A Study on the Impact of Spectral Characteristics of Filters on Multispectral Image Acquisition

Xingbo WANG,[1,2] Jean-Baptiste THOMAS,[1]
Jon Yngve HARDEBERG,[2] Pierre GOUTON[1]
[1] Laboratoire Electronique, Informatique et Image, Université de Bourgogne, France
[2] Norwegian Colour and Visual Computing Laboratory, Gjøvik University College, Norway

ABSTRACT

In every aspect, filter design plays an important role in an image acquisition system based on a single image sensor and a colour filter array (CFA) mounted onto the sensor. Complementary CFAs are used by some colour cameras in the interest of higher sensitivity, which motivated us to employ filters of wide pass bands in the effort to adapt CFA for multispectral image acquisition. In this context, filter design has an effect on the accuracy of spectrum reconstruction in addition to other aspects. The results show that wider bandwiths in general result in more faithful spectrum reconstruction and higher signal-to-noise performance.

1. INTRODUCTION

The success gained by colour filter array (CFA) based single-sensor colour imaging systems has awakened particular interest from the academia and the industries in extending the colour filter array into multispectral domain by integrating more than three types of filters into one filter array, which results in a multispectral filter array (MSFA).

In general, development of a MSFA based multispectral imaging system involves filter design, mosaic tessellation and demosaicking. Spectral characteristics of filters make a direct impact on spectrum reconstruction from the multispectral sensor response. Further filters of wider bandwidth may reduce the incoming radiant power absorbed and reflected by the filters thus boosting the sensitvitity and improving the efficiency of energy use. In addition, it may also increase the spectral overlap between filters hence increasing the correlation between channels and offering benefits to modern demosaicking algorithms taking advantage of inter-channel correlation. Following our previous research (Wang *et al.* 2013), we focus in this work on the impact of spectral characteristics of filters on the accuracy of spectrum reconstruction in the context of a multispectral image acquisition system.

The following parts of the article begins by an introducion of filter design in Section 2 followed by a description of three spectrum reconstruction methods in Section 3. Section 4 explains the procedures and conditions of the experiments, and demonstrate the results, which leads to the conclusions drawn in Section 5.

2. DESIGN OF FILTERS

The most common CFA design is known as Bayer filter mosaic (Bayer 1976). Since then the pattern has been employed in its original state, and a spectrum of modified arrangements have been proposed. Among the derivatives of Bayer mosaic, some possess complementary colour filters in comparison to the primary colour filters utilised in the original patent, in the interest of higher sensitivity (Parulski 1985). Further, two distinct types of filter design, namely narrow-band and broad-band, are commonly seen in the multispectral capture (Imai *et al.* 2000). The spectral transmittances of the filter mosaic exert direct influence on the responsivity of an imaging system which in turn has an effect on system sensitivity, signal-to-noise performance as well as accuracy of spectral reconstruction.

