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Spatial Arrangement of Color Filter Array for Multispectral Image Acquisition

Raju Shrestha, Jon Yngve Hardeberg and Rahat Khan

The Norwegian Color Research Laboratory, Gjøvik University College, Gjøvik, Norway

ABSTRACT

In the past few years there has been a significant volume of research work carried out in the field of multispectral image acquisition. The focus of most of these has been to facilitate a type of multispectral image acquisition systems that usually requires multiple subsequent shots (e.g. systems based on filter wheels, liquid crystal tunable filters, or active lighting). Recently, an alternative approach for one-shot multispectral image acquisition has been proposed; based on an extension of the color filter array (CFA) standard to produce more than three channels. We can thus introduce the concept of multispectral color filter array (MCFA). But this field has not been much explored, particularly little focus has been given in developing systems which focuses on the reconstruction of scene spectral reflectance.

In this paper, we have explored how the spatial arrangement of multispectral color filter array affects the acquisition accuracy with the construction of MCFAs of different sizes. We have simulated acquisitions of several spectral scenes using different number of filters/channels, and compared the results with those obtained by the conventional regular MCFA arrangement, evaluating the precision of the reconstructed scene spectral reflectance in terms of spectral RMS error, and colorimetric ΔE^*_{ab} color differences. It has been found that the precision and the the quality of the reconstructed images are significantly influenced by the spatial arrangement of the MCFA and the effect will be more and more prominent with the increase in the number of channels. We believe that MCFA-based systems can be a viable alternative for affordable acquisition of multispectral color images, in particular for applications where spatial resolution can be traded off for spectral resolution. We have shown that the spatial arrangement of the array is an important design issue.

Keywords: Color filter array, CFA, MCFA, spatial arrangement, multispectral imaging

1. INTRODUCTION

Most commercial digital cameras provide 3-channel output, usually Red, Green and Blue (RGB). In order to reduce the cost, the use of one sensor (CCD/CMOS) per channel has been avoided with the use of color filter array (CFA) in front of the sensor. Introduction of a CFA also facilitates real time capture of color images with exact registration and robustness. The most commonly used CFA in commercial digital cameras is the Bayer filter.[1] Use of color filter array based image capture has now been widely accepted in the industry. Color filter array can be interesting for multispectral imaging also, where more than three channels are used to capture the image. At present, most of the multispectral image acquisition systems use multiple subsequent shot technology which prevents it to capture scenes in motion. Use of CFA in multispectral imaging could be one of the promising techniques to make it capable of one shot imaging.

Construction of a multispectral acquisition system based on CFA is not a new concept. To our knowledge, the first proposal to design a multispectral acquisition system based on a CFA was made by Baone and Qi.[2] The focus of this work was to build a multispectral camera for classification. In those systems, they have used 4 additional bands in MWIR (Middle Wave Infra Red) and LWIR (Low Wave Infra Red). They have also proposed a new demosaicking algorithm that tries to better restore the image by maximizing a-posteriori probability. A very recent work by Lu et al.[3] has also focused on constructing multispectral CFA to capture a NIR (Near Infra Red) band along with the visible bands. The purpose of this work was the simultaneous capture of high quality visible and NIR image pair. Another work by Brauers et al.[4] is based on construction of a CFA with narrow band filters in the visible range. Here also, a demosaicking algorithm has been proposed which tries to use the inter-band correlation by low pass filtering channel differences.

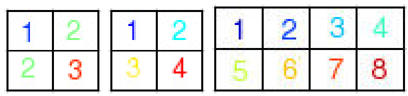
A CFA based multispectral camera introduces several issues that needs to be handled. Firstly, the choice of the number of filters and their selection for the acquisition system. Secondly, the spatial arrangement of the filters, and finally, the demosaicking algorithm. A number of works have been carried out in the field of filter selection for multispectral acquisition systems, e.g. the work by Hardeberg et al.[5] However, all of them deal with acquisition systems that take multiple subsequent shots. Much work has also been done on demosaicking algorithms,[6–15] mostly for 3-channel images. These demosaicking algorithms can also be used in a multispectral CFA directly or with little modification. But probably the area that has got least attention in the field of multispectral CFA design is the spatial arrangement of the filter array. However, Miao et al.[16] has proposed spatial arrangement of CFA filter based on the probability of appearance of the corresponding band.

