A deep survey in the Applications of demosaicking

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***Abstract*—Image demosaicking is a basic research topic in different imaging system with the purpose to interpolate full-resolution color images from so-called color filter array (CFA) raw samples. Recent years, many demosaicking methods were proposed in imaging system with various CFA patterns to produce diferent image. In this article, we provide a systematic survey of over thirty published works in this field. Our review attempts to illustrate important issues to demosaicing and identify fundamental differences among competing approaches. we also give a deep survey on the application of the demosaicking in different imaging system such as HDR imaging system, Multispectral imaging system and so on with different CFA patterns.**

Keywords-demosaicking; Color Filter Array; imaging system

I. INTRODUCTION

Digital still color cameras have gained significant popularity in recent years. Common image sensors, such as charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) sensor, are widely used to capture digital images. The CCD or CMOS sensors, however, are monochromatic devices. Therefore, to capture color information using such sensors, digital camera manufacturers place a color filter on top of each sensor cell. digital camera manufacturers of three-sensor model cameras utilize a prism behind the lens to divert the red, green, and blue image components to their respective sensor as shown in Figure 1. The resulting color image is produced by registering three grayscale (monochromatic) images, which requires precise mechanical and optical alignment. Besides, each sensor requires specific driving electronics and has to be registered precisely. These extreme requirements increase the expense of the sensor system which is already the most expensive component of a digital camera.

For cost reasons, when the currently available digital still color cameras (DSC) capture a color image, for each pixel, only one part of the color information of the three color channels is captured based on a single CCD sensor or CMOS sensor. This design choice necessitates the use of color filter arrays. The color channel layout on a color filter array determines which channel will be captured at each pixel location.This process can be seen in Figure 2,from which it is easily observed that at each pixel position only one of the three primary components can be captured. Using the CFA raw data, in order to get a full-color image,an appropriate interpolation method called CFA interpolation is adopted to recover the other two color components by neighbor pixels at each point. The process of getting a full-color image by CFA interpolation is also known as demosaicking[1-2]. An example of a digital camera's image processing flowchart can be seen in Figure 3. For convienent, the CFA is designed as checkerboard format according to different arrangement modes and different proportion of color components. Among these CFA patterns, the most common CFA in digital still cameras uses a color arrangement based on the Bayer pattern [1].

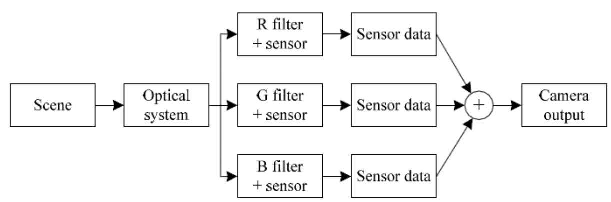

Figure1. Structure of a three-sensor digital camera.

Demosaicking has been researched for the pasted decades as the key technology in variable imaging system with different applications. Currently, the investigation is mainly focused on the RGB-CFA based demosaicking or color filter array interpolation methods with the purpose to introduce the cutting-edge interpolation methods. However, there is no systematic survey in the demosaicking application even there are many researches in new application of single sensor imaging system which is listed in table I. It can be seen that demosaicking is still a crucial research topic in many fields related to imaging system.

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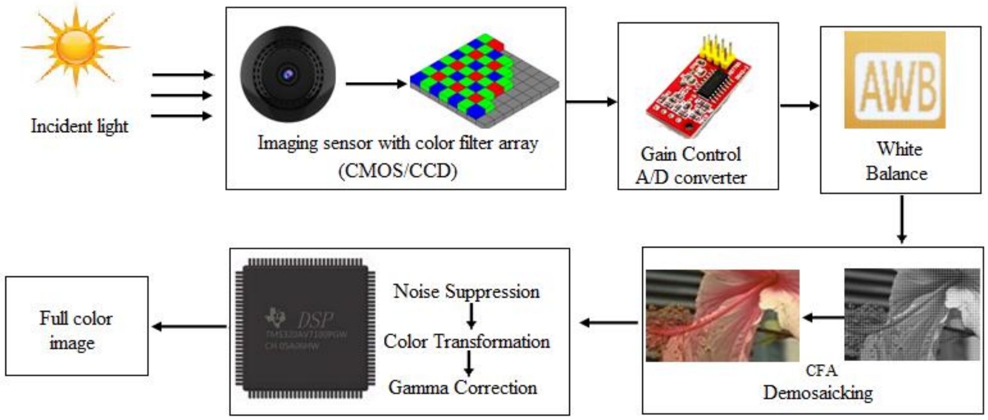

