A Novel Image Interpolation Method Using the Bilateral Filter

Jong-Woo Han, Jun-Hyung Kim, Sung-Hyun Cheon, Jong-Ok Kim, *Member*, IEEE, and Sung-Jea Ko, *Senior Member*, IEEE

Abstract —*In general, since the noise deteriorates the interpolation performance in digital images, it is effective to employ denoising prior to the interpolation. In this paper, we propose a novel interpolation framework in which denoising and image sharpening methods are embedded. In the proposed framework, the image is first decomposed using the bilateral filter into the detail and base layers which represent the small and large scale features, respectively. The detail layer is adaptively smoothed to suppress the noise before interpolation and an edge-preserving interpolation method is applied to both layers. Finally, the high resolution image is obtained by combining the base and detail layers. Experimental results show that the proposed algorithm outperforms the conventional methods while suppressing blurring and jagging*[1].

Index Terms — Image interpolation, bilateral filter, denoising, unsharp masking.

I. INTRODUCTION

In these days, variable size images are delivered to users from different multimedia sources such as mobile phone, digital camera, and Internet. When the resolution of the received image is low, the users highly desire to magnify the image and appreciate it via the high resolution (HR) display devices. To construct and display HR images from low resolution (LR) images, simple conventional interpolation methods such as replication, bi-linear, and bi-cubic have been popularly used in the consumer appliances. However, these methods tend to produce severe jagging and blurring in the HR image.

To solve these problems, various methods have been proposed. The super-resolution (SR) method is one of the attractive solutions to produce the HR image [1]. However, since the multiple reference images are often required for SR, the large memory is necessary to store the references and the computational complexity is steeply increased to register the reference images. Besides, the registration error can cause unexpected artifacts including noise amplification. To reduce the complexity, Freeman et al. [2] introduced a fast and simple one-pass SR technique to generate the HR image using a single reference image. To further improve [2] while decreasing the computational load, Sun et al. [3] utilized the primal information of the input LR image, such as edge, ridge, and corner.

The polynomial-based [4], edge-based [5]-[7] and reconstruction-based [8] interpolation methods are also widely researched, which are generally much simpler than the SR based method. The polynomial-based methods assuming that the pixel value changes smoothly may yield the blurred HR image especially near the object boundary [9], thus requiring a post sharpening process [10]. To solve this problem, some edge-based interpolation methods have been introduced [5]-[7]. In order to generate the sharp HR image, these methods explicitly [5] or implicitly [6], [7] estimate the edge information that plays an important role in the interpolation. The reconstruction-based method [8] generates the high quality HR image which minimizes the reconstruction error. This method updates the output image to reduce the reconstruction error by iteratively up and down sizing the input image. Therefore, it requires many repetitions to obtain the sharp HR image [11].

The aforementioned methods can achieve high quality HR images, but the computational complexity is still disturbing the real-time implementation. Moreover, these methods generally assume that the interpolation is performed in the noise-free environment which is unrealistic [12]. Especially, the edge-based methods require denoising because noise can decrease the accuracy of the estimated edge information and yield artifacts in the generated HR image. Conventional denoising methods which are widely used in the digital image processing fields [13]-[15] can be utilized before interpolation.

Bilateral filtering is a non-linear method to effectively smooth images while preserving sharp edges intact [16]. This filter has been popularly used in many image-processing applications [17], [18]. In this paper, we propose a novel interpolation framework using the bilateral filter to generate the sharp HR image even when the input image is noisy. In the proposed framework, the bilateral filter [16] first decomposes an LR image into the detail and base layers which represent the small and large scale features, respectively. The noise in the detail layer is suppressed while preserving image structures in the base layer, since the noise mainly appears in the detail layer after decomposition. Then, the base and detail layers are magnified using a simple edge-preserving interpolation method. The detail layer is amplified and added to the interpolated base layer to compose the HR image.

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The rest of this paper is organized as follows. The proposed method is introduced in Section II. In Section III, the experimental results are given. Finally, the conclusion is discussed in Section IV.

II. Proposed Method

Fig. 1 illustrates the proposed method consisting of three steps including image decomposition using the bilateral filter, edge-preserving interpolation, and image composition with sharpening. We first briefly review the bilateral filter, and then describe the proposed method in detail.

