Evaluation of the Colorimetric Performance of Single-Sensor Image Acquisition Systems Employing Colour and Multispectral Filter Array

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Abstract. Single-sensor colour imaging systems mostly employ a colour filter array (CFA). This enables the acquisition of a colour image by a single sensor at one exposure at the cost of reduced spatial resolution. The idea of CFA fit itself well with multispectral purposes by incorporating more than three types of filters into the array which results in multispectral filter array (MSFA). In comparison with a CFA, an MSFA trades spatial resolution for spectral resolution. A simulation was performed to evaluate the colorimetric performance of such CFA/MSFA imaging systems and investigate the trade-off between spatial resolution and spectral resolution by comparing CFA and MSFA systems utilising various filter characteristics and demosaicking methods including intra- and inter-channel bilinear interpolation as well as discrete wavelet transformed based techniques. In general, 4-band and 8-band MSFAs provide better or comparable performance than the CFA setup in terms of CIEDE2000 and S-CIELAB colour difference. This indicates that MSFA would be favourable for colorimetric purposes.

Keywords: Colorimetric performance · Colour filter array · Multispectral imaging · Single-sensor

1 Introduction

Single-sensor trichromatic imaging systems mostly employ a colour filter array (CFA) in order to sense a portion of the incoming spectra selectively on a pixel-by-pixel basis. An example of CFA that has achieved commercially notable success is known as Bayer filter mosaic consisting of three types of filters, i.e., red,

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blue and green [2], as shown in Figure 1. Thanks to the spatial and spectral inter-pixel correlation an image may possess, the lost information about the incident stimuli can be estimated through demosaicking. Demosaicking is an operation in the image processing chain carried out on the mosaicked image read from the sensor. Consequently each pixel will comprise three components, thereby recovering a full colour image. The success gained by the CFA based single-sensor colour imaging systems has awakened particular interest from the academia and the industries in generalise this concept to the multispectral domain by integrating more than three types of filters into one filter array, which results in the multispectral filter array (MSFA). Two instances of MSFAs can be seen in Figure 2 and 3.

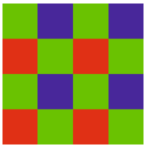

Fig. 1. Bayer CFA

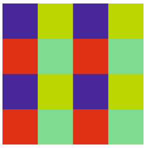

Fig. 2. 4-band MSFA

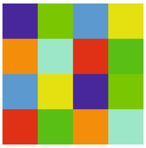

Fig. 3. 8-band MSFA

In general, the development of a MSFA based imaging system involves design of filter transmittances, spatial arrangement of mosaic patterns paired with an associated demosaicking algorithm, and a regression process to recover colorimetric or spectral information.

In recent years, sustained research effort went into designing multispectral filter array (MSFA) [15] and developing associated demosaicking algorithms [1,3,14,16,17,21,22]. Also widely explored is the influence of filter characteristics on colour/spectrum reproduction [9,19,23,24]. Nevertheless, to our best knowledge, little is known about how filter design and demosaicking algorithms affect the colorimetric performance of a CFA and particularly MSFA image acquisition system.

In comparison with CFAs, MSFAs populate higher number of channels, thus reducing the number of pixels assigned to a certain channel for a given sensor. Obviously this lowers spatial resolution, however MSFA may offer higher spectral resolution. While the former effect generally lowers the colorimetric performance of the system, the latter should improve the accuracy of colour reproduction. It is therefore of particular interest to evaluate the colorimetric performance of such MSFA imaging systems and investigate the trade-off between spatial resolution and spectral resolution by comparing CFA and MSFA systems utilising various filter characteristics and demosaicking methods.

The following sections of the paper are organised as follows. We first present the methods used including the simulated framework illustrated in Section 2.1, the filter design strategy described in Section 2.2, the mosaic generation demonstrated in Section 2.3, the demosaicking algorithms introduced in Section 2.4, the colour and spectral reflectance estimation method for device calibration presented in Section 2.5, the evaluation means explained in Section 2.6 and the experimental conditions listed in Section 2.7. Results are shown in Section 3 that leads to reasonable conclusions drawn in Section 4.