Figure 3. An example of a digital camera's image processing flowchart. The flowchart shows how the raw CFA data proceeds from the formation to the viewer. The composition and order of components differ according to camera manufacturers.

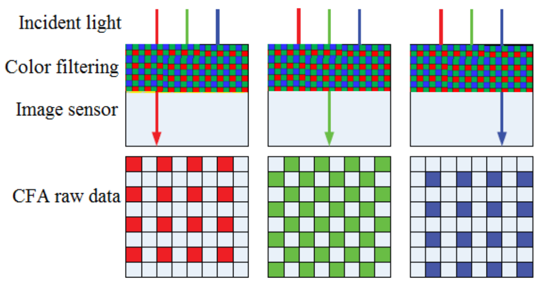

Figure 2. The process of CFA raw data.

TABLE I. THE SURVEY ASSIGNMENT IN THIS WORK

Demosaicking methods classification	Frequency domain based demosaicking methods; Spatial domain based demosaicking methods; CNN-based demosaicking method; GAN-based demosaicking method; Residual Interpolation for demosaicking.
CFA patterns	RGB-CFA; WRGB CFA; RGB-NIR CFA, SFA; MSFA
Applications	Demosaicking; Image compression; Demosaicking+deweathering; Demosaicking +enhancement; Demosaicking +denoising; Demosaicking +HDR imaging; Demosaicking for Multispectral Image; Demosaicking for Medical Image; Demosaicking for Underwater Image; Demosaicing +Super-Resolution; Image Authentication
Evaluation factors	PSNR; CPSNR, FSIM, SSIM, CIELAB Δ_E

The remainder of the paper is organized as follows. Firstly, we conduct investigation in variable CFA patterns adopted in different imaging system in Section II. After this, we secondly introduce the recent demosaicking algorithms with different technologies in Section III. Also, the demosaicking application in different imaging system were introduced in Section III. Finally, we provide conclusions in Section IV.

II. THE COLOR FILTER ARRAY PETTERN

in most imaging system,the output images are saved in the primary color format (RGB), so in many applications it is optimal to use CFA with these components, because firstly they allow you to initially obtain the required color components, secondly provide acceptable visual quality, and thirdly when using them, relatively simple solutions to the problem of demosaicing are required. Besides the spectral properties, the choice of specific colors depends on many factors, for example, ease of execution, service life, and resistance to weather conditions of dyes. The photosensitivity of the system also depends on the colors of the CFA, since the spectrally-shifted colors make it possible to obtain the best color coverage, however, in most cases the spectral range of such dyes is smaller, which leads to a smaller energy of the light flux incident on the element. In addition, when using arrays with a large number of shades, the complexity of the process of demosaicing increases. This increases the size of the array and the noise associated with the spatial separation of components.

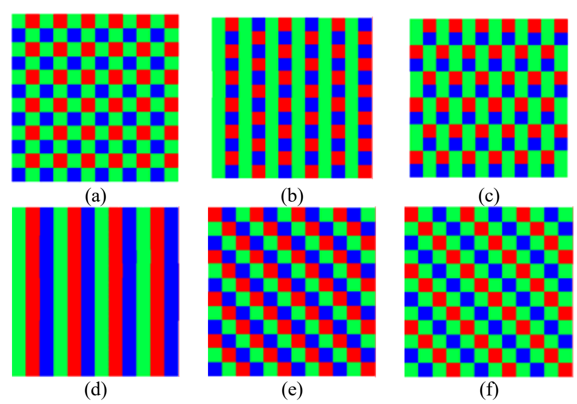

Figure 4. RGB CFAs: (a)Bayer ; (b)Yamanaka ; (c) Rlukac's; (d) vertical stripe; (e)diagonal stripe ; (f) modified Bayer .

