A GENERIC METHOD FOR GENERATING MULTISPECTRAL FILTER ARRAYS

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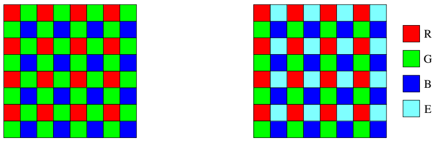
ABSTRACT

The technology of color filter arrays (CFA) has been widely used in the digital camera industry since it provides several advantages like low cost, exact registration, and strong robustness. The same motivations also drive the design of multi-spectral filter arrays (MSFA), in which more than three color bands are used (e.g. visible and infrared). Although considerable research has been reported to optimally reconstruct the full-color image using various interpolation algorithms, studies on the intrinsic properties of these filter arrays as well as the underlying design principles have been very limited. In this paper, we identify the properties a CFA should possess and extend the design philosophy to MSFA. Based on these discussions, we develop a generic MSFA generation method starting from a checkerboard pattern with both rectangular and hexagonal tessellations. By manipulating this pattern through a combination of decomposition and subsampling steps, we can generate MSFAs that satisfy all the design requirements. We show, through case studies, that most of the CFAs currently used by the industry can be derived as special cases. To evaluate the performance of MSFAs, we design a metric, referred as the static coefficient (SC), to measure the uniformity of MSFAs.

1. INTRODUCTION

In the commercial digital color camera market, instead of using three CCDs to capture the red, green, and blue spectral bands for each pixel, the color filter array (CFA) technique is widely used, in which each sensor is covered by an optical filter sensitive to a specified wavelength. In this way, only one spectral component is sensed at each pixel and the other spectral components must be estimated from neighboring pixels. The CFA technique provides advantages like low cost, exact registration, and strong robustness, which have made it very attractive to the industry. Fig. 1 illustrates two popular CFAs used by different digital camera manufacturers.



(a) Bayer array [1] (b) Sony RGBE array [2]

Fig. 1. Examples of popular CFAs.

In recent years, considerable work has been conducted in multispectral imaging, in which more than three bands may be acquired, e.g., visible and infrared (IR), as many objects of interest possess unique signatures in the IR band. For the same reason that promotes CFA over full-color cameras, we have investigated the potential of using multispectral filter arrays (MSFAs) to generate multispectral images. In the multispectral domain, more information need to be estimated at each pixel and the increased number of spectral bands makes the filter array design more complicated.

Most existing CFA techniques use rectangular arrays, because conventionally images are digitized and stored in this way. However, literature [3, 4] shows that the hexagonal array has unique advantages; for example, the hexagonal grid can model the human visual system more precisely, hexagonal sampling eliminates the connectivity ambiguity in the rectangular grid and the distances between a single pixel and its six immediate neighbors are the same.

Lots of research activities in the CFA area have been in the development of optimal interpolation algorithms [5, 6] which reconstruct the full-color image with minimum defects. Little concern, however, has been given to the design of filter array itself, let alone a generic algorithm that guides the design of filter arrays. This has not been a problem for the CFA design since only three bands are involved which is easy to handle manually. However, manually arranging the MSFA pattern poses a big challenge.

In this paper, we first discuss the design requirements for both CFAs and MSFAs. We then develop a generic

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method for the design of MSFA with both rectangular and hexagonal tessellations. Given the number of spectral bands and the probability of appearance of each spectral band, the generic algorithm can derive filter arrays that satisfy all the design requirements. We further show, through case study, that all the CFAs shown in Fig. 1 are simply special cases generated from the generic algorithm.

2. DESIGN REQUIREMENTS

As mentioned in Sec.1, although there is considerable literature in the development of interpolation algorithms, little [7] actually analyzes the design requirements for filter arrays, and all of the discussions are based on CFAs. In this section, we summarize our findings and extend the design requirements from CFA to MSFA.

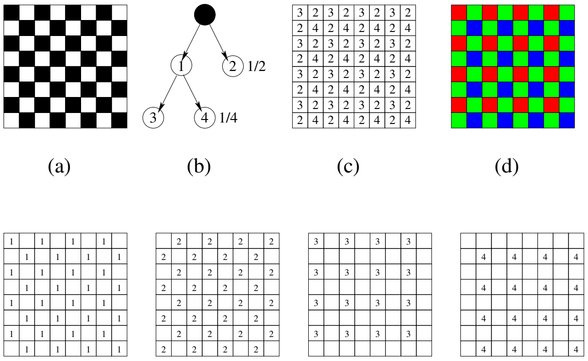
First, consider the *probability of appearance* requirement. One criterion used in the design of CFA (e.g. Bayer array) is that the pattern has to match the sensitivity response of the human visual system. In the design of MSFA, since the objective in multispectral imaging is mostly for better target recognition and separation of the object from clutter, we relate the probability of appearance to the effectiveness of the spectral band in recognizing the target. The spectral band that affects the classification result the most will be assigned more pixels in the filter array. In the context of this paper, we assume the spectral bands and their probability of appearance are given.

