Comparative Study of Demosaicing Algorithms for Bayer and Pseudo-Random Bayer Color Filter Arrays

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Abstract: *The image registration by digital cameras and video cameras requires digital filters to be posed onto the photo-sensitive sensors (CCD and CMOS). The filters are arranged in patterns across the face of the image sensing array. The most commonly used color filter array is Bayer pattern. An alternative of this pattern is a Pseudo-Random Bayer color filter array (CFA). Its structure differs considerably from the regular structure of the original Bayer filter. The purpose of this research is to present a comparison and evaluation of both color filters, based on two criteria: an objective – peak signal-to-noise ratio (PSNR) and subjective (visual quality). The filters efficiency is assessed by experimental studies on a set of test images – vector and real photographic ones. The results obtained during the experiments are presented and discussed.*

Keywords: *Bayer filter, Pseudo-Random Bayer filter, Demosaicing, CFA interpolation, peak signal-to-noise ratio (PSNR), mean squared error (MSE).*

1. INTRODUCTION

Bayer filter [1] is one of the most currently used color filters (Fig. 1a). There are many different realizations of such filters. A Pseudo-Random Bayer (PRB) is one of them. The filter forms by overlaying with pseudo-random pattern, as it is illustrated on Fig. 1b,c. The pseudo-randomness determines by position the blue and red pixels, while the green pixels keep their positions as in the original Bayer filter.

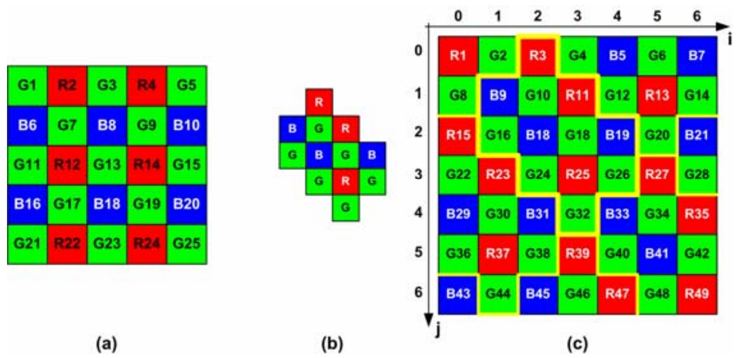


Fig. 1: Bayer and Pseudo-Random Bayer CFAs. (a): Bayer CFA, (b): PRB pattern; (c): pattern, overlaid on matrix 7x7 (PRB CFA). A pattern is outlined with yellow color.

The position of a filter element in Bayer and PRB filters set that in each sensing element (pixel) there is an information of one color component only (R, G or B). To produce the "full-colored" image by analogy of color photo film, each pixel must keep data for the three colors: R, G and B. To obtain the missing color information interpolation is used. These interpolation methods are often called "demosaicing". Demosaicing algorithms interpolate each of the color planes at the position where the corresponding values are missing. A comparative study of different Bayer CFA demosaicing algorithms is presented in [2, 3], and of PRB CFA – in [4]. The purpose of this paper is to compare the applicability of the two types of filters for registration visual information, by modifying some of the best demosaicing algorithms according to the PRB filter structure. Two types of images are used as an experimental data set – vector and real photographic ones. The filters efficiency is assessed by experimental studies, using both evaluation approaches: an *objective* (peak signal-to-noise ratio) and *subjective* – a visual comparison of the quality of the received results.

The paper is organized as follows. Section II, briefly presents some of the demosaicing methods and their essential features. The used test images and the motivation for selecting them are given in Section III. Section IV discusses results, obtained via our experimental studies. Some concluding remarks are provided in the final section.

2. REVIEW OF EXPLORED ALGORITHMS

2.1. Interpolation algorithms for Bayer filter

2.1.1. Freeman interpolation

This method (proposed in [5]) attempt to reduce the effects of fringing by removing sudden jumps in hue, interpreted in a similar way as in Cok's algorithm [6]. Median filtering is used to remove such jumps while preserving important hue changes.

In the first step of the algorithm, complete bilinear interpolation of RGB components is performed (Fig. 2). Difference images R-G and B-G are subsequently constructed and filtered by median filter. Resulting differences are then used with original measurements to compute all the RGB values in each pixel. This is possible as we have one value and two differences for each pixel.

