LETTER

Edge-Preserving Cross-Sharpening of Multi-Modal Images

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SUMMARY We present a simple technique for enhancing multi-modal images. The unsharp masking (UM) is at first nonlinearized to prevent halos around large edges. This edge-preserving UM is then extended to cross-sharpening of multi-modal images where a component image is sharpened with the aid of more clear edges in another component image.

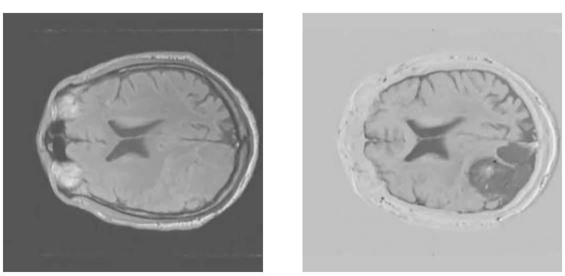
key words: *unsharp masking, multi-modal image, cross-sharpening, halo*

1. Introduction

The unsharp masking (UM) is popularly used for sharpening of single image. The UM, however, produces conspicuous halos around edges with large discontinuity of intensity. Such edges are already sharp, and thus their sharpening is no longer needed and rather hinders our visual perception. We, therefore at first, extend the UM for preserving large edges.

We next extend this single-image edge-preserving UM to multi-modal images. Examples of multi-modal images are flash and no-flash pair of photographs, multi-exposure or multi-lighting photos, medical multi-modal and satellite hyper-spectral images. In multi-modal images, edge detection intensity is different in each component image. A structure is clearly detected in a spectrum band while almost unseen in another band.

For instance, in two MR images of a brain shown in Fig. 1, two eyes can be detected only in the MRI-1 while the tumor in the left-back brain is clearly seen only in the MRI-2. This is an example of multi-modal image where individual UM for each component image is insufficient. We can enhance weak edges in a component image with the help of other component images where those edges are clearly detected. We propose, in this letter, such cross sharpening technique for enhancement of multi-model images.



(a) MRI-1 (b) MRI-2

Fig. 1 Bi-modal MR images of a brain.

This cross-UM is similar to the cross bilateral filter (BF) [1] which is an extension of single-image smoothing with BF [2] to multi-modal images. In the cross-BF, smoothing of a target image is controlled by another reference image. Similarly in our cross-UM proposed in this letter, sharpening of a target image is controlled by another reference image.

We focus on sharpening of images, while noise suppression is out of the scope of this letter. Various nonlinear UM techniques have been developed for sharpening edges while suppressing noise [3], [4]. The nonlinearity introduced in this letter is different from them.

2. Edge-Preserving UM of Single Image

Let the pixel value of a monochromatic image be d_{ij}. Outputs of the popular unsharp masking (UM) are given by

$$f_{ij} = d_{ij} + \delta \sum_{l=-p}^{p} \sum_{m=-p}^{p} s_{lm}(d_{ij} - d_{i+l,j+m}) \tag{1}$$

where $s_{lm} = e^{-(l^2+m^2)/2\sigma_s^2} / \sum_l \sum_m e^{-(l^2+m^2)/2\sigma_s^2}$. For instance an output of UM of $p = 10, \sigma_s = 1.5, \delta = 5$ for the MRI-1 in Fig. 1 (a) is shown in Fig. 2 where black halos appear around the outer boundary of head and also white halos in peripheral cortices. This is caused by large overshoots there. Such edges are sharp already in Fig. 1 (a), hence no more enhancement is needed for them.

We therefore incorporate a range weight v_{ijlm} into Eq. (1) in addition to the spatial weight s_{lm} in a similar way in the bilateral filter [2]. We extend Eq. (1) to

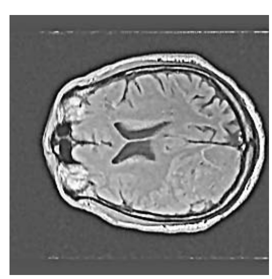


Fig. 2 Ordinary unsharp masking for Fig. 1 (a).

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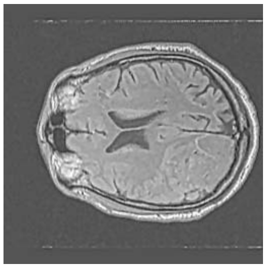


Fig. 3 Edge preserving UM for Fig. 1 (a).

$$f_{ij} = d_{ij} + \delta \sum_{l=-p}^{p} \sum_{m=-p}^{p} s_{lm} v_{ijlm} (d_{ij} - d_{i+l,j+m}) \tag{2}$$

where $v_{ijlm} = e^{-(d_{ij}-d_{i+l,j+m})^2/2\sigma_1^2}$ which prevents sharpening effect from $d_{i+l,j+m}$ far from d_{ij}. Output of this edge-preserving UM for Fig. 1 (a) is shown in Fig. 3 where both of black and white halos in Fig. 2 almost disappear while fine structure of tissues is sharpened as the same as in Fig. 2. We set $\sigma_s = 1.5, \sigma_1 = 30, \delta = 5$.

