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Enhancing the Performance of Optical Hardware through Software Applications: A Study

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ABSTRACT

The process of image demosaicing, essential for reconstructing full-colour images from incomplete colour samples obtained from a colour-filter array (CFA), has garnered renewed interest, particularly with the prevalent use of the Bayer pattern. This resurgence can be attributed to the growing availability of source codes and executables, facilitating reproducible research in the field. In this article, a thorough survey encompassing over fifty published works on demosaicing since 1999. The objective is to complement prior reviews and provide insights into the evolution and current landscape of demosaicing techniques. By addressing key issues and delineating fundamental differences among various approaches, a thorough overview of the field is made. A notable finding from the survey is the popularity of spatial demosaicing methods, where the initial step involves interpolating the luminance channel, followed by reconstructing the chrominance channels based on the recovered luminance information. The article highlights three crucial areas requiring additional research. Firstly, addressing the difficulty of demosaicking images with low spectral correlation is paramount, along with enhancing our comprehension of the trade-off between spatial correlation and spectral correlation. It is also found that there is a necessity for more comprehensive investigation into evaluating the performance of demosaicking algorithms, particularly concerning the utilization of reference images, and understanding supplementary components within the imaging pipeline.

Keywords:
Demosaicking, Bayer, Colour Filter Array (CFA), spatial demosaicing methods, luminance channel, chrominance channel, spatial correlation, spectral correlation.

1. INTRODUCTION

The development of recent technological advancements in remote communication-based image processing systems has garnered significant interest in today's modern world. Many devices, such as digital cameras, smartphones, consumer electronics, and digital notebooks, are being developed with these advancements in mind. Despite this, digital image processing has faced challenges, including issues with image resolution, noise distortion, color mismatches, and color fading. To address these challenges in new applications, image color sensors can be utilized to enhance the performance of optical hardware. Modern electronic devices typically incorporate a color sensor based on an array known as the Bayer color filter array (CFA). Actual image color sensors, however, are less cost-effective and memory efficient. The color interpolation meths are used to up-sample the down-sampled version of the image. The process of interpolating this is known as demosaicking or de-Bayering. This is a crucial step in digital image processing for recovering full-colour images from the raw data captured by an image sensor with a CFA. Each pixel on a CFA sensor typically records only one of three primary colours (green, red, and blue), leading to a mosaic pattern of colour samples. Demosaicking algorithms aim to estimate the missing colour information at each pixel to produce a true colour image.

A Colour Filter (Bayer Array) placed between the lens and sensor creates a mosaic of colour samples. To obtain a full-colour image of the scene, this mosaic must be converted back into three separate colour planes. This conversion process is known as demosaicking. It involves estimating the missing colours at each pixel by interpolating the colour information from neighbouring pixels. There are many demosaicking methods available to rebuild a true colour image from the subsampled data captured through CFA.

The possible combinations of 2X2 Bayer CFA are shown in **Figure 1**.

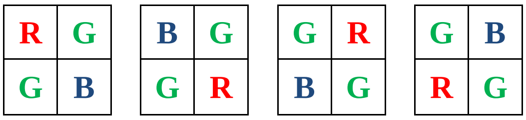

Figure 1 : Possible Bayer CFA patterns.

The extension of this mosaic and the formation of RGB mosaics is shown in **Figure 2**. In this figure the missing values pertaining to red, blue and green samples are shown.

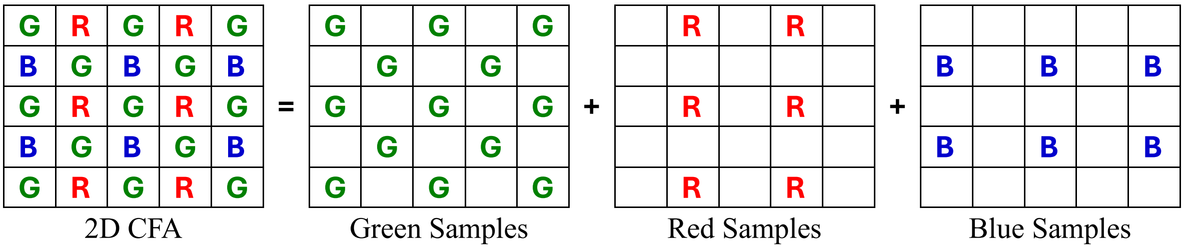

Figure 2 : Formation of RGB Mosaics

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The 2D CFA shown is essentially a mosaic comprised of the original captured colour samples. The mosaic of colour samples captured, resulting to raw image is inherently incomplete. The CFA sensed image is essentially a *gray-scale image*. The demosaicked colour pixels are represented in **Figure 3**

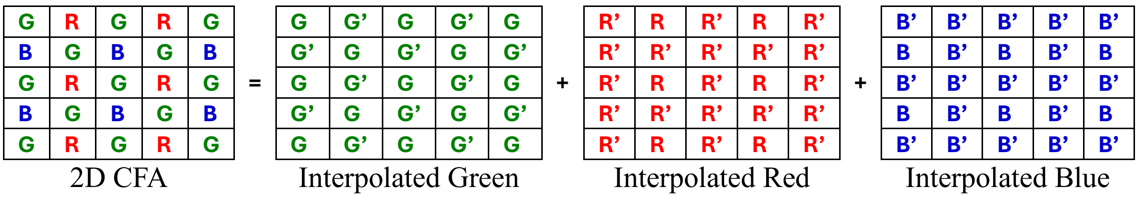

Figure 3 : Demosaicking/ Interpolation Process

Demosaicking Problem Formulation:
Three colour components (R,G, and B) combined produces a color image I is defined as

$$I^k, k \in \{R, G, B\} \quad \textbf{(1)}$$

In each plane $\boldsymbol{I^k}$, a given pixel *P* is characterized by the level of the colour component $\boldsymbol{k}$.
A three colour component vector is defined as

$$\mathrm{I_{xy}} \triangleq (\mathrm{R_{xy}}, \mathrm{G_{xy}}, \mathrm{B_{xy}}), \tag{2}$$

where *R, G, B* are located at spatial co-ordinates (*x*,*y*) location of image *I*.