Second, consider the *spectral consistency* requirement. In order to present the same reconstruction performance across the whole image plane, pixels should always have the same number of neighbors of a certain spectral band within a neighborhood of certain distance.

Third, consider the *uniform distribution* requirement. In a mosaicked pattern, the unmeasured spectral components of a given pixel are estimated from its neighbors. This requires that the filter array for each spectral band can sample the entire image as evenly as possible. If the pixels distribute densely in some regions while sparsely in other regions, serious degradation might occur in the final reconstructed images.

3. MSFA IN THE RECTANGULAR DOMAIN

In order to satisfy all the requirements presented in Sec. 2, we adopt the checkerboard pattern (Fig. 2(a)) as the starting point to generate different filter arrays in the rectangular domain. The selection of the checkerboard pattern is based on a number of properties that this pattern possesses: first, the checkerboard pattern is symmetric horizontally, vertically, and diagonally; second, the black and white blocks are uniformly distributed across the whole board, and thirdly, this pattern has the same sampling frequency in both the horizontal and vertical directions. These properties facilitate the development of a generic MSFA generation algorithm.



(a)

(b)

3	2	3	2	3	2	3	2
2	4	2	4	2	4	2	4
3	2	3	2	3	2	3	2
2	4	2	4	2	4	2	4
3	2	3	2	3	2	3	2
2	4	2	4	2	4	2	4
3	2	3	2	3	2	3	2
2	4	2	4	2	4	2	4

(c)

(d)

1		1		1		1	
	1		1		1		1
1		1		1		1	
	1		1		1		1
1		1		1		1	
	1		1		1		1
1		1		1		1	
	1		1		1		1

(e) label-1

	2		2		2		2
2		2		2		2	
	2		2		2		2
2		2		2		2	
	2		2		2		2
2		2		2		2	
	2		2		2		2
2		2		2		2	

(f) label-2

3		3		3		3	
3		3		3		3	
3		3		3		3	
3		3		3		3	

(g) label-3

	4		4		4		4
	4		4		4		4
	4		4		4		4
	4		4		4		4

(h) label-4

Fig. 2. Case study 1 - the Bayer CFA.

The algorithm can be described in two steps, *decomposition* and *subsampling*, which are better illustrated using a binary tree, as shown in Fig. 2(b). The root represents the initial stage of the algorithm which is the checkerboard pattern. The decomposition and subsampling steps are conducted in an interleaved sequence. For example, the two children, labeled "1" and "2" are generated by the decomposition step and the children labeled "3" and "4" are generated by subsampling the child "1". All the children at the same level of the binary tree have the same probability of appearance $1/2^{level}$, where $level$ refers to the level of the binary tree.

Suppose we need to generate a p-band filter array and each band has its specific probability $r_1, r_2, \cdots, r_p$, where $r_i = \frac{1}{2^n}, n = 1, 2, \ldots$, and $\sum_{i=1}^{p} r_i = 1$, then we need to manipulate the binary tree such that it has p leaves and for leaf i, its probability should be equal to r_i. For example, Fig. 2(b) illustrates how to generate a 3-band CFA with the probability of appearance represented by $1/2, 1/4, 1/4$. In the following, we detail the decomposition and subsampling steps.

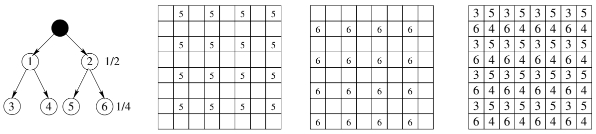
Step 1: Decompose the checkerboard pattern into two images with one of which only contains the white blocks and the other the black blocks. This process is shown in Fig. 2(e) and (f).

Step 2: Downsample by two the patterns generated from step 1 in both the horizontal and vertical directions to keep spectral consistency. The two children generated from downsampling the "label-1" image are shown in Fig. 2(g) and (h).

