Colour image demosaicking via joint intra and inter channel information

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A novel algorithm exploiting joint intra channel colour correlation and inter channel colour difference is presented for interpolating colour filter array data. Experiments on standard database and comparisons with other state-of-the-art methods demonstrate that the joint intra and inter information is effective and comparable.

Introduction: Most of the charge-coupled devices, which use colour filter arrays (CFA), are limited to recording one channel value (red or blue or green) at each position. The process of estimating the missing two values from CFA data is called demosaicking, and the most popular CFA data is Bayer [1] data (Fig. 1).

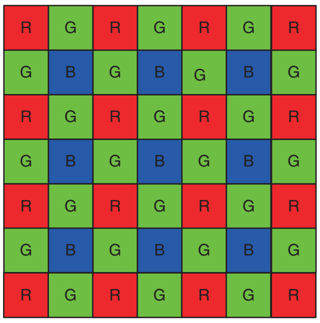

Fig. 1 *Bayer Pattern*

Massive demosaicking algorithms have arisen in recent years [2–12]. However, most of the existing methods are based upon inter channel colour difference interpolation, which can introduce artefacts. This Letter focus on joint intra and inter channel information instead of single colour difference. First, we explore the total variation (TV, intra channel colour correlation) of the Bayer data. Then we treat the process of demosaicking as an inpainting problem. At last, we exploit inter channel colour differences and add them to intra channel colour correlation.

Proposed algorithm: Our method first interpolates green channel via intra and inter channel information. The basic model for green channel demosaicking is

$$\begin{aligned} &\min \quad \alpha IntraError(x) + \beta InterError(x) \\ &\text{s.t.} \quad \| (x-g)_\Omega \|_2 \le \delta, \quad \delta > 0. \end{aligned} \tag{1}$$

where *IntraError* is the error of intra channel interpolation using TV, while *InterError* represents the error using colour difference. α and β are the weight of the two error terms. x is the desired green channel, g is the mosaic green channel, and both of them are stored in a vector. Ω is a mask corresponding to green channel. δ is the controller of error.

In exploiting intra channel colour correlation, we treat the problem of demosaicking as an inpainting problem where each pixel has two missing values [13]. TV involving optimisation is effective in solving inpainting problem. Suppose our mosaic image of green channel is G and the reconstructed green channel image is X. x and g are their vector forms, respectively. Ω and δ are defined as above. Then our basic TV demosaicking model of min $\alpha IntraError(x)$ can be described as

$$\begin{aligned} &\min \quad \sum_{i=1}^{m}\sum_{j=1}^{n} \| (\nabla x)_{i,j} \|_2 \\ &\text{s.t} \quad \| (x-g)_\Omega \|_2 \le \delta \end{aligned} \tag{2}$$

According to Boyd and Vandenberghe [14], and Dahl *et al.* [15], we can define a matrix $\boldsymbol{D} = (D_{(11)}, \ldots, D_{(mn)})^{\mathrm{T}}$ of dimensions $2mn \times mn$ with each element $D_{(ij)} = (e_{i+1+(j-1)m} - e_{i+(j-1)m},\ e_{i+jm} - e_{i+(j-1)m})^{\mathrm{T}}$, where e_k denotes the kth canonical unit vector of length mn. The dual problem of (2) is given by

$$\begin{aligned} &\max -\delta \| (D^{\mathrm{T}}u)_\Omega \|_2 + g_\Omega^{\mathrm{T}}(D^{\mathrm{T}}u)_\Omega \\ &\quad - \gamma \| (D^{\mathrm{T}}u)_{\Omega_{\mathrm{C}}} \|_2 + d_\Omega^{\mathrm{T}}(D^{\mathrm{T}}u)_\Omega \\ &\text{s.t.} \ \| u_{(ij)} \|_2 \le 1, \quad i = 1, \ldots, m, j = 1, \ldots, n \end{aligned} \tag{3}$$

for some suitable vector $\boldsymbol{d}$ and parameter γ. Ω_{C} is the complementary of Ω. And $u \in \mathbb{R}^{2mn}$ is the dual variable [15] of x. In solving (3), we use a first-order method. First, we define $f_d(u) = (1/2)\|u\|_2^2$, and its max value $\Delta d = \max_u f_d(u) = (1/2)mn$. Then for a given tolerance ε, define $\mu = (\varepsilon/2\Delta d)$, $\mathcal{T}_\mu(x) = \max_\mu\{u^{\mathrm{T}}Dx - \mu f_d(u)\}$, its Lipschitz continuous derivatives $\mathcal{L}_\mu = (\|D\|_2^2/\mu)$ and gradient $\nabla\mathcal{T}_\mu(x)$. Our result is given by