An Image captured through a CFA on a single sensor array is defined below.

$$I_{xy}^{CFA} = \begin{cases} R_{xy} & if\ x\ is\ odd\ and\ y\ is\ even \\ B_{xy} & if\ x\ is\ even\ and\ y\ is\ odd \\ G_{xy} & otherwise \end{cases} \tag{3}$$

The color component levels are in the range of 0 to 255 (8-bit quantization considered)

The demosaicking process is defined as given below if x is odd and y is even

$$I_{xy}^{CFA} \xrightarrow{\mathfrak{I}} \hat{I}_{xy} = \begin{cases} R_{xy}, \hat{G}_{xy}, \hat{B}_{xy} & if\ x\ is\ odd\ and\ y\ is\ even \\ \hat{R}_{xy}, \hat{G}_{xy}, B_{xy} & if\ x\ is\ even\ and\ y\ is\ odd \\ \hat{R}_{xy}, G_{xy}, \hat{B}_{xy} & otherwise \end{cases} \tag{4}$$

Where
R_{xy}, G_{xy}, B_{xy} are the pixels captured by the Single Sensor array.
$\hat{R}_{xy}, \hat{G}_{xy}, \hat{B}_{xy}$ are the estimated pixel values.
I_{xy}^{CFA} is the CFA image captured by the Single Sensor array.
$\hat{I}_{xy}$ is the estimate of the missing pixels including the pixels that are captured by Single sensor array.
I_{xy} is the original image.

The effectiveness of the demosaicking algorithms are evaluated using metrics like Mean Squared Error (MSE) and Peak Signal-to-Noise Ratio (PSNR).

Evaluation Metrics

1. **Mean Squared Error (MSE)**
   - Measures the mean of the squares of the errors between the estimated and true colour values.
   - Lower MSE indicates better reconstruction quality.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(I_{true,i} - I_{reconstructed,i}\right)^2 \tag{5}$$

where *N* is the number of pixels, I_{true} is the true colour value, and $I_{reconstructed}$ is the reconstructed colour value.

2. **Peak Signal-to-Noise Ratio (PSNR)**
   - The ratio between the maximum achievable signal power and the power of noise that corrupts its faithful representation.
   - Higher PSNR implies better quality.

$$PSNR = 10\log_{10}\left(\frac{MAX^2}{MSE}\right) \quad \textbf{(6)}$$

where MAX is the highest possible (255 for 8-bit images) pixel value.

By investigating and comparing various demosaicking algorithms using MSE and PSNR metrics, one can gain insights into which methods provide the best balance between computational efficiency and image quality. This process helps in selecting the most appropriate algorithm for specific applications in digital imaging, such as photography, medical imaging, and surveillance.

The paper covers several key aspects of demosaicking algorithms and introduced image demosaicking methodology in this section. The remaining sections are organized as follows. Section 2 discusses the Adaptive Weight of the Color Filter Array and thresholding techniques. Section 3 explores Edge Directional Covariance. Section 4 examines CFA filtering and interpolation methods. Section 5 delves into the compression techniques of the color filter array. Section 6 addresses convolution and correlation-based interpolation methods. Section 7 provides the conclusion of the article. Through these sections, the research aims to study the efficiency and effectiveness of image processing in various software and hardware configurations.

2. ADAPTIVE WEIGHT OF COLOUR FILTER ARRAY AND THRESHOLDING

Chen et al., proposed an algorithm [1] which employs stochastic image interpolation estimation with an adaptive CFA resolution. Additionally, gradient edge detection using heterogeneity projection on the CFA facilitates edge detection during the demosaicking process. The theoretical CFA is designed to avoid issues such as zipper effects, color spots, image blurring, and demoralized missed interpolations, which are common in linearity regularization with graph-based frameworks. This improved interpolation algorithm is poised to deliver high-quality real-time video applications.

With the increasing demand for HD (High Definition) and UHD (Ultra-High-Definition) video content, high standards are being set for video coding technology. HEVC (High Efficiency Video Coding) is the latest video coding technology, developed by the JCT (Joint Collaborative Team) on Video Coding (VC) (JCT-VC), aiming to reduce the bit rate by 50% while maintaining the same visual quality as H.264/AVC high profile. Block-based video compression techniques often suffer from blocking artifacts due to individual block transformation and quantization. To address this, a CFA and deblocking filter proposed [2] by Colin et al., are used to optimize video quality, utilizing linear deviation compensation to automatically interpolate green pixels.

The approach [3] presented by Zhou et al., scales image size, from 32x32 to 64x64, 1024x1024, and even 4096x2048 pixels, particularly when utilizing HEVC, which necessitates varying hardware capacities. Memory and arithmetic operations are also crucial factors. The research development of this article will be scheduled with hardware oriented demosaicking interpolation algorithm using color filter array to address this obstacle. This research focuses on developing a hardware-oriented demosaicking interpolation algorithm using a color filter array to address these challenges.

During the development of sensors for digital colour cameras, imperfect pixels, identified as defective pixels, can emerge. With prolonged camera use, additional defective pixels may appear. These faulty pixels can affect the demosaicking process, where the author proposes an efficient method in this paper to integrate defective pixel removal with demosaicking. This approach ensures that faulty pixels are eliminated during the interpolation process. The suggested adaptive approach adjusts the interpolation order based on the position of the defective pixel. If a defective pixel is near the interpolation stage, a lower interpolation order is favored to ensure it falls outside the interpolation area. On the other hand, a larger order of interpolation [4] is chosen for a more accurate representation when the defective pixel is a far distance from the sampling point. From the literature, it is seen that the performance of the developed adaptive framework of CFA demosaicking concerning interpolation output quality and efficiency of defective pixel elimination is better compared to the existing techniques.