In this paper we have investigated filter arrangements proposed by Brauers et al.[4] and by Miao et al.[16] The approaches has been studied with different number of filters through simulation over several spectral scenes and compare the results in order to explore the effects of spatial arrangement as well as the number of filters on the accuracy of spectral reconstruction from spectral as well as colorimetric point of views. In the rest of this paper, we first discuss the spatial filter arrangement in Section 2. Section 3 discuses the simulation setups detailing the filters selection, demosaicking algorithm, spectral reconstruction and evaluation techniques used. Section 4 presents the simulation results, and finally make conclusion of the paper.

2. SPATIAL ARRANGEMENT OF FILTER ARRAY

In general, there are two domains of CFA arrangements: rectangular and hexagonal.[17–19] Since conventionally images are digitized and stored in rectangular way, and most existing CFA techniques use rectangular arrays, our focus here in this paper, therefore, is basically in the rectangular domain. However, the proposed work can be extended further in the case of hexagonal domain as well.

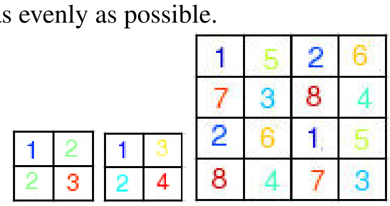
The first naive and simple arrangement of the filters would be to arrange them sequentially in two or more rows depending on the number of filters and repeat the pattern over the entire CFA.[4] Figure 1 presents such simple CFA arrangements for 3, 4 and 8 channels, where the numbers indicate the filter numbers, and the colors indicate the corresponding dominant color of the filter channels as given in Figure 3.



(a) 3 (b) 4 (c) 8

Figure 1. Simple MCFA arrangement with 3, 4 and 8 channels

A generalized algorithm to automatically generate the MSFA given the spectral bands and the probability of appearance of each spectral band has been proposed by Miao.[16] The design of MSFA, unlike CFAs, is not oriented toward the human visual system. Rather, the filters are arranged such that the array would have the best recognition performance on a certain kind of target. Therefore, the probability of appearance has to be application-oriented as well. We assume this parameter is given a-priori. The algorithm is based on the two important design requirement criteria: the *spectral consistency* and the *spatial uniformity*. To present the same reconstruction performance throughout the image plane, pixels should always have the same number of neighbors of a certain spectral band within a neighborhood of certain distance; and this requirement is fulfilled by spectral consistency criteria. The spatial uniformity criteria fulfills the requirement that the filter array for each spectral band samples the entire image as evenly as possible.



