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The multiscale directional bilateral filter and its application to multisensor image fusion

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A B S T R A C T

In this paper, a novel multiscale geometrical analysis called the multiscale directional bilateral filter (MDBF) which introduces the nonsubsampled directional filter bank into the multiscale bilateral filter is proposed. Through combining the characteristic of preserving edge of the bilateral filter with the ability of capturing directional information of the directional filter bank, the MDBF can better represent the intrinsic geometrical structure of images. The MDBF, which is a multiscale, multidirectional and shift-invariant image decomposition scheme, is used to fuse multisensor images in this paper. The source images are first decomposed into the directional detail subbands and the approximation subbands via the MDBF. Then, the directional detail subbands and the approximation subbands are fused according to the given fusion rule, respectively. Finally, the inverse MDBF is applied to the fused subbands to obtain the fused image. Experimental results over visible and infrared images and medical images demonstrate the superiority of our method compared with conventional methods in terms of visual inspection and objective measures.

1. Introduction

With the development of imaging techniques, multiple imaging devices can be used to acquire several different images of the same scene or object. Multiple sensor modalities can enhance the system performance and robustness in a wide range of modern military and civilian imaging applications. However, the increase of sensor modalities results in the "information overload" problem. In addition, viewing multiple sensor modalities simultaneously leads to an unnecessary load on the observer and combining information across a group of observers becomes almost impossible [1]. Some researcher found that multisensor image fusion is an effective technique to solve this problem [2]. Image fusion technique integrates the information from two or more images of the same scene or object into a composite image which is more informative and suitable for human visual perception or computer processing [3]. The benefits of image fusion include wider spatial and temporal coverage, decreased uncertainty and improved reliability [4]. Nowadays, image fusion has been applied to many fields such as military [5], remote sensing [6] and medical aid diagnosis [7].

So far, researchers have developed many image fusion algorithms [8–11], which can be categorized into pixel, feature, and decision levels according to the representation format at which image information is processed [3]. Pixel-level methods merge multiple input images into a single fused image in raw image representation. Compared with feature- and decision-level methods, pixel-level image fusion can preserve more original information. We focus on pixel-level image fusion in this paper.

Since multiscale transforms can effectively extract the important information of images such as lines and details, they are the most commonly used methods to fuse images [12–16]. The classical multiscale transforms include the Laplacian pyramid transform [17], the discrete wavelet transform (DWT) [18], the stationary wavelet transform (SWT) [19] and the dual-tree complex wavelet transform (DTCWT) [20]. To better capture the intrinsic geometrical structure of images, various multiscale geometrical analysis (MGA) methods, including curvelet [6], contourlet [21] and so on [22–24], have been developed. In this paper, we propose a novel MGA method based on the bilateral filter.

The bilateral filter proposed by Tomasi and Manduchi in [25] is a technique to smooth images while preserving edges. At present, the bilateral filter has been applied to various image processing tasks such as denoising, text editing and relighting, and tone management [26]. The kernel of the bilateral filter is space-variant, and it uses the difference between neighbor pixel values which are correlated with edges and details. Therefore, the bilateral filter can smooth images while preserving edges. It is well known that multiscale representation is important for image processing. Fattal et al. proposed the multiscale bilateral filter (MBF) and used it to enhance shape and detail [27]. However, edges and lines in natural images reflect important information of images, and they may

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present various directions. Therefore, the directional filter is very important for image processing to effectively extract the significant information of images. Thus, we propose the multiscale directional bilateral filter (MDBF), which introduces the directional filter bank (DFB) to the MBF to more effectively extract the information of images. The MDBF has proven to be effective in image fusion as shown in this paper.

The remainder of this paper is organized as follows. In Section 2, we review the principle of the bilateral filter and its multiscale extension version, and develop the MDBF through combining the DFB with the MBF. Section 3 proposes the multisensor image fusion method via the MDBF. The experimental results and discussions are presented in Section 4. Finally, concluding remarks and future works are given in Section 5.

2. Bilateral filter and multiscale directional bilateral filter

In this section, we briefly review the basic theory of the bilateral filter and the multiscale bilateral filter, and propose the multiscale directional bilateral filter.

2.1. The basic theory of bilateral filter and multiscale bilateral filter

Gaussian filtering is one of the most used methods for image smoothing. It is a weighted average of the intensity of the adjacent positions with a weight decreasing with the spatial distance to the center position. The underlying assumption of Gaussian filtering is that images vary slowly over space. Nevertheless, this assumption fails at edges. To overcome this problem, the bilateral filter was developed [25]. It is a nonlinear, noniterative and local technique, and can smooth image while preserving edges, by means of a nonlinear combination of nearby pixel values. So far, due to the advantage of preserving edges, the bilateral filter has obtained extensive applications [26]. The bilateral filter combines intensity values based on both their geometric closeness and their photometric similarity, and prefers near values to distant values in both spatial and range domain. Closeness refers to vicinity in the spatial domain, and similarity to vicinity in the range. The bilateral filter (BF) can be viewed as the combination of the spatial filter and the range filter, and it is defined by