The adaptive bilateral filter by Sharmil et al. adjusts the weights [5] based on its vicinity to the color boundaries. If a color border is traversed, weights are further manipulated with minor deviations towards the lower order of interpolation since the nearest pixel value is considered. For smoother areas, the weights are manipulated to give rise to the higher order of interpolation. This is done, as four interpolations are performed in each cardinal direction so that interpolation does not occur in an edge adjacent to the location of a missing pixel. From these interpolations, the classifier developed using the weighted median filter and bilateral filter retrieves the output of the missing color pixel value. In most images, this algorithm has better speed since it maintains color edges sharply with very few errors compared to other demosaicking techniques.

Besides HD (high-definition) image capturing, single-sensor digital still cameras provided with a color filter array (CFA) capture only one color per pixel. CFA demosaicking is devoted to estimating the missing color sample values and generate a full color picture. To maintain sharp color edges and avoid color artifacts, it's essential not to interpolate over edges. Cubic spline interpolation is used for CFA demosaicking, but it typically requires measurements from up to five positions adjacent to the central point of measurement. This indicates that when an image has neighboring edges, cubic spline interpolation may demand measurements from the opposite edge for interpolation, potentially leading to false colors. In such cases, a lower-order spline interpolation may be chosen to avoid incorporating pixel values from the opposite edge. Sharmil .et.al proposes an innovative approach [6] in this document to incorporate different orders of spline interpolation based on the direction of an edge from the estimation point. This method aims to address artifacts near edges more effectively, resulting in more detailed results with fewer color errors.

The CFA interpolation plays a critical role in image processing for low cost digital cameras employed with array of sensors capture the scene. Xiao et. al. presents a unique algorithm [7] based on directional weighting and adaptive edge detection. This approach enhances edge detection by accurately measuring edges and estimating missing color values in various directions. The algorithm calculates thresholds by analyzing pixel values and weighting coefficients based on directional gradients. Experimental results demonstrate visually appealing outcomes, surpassing current composite peak signal-to-noise ratio (CPSNR) demonstration methods. Furthermore, the proposed method maintains numerical complexity comparable to existing methods.

The region-adaptive weight, derived from an edge predictor, prevents excessive smoothing of the interpolated image around edges. An optimization technique proposed by Osama et. al [8], combining the longest continuous descent approach with convex projection is employed to achieve this. The resulting demosaicked image is compared qualitatively and quantitatively to images obtained using existing state-of-the-art demosaicking techniques. Across a set of twenty test images, the proposed approach outperforms all others. Additionally, it requires less computational resources compared to recently proposed alternative projection techniques.

Hyperspectral demosaicking, which aims to approximate complete spectral information from under-sampled raw data captured by a single imaging system with a CFA, poses significant challenges. To address this, Monno et. al. proposed a novel multispectral interpolation algorithm [9]. The algorithm leverages an adaptive framework as spatial support and extends existing up-sampling strategies to Gaussian kernel up-sampling algorithms, adapting them for multispectral demosaicking. Additionally, the author introduces a new CFA design and proposes an adaptive kernel approximation from the raw data captured by this CFA. Experimental results using specific multispectral images demonstrate the feasibility and efficacy of the proposed method.

Sandip et. al. proposed a novel method [10] that leverages non-local redundancy in the image to improve local color reproduction. They utilize several spatial dimensional predictions combined with local gradients to estimate missing color samples. Additionally, non-local pixels near the detected pixel are scanned to refine the local prediction. Instead of using stochastic means filtering, an image segmentation approach is employed to maximize local estimation accuracy. Experimental results demonstrate that the proposed local lateral interpolation and non-local adaptive threshold (LDI-NAT) method outperforms other color demosaicking techniques in edge reconstruction and color interpolation, resulting in visually more accurate color reproduction.

Sharmil et. al introduced a method [11] where the desired direction-based interpolation method (either vertical or horizontal) for the green plane which is determined using edge direction map. Interpolation is then carried out in the chosen direction, utilizing measurements obtained. For instance, if a color edge is adjacent, a lower-order approximation is employed to ensure only samples akin to the missed color point are used, thereby preserving the color edge. Conversely, if a color edge is significantly distant from the missed color value, a higher-order approximation is utilized for enhanced precision. The incomplete color value is subsequently computed by integrating the image with their corresponding approximation orders from both sides. The proposed approach, which selects a single estimation as the output and employs a mixed order of approximation, has shown superior performance compared to traditional techniques.

Sen Wang et. al. proposed a superior form of edge-adaptive color demosaicking [12]. It utilizes an improved edge identifier to detect edges, and then estimates missing color values in the chosen direction. This estimation process employs a weighted average of the Taylor series. Experimental findings demonstrate that the proposed method not only improves subjective visual quality but also achieves a balance between flash memory usage and computational burden. Furthermore, in peak signal-to-noise ratio (PSNR), the proposed method surpasses other existing approaches, exhibiting an average improvement of 1.8 dB across test images.

A novel method for CFA interpolation [13], with a focus on discovering and rectifying faulty pixels while maintaining the integrity of the overall image, is proposed by Sharmil et.al. Initially, the CFA image is analyzed to detect areas with flawed pixels. Then, an adaptive order-statistics multi-shell filter is selectively applied to individual sensor pixels within these problematic regions to address the defective pixels. Subsequently, demosaicking is performed again at these identified flawed pixel positions to generate the final full-color image, devoid of imperfect pixels. Experimental results showcase the efficacy of this approach, highlighting its superiority over alternative CFA demosaicking methods.

