Multi-Spectral Demosaicing Technique for Single-Sensor Imaging

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***Abstract*—A generic-filter array design have been proposed to capture multi-spectral images using hypothetical single-sensor multi-spectral cameras. The design idea is based on uniform sampling of intensity values from each band irrespective of spectral properties of any particular band. A reconstruction technique have also been proposed to linearly interpolate unknown intensity values of other bands at each pixel. Proposed technique was evaluated using two multispectral image datasets where one was of Landsat satellite and another was of cooled CCD camera Apogee Alta U260. Quantitative evaluation of the proposed technique was done using peak signal to noise ratio.**

I. Introduction

Images which are captured over several spectral bands of electro-magnetic spectrum are called multi-spectral images. There are around three to thirty bands in a multi-spectral image and beyond thirty the images are generally called hyper-spectral images. Every object on earth which is above absolute temperature emits radiations of certain wavelengths which can be captured in different bands of multi-spectral images and hence these images have more information content than images captured only in visible bands [1]. Due to their high information content, multi-spectral images have found applications in various domains such as : remote sensing, agriculture, medical imaging, military applications etc.

Multi-spectral sensors can be broadly categorized into three types namely (1) line-scanners (2) whisk-broom scanners and (3) push-broom scanners [2]. Line-scanners and whisk-broom scanners have mechanical and optical parts such as rotating mirror to capture various bands of a multi-spectral image whereas push-broom scanners electronically captures each multi-spectral band using silicon chip technology such as CCD sensors.

In-spite of having lots of applications of multi-spectral images in various domains, they are not as easily accessible as color images due to high cost of multi-spectral cameras. Many multi-spectral cameras have as many CCD-sensors as the number of bands to be captured. The size and cost of a multi-spectral camera increases with the number of CCD sensors requried to capture larger number of bands of electro-magnetic spectrum. To give an example of the cost, consider the five sensor Condor-1000 MS5-VNN-285 which is a five band camera, with three bands as RGB and two bands in the infrared region of electromagnetic spectrum. It costs around 59000 US dollars and the resolution is only 1360×1024. The cost of a single-sensor RGB camera with way more resolution is only a few hundred dollars. The main motivation of this work is to bring down the cost of the multi-spectral cameras by converting them to the single-sensor architecture. Large number of image-sensors causes other complexities such as pixel-to-pixel registration of each band moreover they consumes more power to operate due to complex circuitry as compare to a single-sensor cameras. Therefore it is desirable to have a single-sensor multi-spectral camera which can handle above mentioned limitations to certain extent.

Many single-sensor digital cameras capture color images using Bayer pattern [3] where 50% samples of green band and 25% each of red and blue band are captured. Many linear and non-linear demosaicing algorithms have been proposed in literature for finding missing intensity values at each pixel. A review of some of these algorithms is mentioned in [4]. Linear time gradient-based bilinear interpolation technique have been proposed in [5] where it has been claimed to be superior of many non-linear algorithms. The design idea of Bayer pattern and many such algorithms is based on property of human visual system that human eye is more sensitive to green band as compare to red and blue band. The idea of Bayer pattern may not be directly generalized to develop filters and demosaicing algorithms for multi-spectral images since there are large number of bands each having some specific characteristics.

A multispectral filter array design have been proposed in [6] which is based on probability of appearance of each band to be used in target recognition. Authors claim that their design takes into account spectral consistency which is used to avoid optical crosstalk that causes some artifacts into the image. Authors of that paper also considered spatial uniformity which says that for doing interpolation, uniform sampling is better than random sampling. This filter design is a three step process consisting of finding binary tree based on probability of appearance, finding pixel locations for interpolation using checkerboard selection and finally combining the results to get raw image. However that proposed design of filter array is based on the prior knowledge of probability of appearance of bands. Based on above filter array design a generic demosaicing approach “Binary Tree based Edge Sensing method” (BTES) have been proposed in [7] which is based on exploring edge correlation to do interpolation of missing band values. That algorithm firstly determines which band to interpolate based on probability of appearance of each band and then order of interpolation for each pixels is determined followed by image transforms to do interpolation. A multi-spectral camera design have also been proposed in [8] which is based on extending color filter array design using color channel differences. This is a 3×2 multi-spectral filter on CCD-chip. This design idea was chosen by authors for doing fast bi-linear interpolation to find unknown intensity values. This technique

TABLE I. GENERIC MULTI-SPECTRAL FILTER

B_1	B_2	...	B_{j-1}	B_j
B_2	B_3	...	B_j	B_1
$\vdots$	$\vdots$	...	$\vdots$	$\vdots$
B_{j-1}	B_j	...	B_{j-3}	B_{j-2}
B_j	B_1	...	B_{j-2}	B_{j-1}

is based spectral channel differences which can be considered as a smoothing operation after bi-linear interpolation. This algorithm does not make use of spectral-correlation among bands of a multi-spectral imagery. A Generalized Assorted Pixel (GAP) camera design have been proposed in [9] where authors have proposed filter design that takes samples from multiples bands to get better visual results.

