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LETTER

Color filter array color reproduction using cycle-spinning

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ABSTRACT

Color filter array (CFA) color reproduction aims to produce an image with full color information from its CFA counterpart. Conventional subband synthesis based color reproduction technique utilizes the decimated wavelet transform, which is *not* shift-invariant and could result in ringing artifacts in the resulting color image. To alleviate these artifacts, the *cycle-spinning* (CS) technique is introduced in this Letter to perform CFA color reproduction. Experiments are conducted to demonstrate the superior performance of the proposed approach.

1. Introduction

The aim of *color filter array* (CFA) color reproduction is to produce an image with full color information from its CFA counterpart (e.g., the Bayer pattern), in which only a single color component (i.e., Red, Green or Blue) is presented at each spatial pixel position [1]. Recently, there has been growing interest in developing subband synthesis based algorithms for CFA color reproduction [2,3]. The common feature of these algorithms is to exploit the decimated wavelet transform to estimate the missing pixels at each color channel from their subband counterparts in the other color channels, inspired by that there exists strong inter-channel correlations in high-frequency components of images.

The major challenge inherent with the above subband synthesis based methods [2,3] is that the decimated wavelet transform is *not* shift-invariant. Consequently, non-exact estimation of high-frequency subband coefficients introduces cyclostationarity into the image, which then suffers from ringing artifacts particularly in the neighborhood of discontinuities [4]. To tackle the above challenge, the *cycle-spinning* (CS) technique, which was first introduced in [4], has been proved to be effective against the above artifacts for the purpose of image denoising [4,5], resolution enhancement [6–8] and compression artifacts removal [9]. Motivated by this, the CS technique is introduced in this Letter to perform CFA color reproduction .

Our motivation is that if the input CFA image data is translated, interpolated (using the subband synthesis technique based on the decimated wavelet transform), and then translated back, the result will, in general, be different from the estimate obtained from that without shifting. To justify this, an experiment is conducted using *image* 9 to show that different interpolated color images, which use different translated versions of the CFA image as the input, yield different PSNR performance (see Table 1). Same conclusions are applicable to 200 color images, including indoor and outdoor images, obtained from the Internet. These interpolated images could yield certain artifacts, which are statistically different and could be reduced by linear averaging. Therefore, the average of these interpolated images, is expected to yield less artifacts than the individual interpolated image. It may be argued that whether the linear averaging is the best way to utilize the information from the above multiple interpolated images. This issue is out of the scope this paper. An insightful discussion on this issue can be found in [5]. On the other hand, our experiments presented in Section 3 will verify that the linear average of the above multiple interpolated images yields superior performance to that of the individual interpolated image (without translating).

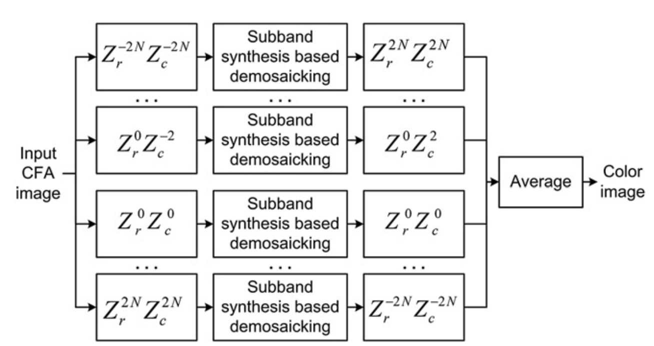

Fig. 1. An overview of the proposed cycle-spinning demosaicking approach, where Z_r and Z_c denote the spatial translation operations in the row and column directions, respectively.

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Fig. 2. Test images (referred to as *Image* 1 to *Image* 10, numbered from left to right and top to bottom).

Table 1
The PSNR (in dB) performance comparison among different interpolated color images using different translated-versions of the CFA image as the input. The CFA image is first translated in both row and column directions, respectively, then interpolated using the subband synthesis technique [3], and finally translated back, and compared with the ground truth (i.e., *Image* 9) to compute the PSNR performance.