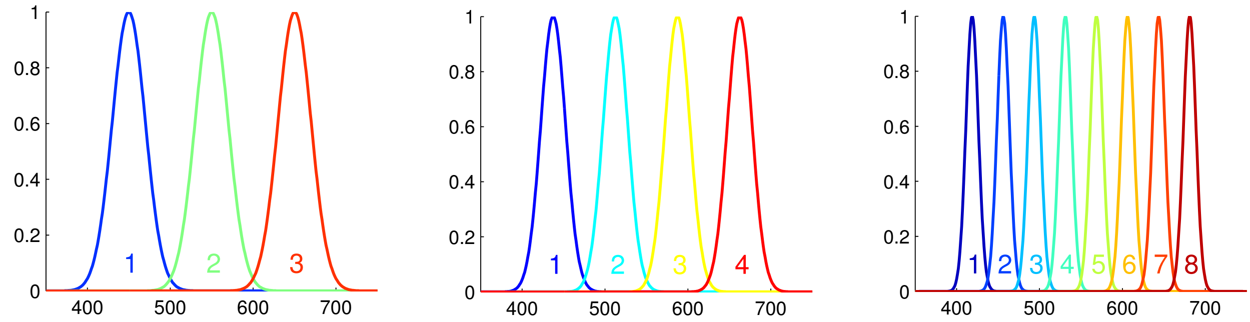
(a) 3 (b) 4 (c) 8

Figure 2. Generalized MCFA arrangement with 3, 4 and 8 channels

The algorithm starts with a checker board pattern. The algorithm progresses by the process of decomposition and sub sampling with the knowledge of probability of appearance of each spectral band on the scene. It means the more the probability of appearance of a spectral band, the more it will appear on the MCFA. It terminates when all the bands on MCFA has the predefined probability. Figure 2 illustrates CFA arrangements based on this algorithm for 3, 4 and 8 channels, assuming that all of our spectral bands have equal probability of appearance. We can see that all the channels have appeared equal number of times in the MCFA except in the case of 3 channels. It also fulfills the other two requirements that is also maintained in all other standard CFAs. The arrangement for 3 channels case is the same as in the basic arrangement, while the arrangement for 4 channels has been changed a bit by swapping the channel 2 and 3. The MCFA arrangement is quite different from the naive arrangement in the case of 8 channels.

3. SIMULATION SETUP

Several methods have been proposed for the selection of filters, particularly for multi-shot based multispectral color imaging.[5] In our simulation here, investigation has been carried out with different number of filters, more particularly 4 and 8, as these will form a complete binary tree with Miao's algorithm, assuming equal probability of appearances. The filters are generated such that their peaks are well spread over the entire visible spectrum. To make it more realistic, the shape of the filters are made to be Gaussian as illustrated in Figure 3 for the three cases with 3, 4 and 8 channels.



(a) 3 channels (b) 4 channels (c) 8 channels

Figure 3. Selection of filters

Since the main purpose of this work is to investigate the influence of the spatial arrangement of the MCFA on the spectral reconstruction, the most simple and basic demosaicking method, the bilinear demosaicking method has been used. We think that it would be sufficient for a fair comparative analysis. The kernel size of $cfasize+1$ has been used for demosaicking with the bilinear interpolation. The process of bilinear interpolation has been well described in.[2]

Both naive and generalized arrangements with 3, 4 and 8 channels as discussed in Section 2 are investigated. Simulation has been carried out with 3 spectral images from Joensuu Spectral Image Database[20] namely, *Young Girl*, *Woman Face* and *Woman Reading* (see Figure 7 for a view of these images).

In order to reconstruct the reflectance spectra from the simulated capture of the scene using the set of filters, the channel responses are considered as monochromatic (more or less). We use the bicubic interpolation for spectral reconstruction, since bicubic interpolation are smoother and produce fewer interpolation artifacts. This interpolation gives a spectra only in the spectral range of the filters. In order to get the complete spectra from 400nm to 700nm, two boundaries of the spectra are linearly extrapolated from the corresponding last two samples. Even though this process does not provide perfect result, this simple reconstruction method fulfills the purpose.

The reconstructed reflectance are evaluated using spectral as well as colorimetric metrics. Most commonly used RMS (Root Mean Square) error has been used as the spectral metric and ΔE^*_{ab} (CIELAB Color Difference) as the colorimetric metric. These metrics are given by the equations:

$$RMS = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left[\tilde{R}(\lambda_j) - R(\lambda_j)\right]^2}$$

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

CIE D65 illuminant and CIEXYZ 1964 color matching functions are used for computation of ΔE^*_{ab}.