A. RGB-CFA

At the present time, variants of arrays of CFA consisting of primary colors (red, green and blue) were proposed in different imaging system[3-6]. Currently, most demosaicking works are based on Bayer CFA pattern which can be seen in Figure 4.(a). It can be clearly seen from Figure 4.(a) that the distribution of green pixel is mainly along horizontal or vertical direction which means it's diffcult to recover the missing green pixel along sloping edge. The same situation happens when using the

CFA patterns in Figure 4.(b-f) to recover the missing color components. It is wel knowen that the quality of the output image can be badly affected by the CPA pattern and demosaicking method im the imaging system, so many new CFA pattern and new demosaicking were proposed to improve the interpolation accuracy. Since in most cases images are saved in the primary color format (RGB), in many applications it is optimal to use CFA with these components, because firstly they allow you to initially obtain the required color components, secondly provide acceptable visual quality, and thirdly when using them, relatively simple solutions to the problem of demosaicing are required.

B. WRGB-CFA, SFA , NIR-CFA ,MSFA and other CFA pattern

A White-RGB CFA presented in [7] is interesting for two aspects. First, it contains pixels of all three primary colors and differs from conventional Bayer CFA by only one pixel (Figure 5.(a)). This property enables very efficient implementation of image processing chain (IPC). Second, insertion of white filter makes CFA more transparent than Bayer's and should improve image quality at poor illumination with minimal impact on color reproduction. This CFA pattern increases the sensor’s light sensitivity and can be adopted in light-starved imaging applications such as traffic monitoring. When using this kind of WRGB-CFA, the produced image can have better quality in low light condition, however the color seperation from the white pixel position is still the challenge. The WRGB-CFA based demosaicking methods can also be seen in [8-11].

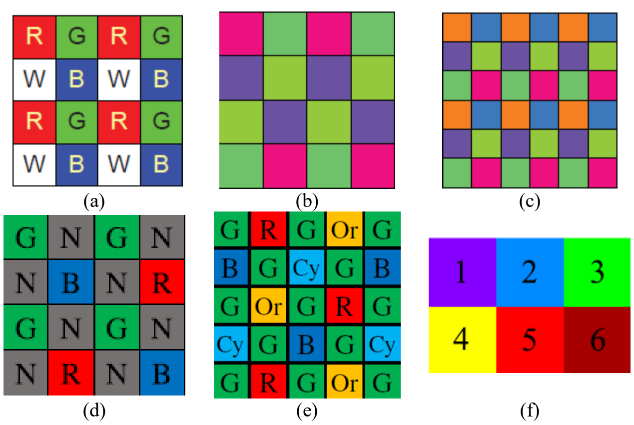

Figure 5. CFAs: (a)WRGB CFA [7]; (b) Hirokawa [12]; (c) Condat [13]; (d) NIR-CFA [14]; (e) five-band MSFA [17]; (f) Brauers and Aach’s MSFA [21] [8].

Specially, a 4 by 4 CFA in Fourier domain was proposed by Hirokawa [12] with the goal to reduce color aliasing and noise, which can be seen in Figure 5.(b). In Figure 5.(c), a CFA pattern with large elementary cell was proposed by Condat in [13],however, this kind of CFA pattern is quite different from conventional demosaicking pattern ,which means it is diffcult for color processing and practical implementation in current imaging system.