II. PROPOSED TECHNIQUE

Basic linear interpolation techniques such as bi-linear interpolation uses neighboring values of the same band to interpolate unknown value at a pixel. This is not a very good strategy because it does not consider inter-band correlation. Our proposed technique is inspired by linear time commercial techniques for color imaging such as [5] which is gradient corrected bi-linear interpolation that incorporates local information from same band as well as nearby bands. We have used same philosophy to propose linear time algorithm for interpolation of missing band values for multi-spectral imaging.

The proposed multi-spectral filter to capture raw image using single-sensor is based on uniform distribution of samples from each consecutive band irrespective of spectral properties of any particular band. Table I shows the design of proposed $j \times j$ generic multi-spectral filter to capture intensity values from j bands using single-sensor. Here B_i represents that intensity of i^{th} band should be captured at that particular pixel $\forall i \in [1, j]$ with $j \in [2, 5]$. Maximum value of j is set to five because currently we have experimented wih with maximum five bands of multi-spectral images. This proposed pattern is easily extensible and repeatable for more bands of multi-spectral images. Uniform patterns are better than some random patterns which gives probabilistic guarantees as opposed to deterministic guarantees given by uniform patterns.

Table II(a) shows an example filter array to capture four bands using single-sensor. After applying this filter array, we get a raw image in which each pixel have intensity value corresponding to one band and remaining three intensity values need to be interpolated so as to reconstruct all four bands. In general if we are capturing j bands of a multi-spectral image using single-sensor then there will be j different repeating patterns occurring in the raw image and for each of these j patterns we need to interpolate $(j-1)$ intensity values at each pixel. Tables II(b), (c), (d), and (e) shows four example patterns with 3×3 window size that will occur in case of four band imagery. Here for each of the four cases, we need to do interpolation of three missing band values at the central pixel.

The interpolation of missing band values is based on exploring dependence of central pixel on the neighborhood pixels of same band as well as other bands. This dependence have been explored by representing intensity value at each pixel as linear combination of intensity values of neighborhood pixels in a window of size $k \times k$:

$$y = \mathbf{u}^T \mathbf{x} \tag{1}$$

where $\mathbf{u}, \mathbf{x} \in \mathbb{R}^{k^2 \times 1}$, vector $\mathbf{u}$ is representing neighboring intensity values and vector $\mathbf{x}$ is representing contribution of corresponding neighboring values to interpolate one of the missing intensity value represented by y. More generally we can represent our interpolation problem for j band multi-spectral image with j repeating patterns and $(j-1)$ missing values at each pixel as follows:

$$Y = AX \tag{2}$$

where $Y \in \mathbb{R}^{M \times (j-1)}$, $A \in \mathbb{R}^{M \times k^2}$, and $X \in \mathbb{R}^{k^2 \times (j-1)}$. Each row of matrix A is made up of k^2 elements from $k \times k$ window and value of k was chosen to be three and five for doing simulations. There will be total M such rows in A having $M = \left\lfloor \frac{m}{k} \right\rfloor \times \left\lfloor \frac{n}{k} \right\rfloor$ with raw image being of size $m \times n$. Each column of X represents coefficients by which neighboring pixels in $k \times k$ window contributed in the interpolation of $(j-1)$ missing band values. Since $M >> k^2$, therefore matrix A will be a tall matrix and the system of equations will become overdetermined which can be solved using least square method. Since there are total j patterns in a j band imagery therefore system of equations (2) was solved $j \times (j-1)$ times to get filters for interpolating missing band values at each pixel. Filter for interpolation are shown in Table V for the case of 4 band image with 3×3 window size.

TABLE II. EXAMPLE OF MULTI-SEPCTRAL FILTER AND FOUR 3×3 REPEATING PATTERNS WITHIN THIS FILTER ARRAY TO CAPTURE FOUR BANDS USING SINGLE-SENSOR.