In today's digital camera production, the manufacturing process inevitably results in some flawed pixels within the high-resolution image sensors. These flawed pixels, often referred to as bad pixels, are typically identified and addressed during the manufacturing process. However, with prolonged use of the camera, additional bad pixels may emerge, particularly under extended periods of usage or at high ISO levels. Given that these bad pixels may still function under normal conditions, it's unnecessary to mark them indefinitely. Due to their interference with the demosaicking process, Sharmil et. al. proposed an effective method [14] in this paper to exclude these bad pixels from the interpolation process. This is achieved by dynamically adjusting the interpolation order. If a bad pixel is located adjacent to the pixel being interpolated, the interpolation duration is reduced. The detection of bad pixels is carried out using a standard deviation-based multi-shell filter setup. Experimental results demonstrate that our proposed approach surpasses existing methods for bad pixel correction. This is accomplished through dynamic adjustment of the interpolation order. When a bad pixel is located adjacent to the pixel undergoing interpolation, we shorten the interpolation duration. Detection of bad pixels is conducted using a multi-shell filter setup based on standard deviation. Experimental results demonstrate that our proposed approach outperforms existing methods for bad pixel.

Color demosaicking is a critical process in single-sensor image acquisition systems equipped with a CFA. Its purpose is to estimate missing primary colors at each pixel location. In the suggested approach [15], Yu proposed a demosaicking process begins by determining the luminance vector. This vector is obtained by employing cubic convolution linearization along the path of the lowest gradient magnitude at every chrominance pixel location. Once the luminance vector is established, the reconfiguration of chrominance channels takes place. This involves merging neighboring chrominance pixels based on spectral correlation. Additionally, sequential filtering is applied to the restored chrominance channels. Sequential filtering acts as a post-processing step, effectively smooth out color errors. Investigational studies have been conducted to evaluate the feasibility and efficacy of this technique. The results of these studies demonstrate the potential of the proposed method in achieving more correct and high-quality color reproduction in demosaicked images.

In their research paper, En Di Ma et. al. proposed a CFA interpolation algorithm [16] optimized for real-time applications on VLSI platforms, aiming for low complexity. The algorithm comprises three key components: an edge detector, an anisotropic weighting model, and a compensator employing filters. Specifically, the anisotropic weighting model prioritizes horizontal details over vertical ones. Furthermore, the compensator utilizes Laplacian and spatial filters for sharpening to improve edge information and mitigate blurring effects. Further, resource sharing and reconfigurable design strategies are used to significantly minimize resource costs. Through experimental estimation, this study demonstrates notable decrease in gate counts or power usage, improve on previous low-complexity strategies by over 8 percent and 91.7 percent, respectively. Additionally, the proposed algorithm enhances performance, as measured by CPSNR, by more than 1.6.

A new adaptive temporal and spatial video demosaicking technique [17] tailored for single-sensor digital video cameras is proposed by Rastilav. Unlike usual methods, this methodology utilizes a bidirectional multi-stage filter that processes spectrally generated inputs. This design enables the algorithm to adapt to the varied characteristics of the observed video, effectively reducing appearance errors and restoring full-color component with cost-effectiveness in mind. Through experimentation detailed in the paper, the superiority of this approach is highlighted. Despite surpassing previously developed computationally efficient video demosaicking approaches, the proposed technique excels in producing visually pleasing images. This suggests its potential for enhancing video quality and usability in various applications.

Lukac et. al. proposed a new demosaicking algorithm [18] specifically designed for single-sensor imaging systems utilizing a Bayer CFA. At the core of this proposed paradigm lies an effective data adaptive filtering principle coupled with enhanced spectral models. By employing a unique type of feature mapping to analyze significant differences among the CFA inputs and randomization coefficients of edge sensing, the system facilitates the development of fully automatic demosaicking approaches suitable for modern digital imaging devices. Moreover, the solutions proposed in the article could potentially enable PC-based raw CFA image demosaicking. Furthermore, the platform is versatile and can serve multiple purposes, including quick access and rendering of recorded images, as well as collaborative manipulation of raw sensor data to meet the needs of end-users. Whether implemented in software or hardware, the suggested system is relatively straightforward to deploy. Exploratory findings denote that the conceptual system excels in terms of widely used objective standards, demonstrating exceptional efficiency, and generating presentation images of remarkable quality in a timely manner. This suggests promising potential for enhancing image processing capabilities and overall user experience in various applications.

The research work [19] done by Keigo et al. addresses numerous concerns commonly associated with demonstration algorithms that implement two-dimensional (2-D) positional interpolation. To evaluate the performance of these algorithms, the article employs a metric neighborhood simulation to compare the number of incorrect color artifacts found in two images. The proposed algorithm attacks these challenges by calculating missing pixels through interpolation in the direction of fewer colored objects, effectively minimizing interpolation artifacts. Furthermore, the issue of aliasing is tackled by employing filter bank techniques for 2-D directional interpolation. This article introduces a nonlinear iterative method to reduce the objects of interpolation. Experimental findings validate the utility of this method, showcasing its effectiveness in justifying color artifacts and enhancing image quality. Overall, the article provides valuable understandings into the development of efficient and reliable algorithms for cost-effective video cameras.

Vitali et al. in their paper [20] delves into two prime findings regarding the preservation of high-frequency data in CFA demosaicking: Firstly, high frequencies are prevalent across all the three-color components, and secondly, high frequencies are vital for preserving image consistency along both the vertical and horizontal axes. The analysis of Color Filter Array (CFA) feedback processes suggests that filtering a CFA image retains high frequencies more effectively than filtering each color variable separately. This insight allows for the development of an effective filter to estimate the green pixel luminance in the CFA image, along with formulating an adaptive filtering solution to calculate the luminance of R and B pixels. Experimental findings, conducted on simulated CFA images and even some raw CFA data, demonstrate significantly lower computational complexity while achieving superior results. Overall, the approach presented in this article outperforms current state-of-the-art methods both technically and PSNR. This highlights its potential for enhancing demosaicking processes and ultimately improving image quality in still camera applications.