Simple evaluation of sharpness in an image is through the gradient of pixel values. We calculate an average gradient intensity $AGI = \sum_{i=1}^{L} \sum_{j=1}^{M} (|\Delta_x d_{ij}| + |\Delta_y d_{ij}|)/LM$ where L and M are the width and height of the image. This AGI value is 38.72 for Fig. 1 (a), 147.35 for Fig. 2 and 99.33 for Fig. 3. Large AGI value of Fig. 2 is due to overshoots around edges.

3. Edge-Preserving Cross UM

Figure 2 and Fig. 3 are results of sharpening of Fig. 1 (a) by itself. Let us next consider sharpening of Fig. 1 (a) of pixel value d_{ij} with the aid of Fig. 1 (b) of pixel value c_{ij}. Because the tumor in the left-back brain is more clearly detected in Fig. 1 (b) than in Fig. 1 (a), it is expected that very weak edges around the tumor in Fig. 1 (a) can be enhanced with the help of the more clear edges in Fig. 1 (b).

In order for such cross-sharpening of d_{ij} with the help of c_{ij}, we add one more additional weight w_{ijlm} to e.q.(2) as

$$f_{ij} = d_{ij} + \delta \sum_{l=-p}^{p} \sum_{m=-p}^{p} s_{lm} v_{ijlm} w_{ijlm} (d_{ij} - d_{i+l,j+m}) \tag{3}$$

where $w_{ijlm} = 1 - e^{-(c_{ij}-c_{i+l,j+m})^2/2\sigma_2^2}$ which induces sharpening of d_{ij} if $|c_{ij} - c_{i+l,j+m}|$ is large. This is the edge-preserving cross-UM (EPCUM) which we propose in this letter. Output of EPCUM for Fig. 1 (a) with the aid of Fig. 1 (b) is shown in Fig. 4 where the left-back tumor is more enhanced than Fig. 3. The AGI value of Fig. 4 is 83.90.

While the fine structures in Fig. 1 (a) are enhanced in Fig. 3, they are only preserved in Fig. 4. This is reasonable because these fine structures are weak in both of Fig. 1 (a) and Fig. 1 (b). In the EPCUM, sharpening effect is exerted on edges only if they are weak in the target image and strong in the reference image. Hence noise in the background area is not enhanced in Fig. 4. Contrastively in the edge-preserving UM which needs no reference image, all weak edges are enhanced. This is the reason for enhanced fine details in Fig. 3, while noise is also enhanced in it.

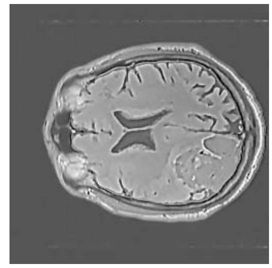


Fig. 4 Edge preserving cross UM (EPCUM) for Fig. 1 (a) with the aid of Fig. 1 (b).

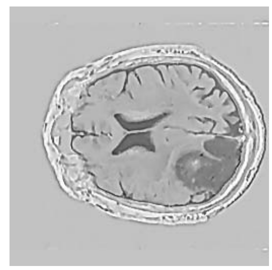


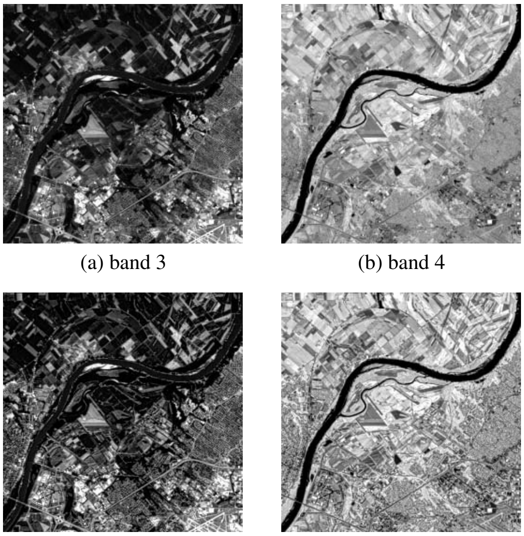
Fig. 5 EPCUM for Fig. 1 (b) with the aid of Fig. 1 (a).