B_1	B_2	B_3	B_4	B_1	B_2	B_3	B_4
B_2	B_3	B_4	B_1	B_2	B_3	B_4	B_1
B_3	B_4	B_1	B_2	B_3	B_4	B_1	B_2
B_4	B_1	B_2	B_3	B_4	B_1	B_2	B_3
B_1	B_2	B_3	B_4	B_1	B_2	B_3	B_4
B_2	B_3	B_4	B_1	B_2	B_3	B_4	B_1
B_3	B_4	B_1	B_2	B_3	B_4	B_1	B_2
B_4	B_1	B_2	B_3	B_4	B_1	B_2	B_3
B_1	B_2	B_3	B_4	B_1	B_2	B_3	B_4
B_2	B_3	B_4	B_1	B_2	B_3	B_4	B_1

(a) Four band filter array

B_3	B_4	B_1
B_4	B_1	B_2
B_1	B_2	B_3

(b) Pattern1

B_4	B_1	B_2
B_1	B_2	B_3
B_2	B_3	B_4

(c) Pattern2

B_1	B_2	B_3
B_2	B_3	B_4
B_3	B_4	B_1

(d) Pattern3

B_2	B_3	B_4
B_3	B_4	B_1
B_4	B_1	B_2

(e) Pattern4

III. EXPERIMENTS AND RESULTS

We did all the experiments in Matlab software using two multi-spectral datasets. Five multi-spectral scenes were extracted from Landsat 7 ETM+ tile of path/ row 146/40 of October 2000, which is freely available at earthexplorer [11]. Each of these five scenes were representing different land cover classes such as urban area, dense forest, river, village area and

TABLE V. TABLE REPRESENTING BAND INTERPOLATION VALUES FOR 4 BAND IMAGE WITH WINDOW SIZE 3×3

Pattern 1			Pattern 2			Pattern 3			Pattern 4		
Band 2			Band 1			Band 1			Band 1		
0.174	0.017	-0.057	-0.014	0.361	-0.038	0.269	0.067	-0.029	0.081	0.153	0.002
0.015	0.427	0.245	0.207	0.410	0.044	0.047	0.392	-0.025	0.098	-0.042	0.284
-0.083	0.326	-0.053	-0.004	0.054	-0.034	-0.024	-0.026	0.317	0.003	0.438	-0.025
Band 3			Band 3			Band 2			Band 2		
0.283	0.008	-0.117	-0.017	0.004	-0.046	-0.005	0.205	-0.059	0.031	0.264	0.004
0.007	0.401	0.212	0.008	0.690	0.184	0.120	0.634	0.004	0.236	0.018	0.128
-0.118	0.223	0.104	-0.056	0.212	0.021	-0.027	0.008	0.126	0.001	0.168	0.164
Band 4			Band 4			Band 4			Band 3		
0.060	0.498	0.013	0.482	-0.028	0.035	-0.055	0.021	0.034	-0.136	0.422	0.047
0.465	-0.080	0.035	-0.017	0.020	-0.008	0.033	-0.090	0.466	0.381	-0.080	0.065
0.012	0.038	-0.051	0.037	-0.015	0.479	0.034	0.499	0.047	0.042	0.101	0.165

TABLE III. PSNR VALUES FOR RECONSTRUCTIONS OF MULTI-SPECTRAL IMAGES FROM DATASET [10] USING DIFFERENT NUMBER OF BANDS AND WINDOW SIZES

	Peak Signal to Noise Ratio (dB)					
Images	B_5W_5	B_5W_3	B_4W_5	B_4W_3	B_3W_3	B_2W_3
Balls	41.66	39.77	42.64	40.50	37.47	46.79
Paints	32.64	30.09	33.96	30.83	33.93	36.28
Lemons	36.92	34.88	37.89	34.50	43.53	41.28
Thread	37.46	35.73	38.78	37.13	40.92	45.09
Clay	40.91	38.29	42.63	38.88	42.42	44.52
Average	37.92	35.75	39.18	36.37	39.65	42.79

TABLE IV. PSNR VALUES FOR RECONSTRUCTIONS OF MULTI-SPECTRAL LANDSAT IMAGES [11] WITH DIFFERENT NUMBER OF BANDS AND WINDOW SIZES

	Peak Signal to Noise Ratio (dB)					
Images	B_5W_5	B_5W_3	B_4W_5	B_4W_3	B_3W_3	B_2W_3
Urban	22.07	29.31	32.15	28.48	30.62	33.97
Village	21.75	25.06	32.25	28.52	31.54	34.50
River	22.07	25.66	31.78	27.47	30.95	33.92
Forest	18.09	24.86	30.38	26.62	30.93	33.92
Delhi	31.61	30.11	34.56	32.96	38.13	42.27
Average	23.12	27.00	32.22	28.81	32.43	35.72

Delhi city. ETM+ sensor have total eight bands including far-infrared and thermal bands and we took data of first five bands i.e. up-to mid-infrared for performing experiments. Another multi-spectral dataset used for experiments was of cooled CCD camera Apogee Alta U260 described in [10] where each image have 31 bands from $400nm$ to $700nm$ wavelength range. We had done experiments with five images from this dataset and considered first five consecutive bands out of total 31 bands.