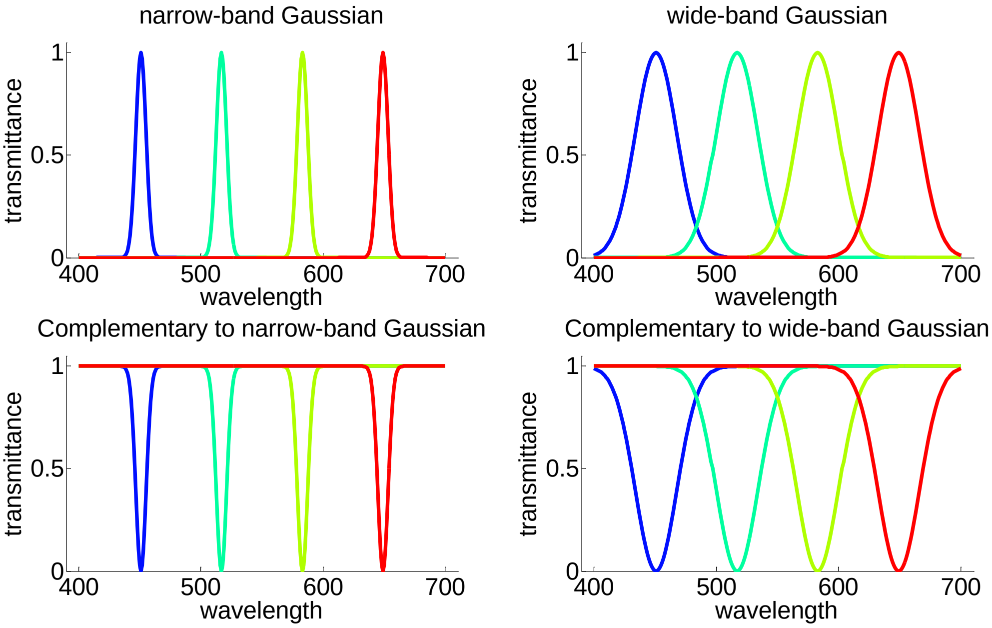

Figure 1: An example of filter design

Inspired by the aforementioned facts, we chose four types of bandwidths. Figure 1 illustrates an example set of filters designed for a four-band multispectral acquisition system. The two graphs in the upper row show narrow-band and broad-band transmittances with FWHM (Full Width at half maximum) of 10 nm and 40nm respectively. The two graphs in the lower row present filter sets complementary to the corresponding sets in the upper row.

3. SPECTRUM RECONSTRUCTION FROM MULTISPECTRAL MEASUREMENTS

Spectrum reconstruction is an inverse problem aimed at an estimation of spectra of high dimension from the corresponding multispectral measurements of lower dimension. In concrete terms, a multispectral capture process can be described in a linear form as

$$\mathbf{R} = \mathbf{QS}, \tag{1}$$

where $\mathbf{R}$ refers to the multispectral responses of dimension $\mathrm{c} \times \mathrm{n}$, $\mathbf{Q}$ correspondes to system responsivities of dimension $\mathrm{c} \times \mathrm{w}$, and $\mathbf{S}$ is the incoming spectra of dimension $\mathrm{w} \times \mathrm{n}$, c is the number of spectral bands captured by the system, w is number of spectral components of incident spectra, and w is the number of spectra.

Spectrum reconstruction aims at an estimation of $\mathbf{S}$ from $\mathbf{R}$. (1) is solvable if $\mathbf{Q}$ is known and invertible, however it is not true in the case of spectrum reconstruction. Nevertheless it can be estimated by means of training where a collection of training spectra $\mathbf{S}_t$ and corresponding responses $\mathbf{R}_t$ are utilised to derive an approximation of $\mathbf{Q}^{-1}$. Three representative methods based on different principles were experimented with to this end.

The method of linear least squares attempts to solve (1) by means of pseudoinverse which leads to (2)

$$\mathbf{S}' = \mathbf{S}_t\mathbf{R}_t^{+}\mathbf{R}, \tag{2}$$

where $\mathbf{S}'$ is an estimation of $\mathbf{S}$ and is a right pseudoinverse of $\mathbf{R}_t$: $\mathbf{R}_t^{+} = \mathbf{R}_t^{T}(\mathbf{R}_t\mathbf{R}_t^{T})^{-1}$.

Imai and Berns (1999) propose to employ PCA (principal component analysis) to anlyse the training spectra, which gives rise to (3)

$$\mathbf{S}' = \mathbf{W}(\boldsymbol{S}_t^{T}\mathbf{W})^{T}\mathbf{R}_t^{+}\mathbf{R}, \tag{3}$$

where $\mathbf{W}$ is of dimension consisting of m most significant eigenvectors of the training spectra by means of PCA. The parameter m is determined so that the RMSE (root mean square error) between $\mathbf{S}_t$ and $\boldsymbol{S}_t'$ is minimised.

Wiener estimation is yet another method taking noise into consideration in the following manner,

$$\mathbf{S}' = \mathbf{S}_t\boldsymbol{S}_t^{T}\mathbf{Q}^{T}(\mathbf{Q}\mathbf{S}_t\boldsymbol{S}_t'\mathbf{Q}^{T} + \mathbf{N})^{-1}\mathbf{R}, \tag{4}$$

where $\mathbf{N}$ is a term reflecting additive noise intrinsic to the system in form of $\sigma^2\mathbf{I}$ with σ^2 being the variance of noise and $\mathbf{I}$ being the identity matrix.

4. EXPERIMENTAL SETUP AND RESULTS

48 hyperspectral image sets were used in this study. 16 of them are from Foster *et al.* (2006) consists of a mixture of rural scenes, and another 32 are from the CAVE project (Yasuma *et al.* 2008) including a wide variety of real-world materials and objects and artificial replicas. For the ease of processing and comparison, all images were interpolated to cover the range between 400 nm and 700 nm with an interval of 1 nm. The number of filters studied ranges from 3 to 9. A framework that simulates the key elements of a multispectral imaging system was built as a testbed. Images were rendered with the illuminant of CIE D65. Evaluation of the performance was carried out by means of the avaerage RMSE evaluated from normalised spectra. The amplitude of noise was determined so that the maximum SNR achieved by a perfect diffuser is 50 dB and the variance is 20% of the level of noise.