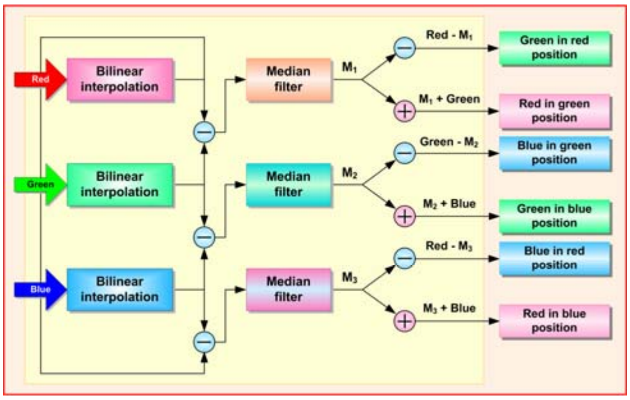


Fig. 2: Diagram of Freeman interpolation

2.1.2. Kimmel algorithm

Kimmel [7] follows Cok's assumption, that within a given "object" the ratios $red/green$ and $blue/green$ are locally constant. This rule falls apart across the edges where the color gradient is high, which are the interesting and problematic locations from reconstruction point of view.

A Kimmel demosaicing algorithm includes three stages:

- Interpolation of green color.
- Interpolation of red and blue colors using the interpolated green color.
- Correction (enhancement) stage.

2.1.3. Tsai-Acharya Interpolation

Tsai-Acharya interpolation method [8] is an adaptive algorithm, based on the concept of '*smooth hue transition'*. The main idea is to assign weight coefficients to the pixels, adjacent to the currently processed one. The pixels values are determined depending upon the correlation amongst the surrounding pixels, whether or not the pixel belongs to the edge.

The Tsai-Acharya interpolation performs on three stages:

- Estimation of all missing Green values.
- Estimation of missing Blue (Red) color component at each pixel location containing Red (Blue) color component only. The green values estimated in the previous step are used in this step. The decision is based on the change of hue value.
- Estimation of missing Red and Blue at green pixels, using the estimated Red/Blue at blue/red pixels in the previous step.

2.1.4. Wenmiao-Peng Interpolation

Wenmiao-Peng algorithm [9] is based on the spatial correlation among pixels along the respective interpolation direction. There are two assumptions:

- The green and blue/red pixel values are well correlated with constant offset.
- The rate of change of neighboring pixel values along an interpolation direction is a constant.

The post processing step is suppressing of noticeable demosaicing artifacts by using median interpolation (Eq. 1 and Eq. 2) by analogy of the Freeman algorithm.

(1) $$G_{x,y} = \frac{(New(R_{x,y}) - M_{RG}) + (New(B_{x,y}) - M_{BG})}{2}$$

(2) $$R_{x,y} = New(G_{x,y}) - M_{RG} \ , \ B_{x,y} = New(G_{x,y}) - M_{BG} \ ,$$

where: $M_{RG} = median\{R_{i,j} - G_{i,j}\}$, $M_{BG} = median\{R_{i,j} - G_{i,j}\}$,

$New(G_{x,y})$, $New(R_{x,y})$, $New(B_{x,y})$ – RGB values after interpolation,

i, j – positions of median filter according to Fig. 1a.

2.2. *Interpolation algorithms for Pseudo-random Bayer filter*

In contrast to the original Bayer filter, the processing of the PRB is complicated by the fact that depending on their neighbors, pixels are divided into more groups. Depending on these groups some of the well known algorithms for interpolation could be fully applied as well as for PRB filter, with others the implementation is possible only for some types of pixels, while third algorithms cannot be executed with this type of pattern. Having in mind Fig. 1c, we have the several positions of the pixels, for which there is a measured value (red, green or blue center) [4]. There are the following types of pixels: three types of red and of blue pixels, and four types of green pixels. The four investigated algorithms (Freeman, Kimmel, Wenmiao-Peng and Tsai-Acharya) are adapted to the structure of the PRB filter. The computation of the particular values and coefficients is related with the type of a given pixel.