Translations in the row direction	0	0	2	2
Translations in the column direction	0	2	0	2
PSNR	31.54	31.85	31.81	32.05

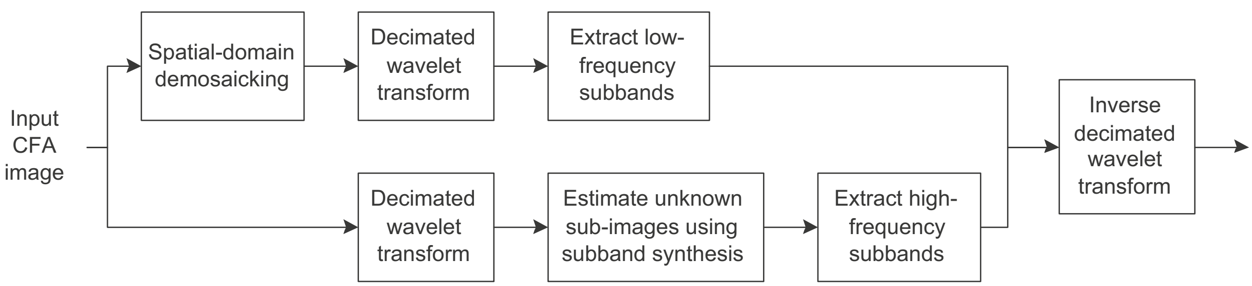

Fig. 3. An overview of the conventional subband synthesis based CFA color reproduction algorithms.

The rest of this Letter is organized as follows. A formulation for the color reproduction problem is provided in Section 2, followed by the proposed color reproduction approach using cycle spinning. Extensive experimental results are provided in Section 3. Finally, Section 4 concludes this Letter.

2. Proposed CFA color reproduction approach using cycle-spinning

2.1. Problem formulation

A mathematical formulation of the CFA color reproduction problem is provided as follows. Take the color reproduction process for the red color channel as an example. Similar formulations are applicable to the green and blue components of the CFA image. Denote $\mathbf{X}_r$ and $\hat{\mathbf{X}}_r$ as the original and reconstructed data of the red color channel, each of which is an $M \times N$ matrix. According to the Bayer pattern [1], the observed red data (denoted as $\mathbf{Y}_r$) can be viewed as a down-sampled version of the original red data $\mathbf{X}_r(1:2:M, 2:2:N)$ with a size of $M/2 \times N/2$ (i.e., one fourth of that of the original data), that is,

$$\mathbf{Y}_r = \mathbf{X}_r(1:2:M, 2:2:N). \tag{1}$$

The aim is to estimate the missing color information of other three sub-images, i.e., $\hat{\mathbf{X}}_r(1:2:M, 1:2:N), \hat{\mathbf{X}}_r(2:2:M, 1:2:N)$, $\hat{\mathbf{X}}_r(2:2:M, 2:2:N)$ based on the observed sub-image $\mathbf{Y}_r$.

2.2. Proposed approach

The objective of the proposed approach (see Fig. 1) is to utilize the CS technique to first generate several spatially translated versions of the input CFA data, then produce their respective color images with full color information using conventional subband synthesis based techniques, finally realign and linearly average the-above reconstructed color images to obtain a final result.

Denote $\hat{\mathbf{X}}_r^{\langle i,j \rangle}$ as the reconstructed data using $\mathbf{Y}_r^{\langle i,j \rangle}$ as the input, which is obtained by translating the observed data $\mathbf{Y}_r$ by i and j pixels in the row and column directions, respectively. Then the final reconstructed image is

$$\hat{\mathbf{X}}_r = average\left\{\hat{\mathbf{X}}_r^{\langle i,j \rangle}\right\}, \quad i \in \Omega_i, j \in \Omega_j, \tag{2}$$

where Ω_i and Ω_j represent the permissable translating parameters for the row and column directions, respectively. The above sub-images (i.e., each $\hat{\mathbf{X}}_r^{\langle i,j \rangle}$) are estimated using subband synthesis based techniques, as illustrated in Fig. 3. First, an initial full color image is estimated (say, using edge-directed interpolation). Then the subband synthesis technique is exploited to estimate the unknown pixels by producing their high-frequency subbands from those of the observed pixels (i.e., $\mathbf{Y}_r$), and obtaining their low-frequency subbands from that of the initially-interpolated image (refer to [2,3] for details).