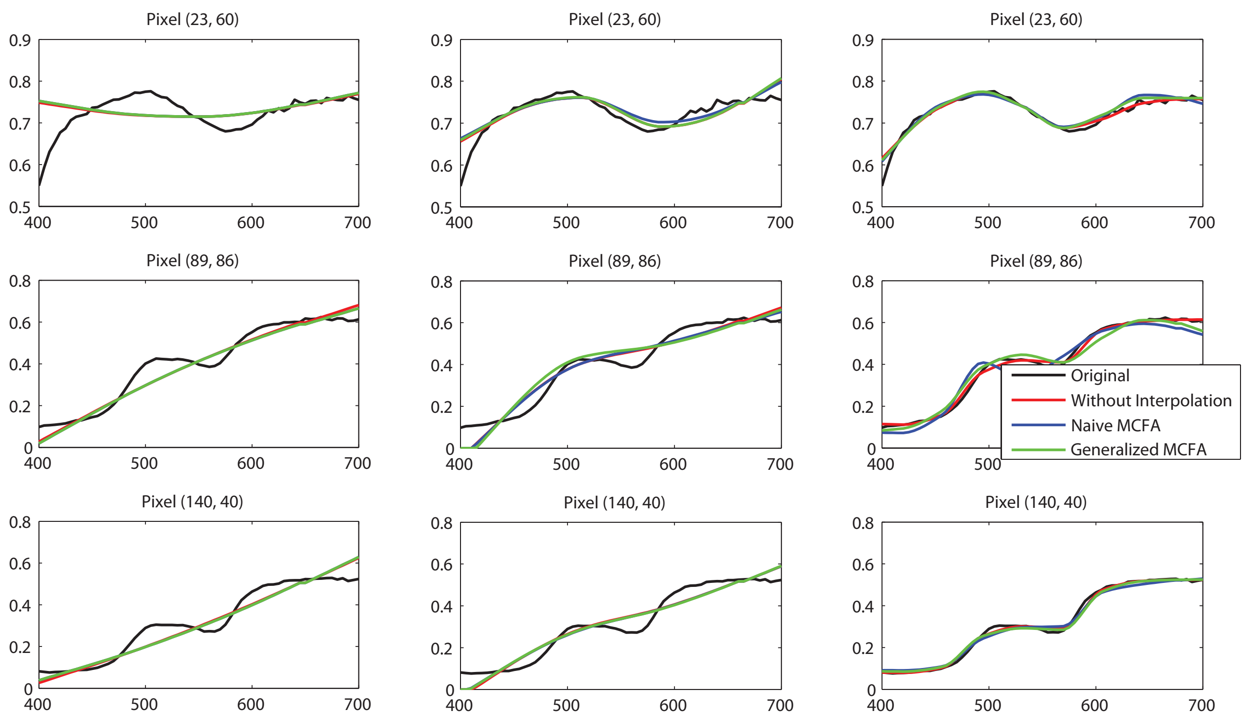
4. SIMULATION RESULTS

For a given number of filters, the simulation computes a multispectral image from the spectral image under the given illuminant (CIE D65). The output is computed with two MCFA patterns as discussed in Section 2 and also without interpolation. The image spectra is then reconstructed from the spectral output image and evaluated with the original spectra as presented in Section 3. Table 1 shows the statistics (maximum and mean) of the reconstruction errors (RMS and ΔE^*_{ab}) with the two MCFAs and without interpolation for 3, 4 and 8 channels cases, and for all the three images. The results shows significant differences in the performances between the two different MCFA arrangements both spectrally and colorimetrically. The generalized MCFA performs better than the naive MCFA and the difference becomes more significant when the number of filter grows, as can be seen with 8 channels where the mean ΔE^*_{ab} difference is more than 0.7, and in general a MCFA comprises more than 6 channels. And as expected, we can see that the performance is much better without interpolation.

