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Colour Filter Arrays: Design and Performance Analysis by Digital Signal Processing Techniques

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Abstract —
This paper describes the look of color filter arrays (CFAs) utilized in the consumer-grade photographic camera, and analyses their influence on the performance of the demosaicking method. Of explicit interest area unit RGB CFAs wide utilized in a single-sensor imaging pipeline. totally different style characteristics of varied image-enabled shopper electronic devices by the various makers result in the many arrangements of the colour filters within the CFA, poignant each performance and machine potency of the demosaicking resolution. in depth experimentation, exploitation 10 RGB CFAs and a universal demosaicking framework, according during this paper indicates that the CFA contains a nice impact on each the target and subjective (visual) quality of the demosaicked, full-color image.

Index Terms — Image-enabled consumer electronics, single-sensor imaging, color filter array, demosaicking.

I. INTRODUCTION

COLOR filter array (CFA) is one of the most distinctive hardware elements in a single-sensor imaging pipeline [1]. The CFA is placed on top of the monochrome image sensor, usually a charge-coupled device (CCD) [2] or complementary metal oxide semiconductor (CMOS) [3] sensor, to acquire the low-resolution color information of the image scene. Each sensor cell has its own spectrally selective filter and thus, the acquired CFA data constitutes a mosaic-like monochrome image (Fig. 1a) [4]. Since the information about the arrangement of the color filters in the CFA is known from the camera manufacturers or it can be obtained using the Tagged Image File Format for Electronic Photography (TIFF-EP) [5], the gray-scale CFA image can be re-arranged as a low-resolution color image (Fig. 1b) [4]. This is the initial operation in the demosaicking process [6]-[8] which uses the concept of spectral interpolation to estimate the missing color components and to produce a full-color image (Fig. 1c) [9].

The arrangement of the color filters in the CFA varies depending on the manufacturer [10]-[14]. Consumer electronic devices, such as various digital still and video cameras, image-enabled mobile phones, and wireless personal digital assistants (PDAs) thus naturally differ in the employed demosaicking solution. Different cost and implementation constraints are expected for a camera which stores the image in the CFA format and uses a companion personal computer to demosaick

(a)
(b)
(c)

Fig. 1. Single-sensor imaging: (a) mosaic-like gray-scale CFA image, (b) colour variant of the CFA image, (c) demosaicked full-color image.

the acquired image data, than for a camera which directly produces the demosaicked image. Other construction differences may result from the intended application (e.g. consumer photography, surveillance, astronomy).

Although mistakenly neglected in the research papers, the choice of the CFA critically influences the accuracy of the single-sensor imaging pipeline [12],[14]. Both the sharpness and the color appearance of the edges and fine details in the demosaicked image depend on the CFA layout in the edge area and its closest neighborhood. If signal structures in the captured image have size smaller than the sampling frequency of an arbitrary color band in the CFA, the demosaicking process usually results in various visual impairments such as aliasing, moire noise and color shifts [4],[8],[15]. Thus, the use of another CFA may eliminate the presence of artifacts in certain areas of the demosaicked image while degrading the image quality in other areas.

In this paper, the demosaicking performance is analyzed with respect to ten different types of the RGB CFA employed in the single-sensor imaging pipeline. In addition to the nine known CFAs with a periodic, pseudo-random or human visual system (HVS)-based structure, this paper introduces a new CFA which completes the available designs. To truly analyze the CFA efficiency, a universal demosaicking framework [14] is employed. Please note that although extensive research has been devoted to demosaicking of the images captured using the Bayer CFA (Fig. 2a) [10], there is no known work addressing the performance issues for other CFAs (Figs. 2b-j) in such a comprehensive and systematic way.

The rest of this paper is organized as follows. The RGB CFAs are introduced in Section II. Motivation and design characteristics are discussed in detail, and the brief description of the universal demosaicking framework suitable to process the CFA image captured using an arbitrary RGB CFA is included, as well. In Section III, the presented CFAs are tested using the universal demosaicking framework and various artificial and natural images. Evaluations of performance, both objective and subjective, are provided. Finally, conclusions are drawn in Section IV.

II. Color Filter Array

Both the design and performance characteristics of the CFA are essentially determined by the type of a color system and the arrangements of the color filters in the CFA [12],[14]. These two basic CFA features specify the construction requirements of the demosaicking solution, thus influencing its efficiency and cost.