In Figure 5.(c), a special CFA pattern was proposed in [14] to produce image under low light condition even in enviroment of night. Due to the RGB-NIR imaging quality is badly affected by both the RGB-NIR sensor characteristics, such as a filter array pattern (FAP) and spectral sensitivity, and the RGB-NIR imaging pipeline converting the mosaic data to the output RGB and NIR images. Also the correlation of RGB-NIR sensor characteristics were under researched to output high quality RGB-NIR image which can be further indroduced in [14-16].

The multispectral extension of the CFA has attracted increasing attention because of its potential for compact and low-cost multispectral image acquisition. However, the demosaicking process for an MSFA poses a challenging problem owing to the very sparse sampling of each spectral band in the multispectral filter array (MSFA). In Figure 5.(e), a five-band MSFA was proposed to produce multispectra image. It can be observed that besides the RGB bands, there are extra bands for Orange and Cyan (denoted as Or and Cy bands, respectively) in the MSFA pattern. In Figure 5.(f), a six-band MSFA was proposed to produce multispectra image. Different from the conventional demosaicking method, the demosaicking process for MSFA is challenging task owing to the very sparse color component of each spectral band in the MSFA. Under this application of MSFA, the conventional demosaicking method will produce serious color artifacts and aliasing. The works of demosaicking using MSFA can be seen in reference[17-22].

III. DEMOSAICKING METHODS AND APPLICATIONS

The conventional demosaicking methods can be classified into three categories: frequency domain demosaicking, spatial domian demosaicking and deep learning based demosaicking. Among the demosaicking methods, the spatial domian demosaicking methods have attracted more attentions since it’s convenient to be embedded in VLSI system for imaging in practical because of their simplicity. Correspondling, there are absolute numerical advantage in their research outputs. Aslo, in this section, we will introduce the applications of demisaicking in different imaging system.

A. Spatial domain demosaicking methods

Theoretically, when using the interpolation-based demosaicking methods, it is best to interpolate the missing color components along edges, rather than across edges. However, because CFA adopts a mosaicked pattern, color components over all color channels are partially missing.It can be observed that in Bayer CFA pattern in Figure 4.(a), it is diffcult to estimate the missing green pixel along sloping edge, in the same while, the Red/blue color information is missing along horizontal and vertical directions. In order to recover the mising color components,different interpolation strategies are applied along the estimated interpolation direction. Among these conventional demosaicking methods, the AFD [24], DL [25], ESF [26], and LPA-ICI [27] methods are implemented only along the horizontal and vertical directions, whereas the DWI [28] and LDI-NAT [29] methods implement along four directions. These four are the north (N), south (S), east (E), and west (W) directions for populating the missing G component at the center color component R/B pixel position; and the northwest (NW), northeast (NE), southwest (SW) and southeast (SE) directions for R/B pixel interpolation at the center B/R pixel position. Particularly, in MEDI [30], the missing color component is interpolated along 12 directions, however, due to unreliable correlation among neighboring pixels in a large sliding window within the same color plane is used, the interpolation artifacts are unavoidable, besides, the computational complexity is too huge for practical application.

In general, multi-direction-based interpolation methods provide better interpolation result than two-direction-dependent interpolation methods only if the interpolation direction is accurately determined along the horizontal and vertical directions[31]. Thus, to expand the edge detection power of the adaptive color plane interpolation method, it is prudent to consider more than two directions. In order to evaluate the interpolation performance we conducted demosaicking simulation using the conventional demosaicking methods listed in Figure 6(b-f). It can be seen that compared with the two or four directional interpolation method, the eight-direction based MDWI method has advantage in preserving the sloping edge.