A. Brief Review of the Bilateral Filter

The bilateral filtering [16] is an edge-preserving smoothing technique which effectively blurs the image but maintains the sharpness of edges intact. Since it consists of two simple Gaussian filters, its computation complexity is not high. Therefore, this filter is popularly applied to consumer multimedia devices [17], [18]. Let **I(x)** and **I(y)** denote the pixel values of the input LR image, where **x** and **y** denote the 2-D positions of the current and neighboring locations, respectively. Then, the filtering result $\mathbf{I}_b(\mathbf{x})$ is obtained as follows:

$$\mathbf{I}_b(\mathbf{x}) = \frac{1}{k(\mathbf{x})} \sum_{\mathbf{y}\in\Omega} c(\mathbf{x},\mathbf{y}) s(\mathbf{I}(\mathbf{x}),\mathbf{I}(\mathbf{y}))\mathbf{I}(\mathbf{y}), \tag{1}$$

where $c(\cdot)$ and $s(\cdot)$ represent the affinity of pixel locations and the similarity between pixel values, respectively, Ω denotes the neighboring pixel locations including the current location, and the normalization term $k(\cdot)$ is denoted as

$$k(\mathbf{x}) = \sum_{\mathbf{y}\in\Omega} c(\mathbf{x},\mathbf{y}) s(\mathbf{I}(\mathbf{x}), \mathbf{I}(\mathbf{y})). \tag{2}$$

To give a higher weight to the pixel which is spatially adjacent to the center pixel, the following function $c(\cdot)$ is used,

$$c(i,j) = \exp\left(\frac{-\| i-j \|_2^2}{2\sigma_c^2}\right), \tag{3}$$

where $\|\cdot\|_2$ and σ_c denote the L_2-norm and the standard deviations of $c(\cdot)$, respectively. The function $s(\cdot)$ indicates the photometric similarity between x and y. Irrespective of the distance between pixels, the similarity of pixel values determines the weight so that pixel values $\mathbf{I}(\mathbf{x})$, $\mathbf{I}(\mathbf{y})$ are utilized as the parameters of the Gaussian filter instead of pixel positions x and y. Therefore, $s(\cdot)$ is defined by

$$s(u,v) = \exp\left(\frac{-\| u-v \|_2^2}{2\sigma_s^2}\right), \tag{4}$$

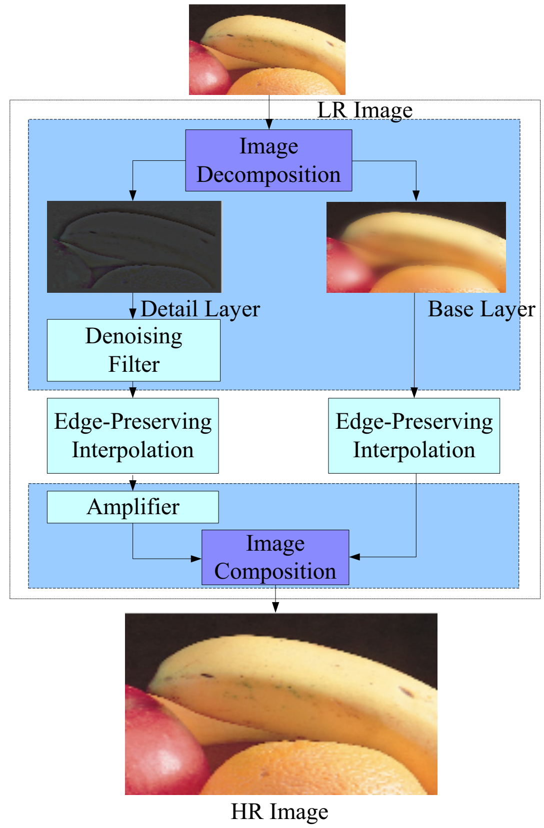


Fig. 1. Architecture of the proposed interpolation method.

where σ_s is the standard deviations of $s(\cdot)$. The adaptive combination of $c(\cdot)$ and $s(\cdot)$ enables the Gaussian filter to be processed along the edge direction. Therefore, compared to the conventional Gaussian filter, the bilateral filter can effectively separate the textual and structural information of the image. However, even though the bilateral filter is widely used, no theoretic manner has been established to determine the optimal σ_c and σ_s. Therefore, these parameters are generally selected by the empirical method. This paper does not consider the optimal parameter selection but borrows results from the previous work of Zhang [19].

