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Aliasing artifacts reduction with subband signal analysis for demosaicked images

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ABSTRACT

Demosaicking is a process used to estimate missing color values from the subsampled color filter array (CFA) image to reduce the cost and volume of a digital still camera. However, by sampling theory, it is known that subsampling a signal causes overlaps of signals in the frequency domain, which is known as aliasing. Most current demosaicking processes cannot completely solve aliasing problem resulting in aliasing artifacts such as false colors and zipper effects. In this paper, we propose an algorithm to remove these aliasing artifacts in demosaicked color images. A luminance image with minimum aliasing is obtained from the CFA image by using a low-pass kernel with cutoff frequencies determined by an approximate model for the Fourier spectrum. An aliasing map is computed by analyzing subband signals of the CFA image based on the high correlation of the high-frequencies of the luminance and color channels. Then, a least squares of the luminance acquisition processes is used to design a cost function with the aliasing map to remove the aliasing artifacts. The experiments demonstrate that the proposed algorithm sufficiently removes aliasing artifacts and improves the quality of the color images.

1. Introduction

In modern image capturing devices, a single sensor covered by the Bayer color filter array (CFA) is widely used to reduce the cost and the size of the sensors in digital still cameras [1]. Generally, the Bayer CFA is installed in front of the sensor so that only one intensity value among three primary colors, red (R), green (G), and blue (B), is captured. To acquire full-resolution color images, a demosaicking process fills the pixels with all the color channels from the CFA images containing subsampled color channels. However, because subsampling a signal causes the overlaps of signals in the frequency domain, as explained by sampling theory, aliasing artifacts such as false colors and zipper effects are often produced in the demosaicking process.

Demosaicking methods to interpolate the missing color channels can be classified, which are the method considering the directions of edges, the method using the cost function based on the image acquirement model, and the method minimizing the residual errors and considering local structures. Firstly, an edge directional demosaicking method using a color ratio model was introduced [2]. The edge directional demosaicking strategy using color difference domains was presented [3]. Based on the inter-channel correlations, an alternating projection demosaicking scheme was designed [4]. Lu et al. proposed a demosaicking method considering the spatial and spectral correlations [5]. By classifying the image region into three types, such as edges, edge patterns, and flat regions, an edge directional demosaicking method was explained [6]. New directional predictors based on Taylor series are used with spatial and spectral correlations and the adaptive fusion strategy improves the green channel interpolation [7]. In addition, with highly correlated channels, the multiscale color gradients were used to combine the color difference estimates to interpolate the red and blue channels [8]. When the directions of edges were determined in the above methods, errors which occur in the demosaicking process produce false colors and zipper effects in high-frequency regions.

Another class of demosaicking methods is based on the cost function that considers the type of CFA arrangements and the properties of the point spread functions (PSF). A least squares that considered the characteristics of the adaptive frequency domain was explained [9]. A regularization approach was explained [10], using prior knowledge about natural color images. In order to preserve the sharp color edges without producing ringing artifacts and color artifacts, a total variation regularization was presented [11]. In addition, a new joint demosaicking and decrosstalk technique which was adaptive to varying spectral correlations by the inverse

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filtering of least squares was introduced [12]. Hirakawa et al. presented a demosaicking operation with a total least squares which is combined with denoising [13]. A least squares methodology was used to find band-pass filters for luminance and chrominance signals [14]. When estimating color images by minimizing the cost functions, artifacts could be produced by the errors of the image acquirement modeling.

The residual interpolation as an alternative to the color difference interpolation, where the residual is a difference between an observed and a tentatively estimated pixel value, was proposed [15]. The approach that a residual interpolation method was deployed iteratively to all the three channels was presented [16]. To infer missing colors, self-similarity within neighboring pixels was used to avoid producing artifacts [17]. The nonlocal redundancy of an image was exploited to improve the local color reproduction result by using multiple local directional estimates of a missing color sample with an adaptive thresholding method [18]. Although artifacts were reduced by minimizing the difference between channels, the high-frequencies of images could not be reconstructed.

To remove aliasing artifacts in demosaicked color images, several post-processing methods have been introduced in recent years. Kimmel proposed the inverse diffusion method along the edge for color image enhancement [2]. To suppress visible color artifacts, the method which smoothed color difference values iteratively and made them constant within an object was proposed [19]. By applying a median filter in the color difference domains, aliasing artifacts were eliminated while the edges were preserved [5]. To remove false colors more effectively, different size of two median filters were used and they were applied adaptively according to the local variances of interchannel differences in the research [20]. In addition, based on a localized color ratio model, a post-processing technique to minimize color differences in the edge regions was explained [21]. In a CFA sensor including the white channel, an edge refinement is applied by considering correlation based on high-frequency reconstruction [22]. All of the above methods were proposed to reduce false colors, however, zipper effects still remained in the demosaicked color images and the improvements of the image quality were limited.