2 Methods

2.1 Simulated Framework

A simulated workflow was constructed so as to conduct the research due to practical difficulties in physical implementation of the MSFAs [12]. As shown in Figure 4, the framework consists of a chain of processing that starts from the hyperspectral images used as virtual optical images. A MSFA mounted sensor is merely a combination of the filter array and the image sensor, and the mosaicked optical image is therefore formed in between. As a result, a hyperspectral image can be considered as a spectrally sampled optical image which will then be spectrally filtered and spatially interleaved by the filter array. In this manner, the process of mosaicking is simulated.

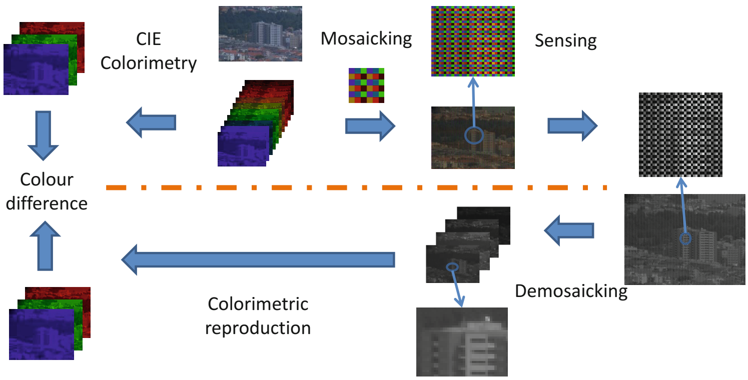

Fig. 4. The experimental framework

Next, an ideal image sensor populating the same number of pixels as the images integrates the incident power at each pixel over the spectrum. Quantum efficiency of the sensor is integrated with the spectral transmittance of filters, so that filter characteristics referred to in this work represent sensor sensitivities. And neither optical crosstalk nor optical/electronic noise is considered in this work.

Mosaic image, namely the sensor output, is actually a digital representation of a spatially or spectrally subsampled and interleaved trichromatic or multispectral image. Therefore, it needs to be interpolated spatially and/or spectrally, in order to recover the information lost in the mosaicking process. In other words, interpolation yields a colour or multispectral image of full spatial resolution.

At this stage, the recovered image is not colorimetrically meaningful as the digital counts have not been assigned any physical meaning. This is addressed by device colour calibration. It first models the device by associating stimuli with known colorimetric characteristics and the corresponding sensor response, and later estimates original colorimetric information of the unknown stimuli from the corresponding sensor response.

CIE tristimulus values are computed before colour difference between the original and reproduced hyperspectral images is calculated.

2.2 Filter Design in MSFA Systems

Among the derivatives of Bayer mosaic, some possess complementary colour filters in comparison to the primary colour filters utilised in the original patent [2].

Literature presents distinct results. It is obvious that complementary colour filters intrinsically bear wider pass-band than their primary counterparts, and it is widely accepted that the former gives rise to better colour reproduction and signal-to-noise ratio in sufficient lighting conditions, whereas the latter offers higher sensitivity as well as resolution [18,19]. Our results, nevertheless, show that appropriate pass-bands outperforms some narrower ones [23,24]. In addition, our previous research on multispectral demosaicking poses the question of filter design in relation to the inter-band correlation [21,22].