B. Image Decomposition and Denoising

Using the bilateral filter, the LR image is decomposed into the detail and base layers. The base layer $\mathbf{I}_b(\mathbf{x})$ can be determined using (1). Then, the detail layer $\mathbf{I}_d(\mathbf{x})$ can be obtained by

$$\mathbf{I}_d(\mathbf{x}) = \mathbf{I}(\mathbf{x}) - \mathbf{I}_b(\mathbf{x}). \tag{5}$$

Since the bilateral filter can effectively extract the details, noise and texture are mostly contained in $\mathbf{I}_d(\mathbf{x})$ [12]. For effective denoising, we use a spatially adaptive thresholding method to preserve textures in the detail layer. Generally, the weighting factor for denoising varies depending on the noise standard deviation σ_n which is generally spatial-variant. Note that there is a strong relationship between amplitudes of coefficients in the corresponding locations of the coarser and finer layers in the Wavelet domain [20]. Similar to the wavelet decomposition, we empirically found the correlation of the singularities between the different layers in the decomposed images by using the bilateral filter. Therefore, for a region with the high gradient energy in the base layer, its corresponding region in the detail layer will also contain high gradient energy. The gradient energies of the base layer $E_b(\mathbf{x})$ and the detail layer $E_d(\mathbf{x})$ are first measured by

$$E_b(\mathbf{x}) = \sqrt{G_X^2(\mathbf{I}_b(\mathbf{x})) + G_Y^2(\mathbf{I}_b(\mathbf{x}))}\,, \tag{6}$$

$$E_d(\mathbf{x}) = \sqrt{G_X^2(\mathbf{I}_d(\mathbf{x})) + G_Y^2(\mathbf{I}_d(\mathbf{x}))}\,. \tag{7}$$

where $G_X(F)$ and $G_Y(F)$ are obtained by using the Sobel operator as follows:

$$G_X(F) = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * F, \tag{8}$$

$$G_Y(F) = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} * F, \tag{9}$$

where the operator $*$ denotes the 2-D convolution.

In order to suppress the noise in the detail layer, we introduce a non-linear filter with the gradient energy of the detail and base layers as follows:

$$\hat{\mathbf{I}}_d(\mathbf{x}) = \frac{|E_b(\mathbf{x})|^2}{|E_b(\mathbf{x})|^2 + \gamma_1 |E_d(\mathbf{x})|^2} \mathbf{I}_d(\mathbf{x}), \tag{10}$$

where γ_1 is a regularization factor which controls the trade-off between denoising and texture preserving performance. Note that the filter in (10) which is Wiener-like, can adaptively suppresses the noise in the detail layer.

C. *Edge-Preserving Interpolation of Each Layer*

The denoised detail and base layers are interpolated separately. We employ a simple edge-based interpolation method which utilizes the directional correlation between pixels. Consider two geometric with different locations of the pixel to be interpolated as shown in Fig. 2. The first configuration contains the pixel to be interpolated in the center of the neighboring pixels in the LR image grid such as I(c) in Fig. 2(a). In Fig. 2(b), pixels I(v) and I(h) are to be interpolated using the second configuration. We predefine the possible edge directions for each geometric configuration. The first configuration contains two edge directions which are diagonal and anti-diagonal. Besides those two directions, the second configuration further considers vertical or horizontal directions as shown in Fig. 2(b). The direction to be used for estimating the missing pixel is selected as follows:

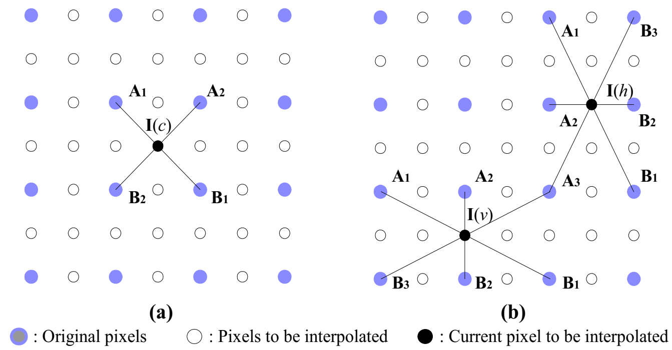


Fig. 2. Two geometric configurations for the interpolation method. (a) First configuration for I(c). (b) Second configuration for I(v) and I(h).

$$d_a^* = \arg\min_{d\in\{1,2\}} \left(|A_d - B_d|\right), \tag{11}$$

$$d_b^* = \arg\min_{d\in\{1,2,3\}} \left(|A_d - B_d|\right), \tag{12}$$

where d_a^* and d_b^* represent the edge directions which minimize intensity change among predefined directions for first and second configuration, respectively. The missing pixel is then interpolated by

$$\mathbf{I}(\cdot) = \frac{A_{d_a^*} + B_{d_a^*}}{2}, \tag{13}$$

where A and B denote the neighboring pixel values in Fig. 2.

D. *Image Composition with Detail Enhancement*

In order to generate the sharp HR image, the interpolated layers are composed using the concept of the adaptive unsharp masking. Therefore, the enhanced HR image $\hat{\mathbf{I}}_{in}(\mathrm{x})$ can be produced by

$$\hat{\mathbf{I}}^{in}(\mathbf{x}) = \mathbf{I}_b^{in}(\mathbf{x}) + \lambda(\mathbf{x})\hat{\mathbf{I}}_d^{in}(\mathbf{x}), \tag{14}$$

where $\mathbf{I}_b^{in}(\mathrm{x})$, $\hat{\mathbf{I}}_d^{in}(\mathrm{x})$, and $\lambda(\mathbf{x})$ represent the interpolated base and detail layers and the weighting factor to decide the sharpness of the generated image, respectively. Since noise can be amplified with $\lambda(\mathbf{x})$, this parameter is local-adaptively changed as follows:

$$\lambda(\mathrm{x}) = 1 + \frac{|E_b^{in}(\mathbf{x})|}{\gamma_2 |\hat{E}_d^{in}(\mathbf{x})|}, \tag{15}$$

where $E_b^{in}(\mathrm{x})$ and $\hat{E}_d^{in}(\mathbf{x})$ are the gradient energies of $\mathbf{I}_b^{in}(\mathbf{x})$ and $\hat{\mathbf{I}}_d^{in}(\mathbf{x})$, respectively. γ_2 is a weighting factor to control the performance of the detail enhancement. To prevent the color distortion, $\lambda(\mathbf{x})$ is limited to

$$\lambda(\mathbf{x}) \le |E_b^{in}(\mathbf{x})|. \tag{16}$$

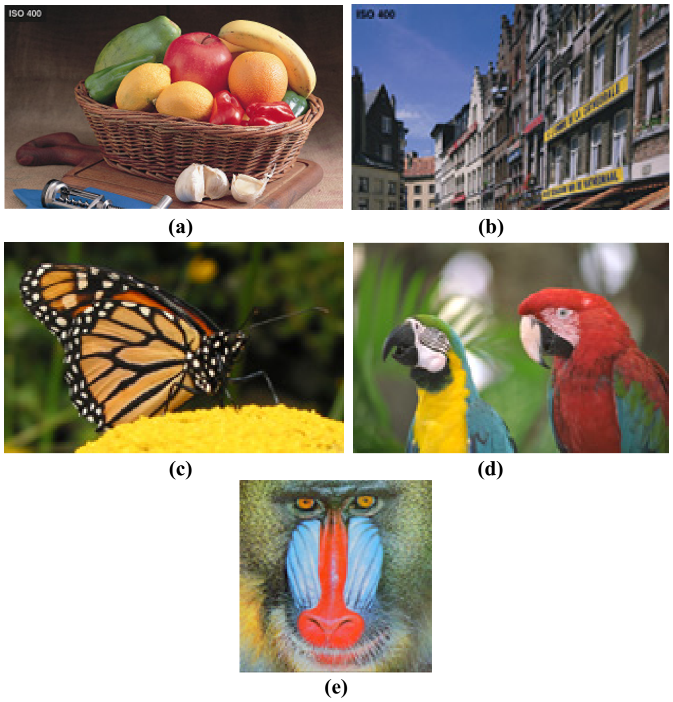


Fig. 3. Test images. (a) *Fruit*. (b) *Cafe*. (c) *Monarch*. (d) *Parrots*. (e) *Baboon*.

