Wavelet-based Color Filter Array demosaicking

J. Driesen, P. Scheunders
Vision Lab, Department of Physics, University of Antwerp
Groenenborgerlaan 171, 2020 Antwerpen, Belgium
Tel.: +32 3 218 04 39; Fax.: +32 3 218 03 18
Email: Jef.Driesen@ua.ac.be, scheun@ruca.ua.ac.be

Abstract

In this paper, a wavelet-based technique for the demosaicking of Color Filter Arrays (CFA) is proposed. Conventional demosaicking techniques perform interpolation of the missing pixels in the YC_rC_b color space, where emphasis is put on an optimal interpolation of the luminance. We make advantage of this by merging the obtained luminance image with interpolated R,G and B images. The merging is performed in a multiresolution way, using the wavelet transform. This postprocessing technique is demonstrated to outperform traditional demosaicking interpolation techniques, visually as well as quantitatively, using two measures, the PSNR and ΔE^*_{ab}, which is a measure for the average color distance between original and demosaicked images in the CIELAB color space.

1 Introduction

Single-sensor digital cameras capture imagery by covering the sensor surface with a color filter array (CFA) such that each sensor pixel only samples one of three primary color values. To render a full-color image, an interpolation process, commonly referred to as CFA demosaicking, is required to estimate the other two missing color values at each pixel.

Some conventional demosaicking techniques are bilinear interpolation, the Bayer reconstruction technique [1] and the gradient-based reconstruction technique [2]. Recently, adaptive techniques for demosaicking were proposed for an improved edge preservation and/or avoiding of color artifacts. These techniques are based on correlations between the color bands [3], fuzzy techniques [4], Markov Random Fields [5] or Neural Networks [6]. Most of the proposed demosaicking techniques perform an interpolation of the missing color components in the YC_rC_b space, where emphasis is put on an optimal interpolation of the luminance image.

In this paper, instead of proposing an alternative technique for the interpolation, we try to employ the higher spatial resolution of the luminance image, by merging it with the interpolated color image. The technique that we propose originates from the field of remote sensing where it is employed to merge images of high spatial resolution with multispectral images of lower spatial resolution [7]. For this merging, multiresolution techniques using the wavelet transform have been the most successful [8, 9]. We employ the wavelet transform for the merging of an interpolated luminance image with an interpolated color image, where the conventional interpolation techniques are applied. The idea behind this merging technique is that the detail coefficients of the wavelet transformed luminance image are merged into the wavelet transform of the color component images, in order to enhance the spatial resolution of the latter, while preserving the color information. We will demonstrate that this technique outperforms conventional demosaicking techniques using PSNR and color distance in the CIELAB color space as objective measures, and visually.

2 Conventional demosaicking techniques

The Bayer pattern (fig. 1) is the most widely used CFA configuration [10]. In this pattern, for 50% of the pixels the green component is given, and for the remaining pixels the given component is red or blue.

2.1 bilinear interpolation

The simplest reconstruction of the colors is given by a bilinear interpolation, in which the missing color components of a pixel are found by averaging the corresponding given components in a 3 by 3 local window around the pixel. For the missing green components, this means an averaging of the 2 horizontal and 2 vertical neighbors. For the missing red (blue) components of a pixel with given green component, this means an averaging of the 2 horizontal or vertical

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

Figure 1. Bayer CFA pattern

neighbors, and for a pixel with given blue (red) component, an averaging of the 4 diagonal neighbors.

2.2 Bayer reconstruction

In this reconstruction [1], a color transform to the YC_rC_b color space is performed. The Luminance image Y is reconstructed from the green components, where the missing green components are found by bilinear interpolation. Then the Chromaticity values C_r (C_b) for the pixels where the red (blue) component is given are found by: $C_r = R - Y$ ($C_b = B - Y$). The missing C_r (C_b) values are found by bilinear interpolation. After this, the result is inversely transformed back to RGB space.

An alternative Bayer reconstruction first finds average values for the R,G and B components by averaging in a 5 by 5 window. Then, these average values are transformed to average luminance $\overline{Y}$ and chromaticity values $C_r = \overline{R} - \overline{Y}$, $C_g = \overline{G} - \overline{Y}$ and $C_b = \overline{B} - \overline{Y}$. An estimation of the luminance is then given by: $Y = R - C_r$ for a pixel with given red component, $Y = G - C_g$ for a pixel with given green components and $Y = B - C_b$ for a pixel with given blue component. Finally, the inverse transform to RGB is performed.