If the probability of all leaves satisfy the user's requirement, then combine all the leaves to form a filter array. Otherwise, treat the patterns generated from step 2 as new checkerboards and go to step 1.

The case study in Fig. 2 actually illustrates how the generic algorithm generates the Bayer CFA. Fig. 2(c) is generated by combining the three patterns in Fig. 2(f), (g) and (h). The corresponding color representation is shown in Fig. 2(d).

Fig. 3 shows another case study where a 4-band MSFA with equal probability of appearance is desired. In order to generate equal probabilities, we have to subsample the "label-2" image to generate the"label-5" and "label-6" image, as shown in Fig. 3(b) and (c). The corresponding binary tree is illustrated in Fig. 3(a). By assigning different colors (R, G, B, E) to labels "3", "6", "4", and "5" in Fig. 3(d), respectively, we actually obtain Sony's new 4-color RGBE CFA [2].



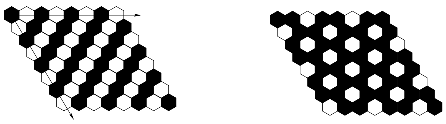
(a) Binary tree (b) label-5 (c) label-6 (d) MSFA

Fig. 3. Case study 2 - Sony's RGBE array.

From the above case studies, it is easy to see that the filter arrays generated from the generic method have the following characteristics: first, each spectral band is arranged symmetrically and uniformly in two orthogonal (horizontal and vertical) directions; second, each band has the same number of neighbors of a certain spectral band; and third, the percentage of each spectral band is determined by the separation process.

4. MSFA IN THE HEXAGONAL DOMAIN

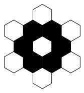
We extend the generic method developed in the rectangular domain to hexagonal domain for the unique properties possessed by hexagonal arrays. A preliminary step we have to consider in this extension, though, is how to define the checkerboard pattern in the hexagonal domain. We derive two options, as illustrated in Fig. 4.



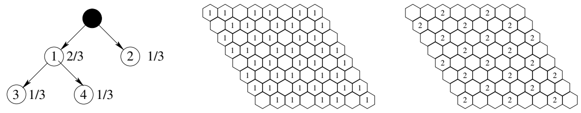
(a) Option 1 (b) Option 2

Fig. 4. Checkerboard patterns in the hexagonal domain.

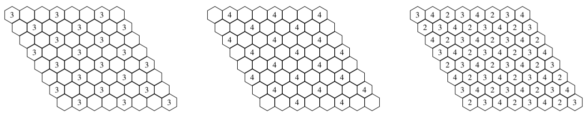
In option 1 (Fig. 4(a)), we introduce a new coordinate system in which the two axes are not orthogonal to each other (forms a 60-degree angle). The checkerboard pattern generated using this coordinate system satisfies all the three properties stated at the beginning of Sec. 3, except that the pattern is only symmetric diagonally and the equal sampling frequency is along the directions of the two non-orthogonal axes.



By analyzing the checkerboard pattern in the rectangular domain, we also find that each block has four 4-adjacent neighbors of different color from and four 8-adjacent neighbors of the same color as the current block, which the option 1 design pattern does not reveal. Therefore, we design the option 2 pattern (Fig. 4(b)) where each black block has three neighbors in black and three in white. Each white block, if viewed in a 12-pixel neighborhood as shown in the right figure, would have six distance-1 neighbors in black and six distance-$\sqrt{3}$ neighbors in white. This option provides nice interleaving patterns between the black and white blocks that resemble those in the rectangular domain. In addition, it shows better symmetry and is 60-degree rotation invariant. However, This pattern does not have equal sampling frequencies between the black and white blocks — the number of black blocks is twice the number of white blocks in Fig. 4(b).



(a) Binary tree (b) label-1 (c) label-2



(d) label-3 (e) label-4 (f) MSFA

Fig. 5. Case study 3 - A 3-band filter array.

The generic algorithm can be applied directly if using option 1 as the checkerboard pattern. When applied to the option 2 checkerboard pattern, the decomposition step is carried out the same in which the black and white blocks are separated. However, the subsampling step needs to be modified since we do not have equal numbers of black and white blocks. Fig. 5 shows an example for creating a 3-band CFA. The patterns in the first row result from the decomposition step. We note that the "label-1" image covers two thirds of the original pattern, and the "label-2" image one third. Since the "label-1" image has more pixels, we call it the "master" image and the "label-2" image the "slave" image. The subsampling step can only be applied to the "master" image, as shown in Fig. 5(d) and (e), generated by subsampling the “label-1” image. The binary tree is shown in Fig. 5(a). By combining the leaves “2”, “3” and “4”, we can generate a 3-band filter array (Fig. 5(f)).