Experiments were done on both datasets with different number of bands and window sizes. Initial one time training was done with another Landsat image of size $2389 \times 2001 \times 5$ to find various filters to interpolate missing intensity values of other bands at each pixel. Training was done with different number of bands with 3×3 window and 5×5 window size which resulted in different filter patterns for interpolation. Total 23 such filter patterns were calculated and an example filter is shown in Table V for the case of 4 band multi-spectral images and 3×3 window size. These filter patterns represents neighborhood relationship of central pixel with intensity values of same and other bands. These values can be directly applied on raw under-sampled image captured using multi-spectral filter of Table I to reconstruct full multi-spectral image.

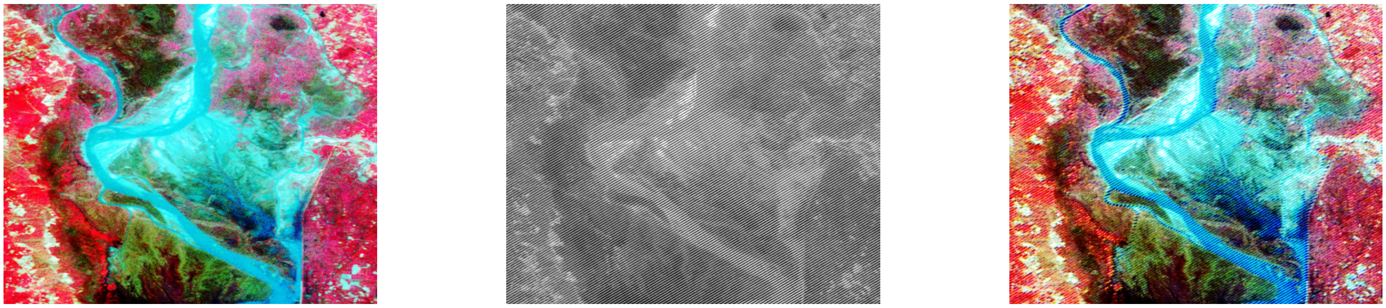
If we capture a four band image using our proposed filter pattern then captured raw image will have intensity values ordered as shown in Table II(a) and there will be four repeating patterns as shown in Table II. Each pixel of raw image will have one known intensity value and three intensity values need to be interpolated. Each pixel will belong to one of the four patterns and for each of these patterns we can apply the filters of Table V to reconstruct full four bands. This operation is linear time because calculations are done for each pixel only once and these operations can be done in parallel as well.

Table III shows the peak signal to noise ratio (PSNR) values for five multi-spectral images from the dataset [10]. Column heading B_jW_k represents that corresponding experiments have been done with j bands of the multi-spectral image in a window size of $k \times k$. For example third column heading B_4W_5 means that experiments have been done with 4 bands and 5×5 window size. Mininum average PSNR values in Table III is $35.75dB$ for the case of five band images which is also a good result consider low sampling rate for five band imagery. Table IV shows result of applying proposed filters on five multi-spectral Landsat images representing different land cover areas. Five spectral bands considered for analysis were blue, green, red, near infrared and, mid-infrared. Average PSNR values in Table IV are less than the average PSNR values in Table III because these satellite images have much high frequency components which caused PSNR values to go down as more number of bands were considered. Another cause for less average value for satellite imagery is that there is high spectral gap in wavelength of lights being captured as compare to dataset in [10]. The high spectral gap causes less spectral correlation in the bands which causes PSNR to go down as more under-sampling is done.

Fig. 1 shows reconstruction result with 4 bands of Landsat image with a window size of 5×5. Original image is shown in Fig. 1a from which raw image of Fig. 1b was simulated by using our proposed generic multi-spectral filter with 4 bands. This raw image is mosaic of intensity value from all bands but only single value at each pixel therefore it is a under-sampled gray image. Filters were applied on this raw image to reconstruct full multi-spectral image shown in Fig. 1c. Since there were four bands and only three bands can be shown in color images at a time therefore results are shown in false color composite showing NIR band in red color, red band in green color, and green band in blue color.

IV. CONCLUSIONS

The proposed generic multi-spectral filter can capture multi-spectral images using single-sensor architecture. It is



(a) Original Image (b) Raw Image (c) Reconstructed Image

Fig. 1. Reconstruction of original image from under-sampled raw image.

easily repeatable as compare to some random patterns which gives probabilistic guarantees as opposed to deterministic guarantees given by uniform patterns. A linear demosaicing algorithm has also been proposed to interpolate missing intensity values at each pixel. The algorithm takes into account spectral correlation among bands and spatial correlation of pixels in a band. The algorithm has been evaluated on two datasets having different spectral gaps. Visual inspection and quantitative evaluation by PSNR suggests that reconstruction quality of simulated raw images captured using single-sensor camera is satisfactory. All experiments were done with upto 5 bands and maximum window size of 5×5 therefore more experiments need to be done with large number of bands to know the limits of the proposed algorithm.

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