2.3 gradient reconstruction

In this reconstruction [2], the luminance is estimated in yet another way, again from the green components. This time, the missing green components are interpolated, depending on edge information that is obtained by looking at the second derivative of the red (or blue) components. This procedure better preserves edges while interpolating. The reconstruction of the chromaticity values is the same as with the Bayer reconstruction.

3 Wavelet-based demosaicking

Since redundant wavelet transforms are favored over orthogonal ones, because of their shift-invariance property, the applied wavelet transform in this paper is the redundant dyadic transform from Mallat [11]. For this transform, the mother wavelets $\psi^x(x,y)$ and $\psi^y(x,y)$ are quadratic spline wavelets of compact support. The detail images $D_j^*(x,y)$ are convolutions in the $*$-direction ($* = x$ or y) with scaled versions of these mother wavelets; the scale parameter j is a power of 2.

The proposed demosaicking technique works as follows.

- In a first step, a luminance image is formed. This can be done in one of the conventional ways (bilinear interpolation of the green pixels as in the Bayer reconstruction, the alternative Bayer reconstruction or the gradient reconstruction). Also, the red, green and blue component images are interpolated in a conventional way. In the presented conventional techniques, the luminance image is of higher spatial resolution than the interpolated RGB image.

- Then, the luminance image and each band of the RGB image is wavelet transformed separately, leading to wavelet coefficients $D^*_{L,j}(x,y), D^*_{R,j}(x,y), D^*_{G,j}(x,y)$ and $D^*_{B,j}(x,y)$.

- The merging procedure works as follows: at each scale and at each position, the wavelet coefficients of each band of the color image are modified according to the corresponding wavelet coefficients of the luminance image. Two merging rules are investigated: the 'replace' rule replaces the coefficients from the color band by the coefficients from the luminance image:

$$\begin{aligned} D^*_{R,j}(x,y) &= D^*_{L,j}(x,y) \\ D^*_{G,j}(x,y) &= D^*_{L,j}(x,y) \\ D^*_{B,j}(x,y) &= D^*_{L,j}(x,y) \end{aligned} \tag{1}$$

  The 'max' rule replaces the coefficients from the color band by the maximum of the coefficients from the luminance and the color band:

$$\begin{aligned} D^*_{R,j}(x,y) &= \text{Max}(D^*_{R,j}(x,y), D^*_{L,j}(x,y)) \\ D^*_{G,j}(x,y) &= \text{Max}(D^*_{G,j}(x,y), D^*_{L,j}(x,y)) \\ D^*_{B,j}(x,y) &= \text{Max}(D^*_{B,j}(x,y), D^*_{L,j}(x,y)) \end{aligned} \tag{2}$$

- Finally the obtained color wavelet coefficients are inversely wavelet transformed to obtain the demosaicked RGB image.

conventional		ΔE^*_{ab}	PSNR (dB)
Bilinear		3.28	25.7
Bayer		3.08	27.2
Bayer2		1.92	28.0
Gradient		1.78	28.2
Merging	depth		
max	1	1.42	28.5
	2	1.43	28.6
	3	1.58	28.5
replace	1	1.38	28.7
	2	1.54	28.7
	3	1.98	28.5

Table 1. Obtained values for ΔE^*_{ab} and PSNR using conventional and wavelet-based demosaicking on the image 'lighthouse'

4 Experiments and discussion

In order to demonstrate the performance of the proposed technique, it is compared to the conventional demosacking techniques: bilinear interpolation, Bayer reconstruction, alternative Bayer reconstruction and gradient reconstruction. As objective measures, the color distance in CIELAB color space, ΔE^*_{ab} and the PSNR of the demosaicked image with the original image are calculated. Using the proposed technique, the different conventional interpolation procedures for the luminance as well as the color component images were all applied. It was found that the results were almost insensitive to the applied interpolation on the luminance, but were very sensitive to the applied interpolation on the color component images. The best results were obtained using the Bayer interpolation procedure. In table 1, results are shown on the 'lighthouse' image for the conventional techniques and for the wavelet-based technique for different values of j and for the two merging procedures 'max' and 'replace'. Bayer2 reconstruction was applied a priori to the luminance image and Bayer to the RGB images. In figure 1, the resulting images are shown for the four conventional techniques and for the 'max' and 'replace' wavelet-based approach for $j = 4$.