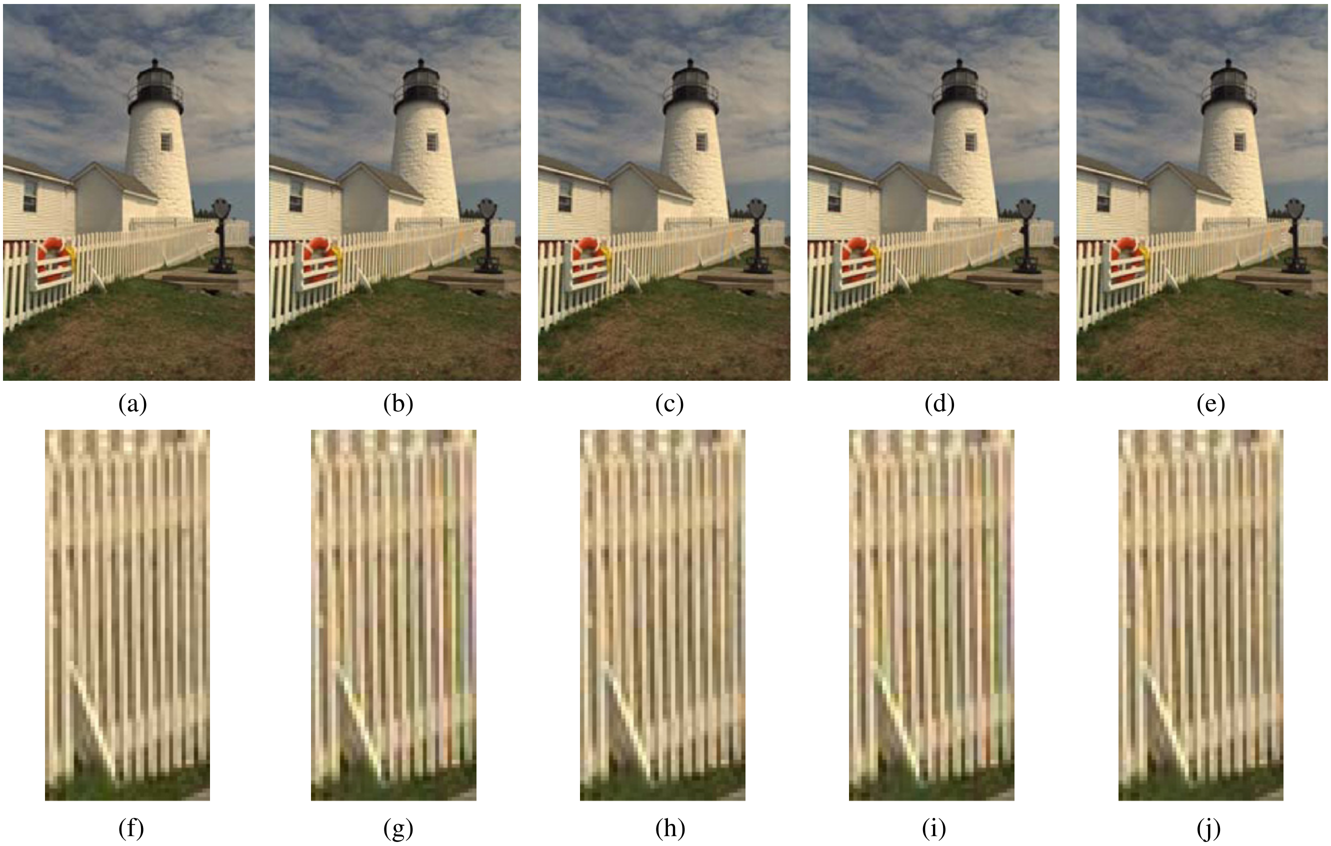

Fig. 4. Various demosaicking results of *Image* 8: (a) original image (ground truth); (b) algorithm [2] (PSNR = 34.05 dB); (c) proposed CS approach + algorithm [2] (PSNR = 35.85 dB); (d) algorithm [3] (PSNR = 34.20 dB); (e) proposed CS approach + algorithm [3] (PSNR = 35.98 dB); (f)–(j) are the zoomed parts of images (a)–(e), respectively.

The proposed approach can be summarized as below:

- For each i and j, where $i \in \Omega_i = \{-2 \times N, \ldots, -2, 0, 2, \ldots, 2 \times N\}$, and $j \in \Omega_j = \{-2 \times N, \ldots, -2, 0, 2, \ldots, 2 \times N\}$. Note that i and j need to be even integer, since the Bayer CFA data is sampled every two rows (columns) in each color channel.
    - Generate a translated version of the input CFA data via circularly translating it by i and j pixels in row and column dimensions, respectively.
    - Perform the color reproduction computation using conventional subband synthesis based methods developed in [2] or [3].
    - Realign the reconstructed color images via circularly translating it by $-i$ and $-j$ pixels in row and column dimensions, respectively.
- Produce the final result via computing the linearly average of the above reconstructed color images.

3. Experimental results

Experiments are conducted to compare the proposed approach with two color reproduction methods [2,3], which are implemented by ourselves, using 10 test images (see Fig. 2). Two image quality evaluation criterions are used; they are (i) PSNR and (ii) ΔS-CIELab [10], both of which are commonly used for evaluating CFA color reproduction methods [1]. A