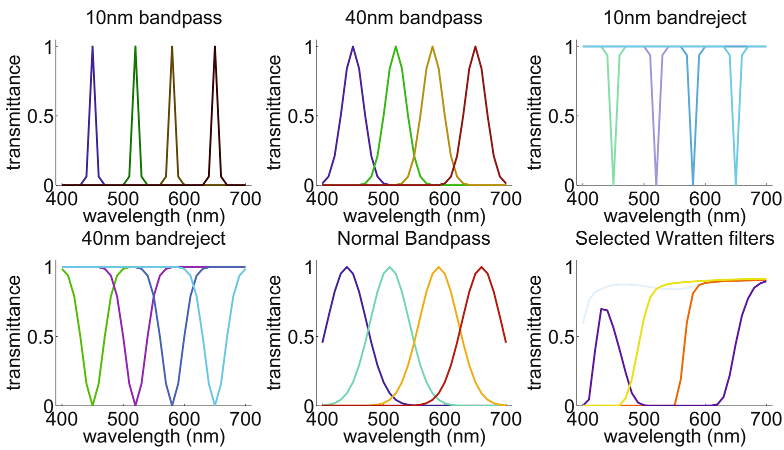

Fig. 5. Transmittances of a 4-band filter set

An instance of 4-band filter set used in this research is depicted in Figure 5. Following the aforementioned findings, we are interested in narrowband and broadband bandpass filters as well as corresponding inverted ones such as bandstop filters. The FWHM (Full Width at Half Maximum) of passband and stopband have been set to 10 nm and 40 nm respectively. In practice, a passband of 10 nm simulates very narrow bandpass filters like LCTF (Liquid Crystal Tunable Filter), a stopband of 10 nm mimics notch filters relying on destructive interference. Similarly, a passband and a stopband of 40 nm resemble the spectral transmittances of thin-film filters.

In addition to the filters mentioned above, we introduced two more types. One is based on the principle that the transmittances of filters should sample the spectrum evenly with their FWHM. The other is in fact the result produced by a filter selection algorithm [7] that chooses a given number of optimal(or sub-optimal) filters from a set of available candidates that are physically practicable, on the assumption that high spectral performance is yielded by the "brightest" filter that transmits the most light combined with other filters which are orthogonal to each other in a vector space. Here we employ a set of transmittance data measured from Wratten filters produced by Kodak, as shown in Figure 6.

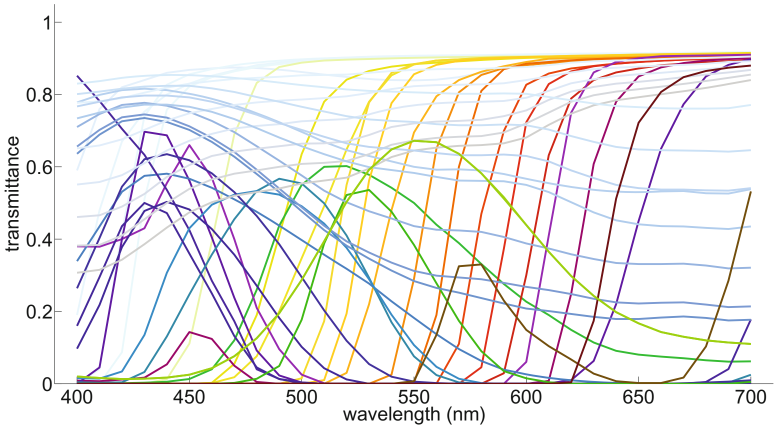

Fig. 6. Transmittances of a set of Wratten filters

2.3 Mosaic Pattern Generation

Filter arrays experimented with in this project were designed with the help of a generic binary tree based generation method of MSFA spatial arrangement starting from a chequerboard pattern introduced by Miao *et al.* [15]. By manipulating the pattern through a combination of decomposition and subsampling steps, the method presented may generate MSFAs that satisfy varied design requirements proposed by the authors including probability of appearance, spectral consistency and uniform distribution. It is shown, through case studies, that most of the CFAs currently used by the industry can be derived as special cases.

2.4 MSFA Demosaicking

A large number of CFA demosaicking algorithms have been proposed over the decades [13]. In this work, we used intra-channel bilinear interpolation, channel difference bilinear interpolation [11] and discrete wavelet transform (DWT) based demosaicking [5].

Bilinear interpolation makes use of merely intra-pixel correlation and estimates unknown colour components by exploiting the spatial correlation between sampled colours in a certain spectral plane, and function plane by plane.

Channel difference interpolation brings inter-channel correlation into play and interpolates the difference between one colour plane and another [11] on the assumption that hue changes smoothly in images.

DWT transforms an image into various frequency bands, and natural images often possess rather similar high-frequency information among these bands, which provides yet another solution to demosaicking problem. This algorithm has been extended to a 4-band MSFA as reported in the literature [22].

2.5 Device Calibration

Colour calibration is an inverse problem aimed at an estimation of the tristimulus values of the stimuli from the corresponding measurements obtained from sensors. In concrete terms, a colour acquisition process can be described in a linear form as

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

where R refers to the sensor responses, Q corresponds to system responsivities and S represents the incoming stimuli.

