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An adaptive nonlocal means filter based on fuzzy domain for laser speckle reduction

Dong-hai Wen [a,*], Yue-song Jiang [a], Yan-zhong Zhang [a], Qian Gao [b]

[a] School of Electronic Information Engineering, Beihang University, Beijing 100191, China
[b] Dalian Communication Sergeant School of Air Force, Dalian 116600, China

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ABSTRACT

A new speckle reduction method, i.e., an adaptive nonlocal means based on fuzzy domain (FANLM), is proposed for polarization imaging despeckling. With this method, speckle is removed by an adaptive nonlocal means in Laplacian pyramid domain. The proposed FANLM method calculates the similarity measure in the fuzzy domain, which can make the similarity measure more precise and accurate. In view of the similarity neighborhood selection problem, an adaptive selection algorithm is proposed. The performance of the proposed FANLM method has been compared with the classic methods. Experimental results show that the visual quality and evaluation indexes outperform the other methods. The researches have important reference values in removing speckle noise.

1. Introduction

Polarization imaging technology gets images encoded by polarization degrees, which provides new information on the image compared with general imaging. It is already used in many aspects, for example, in target identification, aerosol detection [1], and so on. But polarization images are corrupted by speckles, which make images hard to interpret valuable information. So the reduction of speckle is meaningful preprocessing for advance application such as segmentation and feature extraction.

There are intensive researches in the speckle reduction [2,3], which can be broadly categorized as adaptive filter methods [4–11], wavelet transform methods [12–14], total variation methods [15–19], diffusion methods [20–26], and compound methods [27,28]. These algorithms cannot perform well in both despeckling and preserving edges of polarization images simultaneously. Given these premises, the nonlocal approach [29] looks like a potential breakthrough.

An adaptive nonlocal means algorithm based on fuzzy domain is proposed. The proposed method calculates the similarity measure in the fuzzy domain. The singular value decomposition (SVD) is used in the segmentation of gradient field. The *K*-means algorithm is employed in classification. The different block window is applied in different regions.

The paper is organized as follows. In Section 2, the polarization imagery system is presented. In Section 3, the FANLM is proposed. Section 4 compares the proposed approach with some classical speckle reduction methods. Finally, the conclusions are summarized in Section 5.

2. The polarization imagery system

The polarization imagery system is composed of four parts: emission of light, a polarization state generator (PSG), a polarization state analyzer (PSA), and detection and signal processing. The system is presented in Fig. 1. Light is emitted by a laser at 808 nm and passes through the PSG. After reflecting from two mirrors, the beam illuminates the target. The back scattered light is collected by a Cassegrain telescope, passes through the PSA, and is focalized on two CCD matrixes. A computer acquires the data and provides two images encoded in intensity.

In this system, the PSG is composed of a polarizer, a wave plate of retardance equal to 45° ($\lambda/8$ wave plate). The angle of the polarizer axis relative to the x axis is $-72.385°$, and the angle of the fast axis of the wave plate relative to the x axis is 45°. Therefore, the Mueller matrix of the PSG is given by

$$M_{PSG} = \begin{pmatrix} 1 & -\sqrt{2}/\sqrt{3} & -1/\sqrt{3} & 0 \\ -1/\sqrt{3} & \sqrt{2}/3 & 1/3 & 0 \\ -1/\sqrt{3} & \sqrt{2}/3 & 1/3 & 0 \\ -1/\sqrt{3} & \sqrt{2}/3 & 1/3 & 0 \end{pmatrix} \tag{1}$$

* Corresponding author. Tel.: +86 10 82339195.
E-mail address: dh_w10@163.com (W. Dong-hai).

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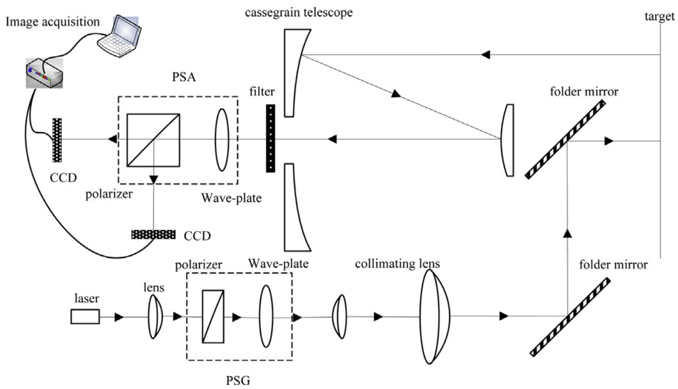

Fig. 1. The polarization imagery system.