III. Experimental Results

To evaluate the performance of the proposed method, we down-sampled several test images which are shown in Fig. 3 by a factor of two. For the proposed method, the parameters for the bilateral filter σ_c and σ_s are set to 1.8 and 30, respectively, and the window size is 11 x 11 [19]. The weighting factors γ_1 in (10) and γ_2 in (15) are given as follows:

$$\gamma_1 = \sum |E_b(\mathbf{x})|^2 / \sum |E_d(\mathbf{x})|^2, \tag{17}$$

$$\gamma_2 = \sum |E_b^{in}(\mathbf{x})| / \sum |\hat{E}_d^{in}(\mathbf{x})|. \tag{18}$$

Then, down-sampled images are up-scaled by using the conventional methods including bilinear [21], edge-based [7], and the proposed method.

First, we compare the performance of the proposed method in the noise-free environment as shown in Fig. 4. The conventional methods [7], [21] are sharpened by using the adaptive unsharp mask [22]. It is easily shown that the proposed method generates sharper HR image while suppressing jagging and halo artifacts.

Next, the denoising performance is compared. The test image is damaged by the Gaussian noise of which noise standard deviation σ_n is set to 10. The conventional methods are recovered by the conventional denoising method based on the bilateral filtering [16]. For this test, the weighting factor $\lambda(\mathrm{x})$ in (14) is set to one. Then, only denoising performance of the proposed method is compared to the conventional methods with the post-processing. The proposed method can preserve the structure of the image better than the conventional methods as shown in Fig. 5. Table I describes the objective image quality of the conventional and proposed methods in terms of PSNR. The proposed method achieves higher PSNR than the conventional methods.