3. EDGE DIRECTIONAL COVARIANCE

A novel picture interpolation algorithm [21] is proposed by Ibrahim et al. is known as the Point Sampling-based Bi-quadratic Patches and Edge-directed approach (PSE). Unlike conventional methods that use image data to clearly construct surfaces, the PSE method adopts a different methodology to ensure specificity in interpolation. The PSE algorithm begins by calculating point sampling values, followed by the construction of a gender fluid-quadratic polynomial surface patch using these sampled points. Through the incorporation of local areas with weighting functions, the entire image structure is made. A key aspect of the PSE method is the introduction of a new edge-directed system for identifying edges and layers to attain model parameters. Unlike typical edge-directed approaches, the PSE considers interactions between the inner representatives of parameters. Studies conducted to assess the efficacy of the PSE methodology reveal that the interpolated images produced establish superior performance in both PSNR estimation and quantitative visual consistency when compared to opposing approaches. This underscores the effectiveness and potential of the PSE algorithm in picture interpolation applications.

In their research article [22], Taeuk et al. presented an innovative edge-adaptive demonstration technique aimed at suppressing artifacts. Despite the existence of numerous demonstration methods, they often encounter challenges related to objects along the edges of the display. To tackle this issue, the approach described by authors first identifies line edge patterns and then interpolates missing pixels along the observed directions to mitigate unwanted artifacts around these edges. Furthermore, to enhance the accuracy of the restored images, correction and synchronization procedures are sequentially applied. Experimental results indicate that this new method yields visually appealing images and surpasses state-of-the-art algorithms in terms of peak signal-to-noise ratio (PSNR). This underscores the effectiveness and superiority of the proposed technique in artifact suppression and image restoration.

In their paper [23] Bae et al. introduced a methodology for interpolation using the methods based edge-direction, to enhance the accuracy of natural images captured by low-resolution cameras in car or CCTV applications. This approach aims to improve the fidelity of images interpolated from low-resolution to high-resolution by precisely approximating the spatial covariance of edges between the two resolutions. The methodology involves adjusting local covariance coefficients obtained from the low-resolution image for interpolation to generate the high-resolution image. To accurately represent the multi-directional edges without increasing complexity, the DCT kernel function is employed. Simulation results from the model demonstrate that compared to traditional linear interpolation and New Edge-Directed Interpolation (NEDI), the proposed demosaicking algorithm significantly improves the accuracy of the demosaicked images. Furthermore, developments in quantitative metrics, such as SSIM and PSNR, and Wiener Filter Coefficients Estimation Accuracy (WEA), are highlighted for precise assessment of image quality. \

In the article [24], Lee et al. introduced an innovative edge-adaptive demonstration technique aimed at mitigating artifacts along line edges. Despite the availability of various demonstration methods, artifacts along edges remain a challenge. The proposed approach first identifies the structure of line edges and then interpolates distorted pixels along the observed path during initial interpolation to eliminate these unwanted artifacts. Subsequently, refining and calibration techniques are applied sequentially to enhance picture consistency. Experimental results confirm that the proposed approach yields visually appealing images and surpasses current demosaicking methods in both PSNR and S-CIELAB mean square error. This highlights the effectiveness and dominance of the proposed technique in artifact suppression and image enhancement.

In their research paper [25] Xin Li et al., proposed an edge-directed interpolation methodology tailored for natural images. The foundational concept entails initially computing local covariance coefficients from a low-resolution image, then using these coefficients to guide the interpolation process for higher resolution. This method exploits the structural resemblance between the covariance patterns of the low-resolution and high-resolution images. The edge-directed nature of the methodology ensures that covariance-based adaptability is applied to balance any arbitrary phase edge by fine-tuning the interpolation coefficients. To mitigate computational complexity, the article advocates for a hybrid approach that alternates between bilinear interpolation and adaptive interpolation based on covariance. The efficacy of the new interpolation algorithm is demonstrated through two primary implementations: grayscale image resolution enhancement and color picture restoration from CCD samples. Simulation results indicate a significant enhancement in the subjective consistency of reconstructed images compared to traditional linear interpolation methods. This underlines the potential of the proposed methodology to improve image quality and fidelity in various applications.

In their paper [26] Ibrahim et al. explained the concept of beam splitters to capture images whereas most optical cameras utilize CFAs and the interpolation process or demosaicking of images through the Color Filter Array (CFA), Authors present an edge intensity filter that is orientation-free and applies it to the demosaicking problem. The outcome produced by the edge intensity filter is utilized to refine the initial interpolation of the green channel and dynamically enforce the law of constant color difference. This straightforward edge-guided approach yields visually attractive results with higher CPSNR, indicating its effectiveness in improving image quality.

4. CFA FILTERS AND INTERPOLATION

Chenhui et al. proposed a novel regularization system in their article [27] for demosaicking by representing images on a weighted graph as a smooth signal. The objective of restoration is formulated as the minimization of signal variance along the graph edges. Initially, the author constructs a weight matrix from an approximation of the true-color image, which indicates the similarity between pairs of pixels. Subsequently, a two-stage computation process is conducted: first, the author assumes that the graph Laplacian is signal-dependent and solves a non-quadratic problem using gradient-based techniques. Then, while ensuring compatibility with the sampled data in each color variable, the author formulates a variance problem on the graph with a fixed Laplacian. Evaluation of the output demonstrates that our methodology effectively mitigates artificial effects and significantly enhances both the quantitative and visual aspects compared to previous demosaicking techniques. Overall, this approach highlights the utility of binding images to signals on graphs, providing a general framework for image demosaicking tasks.