so the Stokes vector of the light passed through PSG is

$$S_{in} = M_{PSG} \times \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ -1/\sqrt{3} \\ -1/\sqrt{3} \\ -1/\sqrt{3} \end{pmatrix} \tag{2}$$

if the target is not the birefringent material, so the Mueller matrix of the target can be expressed as:

$$M_{tar} = \begin{pmatrix} M_{00} & 0 & 0 & 0 \\ 0 & M_{11} & 0 & 0 \\ 0 & 0 & M_{11} & 0 \\ 0 & 0 & 0 & M_{33} \end{pmatrix} \tag{3}$$

so the Stokes vector of the scattered light by the target is given by

$$S_{out} = M_{tar}S_{in} = \begin{pmatrix} M_{00} & 0 & 0 & 0 \\ 0 & M_{11} & 0 & 0 \\ 0 & 0 & M_{11} & 0 \\ 0 & 0 & 0 & M_{33} \end{pmatrix} \begin{pmatrix} 1 \\ -1/\sqrt{3} \\ -1/\sqrt{3} \\ -1/\sqrt{3} \end{pmatrix} = \begin{pmatrix} M_{00} \\ -M_{11}/\sqrt{3} \\ -M_{11}/\sqrt{3} \\ -M_{33}/\sqrt{3} \end{pmatrix} \tag{4}$$

The PSA is composed of a wave plate of retardance equal to 45° ($\lambda/8$ wave plate) followed by a polarization beam splitter. The angle of the wave plate axis relative to the x axis is 45°, and the angle of the fast axis of the polarization beam splitter to the x axis is −72.385°.

The Mueller matrix of the PSA in the parallel state is given by

$$M_{PSA1} = \begin{pmatrix} 1 & -1/\sqrt{3} & -1/\sqrt{3} & -1/\sqrt{3} \\ \sqrt{2}/\sqrt{3} & \sqrt{2}/3 & \sqrt{2}/3 & \sqrt{2}/3 \\ -1/\sqrt{3} & 1/3 & 1/3 & 1/3 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{5}$$

and the Mueller matrix of the PSA in the crossed-state is expressed by

$$M_{PSA2} = \begin{pmatrix} 1 & 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \\ \sqrt{2}/\sqrt{3} & \sqrt{2}/3 & \sqrt{2}/3 & \sqrt{2}/3 \\ 1/\sqrt{3} & 1/3 & 1/3 & 1/3 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{6}$$

so the Stokes vector incident on the CCD in the parallel and crossed state is given by

$$S_{CCD1} = M_{PSA1}S_{out} = \begin{pmatrix} 1 & -1/\sqrt{3} & -1/\sqrt{3} & -1/\sqrt{3} \\ \sqrt{2}/\sqrt{3} & \sqrt{2}/3 & \sqrt{2}/3 & \sqrt{2}/3 \\ -1/\sqrt{3} & 1/3 & 1/3 & 1/3 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} M_{00} \\ -M_{11}/\sqrt{3} \\ -M_{11}/\sqrt{3} \\ -M_{33}/\sqrt{3} \end{pmatrix} = \begin{pmatrix} M_{00} + \frac{1}{3}(2M_{11} + M_{33}) \\ \sqrt{2}/\sqrt{3}(M_{00} - 2/3M_{11} - 1/3M_{33}) \\ -1/\sqrt{3}(M_{00} + 2M_{11}/3 + 1/3M_{33}) \\ 0 \end{pmatrix} \tag{7}$$

$$S_{CCD2} = M_{PSA2}S_{out} = \begin{pmatrix} 1 & 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \\ \sqrt{2}/\sqrt{3} & \sqrt{2}/3 & \sqrt{2}/3 & \sqrt{2}/3 \\ 1/\sqrt{3} & 1/3 & 1/3 & 1/3 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} M_{00} \\ -M_{11}/\sqrt{3} \\ -M_{11}/\sqrt{3} \\ -M_{33}/\sqrt{3} \end{pmatrix} = \begin{pmatrix} M_{00} - \frac{1}{3}(2M_{11} + M_{33}) \\ \sqrt{2}/\sqrt{3}(M_{00} - 2/3M_{11} - 1/3M_{33}) \\ -1/\sqrt{3}(-M_{00} + 2M_{11}/3 + 1/3M_{33}) \\ 0 \end{pmatrix} \tag{8}$$

The intensities detected by the CCD are given respectively by

$$I_1 = M_{00} + \frac{1}{3}(2M_{11} + M_{33}) \tag{9}$$

$$I_2 = M_{00} - \frac{1}{3}(2M_{11} + M_{33}) \tag{10}$$

so the polarization degree P_d is given by

$$P_d = \frac{2\left|M_{11}\right| + \left|M_{33}\right|}{3M_{00}} = \frac{I_1 - I_2}{I_1 + I_2} \tag{11}$$

3. Adaptive nonlocal means filter based on fuzzy domain

The proposed method consists of four steps: normalization, fuzzification, speckle reduction, and defuzzification.

3.1. Image normalization

The distribution of the gray levels in polarization images may vary greatly and the ranges of the intensities are quite narrow. Normalization is a step by mapping the intensity levels of the images in to the given ranges $[I_{\min}, I_{\max}]$:

$$I_{nor} = I_{\min} + \frac{(I_{\max} - I_{\min}) \times (I_o - I_{o\min})}{(I_{o\max} - I_{o\min})} \tag{12}$$

$I_{o\min}$ and $V_{o\max}$ are the minimum and maximum intensity levels of the original image; $I_{\min}$ and $I_{\max}$ are the minimum and maximum intensity levels of the normalized image; I_o and I_{nor} are the gray levels before and after normalization, respectively. Here we choose $I_{\min} = 40$ and $I_{\max} = 200$.