Colour calibration aims at an estimation of S from R. Equation 1 is solvable if Q is known and invertible, however it is not true in the case of colorimetric calibration. Nevertheless it can be estimated by means of training where a collection of training stimuli S_t and corresponding responses R_t are utilised to derive an approximation of Q^{-1}. In this work, we employed the method of linear least squares [8] which attempts to solve (1) by means of pseudoinverse which leads to (2)

$$S' = S_t R_t^+ R \tag{2}$$

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

2.6 Performance Evaluation

An evaluation of the colorimetric performance of CFA and MSFA based imaging systems can be solved by means of colour difference formula. However, considering that the targets are digital images rather than uniform colour patches, a metric incorporating some low-level HVS features, such as S-CIELAB, might be suitable as well and may provide more information.

CIEDE2000 is the latest colour difference formula developed and recommended by the CIE [4]. It further improves perceptual uniformity in comparison with the CIE94 formula by introducing a few revised compensation terms for lightness, chroma and hue respectively. In addition, there are three corresponding parameters that are usually set to 1:1:1 and can be adjusted according to specific applications. For instance, CIE recommended 2:1:1 for textile industry. In this work, we used 2:2:1 to evaluate image colour difference.

The S-CIELAB metric extends the CIELAB Delta E metric to colour images by adding a spatial pre-processing step to the standard CIE $\Delta E_{a^*b^*}$ metric to account for the spatial-colour sensitivity of the human eye [26]. It measures how accurate the reproduction of a colour is to the original when viewed by a human observer.

2.7 Experimental Conditions

The experiments were conducted in such conditions as follows. Spectral range covers the spectrum between 400 nm and 700 nm with 10 nm interval. CIE D65 was used as the illuminant. Among the 48 hyperspectral images used as virtual scenes, 16 are from Foster database [6] and 32 are from CAVE database [25]. Three types of MSFA were considered, namely 3-band CFA, 4-band and 8-band. For the least-square regression, 170 spectral reflectances of natural objects [20] and the corresponding CIE XYZ tristimulus values were utilised as the training targets. Tristimulus values were calculated with colour-matching functions for the CIE 1931 standard colorimetric observer [10]. For the calculation of S-CIELAB colour difference, the viewing distance was set to 60 cm, and the resolution was set to 95.78 dpi, so as to mimic a 23-inch LCD monitor of 1920×1080 pixels and an aspect ratio of 16:9.

3 Results and Discussion

Results are presented in Figure 7 and 8. It is of great moment to realise that the colour difference shown here reflect the overall performance of the system consisting of filter characteristics, spatial arrangements, demosaicking methods as well as colour estimation techniques. However, a comparative analysis of the results reveal some clues.

From the results we can observe that increased number of bands in general offer lower or comparable colour difference especially when paired with 10 nm and 40 nm bandpass filters and a selected range of Wratten filters. In particular, the 40 nm bandpass filters result in the lowest colour difference among all of the methods and configurations, whereas the 10 nm bandstop filters yield significantly larger errors.

In general, the DWT based demosaicking outperforms the other two where the widths of passband are significantly broader, whereas bilinear interpolation

