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Demosaicking using geometric duality and dilated directional differentiation

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A B S T R A C T

This paper presents a new demosaicking algorithm which uses two cost terms: the interpolation error of a low resolution image based on geometric duality and the dilated directional differentiation of color differences. Since a given high resolution image and its low resolution image obtained by sampling have similar edge properties, the proposed algorithm computes the interpolation errors for the candidate directions in the low resolution image, and exploits them as a cost term for the direction. In addition, the interpolation direction can be determined accurately even in the vicinity of object boundaries by dilating the directional differentiation of the color difference values. Through dilation, some pixels, which are in the neighborhood of an edge but classified into a flat region by simple edge detection like the Sobel filter, are reclassified. By combining this edge classifier and the weighted sum of the estimates obtained by Taylor approximation, missing pixels are interpolated. Simulation results show that the proposed demosaicking algorithm is superior to other state-of-the-art algorithms in terms of visual and objective qualities. Furthermore, the computational complexity is comparable with the existing algorithms. Therefore, the proposed algorithm is suitable for real-time implementation.

1. Introduction

Most digital still cameras (DSCs) acquire a color image using a single electronic sensor such as a charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) covered with a color filter array (CFA). The most commonly used CFA in recent years is the Bayer CFA pattern where green (G) components are sampled on a quincunx grid, and red (R) and blue (B) components are obtained by rectangular grids with different phases, as shown in Fig. 1 [1]. That is, each pixel position has only one color component; hence, an estimation process for the two missing components is required, which is known as color interpolation or demosaicking [2,3].

Green components in the Bayer CFA pattern are twice as dense as red or blue components, and are generally considered as a luminance channel because their spectral response seems to be the spectral response of the human visual system [4]. For this reason, most demosaicking algorithms populate green components first, and then the other components are interpolated with the use of the populated green components.

In order to estimate the missing components accurately and effectively, demosaicking algorithms using color differences between the green plane and red/blue planes have been proposed [5–15]. These methods interpolate missing pixels under the assumption that color differences are constant in a small region. However, the assumption does not hold in regions where an edge exists because color differences drastically change. Accordingly, many algorithms perform edge detection first, and then interpolate missing pixels along the detected edge direction, and not across the edge. Adaptive color plane interpolation (ACPI) is an early demosaicking algorithm that provides an edge-sensing interpolation strategy [5]. ACPI makes three predictors, and then chooses one of them via an edge classifier that is composed of the Laplacian second order term for the red or blue plane and the gradient term for the green plane. The effective color interpolation (ECI) method uses color differences between green and red/blue planes to populate missing pixels [6]. Based on ECI, Chang et al. proposed enhanced ECI (EECI) which utilizes pixel differences as weights [7]. After the initial interpolation using the weights, the refinement is applied to improve the initial interpolated values. Adaptive homogeneity-directed (AHD) interpolation is based on color homogeneity in the CIELAB space [8]. To detect a reliable edge, Chung et al. proposed a demosaicking algorithm using the variance of color differences (VCD) [9]. In VCD, missing green pixels are classified into two cases: on a sharp edge and on a non-sharp edge. To determine whether a pixel is on a sharp edge or not, the gradient change in the 5×5 testing window is calculated. Directional filtering and a posteriori decision (DFPD) uses the sum of the gradients in a 5×5 window in the horizontal and vertical directions, respectively [10]. Color demosaicking

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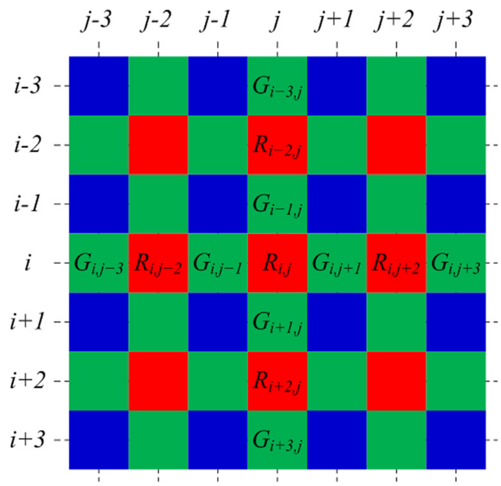

Fig. 1. 7×7 Bayer CFA pattern. i and j are row and column numbers, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with directional filtering and weighting (CDDFW) combines and improves DFPD and EECI [11]. High-order interpolation (HOI) with a weighted median filter proposed by Li and Randhawa makes use of a Taylor series for interpolation and a weighted median filter to select a preferable predictor [12]. Effective demosaicking using subband correlation (EDUSC), proposed by Su et al., introduces a discrete wavelet transform to classify edge pixels [13]. Recently, Chen and Chang proposed an effective demosaicking algorithm based on edge property (EDAEP), where they added fixed weights to the interpolation method of ECI [14].