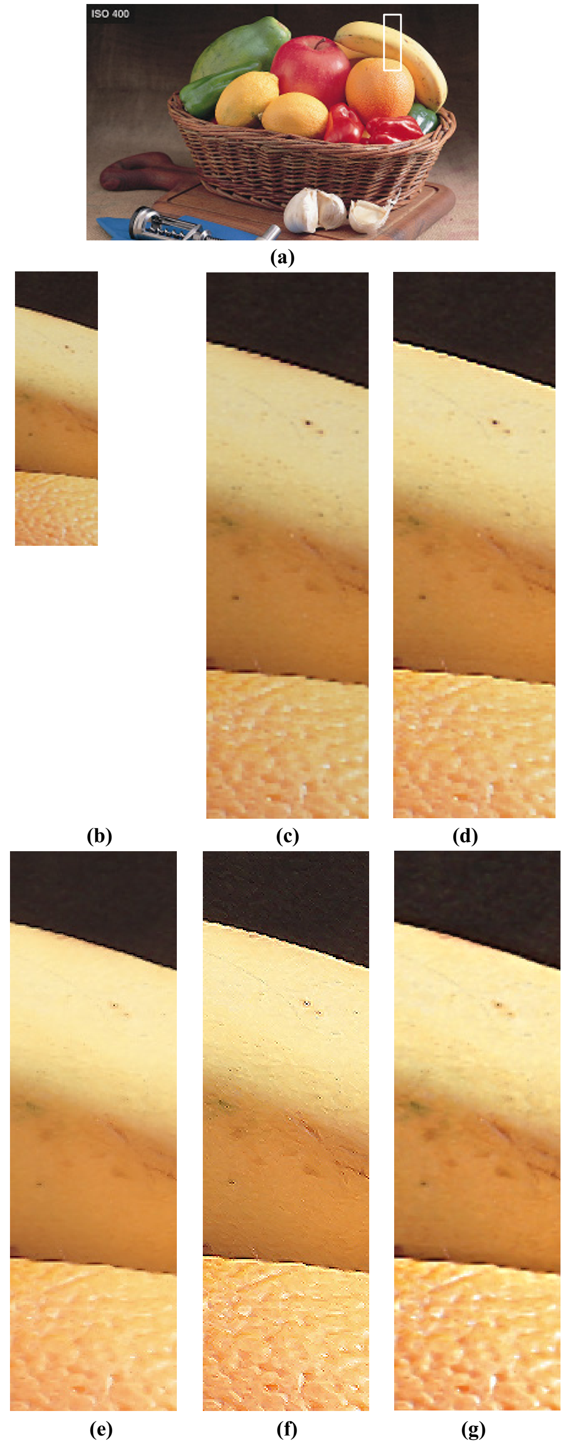


Fig. 4. Comparison of the subjective quality using *Fruit*. (a) Original. (b) LR image. (c) Bilinear. (d) Bilinear followed by unsharp masking. (e) Edge-based interpolation. (f) Edge-based interpolation followed by unsharp masking. (g) Proposed.

(a)

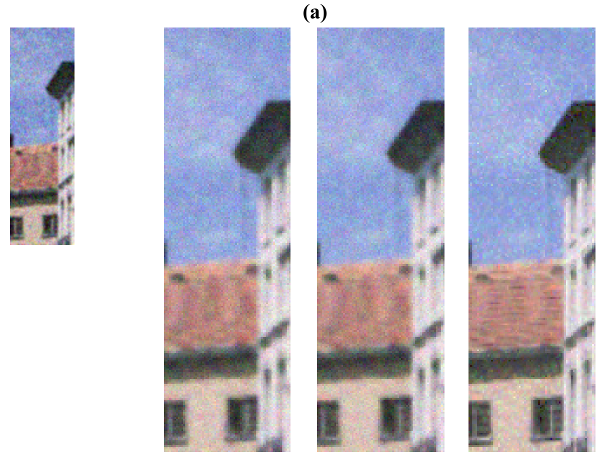
(b) (c) (d)

(e) (f) (g)

Fig. 5. Comparison of the subjective quality using *Fruit* with $\sigma_n = 10$. (a) Original. (b) LR image. (c) Bilinear. (d) Denoising using the bilateral filter followed by bilinear. (e) Edge-based interpolation. (f) Denoising using the bilateral filter followed by edge-based interpolation. (g) Proposed.

In Fig. 6, we compare the subjective image quality of the whole proposed method including the denoising and image enhancement schemes. The bilateral filter and unsharp mask are applied to the conventional interpolation methods. Since the proposed method preserves more textures, the details of the red roof are distinguishable in Fig. 6(e). The noise standard deviation of *Baboon* in Fig. 7 is set to 30. The face of baboon has complex textures which is fragile to the low-pass filtering. Since the conventional methods with bilateral filtering severely alleviate the image quality, the subjective image quality of the proposed method is much better than other methods with endurable noise. Even though unsharp masking is also employed to enhance the image quality, the lost information during the denoising process cannot be fully

(a)



(b) (c) (d) (e)

Fig. 6. Comparison of the subjective quality using *Cafe* with $\sigma_n = 30$. (a) Original. (b) LR image. (c) Bi-linear with pre/post-processing. (d) Local gradient with pre/post-processing. (e) Proposed.

TABLE 1
COMPARISON RESULT OF AVERAGE PSNR PERFORMANCE FOR DENOISED IMAGES (DB)

Image	Noise Variance	Bilinear [21] + Bilateral filter	Edge-based [7] + Bilateral filter	Proposed
Fruit (*1280x768*)	10	25.91	25.91	**27.96**
	20	22.85	22.87	**24.11**
	30	20.73	20.74	**21.79**
Café (*1280x768*)	10	23.94	23.95	**24.55**
	20	20.03	20.12	**20.34**
	30	16.68	19.70	**19.98**
Parrot (*768x512*)	10	26.08	26.00	**26.64**
	20	23.29	23.25	**23.76**
	30	20.50	20.48	**20.85**
Monarch (*1280x768*)	10	25.29	25.42	**25.97**
	20	22.76	22.80	**23.31**
	30	20.32	20.37	**20.72**
Baboon (512x512)	10	23.60	23.55	**25.17**
	20	21.62	21.56	**23.89**
	30	19.64	19.61	**20.48**

recovered as shown in Figs. 7(d) and (f). Besides, the remaining noise is amplified by the unsharp masking as shown in Figs. 7(d) and (f). Unlike the conventional methods, the proposed method effectively suppresses noise while preserving the textures and structures of the input image.