B. Deep learning based demosaicking methods

Recently, deep learning beased demosaicking methods were proposed due to it's advantage in image processing and computer vision. several CNN-based demosaicking algorithms have been proposed [32－34]. Gharbi et al. [32] rearranged a mosaic image to the quarter-resolution image with four channels and generated a full-color image by up-sampling the quarter-resolution image. Tan et al. [33] obtained a demosaicked image using traditional interpolation schemes [35, 36] and then used the residual network to refine it. The architecture of this deep learning network was illustrated in Figure 7. Kokkinos and Lefkimmiatis [34] applied a CNN-based denoiser iteratively to achieve demosaicking. Different from the CNN based deep leaining methods, Luo et al.[23] proposed a GAN-based depp learning network to produce a demosaicked image. In this GAN-based network, a generator, a discriminator and the network loss function are designed to enhance its ability to learn the high-frequency information of images.The generator of GAN employs a deep residual dense network which includes residual dense blocks and remote skipping connections. And the discriminator consists of a series of stacked convolutional units. In the same while, the network loss function is optimized by combining the adversarial loss, the pixel loss and the feature perception loss with the purpose to enhance the performance to the network, more details can be seen in this work.

Although deep-learning-based methods have demonstrated higher performance, they are highly data-dependent and require a large amount of training images, which remain difficult to be collected for non-RGB images. It is also known that reconstruction-based and dictionary-learning-based methods require high computational memory and cost, which is not desirable for integrated sensor systems. Because of these reasons, interpolation-based methods are still widely applied in practical use because of their simplicity.

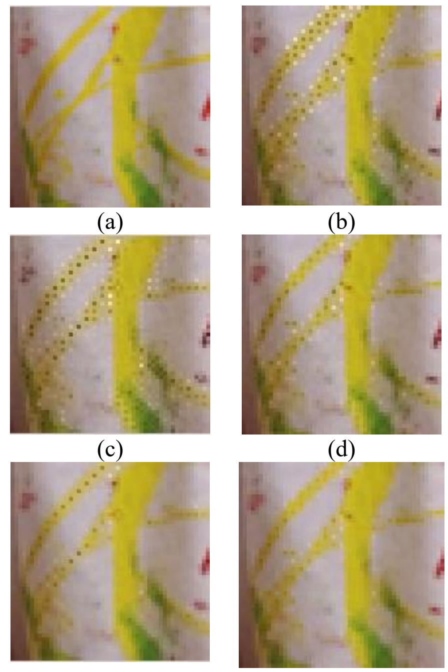

Figure 6. (a) Original #5 image from the McM image dataset and the demosaicked images by (b)AFD [7]; (c) ESF [9]; (d) DWI [11]; (e) LDI-NAT [12] ; and (f) MDWI [14].

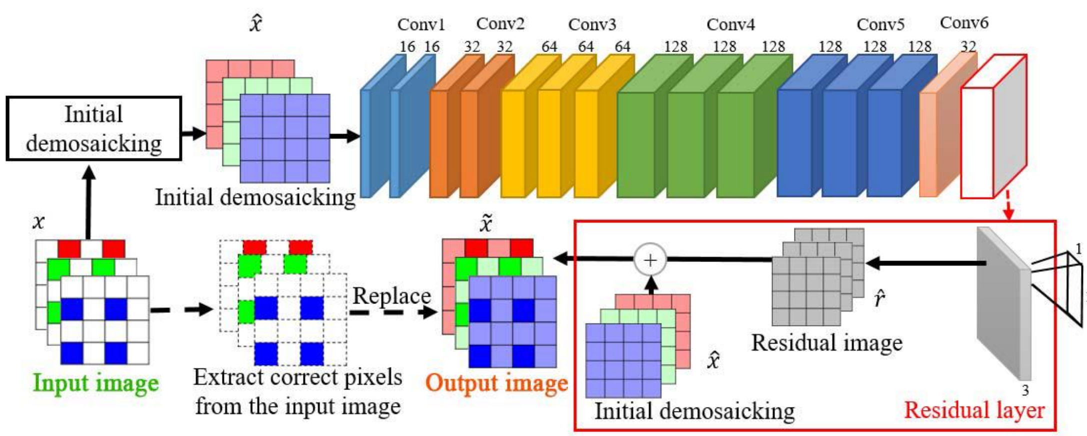

Figure 7. A proposed deep learning network architecture in [16]. An initial demosaicked image $\hat{x}$ is used as an input to a series of fully convolutional layers (without the pooling layers) that represents the input image in a high dimnensional space. The residual layer then transforms it back into the original image dimensions and computes for the residuals from the ground truth image. Since the pixels from the original mosaic image already contains the correct values, we use them to replace the corresponding pixels in the output image.