$$x^{k+1} = \frac{2}{k+3}z^k + \frac{k+1}{k+3}y^k \tag{4}$$

where

$$y^k = d_\Omega + \frac{(\mathcal{L}_\mu(x^k - d) - \nabla\mathcal{T}_\mu(x^k))_\Omega}{\max\{\mathcal{L}_\mu,\ \| (\mathcal{L}_\mu(x^k - d) - \nabla\mathcal{T}_\mu(x^k))_\Omega \|_2/\gamma\}},$$

$$z^k = d_\Omega + \frac{-w_\Omega^k}{\max\{\mathcal{L}_\mu,\ \| w_\Omega^k \|_2/\gamma\}},$$

$$w^k = \sum_{i=0}^{k}\frac{1}{2}(i+1)\nabla\mathcal{T}_\mu(x^i),$$

and k is the number of iteration. Finally x is the information that we exploit as intra colour correlation for green channel. Convert this vector into a matrix, then we get G_{Intra}.

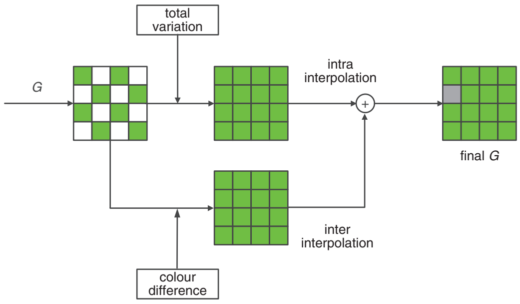

Fig. 2 *Flow chart of green channel interpolation*

We minimise our inter channel error via colour difference based on [11]. We start with an initial green channel colour difference interpolation. Taking red position for example, the colour difference is defined

$$\hat{\Delta}_{\mathrm{g,r}}(i,j) = \frac{\omega_{\mathrm{V}} f \hat{\Delta}_{\mathrm{g,r}}^{\mathrm{V}}(i-1{:}i+1, j)}{\omega_{\mathrm{C}}} + \frac{\omega_{\mathrm{H}} \hat{\Delta}_{\mathrm{g,r}}^{\mathrm{H}}(i-1{:}i+1, j) f^{\mathrm{T}}}{\omega_{\mathrm{C}}} \tag{5}$$

where $\omega_{\mathrm{C}} = \omega_{\mathrm{V}} + \omega_{\mathrm{H}}$ and $f = [(1/4)(2/4)(1/4)]$. $\hat{\Delta}_{\mathrm{g,r}}^{\mathrm{V}}$ and $\hat{\Delta}_{\mathrm{g,r}}^{\mathrm{H}}$ are the colour difference between green and red in vertical and horizontal direction, respectively. The weight ω_{V} and ω_{H} are related to a local window. Then the initial colour difference can be updated via

$$\begin{aligned} \hat{\Delta}_{\mathrm{g,r}}(i,j) = {} & \hat{\Delta}_{\mathrm{g,r}}(i,j)(1-\omega) \\ & + \frac{[\omega_N \hat{\Delta}_{\mathrm{g,r}}(i-2,j) + \omega_S \hat{\Delta}_{\mathrm{g,r}}(i+2,j)]\omega}{\omega_T} \\ & + \frac{[\omega_E \hat{\Delta}_{\mathrm{g,r}}(i,j-2) + \omega_W \hat{\Delta}_{\mathrm{g,r}}(i,j+2)]\omega}{\omega_T} \end{aligned} \tag{6}$$

where $\omega_T = \omega_N + \omega_S + \omega_E + \omega_W$ and ω_N, ω_S, ω_E, ω_W are the weight corresponding to the four directions for a given piexl. The final G value of colour difference is then calculate via

$$\tilde{G}(i,j) = R(i,j) + \tilde{\Delta}_{\mathrm{g,r}}(i,j) \tag{7}$$

For green pixels at blue position, the procedure goes the same,

$$\tilde{G}(i,j) = B(i,j) + \tilde{\Delta}_{\mathrm{g,b}}(i,j) \tag{8}$$

We denote the result G of colour difference as G_{Inter}. Note that G_{Inter} is the result of min $\beta InterError(x)$, then our final G is defined by

$$G = \alpha G_{\mathrm{Intra}} + \beta G_{\mathrm{Inter}} \tag{9}$$

This final G consists of information both within and between colour channels, and thus could provide information that each of them cannot. The process of green channel interpolation can be expressed as Fig. 2.