The main contribution of this paper is the analysis and measurement of aliasing using a mathematical method. In the frequency domain, the CFA image can be represented as the luminance and modulated chrominance signals. Based on this, the proposed method obtains the luminance image including the minimum aliasing and estimates the amount of aliasing by using the subband signals of the color channels and the luminance signal. Furthermore, aliasing artifacts are removed by using the obtained luminance image rather than by minimizing the errors between the color channels.

The remainder of this paper is organized as follows. Section 2 describes the method to estimate a luminance image and an aliasing map. In addition, the proposed cost function for removing aliasing artifacts is explained. Section 3 demonstrates good performance of our proposed method. We conclude this paper in Section 4.

2. Proposed algorithm

An overall block diagram of the proposed algorithm is illustrated in Fig. 1. From using the CFA image, the luminance image and aliasing map are estimated. Then, the least squares problem of the luminance image acquisition models with the aliasing map is solved to estimate a color image without aliasing artifacts.

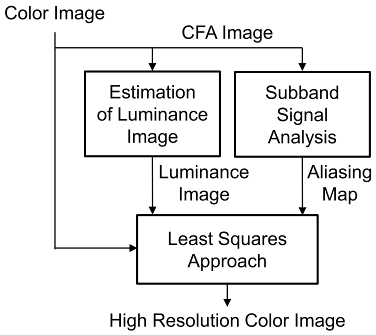
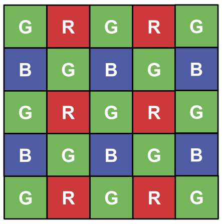


Fig. 1. Block diagram of proposed algorithm.



G	R	G	R	G
B	G	B	G	B
G	R	G	R	G
B	G	B	G	B
G	R	G	R	G

Fig. 2. Pattern of Bayer CFA image.

2.1. Estimation of luminance image

Let $f_C[n_1, n_2]$ express the CFA image whose size is $N_1 \times N_2$ in the pixel location n_1 and n_2 for the horizontal and vertical axes where $n_1 = 0, \cdots, N_1 - 1$ and $n_2 = 0, \cdots, N_2 - 1$. The color channels R, G, and B are denoted as $f_R[n_1, n_2]$, $f_G[n_1, n_2]$, and $f_B[n_1, n_2]$, respectively. Likewise, the subsampled color channels in the CFA image are denoted as $f_R^s[n_1, n_2]$, $f_G^s[n_1, n_2]$, and $f_B^s[n_1, n_2]$, respectively. According to the Bayer pattern as plotted in Fig. 2, we formulate the CFA signal $f_C[n_1, n_2]$ with the subsampled color channels in the discrete domain as

$$f_C[n_1, n_2] = f_G^s[n_1, n_2] + f_R^s[n_1, n_2] + f_B^s[n_1, n_2], \tag{1}$$

where the subsampled color channels are represented with subsampling functions as

$$\begin{aligned} f_G^s[n_1, n_2] &= f_G[n_1, n_2](1 + (-1)^{n_1+n_2})/2 \\ f_R^s[n_1, n_2] &= f_R[n_1, n_2](1 - (-1)^{n_1})(1 + (-1)^{n_2})/4 \\ f_B^s[n_1, n_2] &= f_B[n_1, n_2](1 + (-1)^{n_1})(1 - (-1)^{n_2})/4. \end{aligned} \tag{2}$$

The color channels $f_R[n_1, n_2]$, $f_G[n_1, n_2]$, and $f_B[n_1, n_2]$ are expressed as a luminance and two chrominance signals $f_L[n_1, n_2]$, $f_{C_1}[n_1, n_2]$, and $f_{C_2}[n_1, n_2]$ by using the following linear decomposition equation,

$$\begin{pmatrix} f_L \\ f_{C_1} \\ f_{C_2} \end{pmatrix} = \frac{1}{4} \begin{pmatrix} 1 & 2 & 1 \\ -1 & 2 & -1 \\ -1 & 0 & 1 \end{pmatrix} \begin{pmatrix} f_R \\ f_G \\ f_B \end{pmatrix}. \tag{3}$$

Applying $-1 = e^{j\pi}$ to (2) and using (3), the CFA signal in (1) is rewritten as

$$\begin{aligned} f_C[n_1, n_2] = f_L[n_1, n_2] &+ f_{C_1}[n_1, n_2] e^{j\pi(n_1+n_2)} \\ &+ f_{C_2}[n_1, n_2] e^{j\pi n_1} - f_{C_2}[n_1, n_2] e^{j\pi n_2}. \end{aligned} \tag{4}$$

Applying the Fourier transform to this, (4) becomes as

$$\begin{aligned} F_C(u, v) = F_L(u, v) &+ F_{C_1}(u - \pi, v - \pi) \\ &+ F_{C_2}(u - \pi, v) - F_{C_2}(u, v - \pi). \end{aligned} \tag{5}$$