Table 1. Statistics of estimation errors

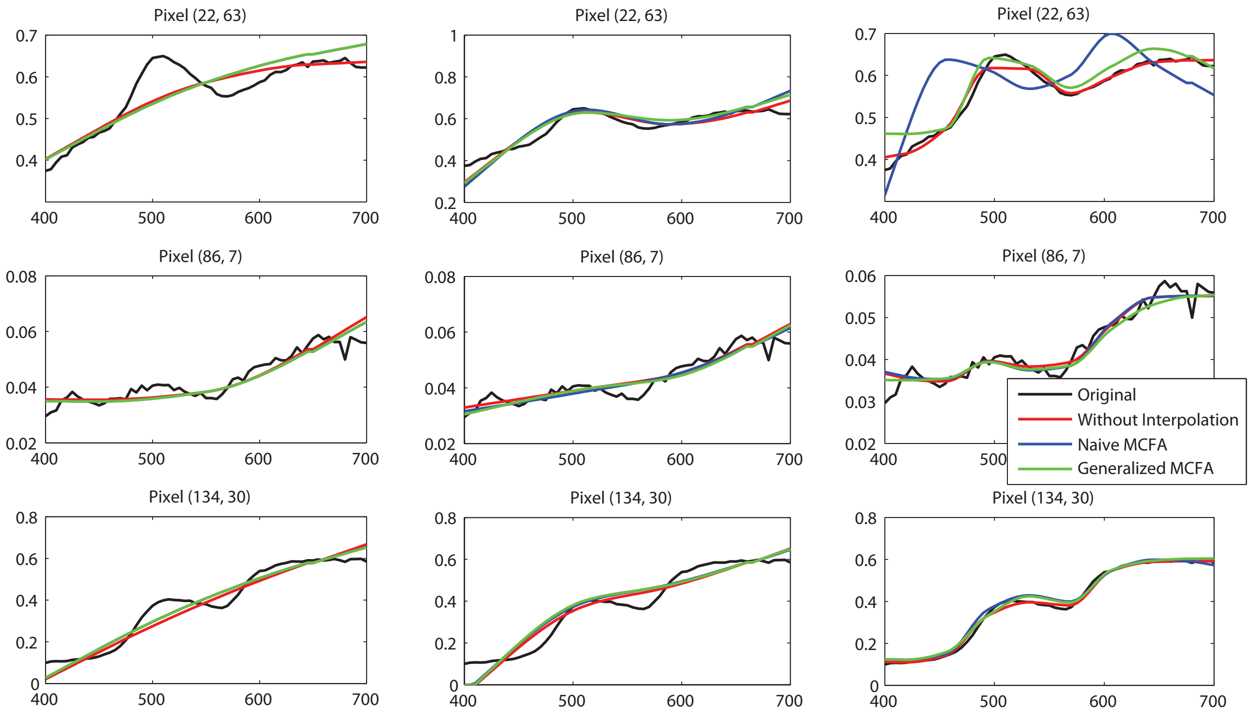
Image	No. of Channels	Naive MCFA				Generalized MCFA				Without Interpolation			
		RMS		ΔE^*_{ab}		RMS		ΔE^*_{ab}		RMS		ΔE^*_{ab}	
		Max	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**	**Max**	**Mean**
Young Girl	**3**	0.0104	0.0024	17.5091	2.1640	0.0104	0.0024	17.5091	2.1640	0.0079	0.0022	7.4591	1.8110
	4	0.0091	0.0022	15.7984	2.2303	0.0094	0.0021	17.7421	2.2429	0.0082	0.0019	6.3428	1.7862
	8	0.0138	0.0018	21.9766	2.2421	0.0086	0.0011	14.3224	1.3315	0.0082	0.0005	1.0263	0.3506
Woman Face	**3**	0.0111	0.0020	19.5894	1.9545	0.0111	0.0020	19.5894	1.9545	0.0059	0.0019	5.0214	1.6064
	4	0.0093	0.0020	14.0680	1.9184	0.0096	0.0020	14.9213	1.8998	0.0042	0.0018	5.4402	1.4972
	8	0.0126	0.0018	21.8870	2.0170	0.0097	0.0012	15.9888	1.1704	0.0012	0.0006	0.6862	0.2953
Woman Reading	**3**	0.0084	0.0019	14.8652	1.3027	0.0084	0.0019	14.8652	1.3027	0.0082	0.0018	4.8398	1.0418
	4	0.0091	0.0016	15.7678	1.7728	0.0084	0.0016	12.7343	1.7591	0.0082	0.0015	5.9691	1.5387
	8	0.0110	0.0012	16.4156	1.4463	0.0084	0.0008	16.4161	0.8694	0.0076	0.0004	0.6000	0.2130

The spectra of the original along with the reconstructed images with different MCFAs for all three images are shown in Figures 4, 5 and 6 respectively. For illustrations, three random pixels are picked and the spectra for these pixels in the three images are shown in these figures.