From the results we can conclude that:

- The wavelet-based techniques outperform the conventional techniques with respect to ΔE^*_{ab}-value as well as PSNR.
- For larger values of j, the performance of the wavelet-based techniques goes down. This is especially true for the ΔE^*_{ab}-value. This is due to a deviation of the colors, which can be seen visually. The effect is less prominent using the 'max' merging rule.
- The wavelet-based approaches result in an improved reconstruction of edges, with less aliasing effects. This can clearly be seen visually.

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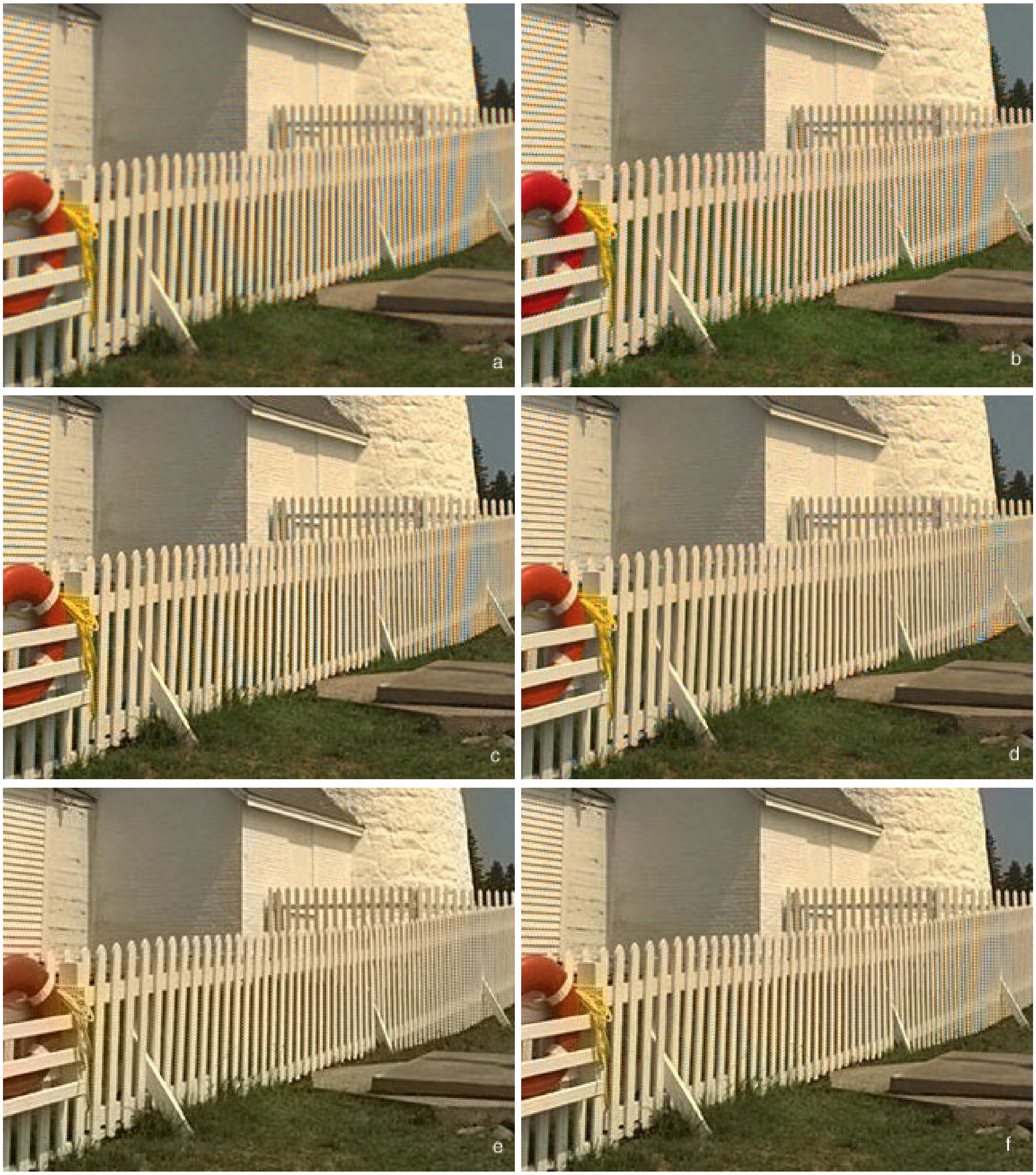

Figure 2. Demosaicked results of the image ’lighthouse’, using a: bilinear interpolation; b: the bayer reconstruction; c: the alternative Bayer reconstruction; d: the gradient reconstruction; e: wavelet-based reconstruction using the ’replace’ rule; f: using the ’max’ rule.