S.C. Pei et al. on their article proposed a novel method [28] for interpolating color filter arrays (CFAs) in digital still cameras (DSCs). The method leverages a straightforward image structure that correlates the red (R), green (G), and blue (B) channels. By defining constants KR and KB to represent the relationships between green (G) and red (R), and green (G) and blue (B) respectively, the author exploits the smooth contrasts of KR and KB across a limited region in real-world images, making it an ideal property for interpolation. A key contribution of this research is the introduction of a low-complexity interpolation technique aimed at enhancing frame accuracy. The author establishes that the proposed method's frequency response surpasses that of traditional approaches. Simulation results further confirm that the suggested technique achieves excellent image quality on standard images. Specifically, the luminance frequency of the proposed system outperforms the bilinear system by 6.34-dB PSNR, while the chrominance channels show an overall increase of 7.69-dB PSNR. Despite its effectiveness, the suggested approach maintains simplicity similar to traditional vector quantization algorithms, requiring only basic add and change operations. This underscores the practicality and efficiency of the proposed interpolation method for real-world applications in digital imaging.

A probabilistic estimation approach [29] to evolutionary CFA interpolation is presented by Hung et al. An image is modeled as a 2-D dynamically stationary Gaussian process by implementing an edge-sensitive weighting strategy based on the stochastic characteristics of equally balanced edge indicators and ensures robustness towards aliasing. Experimental studies indicate that the algorithm can successfully eradicate the existence of visible objects. In order to prove the supremacy of the suggested algorithm, an efficient way to compare PSNR and MSE is given.

Zhang et al. proposed a novel method for demosaicking method [30] leveraging the non-local redundancy existing in the image to improve local color reproduction. Firstly, multiple regional lateral projections of missing color samples are identified and combined based on local gradients. Additionally, non-local pixels like the predicted pixel are scanned to refine the local prediction. Instead of conventional non-local means filtering, an adaptive thresholding approach is recommended for maximizing local estimation. This strategic shift from pixel-level to conceptual-level refinement enhances the final reconstruction process. As proven by experimental results, the proposed method with local directional interpolation and non-local adaptive thresholding outperforms many existing state-of-the-art methods for CDM. It is very effective in edge-detail retention and low-level artifacts of color interpolation, thereby realizing a better visual fidelity in color photo reproduction.

A novel method [31] proposed by Zhao et al. combines DWT and NEDI to enhance the resolution of geometrically distorted satellite images, particularly focusing on restoring edge information in high-frequency (edges) sub-bands. The image was first decomposed into the four frequency sub-bands by DWT. After this operation, NEDI was applied to the three high-frequency sub-bands and the original image for correction of distortion geometry, enhancement of edge detail, and its iterative procedure. An adaptive thresholding technique is employed to filter approximate wavelet coefficients, preserving edges while reducing noise in the high-frequency sub-bands. Finally, the image is reconstructed using inverse DWT. To evaluate the proposed method's effectiveness across various satellite image types, four specific criteria have been established. A dataset comprising publicly available satellite images is utilized for validation purposes. Both qualitative and quantitative results indicate the dominance of the proposed method over traditional image demosaicking techniques.

5. COMPRESSION TECHNIQUE OF COLOR FILTER ARRAY

Digital cameras are now ubiquitous for both casual and professional use. However, the raw images taken by sensors often come in the form of mosaic images, known as the CFA. However, uncompressed mosaic files can be significantly larger than those saved in JPEG format, sometimes over 30 times larger. Therefore, there is a need for effective compression techniques for mosaic images. Existing techniques often require custom decompression tools for reconstruction.

In their article Miguel et al., introduced a novel compression pipeline [32] that addresses these challenges. It allows for lossless retrieval of mosaic images from compressed files and enables direct display using a JPEG 2000 compliant image reader, without the need for custom decompression tools. Experimental results demonstrate that this pipeline achieves excellent visual quality while maintaining competitive compression efficiency compared to the existing techniques for mosaic image compression.

In a research article Yang et al., suggested a new method [33] to directly obtain more precise gradient / edge data on mosaic images. Next, we introduce an innovative adaptive heterogeneity-projection technique, which uses an appropriate mask scale for each pixel based on spectral correlation in spatial domain. This is accompanied by a new optimization in edge-sensing demosaicking that brings the gradient and edge information obtained into adaptive values of heterogeneity projection. The proposed high-resolution demosaicking optimization method proposed has higher image quality performance than many recently published algorithms, as evidenced by tests on 24 commonly used images.

Sampling systems for color mosaics are widely used in electronic cameras. However, a common issue with current color demosaicking algorithms is the lack of coherence in sample interpolations across multiple primary color channels, leading to undesirable color artifacts. To address this, a new primary-consistent gentle-decision system (PCSD) for color interpolation is proposed [34] by Xiaolin et al. In the PCSD system, the author makes several assumptions about edge or texture guidance and then generates multiple hypotheses for a displaced color sample. A primary-stable interpolation method is employed to render the images, ensuring that all three major elements of color are estimated in the same direction. By evaluating various interpolation hypotheses in the restored full colour image and choosing the best one through an best statistical judgment or inference procedure, the final approximation of a color sample is obtained. The PCSD system offers a robust color rendering process and effectively eliminates specific types of colour artifacts present in current demosaicking strategies. Extensive experimental results exhibit that the PCSD algorithm significantly enhances image quality in both subjective and quantitative assessments. In some cases, the improvement can be as high as 7 dB compared to competing methods.

The DSP chip serves as a pivotal component within a video recording framework. In the research article Hsia et al., proposed [35] the development of high-performance algorithms with near-zero complexity for the camera's imaging system. The core functionalities include missing colour estimation, white balance, automatic gain control, edge enhancement, and image enhancement techniques. Simulations exhibit the efficacy of this approach, particularly for color-filter-array style cameras. The DSP processor is constructed around these established algorithms. Prototyping begins with a single FPGA unit, followed by the realization of its ASIC counterpart using a CMOS process of 0.35um. Integration of additional components onto a single large PCB effectively yields a real-time camera system boasting resolutions of 1270x792.

