(x,y)\right]^2}{MN}, \tag{3}$$

where $R(x,y)$ and $F(x,y)$ are the reference image of size 512×512 and interpolated image of size 512×512, respectively. The reference images are created by resizing or zooming out the input image. On the other hand, the interpolated images are obtained using the methods such as the nearest neighbour, bilinear, bicubic and the proposed edge dominated interpolation algorithm.

5.3.2. SSIM

The Structural Similarity Index (SSIM) (Priyadharsini *et al.*, 2017a) is a measurement system to compare the similarity of two images, which is defined in Eq. (4):

$$\mathrm{SSIM}(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}, \tag{4}$$

where μ_x and μ_y are the average values of x and y, σ_x^2 and σ_y^2 are the variance of x and y, σ_{xy} is the covariance of x and y, and $c_1 = (k_1L)^2$, $c_2 = (k_2L)^2$ where c_1 and c_2 are variables used to avoid instability with weak denominators, L is dynamic range of pixel values, and $K_1 = 0.01$ and $K_2 = 0.03$ are constant value by default.

Tables 1 and 2 show the PSNR and SSIM values for the higher resolution image obtained from the near-

Table 1. PSNR [dB] for the higher resolution image obtained from various methods.

Acoustic image	NN	Bilinear	Bicubic	Kriging	Triangulation	NEDI	MEDI	Proposed method
Image 1	17.6136	19.82	20.5666	18.25	20.89	20.988	22.04	23.0408
Image 2	20.5029	22.7924	25.1127	19.23	21.51	21.692	28.25	26.7096
Image 3	23.461	25.5809	26.8301	25.634	23.457	25.352	28.45	29.0125
Image 4	20.2771	22.7031	25.715	20.121	21.01	22.24	27.23	27.2347
Image 5	21.7645	24.1869	27.0636	20.58	23.28	24.56	28.76	29.9932
Image 6	19.2297	20.9943	22.4412	21.898	19.34	21.98	23.47	24.7558

Table 2. SSIM for the higher resolution image obtained from various methods.

Acoustic image	NN	Bilinear	Bicubic	Kriging	Triangulation	NEDI	MEDI	Proposed method
Image 1	0.41373	0.38762	0.50867	0.4426	0.3324	0.7451	0.8263	0.84613
Image 2	0.75562	0.7841	0.87275	0.6564	0.6475	0.7283	0.889	0.92092
Image 3	0.55355	0.57382	0.67877	0.6410	0.5303	0.757	0.873	0.93024
Image 4	0.78177	0.81343	0.90744	0.7200	0.7472	0.893	0.8991	0.91442
Image 5	0.78751	0.81516	0.90349	0.7385	0.738	0.847	0.8455	0.92153
Image 6	0.62029	0.61509	0.73978	0.5102	0.628	0.835	0.8542	0.8649

est neighbour, bilinear, bicubic, kriging, triangulation, NEDI, MEDI, and the proposed interpolation method. The results show that compared to other interpolation methods, the proposed method has preserved the edges and also the quality of the interpolated image.

6. Conclusion

This paper proposes the edge preserving interpolation technique which reconstructs the higher resolution image from its lower resolution counterpart. The exploration of objects under the sea is a great work in the field of oceanography. The acoustic images acquired from the side scan sonar are visually low-quality images affected by speckle noise where the living and non-living resources that are not seen clearly. The objects in the seafloor can be easily seen when the images are upsampled. The state-of-the-art methods create many artefacts including blur effect when applied on the images. The proposed method handles the interpolation process in two passes. The gradient along with the diagonal directions are obtained in the first pass, and the gradient along with the horizontal and vertical directions are calculated in the second pass. The interpolated image is reconstructed by adding the interpolated grid with gradient values. The proposed work and the performance measures were implemented using Matlab. The results proves that the proposed work performs well both in terms of subjective and objective quality. The interpolation can be further used for detecting the objects in the acoustic images.

Appendix

Algorithm 1.

1. Smooth the input image $I[m,n]$ using Wiener filter.
2. Read the size of the smoothed image:

$$[m,\, n] = \mathrm{size}[I];$$

$$i_m = 2 * m;$$

$$i_n = 2 * n,$$

where m, n are numbers of rows and columns in the input images, and i_m, i_n are numbers of rows and columns in the interpolated image.