After getting the final G interpolation, red and blue channels are exploited via only inter channel colour difference. For red values at blue position,

$$\tilde{R}_{i,j} = \tilde{G}_{i,j} - \tilde{\Delta}_{g,r}(i-3:i+3, j-3:j+3) \otimes p_{rb} \tag{10}$$

where $\otimes$ denotes element-wise matrix multiplication and subsequent summation, and

$$\boldsymbol{p}_{rb} = \begin{pmatrix} 0 & 0 & -1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 10 & 0 & 10 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 10 & 0 & 10 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & -1 & 0 & 0 \end{pmatrix} \times \frac{1}{32}$$

For red values at green position,

$$\begin{aligned} \tilde{R}_{i,j} &= G_{i,j} \\ &- \frac{\omega_V[\tilde{G}(i-1,j) - R(i-1,j) + \tilde{G}(i+1,j) - R(i+1,j)]}{2(\omega_V + \omega_H)} \\ &+ \frac{\omega_H[\tilde{G}(i,j-1) - \tilde{R}(i,j-1) + \tilde{G}(i,j+1) - \tilde{R}(i,j+1)]}{2(\omega_V + \omega_H)} \end{aligned} \tag{11}$$

Blue values at red or green position are interpolated the same as red channel interpolation.

Table 1: Comparison of different CFA methods on average

Image	PSNR			CPSNR
	Red	Green	Blue	
Adaptive	34.55	38.21	35.26	36.13
LMMSE	36.97	40.63	36.76	37.69
AHD	35.23	38.47	35.01	35.87
LPA-ICI	37.40	40.82	37.08	38.05
GBTF	37.22	40.05	37.03	37.94
RI	37.06	40.56	36.75	37.66
MSG	37.56	41.15	37.35	38.31
MLRI	37.86	40.99	37.31	38.32
Proposed	38.45	42.31	37.91	38.96

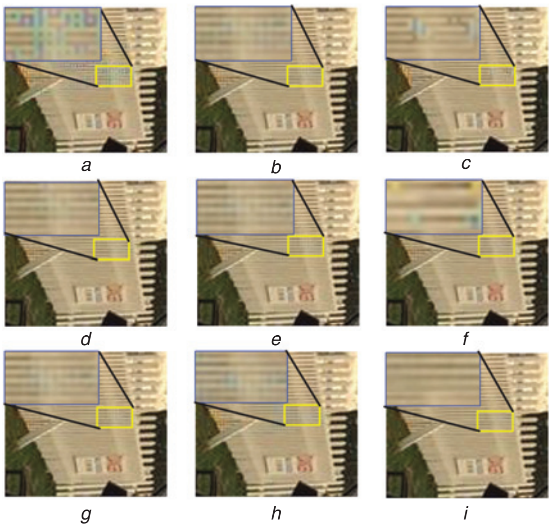

Fig. 3 *Comparison with eight state-of-the-art algorithms on Kodak 19 Image*

a Adaptive
b Lmmse
c AHP
d LPA-ICI
e GBIF
f RI
g MSG
h MLRI
i Proposed

Experiment results: We evaluate our algorithm on Kodak and IMAX image set. We compare our joint method with eight state-of-the-art algorithms, adaptive [5], directional linear minimum mean square-error estimation (DLMMSE) [6], adaptive homogeneity directed (AHD) [7], local polynomial approximation-intersection of confidence intervals (LPA-ICI) [8], gradient-based threshold free (GBTF) [9], residual interpolation (RI) [10], multi-scale gradient (MSG) [11] and minimised Laplacian residual interpolation (MLRI) [12]. We present both objective and subjective quality evaluation. The objective criterion (shown in Table 1) is colour peak signal to noise ratio (CPSNR). The value shown in Table 1 is the average value of Kodak and IMAX. A visible comparison (subjective) of nine algorithms on Kodak 19 image is shown in Fig. 3. Adaptive [5] and AHD [7] have severe artefacts, and DLMMSE [6], LPA-ICI [8], GBTF [9], RI [10], MSG [11] and MLRI [12] are more likely to introduce slightly zipper effect. Our method is promising for it has less artefact and zipper effect.

Conclusion: A novel algorithm incorporating intra channel colour correlation with inter channel colour difference for demosaicking is proposed. The method exploits the intra channel colour correlation via treating the demosaicking problem as an inpainting problem, and it is solved via a TV-norm involving optimisation. Then this correlation is introduced into the framework of demosaicking using colour difference. Experiment results indicate that this joint method is promising in latter use.

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One or more of the Figures in this Letter are available in colour online.

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