Several methods exploit the frequency property of the CFA image. Regularization approaches to demosaicking (RAD) utilize the frequency property to estimate the luminance components, and provide spatially adaptive regularization [16]. Dubois introduced a luma-chroma demultiplexing algorithm [17], and then used a least-squares strategy to design an optimal filter [18].

In this paper, a new demosaicking algorithm is proposed in order to improve the quality of the reconstructed images. The proposed algorithm is composed of three steps: predictor generation, edge classification, and refinement. The proposed algorithm uses three predictors, which are based on a Taylor series. To provide a more accurate and pleasing method to determine edge direction, the interpolation errors based on geometric duality and the dilated differential differentiations are considered as costs. For refinement, we use weighted sum strategy in color difference plane, where the weights used for predictor generation are re-used.

The remainder of the paper is organized as follows. Section 2 describes the related work such as Taylor approximation in demosaicking and edge dilation. The details of the proposed algorithm including the three steps are explained in Section 3. Section 4 reports detailed simulation results and comparisons in terms of objective quality measures and computational complexity. Conclusions are presented in Section 5.

2. Related work

2.1. Taylor approximation in demosaicking application

A real- or complex-valued function, $f(x)$, that is infinitely differentiable at a real or complex number, a, can be represented by a Taylor series [19,20]:

$$f(x)=f(a)+f'(a)\cdot(x-a)+\frac{f''(a)}{2!}\cdot(x-a)^2+\frac{f^{(3)}(a)}{3!}\cdot(x-a)^3+\cdots, \quad (1)$$

where the first derivative should be expressed as the discrete form, central difference approximation, for color interpolation as follows:

$$f'_i=\frac{f_{i+1}-f_{i-1}}{(i+1)-(i-1)}. \quad (2)$$

Considering the Bayer CFA shown in Fig. 1 and assuming that the color differences between the green and red or blue planes ($KR=G-R$, $KB=K-B$) are quite constant in small areas, a green pixel value at a red pixel position is approximated from the west to the center by

$$\tilde{G}^W_{i,j}=G_{i,j-1}+\frac{R_{i,j}-R_{i,j-2}}{2}+\frac{G_{i,j+1}-2G_{i,j-1}+G_{i,j-3}}{8}. \quad (3)$$

The approximations from east, north, and south can be obtained in a similar way. The HOI uses these four directional approximations as predictors, and applies a weighted median filter [12]. In the proposed method, we use three estimates generated by the weighted sum of the approximations and apply a new edge classifier, the details of which will be explained in Section 3.

2.2. Edge dilation

Edge information is generally perceived by the human visual system when the pixel intensity difference between two adjacent objects is large enough. Considering this property, most edge detection algorithms such as Prewitt and Sobel edge detectors determine whether a pixel is on an edge or not using a 1st or 2nd order differential value as follows [16]:

$$I'^H_{i,j}=|\nabla^H I_{i,j}|,$$
$$I'^V_{i,j}=|\nabla^V I_{i,j}|, \quad (4)$$

where ∇^H and ∇^V are the operators to calculate the directional differential values along the horizontal and vertical directions, respectively. Fig. 2(b) and (c) shows the differential images generated by a Sobel mask:

$$I'^H=\left|I*\begin{bmatrix}1&0&-1\\2&0&-2\\1&0&-1\end{bmatrix}\right|,\quad I'^V=\left|I*\begin{bmatrix}1&2&1\\0&0&0\\-1&-2&-1\end{bmatrix}\right| \quad (5)$$

where $*$ is the convolution operator and the range is rescaled to [0, 255] for visual expression. Fig. 2(d) and (e) shows the edge maps obtained by a thresholding process:

$$map^H_{i,j}=\begin{cases}1 & \text{if } I'^H_{i,j}+T<I'^V_{i,j}\\0 & \text{otherwise}\end{cases}$$
$$map^V_{i,j}=\begin{cases}1 & \text{if } I'^V_{i,j}+T<I'^H_{i,j}\\0 & \text{otherwise}\end{cases} \quad (6)$$

where threshold T is a predetermined value, which provides a middle zone where a pixel does not belong to the horizontal or the vertical edge. We set predetermined value $T=15$. As one can observe, edge maps generated by the Sobel edge detector consist of very thin lines located on the borderlines of objects. In that case, pixels in the vicinity of a borderline but not on the borderline are determined as non-edge and are therefore interpolated by inappropriate estimates.

In order to tackle this problem, an edge dilation scheme is applied in the proposed algorithm. Let Fd be the dilation filter.