3. TEST IMAGES FOR COMPARISON OF DEMOSAICING METHODS

To compare the demosaicing algorithms 12 images are generally used: 6 are synthetic vector images (1024x1024 pixels) and 6 are photographic images (768x512 pixels) from the *Kodak test bed*: *RedRidingHood, Statue, LightHome, Flowers, Parrots, Girl* (Fig. 3). The synthetic images (Fig. 3 (1)-(6)) are created with Adobe Illustrator, after which they are rasterized with Adobe Photoshop. *Test images*$_{1,2}$ are used for evaluation of the algorithms for reproducing smoothing transitions. *Test image*$_3$ contains a lot of high frequency pattern in the form of black and white sharp edges in different angles, divided in several semicircles for evaluation of the resolution. Each wedge is 2 degree wide, so the black and white rays are with a period of 4 degrees. *Test image*$_5$ imitates the regular structure of Bayer filter and the pixels in images. *Test image*$_4$ and *Test image*$_6$ are selected to display artifacts, caused by different black and white stripes. Real photographic images are selected so as to contain abrupt transitions as well as smooth ones, pastels and saturated colors, details with high spatial frequency.

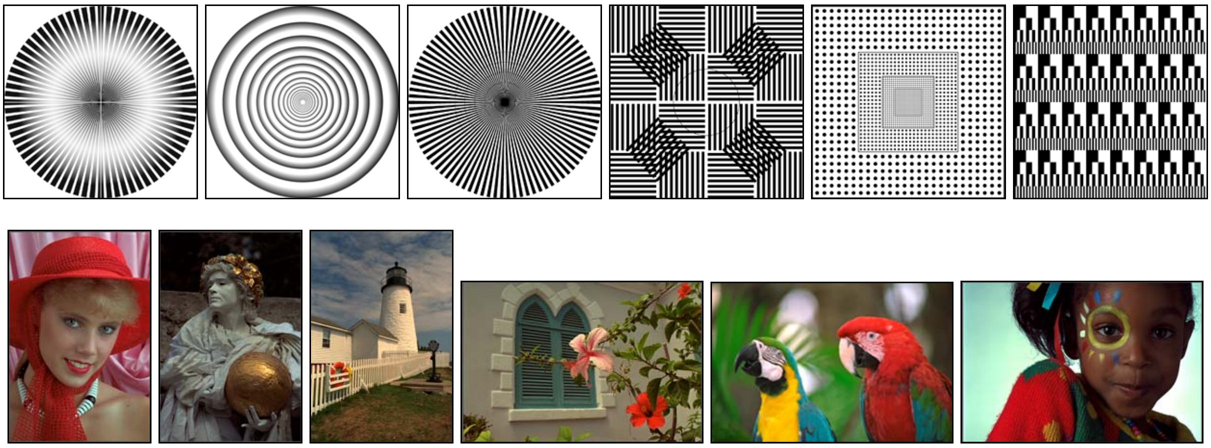


Fig. 3: Collection of 12 test images (images are numbered from (1) to (12) in order of left-to-right and top-to-bottom)

4. RESULTS AND DISCUSSION

Results from the described in Section II demosaicing algorithms for Bayer and PRB CFAs, applied over both types test images are shown in Figs. 4-8. For objective metric PSNR is used. Although, this approach is not directly connected with the human visual system, it is widely used because of easy interpretation of results.

4.1. Artifacts evaluation (visual comparison)

In Fig. 4 some of the basic shortcomings of demosaicing algorithms are shown (*Test image*$_9$): *zipper effect, corrode effect, blurring, and isolated bright dots*. *Zipper effect (fringe artifact)* appears when it is interpolated around edges, where the color leap is abrupt. In this case, the edges look like zipper or colored fringes of a carpet. The effect is most visible in Tsai-Acharya (T-A) interpolation for both filters, but it can be found in the Freeman's method as well. In Kimmel interpolation for Bayer filter, small *blurring* (smoothing) of image is observed. Kimmel for PRB introduces a few *false bright dots*. *"Corrode"* effect, described in [4], can also be observed here. Wenmiao method gives best results for both filters.

Fig. 4: Region of interest (ROI) of test image$_9$. Images are numbered from (a) to (h) in order of left-to-right and top-to-bottom: (a) Freeman for Bayer; (b) Freeman for PRB; (c) Kimmel for Bayer; (d) Kimmel for PRB; (e) Wenmiao for Bayer; (f) Wenmiao for PRB; (g) Tsai-Acharya for Bayer; (h) Tsai-Acharya for PRB.