The results obtained with the three methods illustrate similar tendencies, therefore results obtained with method 1 is shown only in Figure 2. Clearly the complementary filter sets outperform the primary filter sets. Filters complementary to the narrow-band primary filter set possess wider pass band than their wide-band counterparts. Nevertheless the inverse relationship between the performance and the bandwidths seems not entirely true, as indicated by the dotted line and the dash-dotted line.

5. CONCLUSIONS

We tested the performance of three spectrum construction methods with four types of filter designs. It verifies our hypotheses that filters of wider pass bands benefit multispectral acquisition in terms of higher accuracy as well as higher SNRs especially in low light conditions. The results merit closer examination and further theoretical analyses. And preliminary experiments have shown that wider filter bandwidths increases degree of overlap between filters therefore increasing the inter-channel correlation on which modern demosaicking algorithms rely.

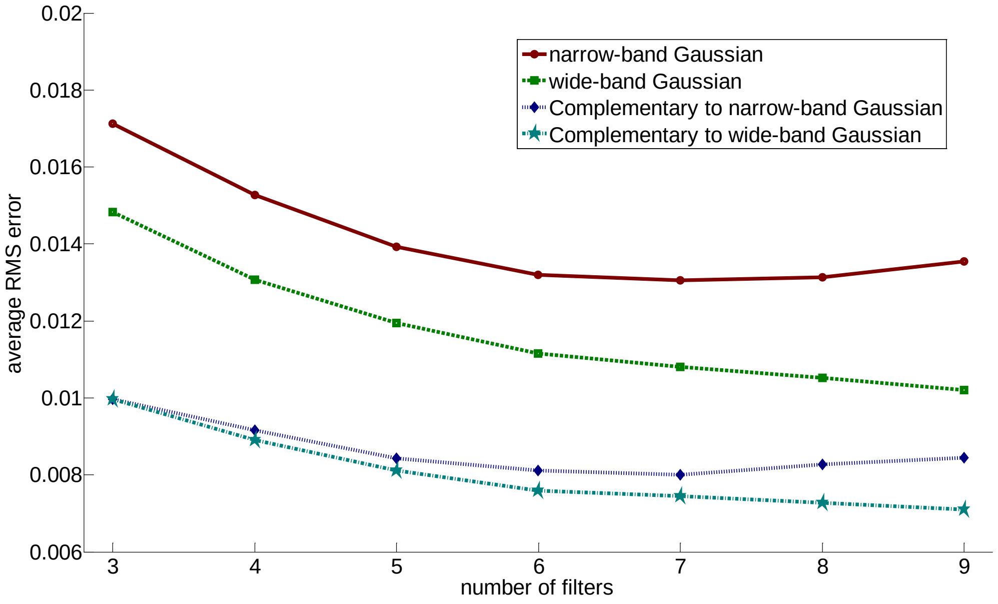

Figure 2: Results obtained with Least Squares Method

ACKNOWLEDGEMENTS

The authors thank the Regional Council of Burgundy in France and Gjøvik University College in Norway for funding the research work.

REFERENCES

Bayer, B.E. 1976. *Color imaging array*, Patent, US 3971065.

Foster, D.H., L. Amano, S.M.C. Nascimento and M.J. Foster 2006. *Frequency of metamerism in natural scenes*, J. Opt. Soc. Am. A, 23(10), 2359–2372.

Imai, F.H. and R.S. Berns 1999. *Spectral estimation using trichromatic digital cameras*, Proceedings of the International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives, 42-49.

Imai, F.H., M.R. Rosen, and R.S. Berns 2000. *Comparison of spectrally narrow-band capture versus wide-band with a priori sample analysis for spectral reflectance estimation*, Proc. of the 8th Color Imaging Conference, 234-241.

Parulski, K.A. 1985. *Color filters and processing alternatives for one-chip cameras*, IEEE Transactions on Electron Devices, 32(8), 1381-1389.

Wang, X., J.B. Thomas, J.Y. Hardeberg and P. Gouton 2013. *Median filtering in multispectral filter array demosaicking*, Proc. SPIE, vol.8660.

Yasuma, F., T. Mitsunaga, D. Iso and S.K. Nayar 2008. *Generalized assorted pixel camera*, Tech. Report, Department of Computer Science, Columbia University.

Address: Xingbo Wang, Faculty of Computer Science and Media Technology,
Gjøvik University College, Teknologivegen 22, 2815 Gjøvik, NORWAY
E-mails: xingbo.wang@hig.no, jean-baptiste.thomas@u-bourgogne.fr,
jon.hardeberg@hig.no, pierre.gouton@u-bourgogne.fr