$$\mathrm{BF}[I]_{\mathbf{p}} = \frac{1}{W_{\mathbf{p}}}\sum_{\mathbf{q}\in\mathcal{S}} G_{\sigma_s}(\|\mathbf{p}-\mathbf{q}\|)G_{\sigma_r}(I_{\mathbf{p}}-I_{\mathbf{q}})I_{\mathbf{q}} \tag{1}$$

$$\text{with}\quad W_{\mathbf{p}} = \sum_{\mathbf{q}\in\mathcal{S}} G_{\sigma_s}(\|\mathbf{p}-\mathbf{q}\|)G_{\sigma_r}(I_{\mathbf{p}}-I_{\mathbf{q}}), \tag{2}$$

where $\mathbf{p}$ and $\mathbf{q}$ are two-dimensional vectors representing the spatial location of the image, $I_{\mathbf{p}}$ and $I_{\mathbf{q}}$ are the intensity values of the location $\mathbf{p}$ and $\mathbf{q}$ respectively, $\mathcal{S}$ denotes the neighborhood of the pixel $\mathbf{p}$, $W_{\mathbf{p}}$ is a normalization factor, $G_\sigma = \exp(-x^2/\sigma^2)$, G_{σ_s} is a spatial Gaussian function that decreases symmetrically as distance from the center increases, and G_{σ_r} is also a Gaussian function that decreases with the increase of the intensities difference between $I_{\mathbf{p}}$ and $I_{\mathbf{q}}$. Parameters σ_s and σ_r, which are the standard deviations of Gaussian functions G_{σ_s} and G_{σ_r} respectively, determine the amount of filtering for the image I.

The bilateral filter is often used to decompose an image into an approximation subband and a detail subband. The approximation subband is obtained by applying Eq. (1) to the original image, and the detail subband is the difference between the original image and the approximation subband. However, generally, one level of the decomposition is not enough to extract the important information of images since images may contain information of various resolutions. Fattal et al. extended the original bilateral filter into multiscale form [27]. An idea of the dyadic wavelet transform known as the *à trous* algorithm is used in the multiscale bilateral filter (MBF), which is defined as

$$I_{\mathbf{p}}^{j+1} = \frac{1}{W_{\mathbf{p}}}\sum_{\mathbf{q}\in\mathcal{S}} w^j(\mathbf{p}-\mathbf{q})G_{\sigma_r}(I_{\mathbf{p}}^j - I_{\mathbf{q}}^j)I_{\mathbf{q}}^j \tag{3}$$

$$\text{with}\quad w^j = (\mathbf{x})\begin{cases} G_{\sigma_s}\left(\left\|\frac{\mathbf{x}}{2^j}\right\|\right) & \text{if } \frac{\mathbf{x}}{2^j}\in\mathcal{Z}^2 \quad \text{and} \quad \left\|\frac{\mathbf{x}}{2^j}\right\| < m \\ 0 & \text{otherwise} \end{cases}, \tag{4}$$

where j denotes the jth level of the decomposition, $W_{\mathbf{p}}$ is still a normalization factor and similar to Eq. (2). The neighborhood $\mathcal{S}$ is modified so that the pixel location $\mathbf{q}$ addresses only the points where w^j is non-zero. The MBF is iterated over approximation subbands according to Eq. (3). After J levels multiscale bilateral filtering, the image is decomposed into an approximation subband and J detail subbands. The MBF is a shift-invariant scheme because it uses a technique based on the *à trous* algorithm which is shift-invariant.

2.2. Multiscale directional bilateral filter

The edges and lines in images may have various directions due to the intrinsic geometrical structure of typical natural images. For

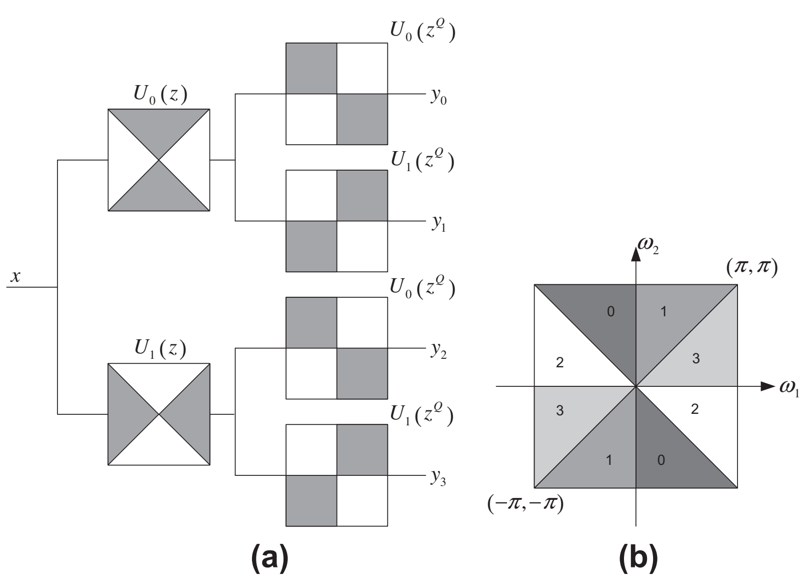

Fig. 1. Four-channel nonsubsampled directional filter bank constructed with two-channel fan filter banks. (a) Filtering structure. (b) Corresponding frequency partitioning.