By comparing the different MSFAs (Fig. 6) generated from the two optional checkerboard patterns, we make the following observations: first, each spectral band in the MSFAs generated from the option 1 pattern (option-1 MSFAs) has a probability of appearance of $r_i = \frac{1}{2^n}, n = 1, 2, \cdots$, while that from the option-2 MSFAs is $r_i = \frac{1}{3^n}$ or $r_i = \frac{2}{3^n}, n = 1, 2, \cdots$. Depends on the preset probability of appearance, different hexagonal checkerboard patterns should be used; second, in a 6-pixel neighborhood, each pixel in option-2 MSFAs always has the same number of a certain spectral band, although the arrangement might vary, while for option-1 MSFAs, we have to use the 12-pixel neighborhood.

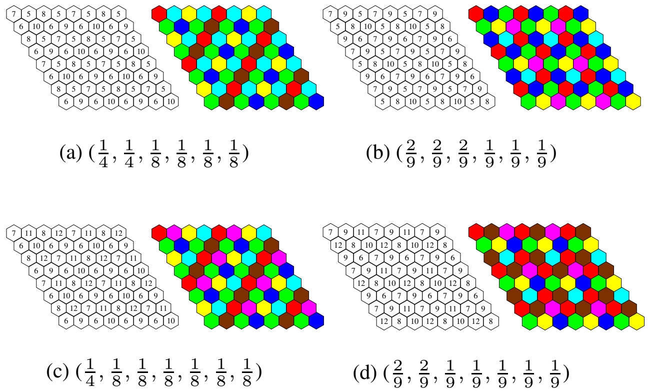
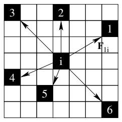

(a) $(\frac{1}{4}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8})$
(b) $(\frac{2}{9}, \frac{2}{9}, \frac{2}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9})$
(c) $(\frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8})$
(d) $(\frac{2}{9}, \frac{2}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{9})$

Fig. 6. Examples of option-1 ((a) and (c)) and option-2 ((b) and (d)) MSFAs with 6 and 7 bands. The fractal numbers reprent the probability of appearance.

5. PERFORMANCE EVALUATION OF MSFAS

To quantify the performance of an MSFA, we develop a metric, referred to as the *static coefficient* (SC), to measure the uniformity of MSFAs. This metric is based on the electrostatic force model, where under the effect of electrostatic force, point charges with the same polarities repel each other while charges with different polarities attract each other. We expect a uniform distribution should have a force of zero.



Let P represent an MSFA with K spectral bands, which can be decomposed into different filter planes $P_1, P_2, \ldots, P_K$. In each plane, we assume all the pixels have the same polarity of charges. For pixel i and all its neighbors within a fixed neighborhood, as illustrated in the right figure, the total force $\mathbf{F}_i$ can be formulated as $\mathbf{F}_i = \sum_{k \in \mathcal{N}_i} \mathbf{F}_{ki}$ where $\mathbf{F}_{ki}$ is the force exerted on pixel i by its neighbor k, and $\mathcal{N}_i$ is the set of neighboring pixels of i. We can then find out the force distribution of filter plane $P_j, j = 1, 2, \ldots, K$, which has mean μ_j. The static coefficient (SC) of the MSFA can be calculated by $SC = \frac{1}{K} \sum_{j=1}^{K} \mu_j$, and $\mu_j = \frac{1}{N_j} \sum_{i=1}^{N_j} \|\mathbf{F}_i\|$ where K indicates the number of spectral bands, and N_j the total number of pixels in spectral band j. $\|\cdot\|$ is the 2-norm calculating the magnitude of the force. The following table lists the SC of several filters patterns generated from the generic algorithm. From the results, we see that the rectangular and option 1 hexagonal patterns present high uniformity.

	4-band	5-band	6-band	7-band
Rectangular	0	0	0	0
Option 1 hex	0	0	0	0
Option 2 hex	4.0	6.4	8.0	4.6

6. CONCLUSION

We described a generic algorithm that can generate MSFAs of different numbers of spectral bands in both rectangular and hexagonal sampling domains. We also showed, through case studies, how a couple of CFAs used in the digital color camera industry can be generated using this generic algorithm. In the future work, we will find other metrics to quantitatively evaluate the performance of these filter arrays and derive a generic demosaicking algorithm.

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