A. CFA Design Guidelines

Today's color systems [4],[12] used in various CFA designs utilize: i) tri-stimulus color basis (RGB, YMC), ii) mixed primary/complementary colors (MGCY), and iii) four and more color concepts (e.g. RGB combined with white and/or color with shifted spectral sensitivity). Since the individual color filters are usually layers of transmitive (organic or pigment) dyes [16], the choice of dyes depends on the factors, such as ease of application, durability, and resistance to aggressive atmospheric conditions. Assuming light sensitivity as another criterion in the CFA design, the complementary or spectrally shifted color filters obtained by layering the dyes corresponding to the primary RGB colors (Fig. 3), are naturally less sensitive to the incoming light than the primary color filters obtained using a single-dye layer.

Focusing on the colorimetric properties, more accurate hue gamut is usually obtained by the CFAs based on mixed colors or various four-(or more) color concepts [12]. On the other hand, these designs may extremely increase the complexity of the demosaicking process [14]. In addition, the utilization of the mixed primary/complementary colors in the CFA often limits the useful range of the darker colors [12]. Since the images are commonly stored in the RGB color format and the tri-stimulus RGB system offers the way to acquire the image data in the required format, RGB CFAs constitute the most practical solution which may achieve the essential trade-off between the accuracy of the visual scene representation and the demosaicking complexity. For the same reason, the RGB CFAs are used throughout this paper.

Visual inspection of the RGB CFAs shown in Fig. 2 reveals that the arrangement of color filters in the array usually varies significantly. The difference in the CFA layout should be attributed to the effort of the camera manufacturers to obtain [12]: i) cost-effective image reconstruction, ii) immunity to color artifacts and color moiré, iii) robustness of the array to image sensor imperfections, and iv) immunity to optical/electrical cross talk between neighboring pixels.

The real-time processing constraints imposed on the digital camera usually require to simplify the demosaicking process as much as possible. This request is satisfied by the periodic CFAs (Figs. 2a-f), whereas the various pseudo-random CFAs (Figs. 2g-j) make the restoration process more complex due to their aperiodic nature. On the other hand, images captured using pseudo-random (or random) CFAs are usually more immune to color moiré effects [12]. Sensitivity of the array to color artifacts in the demosaicked image can be also reduced through the availability of the pixels' neighborhoods constituted by all three primary colors (Figs. 2d-f) and/or by allocating the larger amount of CFA locations to the G plane

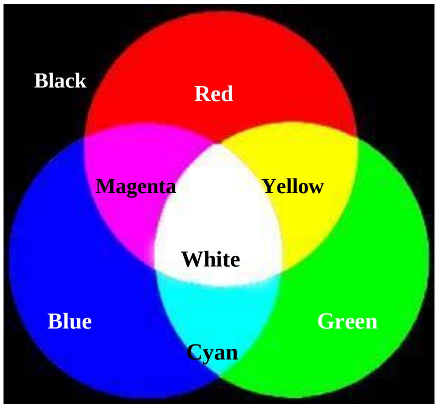

Fig. 3. Additive color mixing concept. Any spectrally shifted color can be obtained using the different amount of the three RGB primary colors.

(Figs. 2a-c,g,i,j). Since the frequency of the G color band is close to the peak of the human luminance frequency response [17],[18], privileging the G color filters in the CFA layout improves the perceived sharpness of the captured image.

Image sensor imperfections are usually observed along rows or columns of the sensor cells and thus, the CFAs shown in Figs. 2e,f should avoid the visual impairments resulting from the sensor defects. Immunity to optical/electrical cross talk between neighboring pixels can be increased by creating the CFA with the fixed number of neighbors corresponding to each of the three primary colors. This request is even more important due to the fact that diagonally located neighbors have a lower cross-talk contribution than the vertically or horizontally located neighbors [12], making the CFAs shown in Figs. 2g-j the worst solutions in terms of this criterion.

Since no CFA satisfies all design conditions, manufacturers usually select the CFA layout according to the type and resolution of the image sensor, camera optical system, image processing capabilities of the device, and the intended application. However, once the CFA layout is selected to acquire the CFA image data, the visual quality of the demosaicked full-color image depends on the ability of the demosaicking solution to overcome various spatial, structural and spectral constraints imposed on the single-sensor device during the image formation and color reconstruction.

B. Universal Demosaicking Framework

The acquired CFA image is a $K_1 \times K_2$ gray-scale mosaic-like image $z: Z^2 \rightarrow Z$ with the single scalar value $z_{(r,s)}$ located at each spatial location (r,s). Operating along the row and column coordinates $r = 1, 2, ... K_1$ and $s = 1, 2, ... K_2$, respectively, the information about the R ($k = 1$), G ($k = 2$), or B ($k = 3$) color filters in the CFA can be stored using the location flags $d_{(r,s)k}$ obtained either from the CFA layout or using the TIFF-EP storage format [14]. Following the dimensions of the CFA image z, a