When there is smoothing transitions (*Test image$_2$*) most of the algorithms, except Kimmel for PRB and T-A for both filters, interpolate very well. Since the diagonal top-left to bottom-right in PRB filter is not well balanced with blue and red color (Fig. 1c), theoretically the number of artifacts there should be maximal. Exactly the same effect (*green-blue diagonal*), is strongly expressed visually as well in Kimmel and T-A interpolations (Fig. 5a, b). In Wenmiao (Fig. 5c), this effect is almost missing. In the center of the star (*Test image$_1$*, Fig. 5d-f), where there is a high spatial frequency, all algorithms introduce another demosaicing effect – *aliasing*. Between the individual parts of the star, *zipper effect* in Freeman and T-A interpolations for Bayer filter, and T-A for PRB is observed. Such effect is missing in Wenmiao interpolation for both filters.

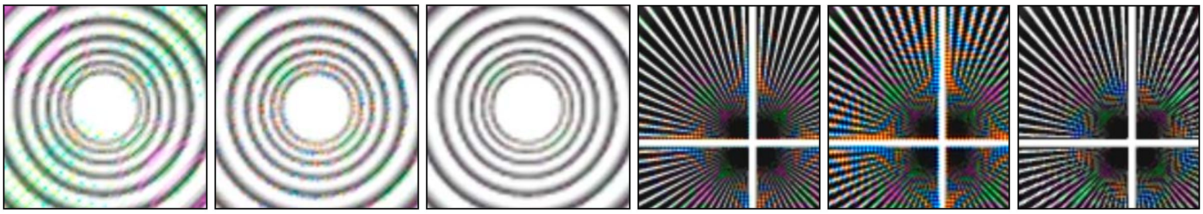


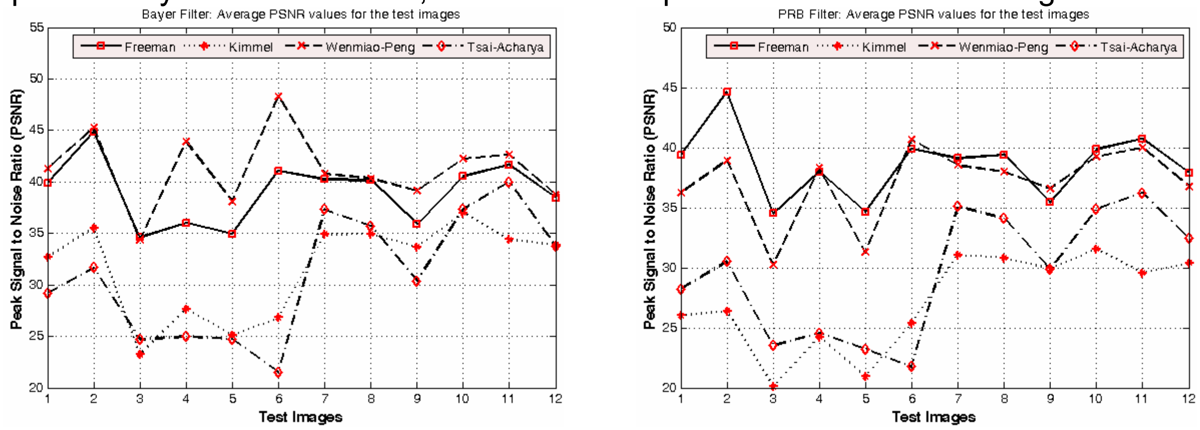
Fig. 5: *Green-blue diagonal* effect and *aliasing*. Images are numbered from (a) to (f) in order of left-to-right – (a)-(c) ROI of test image$_2$: Kimmel, Tsai-Acharya and Wenmiao for PRB; (d)-(f) ROI of test image$_1$: Tsai-Acharya for Bayer and PRB, Wenmiao for PRB.

For *Test image$_{11}$* Kimmel's algorithm introduce another effect for both filters – *posterization* – replacement of big parts in the images with one homogeneous color (Fig. 6b, c). Such an effect is caused from the incorrect reconstruction of the green color component in the yellow areas of the image.

Fig. 6: Posterization effect. Images are numbered from (a) to (d) in order of left-to-right. ROI of test image$_{11}$: (a) – original; (b) – Kimmel for Bayer; (c) – Kimmel for PRB; (d) – Wenmiao for PRB.