In their research work Chen set al., introduced a color linearization processor [36] designed specifically for image sensors employing color-filter-array (CFA) technology. Through the utilization of path determination, the author proposes a refined technique for estimating color differences. Simulation results highlight the superiority of this approach in achieving a favorable balance between quality and complexity compared to existing methods. Furthermore, the article outlines the development of a cost-effective architecture featuring a pipeline structure, optimized for real-time applications. Successfully validated on an FPGA platform, the color interpolation processor system demonstrates efficient performance with minimal resource requirements, utilizing approximately 25 K gates and six-line buffers within a 0.18um phase.

Lukac et. al. [37] described a technique that focuses on post-processing to improve the visual appearance of full-color images generated by low-cost digital cameras mounted with CFA on Single sensor array used to capture the pictures or videos which utilizes the software interpolators to estimate the missing pixels. The proposed method primarily targets the correction of visual artifacts, particularly false colors, while also maintaining picture sharpness. The approach relies on a local colour ratio model and the Bayer CFA pattern which is fundamental to the arrangement of color filters on image sensors. By leveraging these factors, the technique effectively identifies and corrects inaccuracies in color representation without sacrificing image clarity. Importantly, the proposed method achieves significant improvements in visual quality while maintaining a balance in terms of quantitative measures of image consistency. This shows that the technique not only enhances the subjective visual experience but also performs well when assessed using objective metrics.

Chen [38] and his team employed an edge path tracking system through voting-based technique and a lateral weighted interpolation system, presented a novel color image demosaicking algorithm. This approach accurately calculates the interpolation path for the central missing color variable using an electoral strategy. By examining the intra-channel gradient interaction among neighboring pixels, the missing color portion at the center is interpolated along the calculated path using a gradient-weighted interpolation technique. Experimental results prove that the algorithm proposed yields greater performance in both quantitative metrics and subjective image characteristics compared to other recent demosaicking algorithms.

A novel color interpolation technique [39] is proposed by Lukac et al., for low-cost commercial cameras, focusing on color vectors. This method introduces a modern type of difference plane and utilizes an adjustment technique to enhance color visibility and eliminate edge blurring present in previous methods. Through Experimental results it is proved that the proposed method shows superior efficiency compared to existing color interpolation methods.

A generic color-ratio model [40] appropriate for CFA interpolation techniques was introduced by Lukac et al., in the context of single sensor imaging methods. The first proposed approach involves linearly rotating the CFA inputs, while the second approach employs scaling and shifting operations to normalize color samples in the input of the CFA interpolator. Utilizing these models enhances the performance of the existing demosaicking algorithms significantly. Experimental outcomes shows that the proposed method demonstrate superior efficiency in upsampling the sub sampled image, effectively eliminating issues such as color moiré, aliasing, and color variations.

6. CONVOLUTION AND CORRELATION BASED INTERPOLATION

Kehtarnavaz et al., introduced a CFA interpolation algorithm [41] designed to reconstruct the missing colours in CFA based digital cameras. Referred to as C2D2, this algorithm leverages colour correlation and directional derivative characteristics of neighboring colour pixels. Notably, C2D2 stands out for its lack of user-defined parameters, a common requirement in several edge-adaptive CFA algorithms. Two others widely used edge-adaptive algorithms serve as benchmarks for analytical and subjective comparisons. Results demonstrate that, across both RGB and Lab* color spaces, the proposed algorithm consistently yields lower MSEs.

Feng et al., in their article [42], employed a technique through data hiding is employed for raw images rather than just the full-resolution color images. The author selects the most common Bayer pattern from various CFA patterns and integrates the given concept into the pseudo host, ensuring high similarity within the R, G and B channels. The pseudo host is derived from a basic image generated by specifying the key through truncating this pattern. This approach offers enhanced protection and reduces artifacts associated with embedding codes. By leveraging structural associations in both the R and B channels, the quantization scale parameters are adaptively adjusted to eliminate visual distortion. The core framework also provides a watermarking solution aimed at jointly mitigating demosaicking and JPEG compression, with the goal of minimizing optical distortion. Extensive simulations are conducted to assess the robustness and clarity of the proposed approach under various demosaicking techniques and JPEG compression scenarios. The findings suggest that data hiding results in fewer traces of demosaicking artifacts and improved robustness across different demosaicking methods.

Yang et al., presented an adaptive area demonstration technique [43] utilizing multi-gradients to decrease colour artifacts. The author computes the green component first based on gradient operators and a weighted average process. Subsequently, the chrominance channels are restored using the constant-hue laws. The optimization of outcome is achieved through correlation of information. Simulation experiments demonstrate that the proposed algorithm enhances PSNR, sharpens the texture and base of the image, and improves overall image clarity.

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Objects suffer from extremely visible color irregularities if demosaicking is not done properly. In their article [44], Gunturk et al., introduced a new technique of demosaicking that effectively utilizes inter-channel correlation in an interchanging-projections system. The author compared this approach with six existing demonstration methods, and it is observed that it outperforms all the existing approaches, both subjectively and objectively.

W Lu et al., introduced a novel algorithm [45] employing two enhancements to CFA demosaicking: a modern and refined demosaicking method aimed at generating high-quality full colour images. The proposed CFA interpolation method comprises two main stages: an interpolation stage that estimates missing colour values based on spatial frequency correlations between neighboring pixels, and a post-processing stage that uses adaptive median filtering to mitigate visible demosaicking artifacts. Additionally, the author introduces two different image metrics to assess the efficiency of different demosaicking approaches, addressing the limitations of existing metrics. The first type evaluates demosaicked image accuracy by separately computing PSNR and CIELAB values for edges and smooth areas, while the second type examines a significant demosaicking artifact known as "zipper." Through comparisons with existing approaches using multiple test images, the author evaluates the efficacy of the new demosaicking system and image metrics.