3. Initialize the output image I' with zeros:

$$I' = \mathrm{zeros}(i_m,\, i_n).$$

4. Assign the input image $I[m,n]$ to $I'[i_m,i_n]$:

$$I'(1:2:m-1,\, 1:2:m-1) = I.$$

5. // Call pass I of the proposed interpolation method to find the gradient along with diagonal directions:

$$G_d = \text{pass I\_diagonal\_gradient } (I').$$

6. // Call pass II of the proposed interpolation method to find the gradient along with horizontal and vertical directions:

$$G_{hv} = \text{pass II\_hori\_vert\_gradient } (I').$$

7. Calculate the gradient or the edge weight of a pixel and add the gradient to the output image I':

$$G = G_d + G_{hv};$$

$$I' = I' + G.$$

8. Using the nearest pixel values, fill in the unknown pixels and add I' to the image to get the interpolated resultant image.

Function pass I_diagonal_gradient (I')

// Pass I of the proposed interpolation method to find the gradient along diagonal directions $(x,y) = 4$
for $i = x:2:i_m - x$
 for $j = y:2:i_n - y$
calculate the gradient along 45° diagonal pixels direction

$e_1 = [I'(i-1,j-3) - I'(i-3,j-1)]$;

$e_2 = [I'(i+1,j-3) - I'(i-1,j-1)]$
 $+[I'(i-1,j-1) - I'(i-3,j+1)]$;

$e_3 = [I'(i+3,j-3) - I'(i+1,j-1)]$
 $+[I'(i+1,j-1) - I'(i-1,j+1)]$
 $+[I'(i-1,j+1) - I'(i-3,j+3)]$;

$e_4 = [I'(i+3,j-1) - I'(i+2,j+2)]$
 $+[I'(i+2,j+2) - I'(i-1,j+3)]$;

$e_5 = [I'(i+3,j+2) - I'(i+2,j+3)]$;

 $G_1 = e_1 + e_2 + e_3 + e_4 + e_5$;

calculate the gradient along 135° diagonal pixels direction

$e_1 = [I'(i-3,j+1) - I'(i-1,j+3)]$;

$e_2 = [I'(i-3,j-1) - I'(i-1,j+1)]$
 $+[I'(i-1,j+1) - I'(i+1,j+3)]$;

$e_3 = [I'(i-3,j-3) - I'(i-1,j-1)]$
 $+[I'(i-1,j-1) - I'(i+1,j+1)]$
 $+[I'(i+1,j+1) - I'(i+3,j+3)]$;

$e_4 = [I'(i-1,j-3) - I'(i+1,j-1)]$
 $+[I'(i+1,j-1) - I'(i+3,j+1)]$;

$e_5 = [I'(i+1,j-3) - I'(i+3,j-1)]$;

 $G_2 = e_1 + e_2 + e_3 + e_4 + e_5$;

 $G_d = G_1 + G_{v2}$; // Gradient along diagonal direction

Function pass II_hori_vert_gradient (I')

// Pass II of the proposed interpolation method to find the gradient along horizontal and vertical directions $(x, y) = 4$
for $i = x : 2 : i_m - x$
for $j = y : 2 : i_n - y$
calculate the gradient along horizontal pixels direction

$$e_1 = [I'(i-3, j-2) - I'(i-3, j)] + [I'(i-1, j-2) - I'(i-1, j)] + [I'(i+1, j-2) - I'(i+1, j)];$$

$$e_2 = [I'(i-2, j-3) - I'(i-2, j-1)] + [I'(i-2, j-1) - I'(i-2, j+1)];$$

$$e_3 = [I'(i, j-3) - I'(i, j-1)] + [I'(i, j-1) - I'(i, j+1)];$$

$$G_h = e_1 + e_2 + e_3;$$

calculate the gradient along vertical pixels direction

$$e_1 = [I'(i-2, j-3) - I'(i, j-3)] + [I'(i-2, j-1) - I'(i, j-1)] + [I'(i-2, j+1) - I'(i, j+1)];$$

$$e_2 = [I'(i-3, j-2) - I'(i-1, j-2)] + [I'(i-1, j-2) - I'(i+1, j-2)];$$

$$e_3 = [I'(i-3, j) - I'(i-1, j)] + [I'(i-1, j) - I'(i+1, j)];$$

$$G_v = e_1 + e_2 + e_3;$$

$G_{hv} = G_h + G_v$; // Gradient along horizontal and vertical direction

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