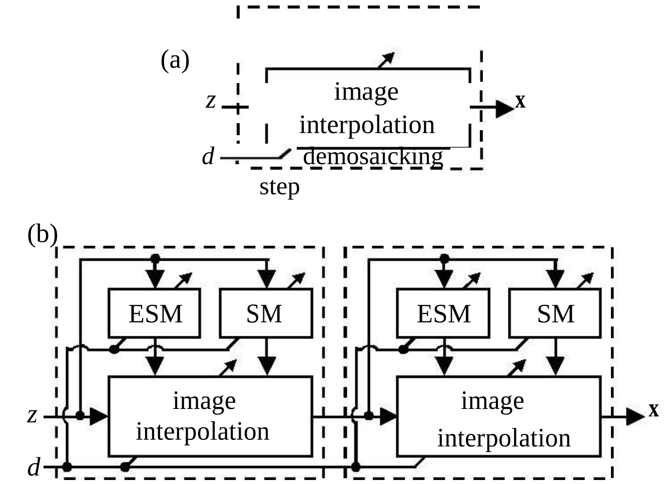

Fig. 4. Two basic solutions designed within the universal demosaicking framework [14]: (a) non-adaptive component-wise solution, (b) edge-sensing spectral model based solution with the postprocessor.

$K_1 \times K_2$ vectorial field $d: Z^2 \rightarrow Z^3$ of the corresponding location flags $d_{(r,s)k}$ is initialized using the default value $d_{(r,s)k} = 1$ to indicate the presence of the k-th color filter at the sensor location (r,s), and using the flags set to $d_{(r,s)k} = 0$ in all other

The CFA image z is used as the input to a demosaicking solution which performs spectral interpolation [9] to obtain a $K_1 \times K_2$ demosaicked full-color image $\mathbf{x}: Z^2 \rightarrow Z^3$. The demosaicking process starts by re-arranging the CFA image (Fig. 1a) to its color variant (Fig. 1b). Using the location flags $d_{(r,s)k}$, the scalar CFA image data $z_{(r,s)}$ are transformed to the corresponding vectorial representation $\mathbf{x}_{(r,s)} = [x_{(r,s)1}, x_{(r,s)2}, x_{(r,s)3}]$ with $x_{(r,s)k}$ denoting the intensity in the R ($k = 1$), G ($k = 2$), or B ($k = 3$) channel of the color image $\mathbf{x}$. Thus, the process produces the color vector $\mathbf{x}_{(r,s)} = [z_{(r,s)}, 0, 0]$ for $d_{(r,s)1} = 1$, $\mathbf{x}_{(r,s)} = [0, z_{(r,s)}, 0]$ for $d_{(r,s)2} = 1$, and $\mathbf{x}_{(r,s)} = [0, 0, z_{(r,s)}]$ for $d_{(r,s)3} = 1$. Given the location flags $d_{(r,s)k} = 0$ denoting the missing components in $\mathbf{x}_{(r,s)}$, the corresponding values of $x_{(r,s)k}$ are set equal to zero to denote their portion to the coloration of the color image $\mathbf{x}$ shown in Fig. 1b.

To produce a full-color image (Fig. 1c), the missing components are estimated at each spatial location (r,s) from the available neighboring components using the concept of image interpolation [9]. Using a 3×3 sliding window instead of the specialized shape masks known from the Bayer CFA-based demosaicking solutions (e.g. [1],[4],[6]-[8],[15]-[22]), the universal demosaicking framework [14] is directly applicable to an arbitrary CFA shown in Fig. 2. By localizing the flags $d_{(r,s)k} = 0$ used to indicate the spatial location (r,s) in the k-th color channel to be demosaicked and utilizing the control mechanism to prevent from operating in areas which lack adequate input information, the framework obtains the essential flexibility and independence from the CFA layout. In addition, the framework offers a number of design and processing options to demosaick the acquired CFA data, ranging from the cost-effective non-adaptive component-wise solutions (Fig. 4a) to sophisticated solutions (Fig. 4b) which use the edge-sensing mechanism (ESM), the spectral model (SM) and the postprocessor to produce the demosaicked image pleasing for viewing. The interested reader can find the detailed description of the universal demosaicking framework and the two considered here solutions.

IV. Conclusion

This paper bestowed the planning, analysis and performance evaluation of the colour filter array (CFA) that is that the most crucial part within the single-sensor client electronic device accustomed capture the visual scene. Of specific interest were RGB CFAs attributable to the relative simplicity of the demosaicking method and also the natural affiliation to the commonly used RGB format for displaying and storage of the captured pictures. The universal demosaicking framework was used to guide the performance analysis of the 10 RGB CFAs individually utilized within the single-sensor imaging pipeline. Experimentation performed here suggests that the choice of the CFA critically affects the number of varied visual impairments, like color shifts, artifacts, and aliasing effects, gift within the demosaicked image.

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