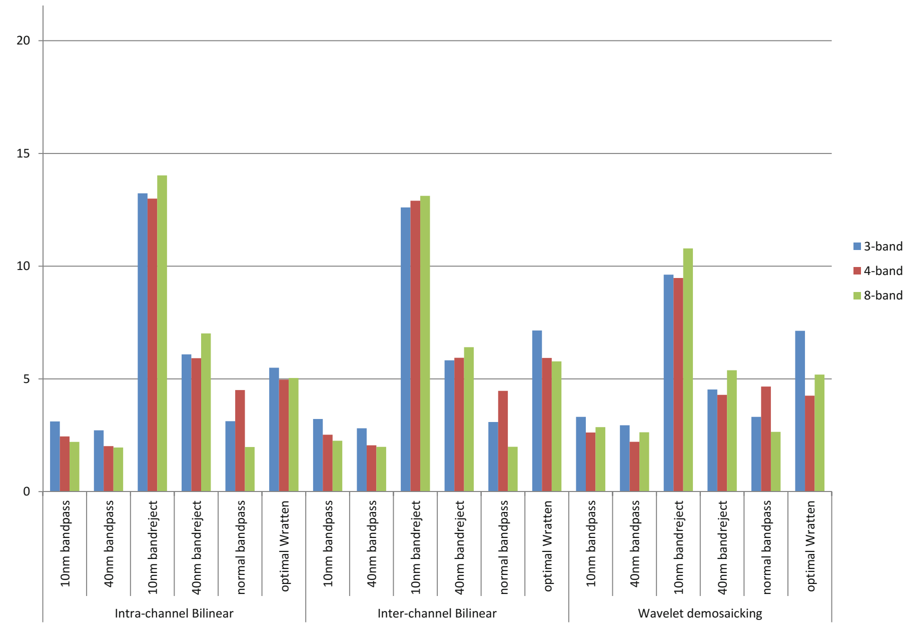

Fig. 7. Average CIEDE2000 colour difference among test images

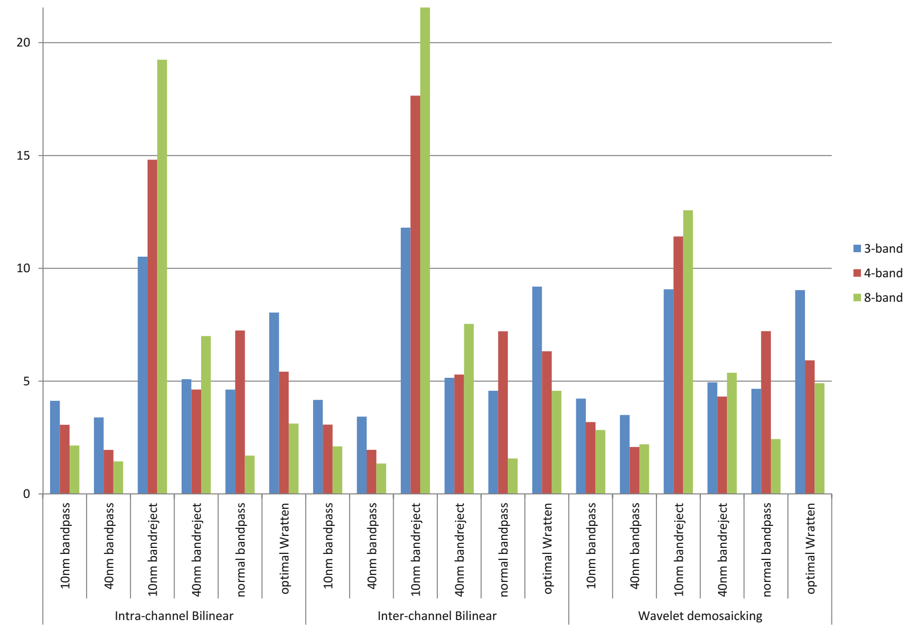

Fig. 8. Average S-CIELAB colour difference among test imags

carried out on channel differences does not perform satisfactorily. This is also related to insufficient high-frequency components in the image databases [22], as inter-channel demosaicking should benefit from inter-channel correlation at high frequencies and broader passbands may boost this correlation.

In most cases S-CIELAB results coincide with CIE DE2000 ones, although the former tends to exaggerate the discrepancy of the results between the CFA and the MSFAs.

4 Conclusion

A simulation was performed to investigate the colorimetric performance of MSFA based image acquisition systems. In total, 48 virtual scenes were captured by the simulated camera for 3-band, 4-band and 8-band MSFAs respectively, each paired with 6 different types of filter characteristics and 3 demosaicking algorithms. Results were all transformed to CIE XYZ tristimulus values and evaluated with CIEDE2000 (2:2:1) and S-CIELAB colour difference. CIEDE2000 and S-CIELAB results coincide in most cases. In general, the 4-band MSFA provides better or comparable performance in comparison with the 3-band setup except the case of 10 nm bandreject and normal bandpass filters. Similarly the 8-band MSFA delivers higher colour accuracy expect the case of 10 nm and 40 nm bandreject filters. Therefore MSFA is generaly helpful for an application where colorimetric reproduction is required.

Moreover, it is obvious to see that spectral characteristics of a filter set not only make a direct impact on the colour reconstruction, but also influence the spectral correlation of the observed image on which some demosaicking methods depend.

Certainly the validity of the results obtained in this work is limited by the realisticness of the simulation. In a real system, the presence of various types of noise will probably impact the results. However, this laid a foundation for the design of a new MSFA sensor planned in 2015 [12].

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