Traditionally, quantitative methods for assessing image fidelity have primarily aimed to quantify the errors or discrepancies between a corrupted image and the reference image, leveraging insights from various characteristics of the human visual system. Recognizing the human visual system's strong inclination towards extracting structural data from images, Wang et al., proposed an additional quality assessment approach [46] that specifically focuses on the loss of structural details. As an embodiment of this concept, the author develops a Structural Similarity Index and demonstrates its efficacy with a series of illustrative examples. Furthermore, the index's performance is evaluated by comparing subjective evaluations and existing objective methods on a dataset of images compressed using both JPEG and JPEG2000 compression algorithms.

While modern demosaicking techniques are highly effective in making such extrapolations with limited data, they encounter challenges when the local geometric information cannot be derived from adjacent pixels. In such cases, images containing uncertainty, fine periodic patterns, or troublesome objects like the zipper effect, blurring, and color spots may appear. The study made by Antoni et al., in their work [47] contributes by demonstrating that these unwanted artifacts can be mitigated by leveraging the self-similarity of the image to extrapolate missing colors. Detailed investigations show that even in challenging scenarios, effective solutions can be devised. To validate these findings, comprehensive comparisons with existing algorithms will be conducted using two widely used image databases.

To restore missing color elements, the author proposes a method [48] based on edge-direction weighting and local gain adjustment. Simulations illustrate that the proposed method achieves a balance between quality and complexity compared to other algorithms. Leveraging an evolutionary approach, an architecture comprising a pipeline schedule is optimized for real-time processing is proposed. The VLSI architecture employs a time-sharing method to interpolate different colors using a standard kernel for computation, thereby minimizing circuit complexity. This Colour interpolation processor system has been successfully tested using an FPGA unit, requiring only around 10 K gates and two-line buffers.

Modern still color cameras employ a monolithic series of color filters positioned over a charge-coupled system design to capture the color spectrum. Every pixel in the resulting mosaic samples just one colour band. To restore a high-resolution color image, neighboring pixels approximate the values of the color bands not sampled at a particular spot. This process, known as demosaicking, is crucial for generating full-color images from the mosaic. In their work [49] Ramnath et al., implemented and analyzed several widely used demosaicking approaches using error measures such as MSE in the RGB colour space and perceived error in the CIELAB color space [49] (Rajeev Ramanath, William A, 2002).

The efficacy of a demosaicking algorithm hinges on its ability to leverage domain knowledge to constrain the potential solutions for accurately reconstructing the true color image. In th study [50], Gao et al., proposed a novel approach termed the color demonstration minimization approach, which integrates both spectral and spatial sparse representations of natural images. The spectral constraints are derived from a physical contrast enhancement model, while the sparse spatial representation is based on an interpretation of the adaptive principal component analysis window. Remarkably, the proposed technique outperforms existing methods by a significant margin in terms of Peak Signal-to-Noise Ratio (PSNR), particularly in challenging scenarios of color demosaicking, while also achieving superior visual quality.

The primary objective of the paper [51] authored by Su et al., is to develop theoretical formulas for estimating the missing pixels from noisy which very difficult through traditional interpolation methods. To address this limitation, a theoretical study convolution-based interpolation is made. The theoretical derivations are supported with numerical experiments. The proposed formulas offer a simpler, more concise, and more general approach compared to existing approaches. Furthermore, the paper introduces an approximate sinusoidal formula to streamline the estimation process of noise-induced bias. This formula enables quick, easy, and accurate estimation while also shedding light on how sophisticated interpolation methods can effectively mitigate noise-induced bias. Additionally, the paper quantitatively characterizes the dependencies of noise in the spatial domain. Ultimately, the primary aim of this research is to facilitate the accurate assessment of speckle patterns, thereby contributing to the standardization of for Digital Image Correlation (DIC) applications for speckle patterns.

Table 1 : List of important demosaicking methods and highlights

Sl. No	Author Name	Year	Type of method	Highlights
1	Wei Zhou et al.,	2016	High Throughput, Multi parallel HEVC method	Compared four parallel filtering method on boundary judgment
2	Shen-Yu Shih	2006	Optimal Deblocking for Advance video coding	Five stages of pipelining method applied in H.264 with State-of-the-art design
3	Rangababu Peesapati et al.	2017	Streaming Deblocking filter for HEVC	Designed Multiple edges simultaneously without affecting the neighboring blocks
4	Swamy Baldev et al.,	2018	Efficient Streaming Deblocking with SAO Filter	To design with transpose block to the original neighboring block with using three stage of pipeline architecture
5	Claudio Machodo Dinz et al.,	2015	Standard method of Deblocking Hardware method for High Efficiency Video	Design data path with highly optimized HEVC Deblocking method

7. CONCLUSIONS

In this article approximately 50 demosaicking algorithms are explored. A growing interest in refining these methods within digital image processing. Highlighting the significance of enhancing restored image quality across various processing methodologies, special attention is given to the pivotal role of CFA demosaicking in achieving high resolution for HEVC-based real-time video applications. Most demosaicking algorithms employ sequential strategies, starting with the recovery of the Green (luminance channel) before reconstructing the Red and Blue (chrominance) channels. Spatial adaptation, whether gradients (deterministic) Variance/Covarience (statistical), is identified as crucial for optimal performance. Comparative analyses of over 50 leading algorithms underscore the importance of simultaneously leveraging spatial and spectral correlations. Additionally, ad-hoc fusion techniques, such as averaging different demosaicked images, show potential for further enhancing results. This article identifies three key areas warranting further research. Firstly, addressing the challenge of demosaicking images with weak spectral correlation remains a priority, along with gaining a deeper understanding of the spatial-spectral correlation trade-off. Secondly, developing a more systematic fusion strategy could help mitigate mismatches between assumed models and observed data. Lastly, there is a call for more thorough investigation into evaluating demosaicking algorithm performance, especially concerning the use of reference images and understanding additional components in the imaging pipeline. It is also to be noted that the AI related solutions are to be worked out for better demosaicking results.

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