larger PSNR value and/or a smaller ΔS-CIELab value indicates a better image quality. The wavelet transform is implemented using the *Daubechies* 9/7 filters. The translation parameter (i.e., N) used in the proposed cycle-spinning approach is experimentally selected to be 3. As

Table 2
The PSNR (in dB) performance comparison.

Test image	Method [2]	Proposed CS + method [2]	Method [3]	Proposed CS + method [3]
1	28.02	29.68	28.00	29.64
2	37.05	37.76	36.86	37.32
3	33.27	34.30	33.33	34.34
4	33.87	35.04	33.83	34.92
5	30.60	31.65	30.63	31.64
6	37.11	39.27	37.01	39.16
7	34.37	35.44	34.43	35.41
8	34.05	35.85	34.20	35.98
9	31.49	33.55	31.54	33.60
10	37.96	39.28	38.18	39.41

The output PSNRs have been averaged over Red, Green and Blue color channels.

Table 3
The ΔS-CIELab [10] performance comparison.

Test image	Method [2]	Proposed CS + method [2]	Method [3]	Proposed CS + method [3]
1	4.07	3.94	3.55	3.40
2	1.02	0.95	1.03	0.96
3	1.60	1.47	1.63	1.50
4	1.55	1.42	1.69	1.58
5	2.63	2.41	2.64	2.44
6	0.88	0.78	0.92	0.82
7	1.37	1.26	1.40	1.33
8	1.43	1.30	1.45	1.35
9	1.55	1.39	1.62	1.45
10	0.70	0.65	0.72	0.69

seen from Tables 2 and 3 (for objective performance comparison), plus Fig. 4 (for subjective performance comparison), the proposed approach always outperforms the methods [2,3].

4. Conclusions

The CS technique has been successfully introduced in this Letter to perform CFA color reproduction. The proposed approach yields superior objective and perceptual performance to a number of approaches developed in the literature, as verified in experimental results.

Acknowledgments

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