C. Frequency domain demosaicking methods

Another class of demosaicking algorithms [37-40]are based on the structure of the CFA in the frequency domain. It reconstructs an image by filtering the CFA to extract the luma and chrominance components using frequency Domain and Wavelet Methods. Though the C. Frequency domain based demosaicking algorithm mostly produces excellent results in regular region, however false colors may appear at high frequency components of the reconstructed image such as edges and texture details. Besides, it is also too complex to design such filter in VLSI system for real-time application .

D. The demosaicking applications

- **Demosaicking+image enhancement**: such application include the image enhancement technologies such as denoising, deblurring, Super-Resolution Reconstruction, deweathering, false color correction, which can be seen in [41-45].
- **Demosaicking+special imaging system**: such application include the hyperspectral/multispectral imaging ,underwater imaging system, HDR imaging system, which can be seen in [15-22,46-50].
- **Demosaicking+ Image Authentication**: this kind of application is used to analyze color filter array pattern and demosaicing algorithm, then use this information for image authentication. Also, based on the Characteristic of CFA pattern and demosaicking method ,it can be helpful to Camera Model Identification . These works can be seen in[51-52].

E. Evaluation methods

Performance evaluation of demosaicing algorithms was first systematically studied by several psychologists [53]. A commonly used quantitative measure for evaluating demosaicking algorithms is mean square error (MSE) or equivalently peak signal to noise ratio (PSNR) ($PSNR = 10\log_{10}\frac{255^2}{MSE}$ (dB)). Specially, for color image quality evaluation, the CPSNR is used to estimate the demosaicking performance in[58]. In work[54], the mean absolute difference (MAD) and normalized color difference (NCD)[55] are also used as supplementary criterion. It is also argued that Euclidean distances in the perceptually uniform CIELab and CIELuv spaces and the s-CIELab[56] are better measures considering the human visual perception. Therefore, we have seen an increased number of paper using s-CIELab metric in their performance comparison [57]. It is well known that PSNR based evaluation method is not a good indicator of demosaicking performance, because the interpolation errors mainly occur around the (color) edges, which account for only a small portion of the image pixels. For better evaluation, in some demosaicking works, the performance of interpolation method is often measured by FSIMc [59] or SSIM[60]. Besides, in order to evaluate the efficiency of the proposed method, CPU processing time is also used as a factor to check its efficiency.

All those objective measures assume the availability of a reference image. Unfortunately, such assumption does not always hold since the output of any digital camera has already been processed by a pipeline including optical low-pass filtering and demosaicing. Since different cameras may have different demosaicking algorithms, some bias is inevitable, which deviate from the ground-truth (an image acquired from 3CCD camera). To the best of our knowledge, computer-based simulation has been used in all published works on demosaicing - i.e., full-resolution color images acquired from single-CCD cameras are first down-sampled according to a specific CFA pattern and then the reconstructed images are compared with the “original” quantitatively. The only justification we have for this approach is that the original full-resolution color images do visually appear pleasant (therefore can be used as the reference even if they have been through processing pipeline).

Compared with objective evaluation, the objective evaluation is more attracted to determine the interpolation artifacts such as the color aliasing, false color, blurring on the edge and fuzy texture details. Generally, only the demosaicking have better performance in both subjective and objective evaluation performance, it can be used in imaging system.

IV. CONCLUSIONS

In this work, we conducted a deep survey of the recent demosaicking methods and their applications. We firstly indroduced the beaic conception of demosaicking and explained how it works in the imaging system. Then we dive deep investigation in the defferent CFA patterns and the demosaicking methods based on these CFA patterns. we also give a deep survey on the application of the demosaicking in different imaging system such as HDR imaging system, Multispectral imaging system and so on with different CFA patterns.

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