4.2. PSNR evaluation (objective comparison)

For Bayer filter Wenmiao's algorithm outperforms the other algorithms (Fig. 7a). Similar results can be seen, applying Freeman's algorithm, as it is in the case of *Test image*$_3$ where the results are better than in the rest of algorithms. Freeman's algorithm performs poorly when the images contain a lot of horizontal or vertical "stripes", or regular structure (*Test images*$_{4,5,6,9}$) because it first performs a linear interpolation for green channel, which is a blur process. Kimmel's and Tsai-Acharya' algorithms show approximately the same results, as both don't cope well with the vector images.

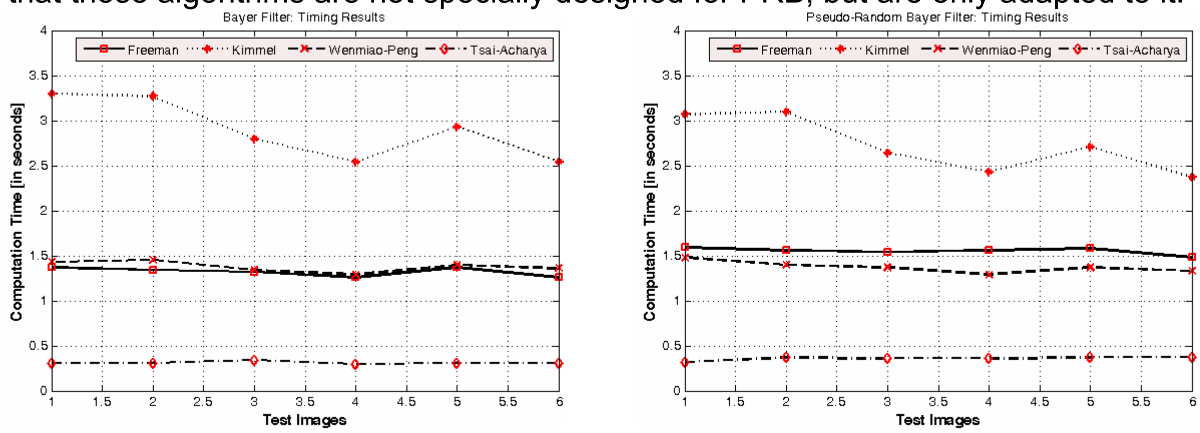


(a) (b)

Fig. 7: Average PSNR-RGB values for each test image – (a) Bayer CFA; (b) PRB CFA

For PRB filter Freeman's algorithm works better than the other algorithms (Fig. 7b). This fact could be explained with the easier adaptation of this algorithm to the structure of PRB filter – the unbalanced top-left to bottom-right diagonal in PRB filter has no influence over the interpolation. On the other hand, for *Test images*$_{4,6,9}$ Wenmiao's algorithm has better PSNR (for the same reasons, mentioned above).

Comparing the results, obtained from Bayer and PRB filters over the all experimental image data set, for only two images (*Test image*$_4$ for Freeman algorithm and *Test image*$_6$ for Tsai-Acharya algorithm), PRB filter works better. The main reason is that those algorithms are not specially designed for PRB, but are only adapted to it.



(a) (b)

Fig. 8: Timing results for test images$_{1\text{-}6}$ – (a) Bayer CFA; (b) PRB CFA

4.3. Computation time evaluation

Timing tests were performed on a 2.0GHz Intel Core2 Duo T7250 processor, RAM 2038 MB. The learned interpolation algorithms have been compared and the results for

Test images$_{1-6}$ are presented on Fig. 8. The Tsai-Acharya' algorithm is faster, in contrast to the Kimmel's algorithms, which is the slowest, because of the final post processing (correction) stage, which performs 3 times. For Bayer CFA, the Freeman's algorithm is slightly faster than the Wenmiao's algorithm. It is interesting to note that Kimmel's algorithm, adapted for PRB filter, works faster with all of the test images than its original version for Bayer filter.

5. CONCLUSION

Our results show that despite the unbalanced structure along one of the diagonals of PRB filter and the most complicated developing approach, it is able to reconstruct the images as good as the original Bayer filter, especially for Freeman interpolation. Consequently, when using algorithms, specially created to take into account the specifics of this filter's structure, as well as in modifying others well known demosaicing algorithms, such filter could be used successfully in real practice.

ACKNOWLEDGMENTS

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6. REFERENCES

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