This EPCUM can be applied to images with the exchange of the target image and the reference one. In the above experiments, Fig. 1 (a) is the target and Fig. 1 (b) is the reference. We next exchange them. Figure 5 shows a result of EPCUM for Fig. 1 (b) with the aid of Fig. 1 (a). While the outer boundary of head and structures around eyes are vague in Fig. 1 (b), they becomes sharpened in Fig. 5. We set $\sigma_s = 1.5, \sigma_1 = 30, \sigma_2 = 10, \delta = 15$ in Fig. 4 and Fig. 5. The AGI value is 27.45 for Fig. 1 (b) and 91.60 for Fig. 5.

Note the difference between EPCUM and image fusion techniques popularly used for multi-modal images. The most apparent difference is that the EPCUM outputs n images (in the above example, $n = 2$) when we have n input images, while the image fusion methods combine these n inputs into 1 output image.

An advantage of the EPCUM over image fusion methods lies in preservation of the ordering of grayscale values. For flash/no-flash and multi-exposure photos, grayscale value ordering is preserved in fused image because the rank-order of pixel values is aligned for all component images. However the gray-scale value ordering varies for each component image in medical and satellite multi-modal images. This tonal polarity conversion can be seen, for instance, at the nose between eyes in Fig. 1 (a) where nose is darker than brain while in Fig. 1 (b) nose is brighter than brain. For such multi-modal images, some important structures often disappear by mutual cancellation in the fused image. In the EPCUM, grayscale value ordering is preserved.

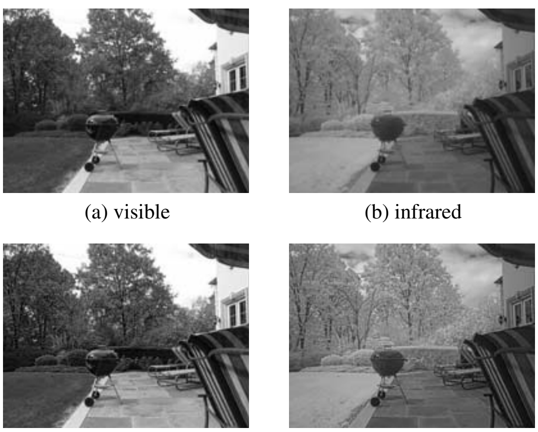
Figure 6 shows another example of multi-modal image. Figure 6 (a) is the band 3 and Fig. 6 (b) is band 4 in a LANDSAT image composed of 7 bands spectrum. Fig-



(a) band 3 (b) band 4

(c) EPCUM of (a) (d) EPCUM of (b)

Fig. 6 LANDSAT images.



(a) visible (b) infrared

(c) EPCUM of (a) (d) EPCUM of (b)

Fig. 7 Visible and infrared images.

ure 6 (c) is an enhanced Fig. 6 (a) with the aid of Fig. 6 (b) and Fig. 6 (d) is vice versa. Farm fields in Fig. 6 (a) is sharpened in Fig. 6 (c), on the other hand, fine streets in Fig. 6 (b) is enhanced in Fig. 6 (d). The AGI values of Fig. 6 (a),(b),(c) and (d) are 191.46, 174.10, 246.45 and 243.20. We set $\sigma_s = 1.5, \sigma_1 = 30, \sigma_2 = 10, \delta = 3$.

At last, Fig. 7 (a) shows a photograph of a garden in a visible spectrum and Fig. 7 (b) is its near-infrared shot. Figure 7 (c) is an enhanced Fig. 7 (a) with the aid of Fig. 7 (b) and Fig. 7 (d) is vice versa. The hedge at the center of Fig. 7 (a) is enhanced in Fig. 7 (c) while trees in the background in Fig. 7 (b) is sharpened in Fig. 7 (d). The AGI values of Fig. 7 (a),(b),(c) and (d) are 108.95, 58.25, 154.70 and 132.71. We set $\sigma_s = 1.5, \sigma_1 = 30, \sigma_2 = 10, \delta = 5$.

The proposed EPCUM increases the AGI value without producing halos as is observed in the results in Fig. 6 and Fig. 7.

4. Conclusion

We have presented a technique for cross sharpening of multi-modal images and demonstrated that weak edges in a component image can be enhanced with the aid of strong edges in another component image. This is in significant contrast to cross bilateral filtering of multi-modal images where, for instance, cross BF of Fig. 1 (a) with the aid of Fig. 1 (b) blurs the edge of outer boundary of head in Fig. 1 (a).

Our sharpening technique is useful for pre-processing of each component image in a multi-modal image before they are fused. In addition to halos, amplification of noise is also a problem in practical use of unsharp masking [3], [4]. The combination of cross-denoising and cross-sharpening is the subject of future research.

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