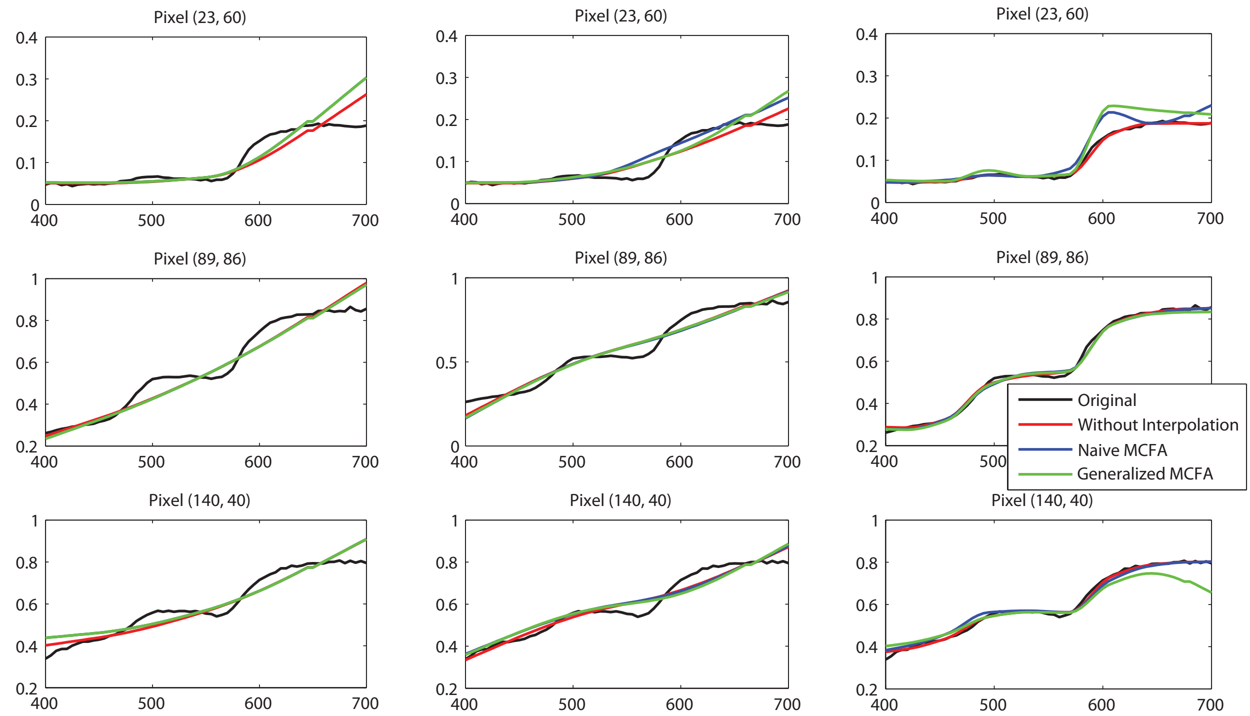
(a) 3 channels (b) 4 channels (c) 8 channels