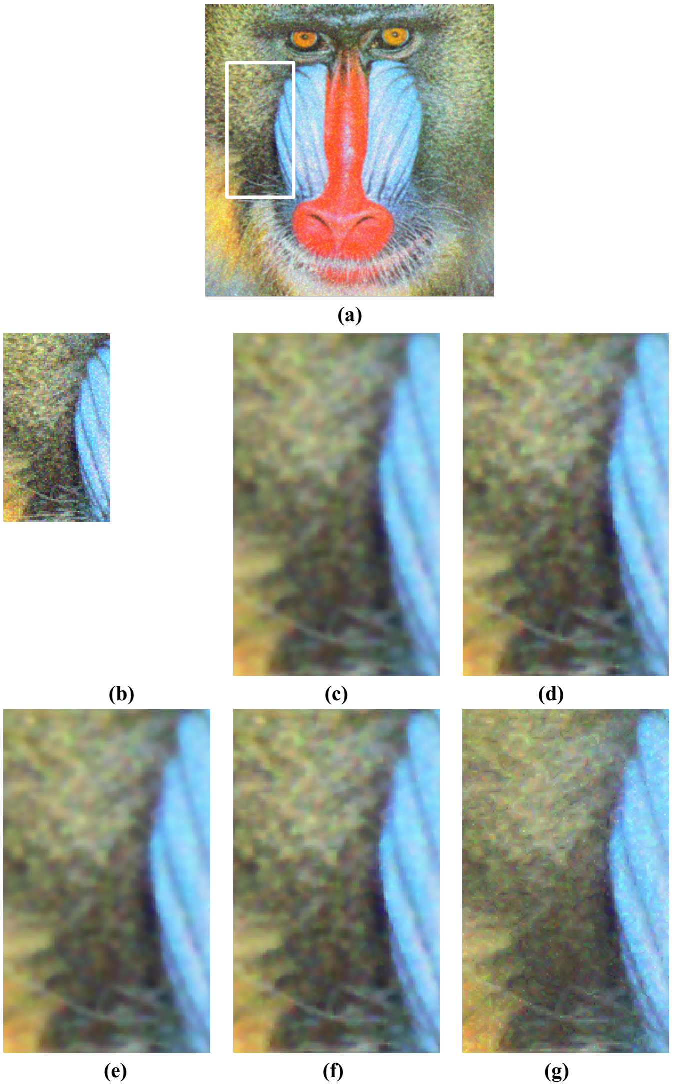


Fig. 7. Comparison of the subjective quality using *Baboon* with σ_n = 30. (a) Original. (b) LR image. (c) Bi-linear. (d) Bi-linear with pre/post-processing. (e) Local gradient. (f) Local gradient with pre/post-processing. (g) Proposed.

IV. Conclusion

In this paper, we proposed the novel interpolation method to handle the noisy input image. Since the bilateral filter effectively decomposes the input LR image into the detail and base layers, we can only deal with the noise in the detail layer. We empirically proved that the gradient energies in the corresponding region between the detail and base layers have the strong relationship. Therefore, depending on this relationship, it may be easy to distinguish texture information from the noise. The proposed method shows subjectively and objectively better performance to generate the sharp HR image from the LR image even when it contains the noise.

Since the bilateral filter is simple to implement and easy to use, the proposed method can be used in many portable multimedia applications which may acquire the noisy LR image. For example, when the LR images taken by the cell-phone camera in the low-light environment are required to be displayed in the HR display devices, the proposed method can be one of the attractive solutions to generate the sharp HR image without artifacts. Furthermore, it can be useful in image demosaicking method for digital cameras employing color filter array such as Bayer pattern.

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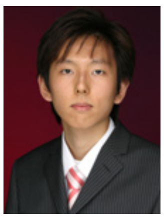

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