Figure 4. Original and reconstructed spectra for *Young Girl* image



(a) 3 channels (b) 4 channels (c) 8 channels

Figure 5. Original and reconstructed spectra for *Woman Face* image



(a) 3 channels (b) 4 channels (c) 8 channels

Figure 6. Original and reconstructed spectra for *Woman Reading* image

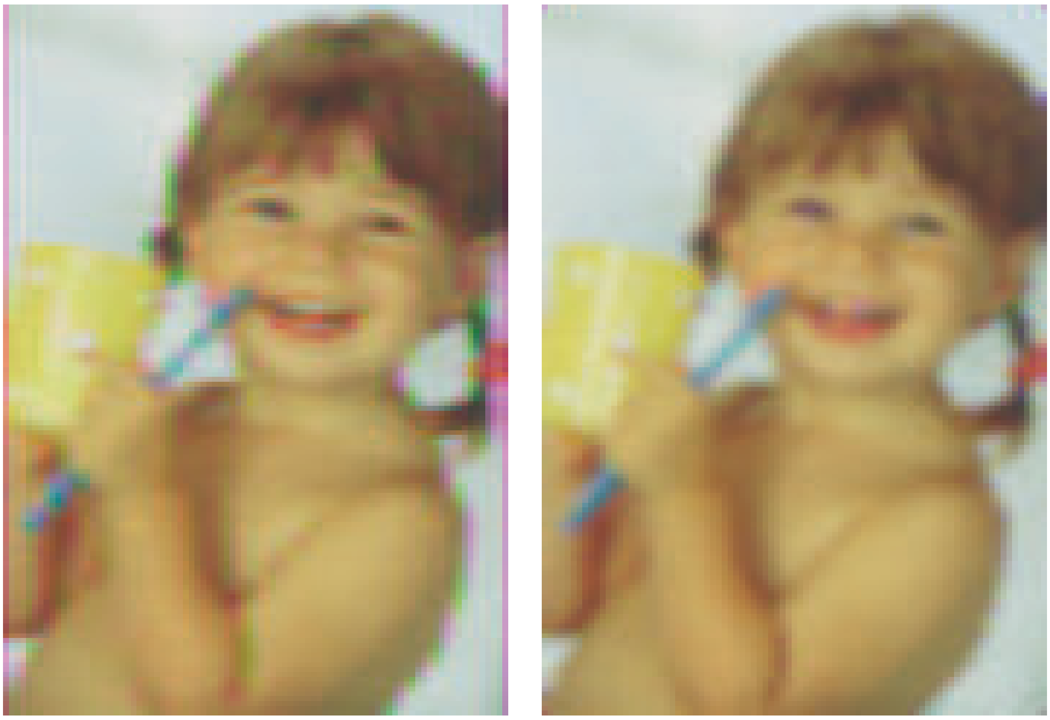
We can see that the reconstructed spectra get more closer to the original spectra with the increase in the number of filters. There is not much difference in the estimated spectra with two MCFA arrangements with smaller number of filters as can be seen with 4 channels. However, the difference becomes more significant as the number of channels grows. This can be clearly seen from the spectra with 8 channels where the generalized MCFA gives better performance than the naive MCFA.

The reproduced images from the reconstructed spectra along with the original are shown in Figure 7. The figure shows the reproduced images with two different MCFA arrangements and without interpolation, for 3, 4 and 8 channels cases.

(a) Young Girl (b) Woman Face (c) Woman Reading

Figure 7. Original and reconstructed images with 3, 4 and 8 channels

We can see the difference in the color and the quality of the images in the reconstructed images with the different number of channels and with different MCFA arrangements. The color of the images becomes better and more natural with the increase in the number of channels from 3 to 8. If we look into these images more closely, we can see some visible block effects and also some false colors in the images reconstructed with naive MCFA compared to that with the generalized MCFA. This can be clearly seen in the zoomed versions of the reconstructed images with 8 channels in Figures 8, 9 and 10. The false colors and block effects are more prominent in and around the edges. Moreover, the filter pattern of the naive MCFA for 8-channels is not a square type, rather a 4×2 (see Figure 1(c)) and hence does not fulfill the spectral consistency requirement. This causes a band of false color at the left and right edges of the image. The images obtained from generalized MCFA appear more smoother and of better quality, thus clearly indicating the importance of the spatial arrangement of MCFA.



(a) Naive MCFA (b) Generalized MCFA

Figure 8. Zoomed images of *Young Girl* with 8 channels

(a) Naive MCFA (b) Generalized MCFA

Figure 9. Zoomed images of *Woman Face* with 8 channels

(a) Naive MCFA (b) Generalized MCFA

Figure 10. Zoomed images of *Woman Reading* with 8 channels

5. CONCLUSION

This paper has investigated the influence of the spatial arrangement of MCFA with the different number of filters/channels in MCFA based multispectral systems. It has been found that there is significant effect of the spatial arrangement of MCFA on the performance of a multispectral system as the number of channel increases. This verifies the importance of the spatial arrangement in the MCFA based multispectral camera design. The generalized MCFA that fulfills the two requirements of CFAs: spectral consistency and spatial uniformity, shows better results than naive MCFA arrangement. The results are based on the simple bilinear demosaicking algorithm. It would be interesting to further work on MCFA for more advanced and specialized demosaicking algorithm, and as a future work, the study can be made with other number of filters where the probability of appearances are not equal for all the channels.

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