A METHOD OF COLOR FILTER ARRAY INTERPOLATION WITH ALIAS CANCELLATION PROPERTIES

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ABSTRACT

Digital still cameras use a single charge-coupled device (CCD) sensor array and a color filter array (CFA) to sample a full-color image. Thus, the measured image is an interleaving of the subsampled red, green, and blue images. The red and blue images are sampled at a lower rate, so if standard interpolation techniques are used, the reconstructed red and blue images will be missing some high-frequency information and could contain distortions from aliasing. This paper proposes a method of CFA interpolation that combines information from the green image with the subsampled red and blue images to attack these problems. The green high-frequency information is added to the interpolated red and blue images to increase the sharpness of the output and is also used to estimate the aliasing in the interpolated red and blue images, providing a means of reducing the appearance of the aliasing distortions.

1. INTRODUCTION

A digital color image requires measurement of light energy across the wavelength spectrum at each pixel location. Typically, three measurements are made at each pixel location, denoted red (R), green (G), and blue (B). Low-cost digital still cameras use a single charge-coupled device (CCD) sensor array to measure a color image. Because the CCD is not spectrally selective, a color filter is manufactured onto each sensor of the CCD sensor array, allowing only one part of the wavelength spectrum to be measured by each CCD sensor cell. The arrangement of these color filters is known as the color filter array (CFA); the most commonly used CFA is the Bayer CFA, whose arrangement is shown in Fig. 1. The output of the CCD consists of three downsampled signals representing the red, green, and blue images. To generate a full-color image, these downsampled signals need to be interpolated to the resolution of the sensor array.

Using standard interpolation techniques, a filter is designed to pass the low-frequency information and reject the high-frequency spectral images. In the context of this problem, a rectangular lowpass filter is used to interpolate the red and blue images and a diamond-shaped lowpass filter is used to interpolate the green image. These filters are specified in Fig. 2. For the CFA interpolation problem, this approach has two drawbacks:

$$\begin{matrix} G & R & G & R \\ B & G & B & G \\ G & R & G & R \\ B & G & B & G \end{matrix}$$

$$= \begin{matrix} 0 & R & 0 & R \\ 0 & 0 & 0 & 0 \\ 0 & R & 0 & R \\ 0 & 0 & 0 & 0 \end{matrix} + \begin{matrix} G & 0 & G & 0 \\ 0 & G & 0 & G \\ G & 0 & G & 0 \\ 0 & G & 0 & G \end{matrix} + \begin{matrix} 0 & 0 & 0 & 0 \\ B & 0 & B & 0 \\ 0 & 0 & 0 & 0 \\ B & 0 & B & 0 \end{matrix}$$

Fig. 1. Arrangement of color filters in Bayer CFA.

1. The red and blue images could be missing high-frequency components that are present in the green image.
2. The red and blue images are more prone to alias than the green image, causing color moiré patterns in the reconstructed image.

A broad range of approaches has been proposed in the literature. Adams proposed a method of directional interpolation, where a preferred interpolation direction is chosen for each pixel, based on image content [1]. Other methods using the directional approach can be found in [2], [3] and [4]. These methods provide good results; however, the algorithms are more complex because they require analysis of the image at each pixel. Neural networks have been used for CFA interpolation in [5]. CFA interpolation with B-splines has been analyzed in [6]. Taubman proposed a method of generating a linear, minimized mean square estimator (LMMSE) filter to provide the optimal (in the mean square sense) reconstructed image, reporting good reconstruction results [7].

In this paper, a method based on standard signal processing theory is discussed that allows the reconstruction of high-frequency content in the red and blue images. This method adds high-frequency information from the green image to the red and blue images and also uses the green high-frequency information to estimate the aliasing in the red and blue images, thus providing a means of reducing

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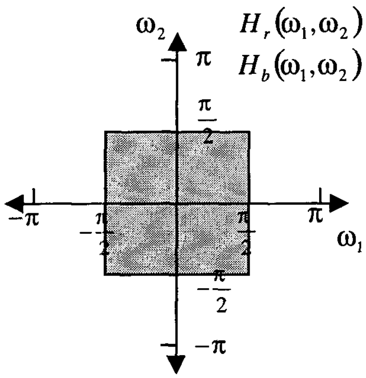
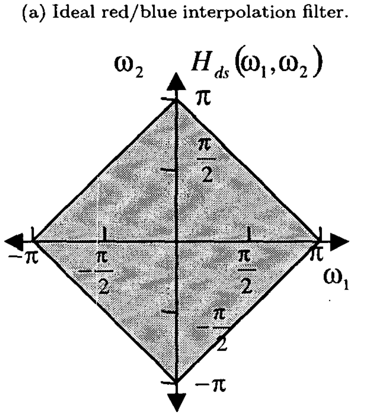


(a) Ideal red/blue interpolation filter.



(b) Ideal green interpolation filter.

Fig. 2. Ideal interpolation filters for Bayer CFA interpolation.

the amount of aliasing in the reconstructed image. Section 2 outlines the theory for this method. Section 3 derives an efficient implementation of the algorithm. Section 4 provides results showing the advantages of the proposed method and Section 5 discusses future research.

2. THEORY OF PROPOSED METHOD

Referring to Fig. 1 and accounting for the phase differences in the sampling grids, the three sampled image signals are represented by their Z-Transforms in (1), (2), and (3). The $X(z_1, z_2)$ terms contain the desired low frequency information and the $X(-z_1, z_2)$, $X(z_1, -z_2)$, and $X(-z_1, -z_2)$ terms are the sampling aliases, which could distort the output if the input signal contains high frequencies.

$$\begin{aligned} R_s(z_1,z_2) &= 1/4\ R(z_1,z_2) - 1/4\ R(-z_1,z_2) \\ &\quad +1/4\ R(z_1,-z_2) - 1/4\ R(-z_1,-z_2) \quad (1) \\ G_s(z_1,z_2) &= 1/2\ G(z_1,z_2) + 1/2\ G(-z_1,-z_2) \quad (2) \\ B_s(z_1,z_2) &= 1/4\ B(z_1,z_2) + 1/4\ B(-z_1,z_2) \\ &\quad -1/4\ B(z_1,-z_2) - 1/4\ B(-z_1,-z_2) \quad (3) \end{aligned}$$

With the Bayer CFA, the red and blue images are sampled at a lower rate than the green image, but by using information from the green image, the red and blue images can be reconstructed with the same frequency content as the green image. In a typical image, the three images are very well correlated. A simplified color image model has been presented as (4)[1], where the color channels are separated only by an additive constant; thus, the high-frequency information in the separate images is identical. Therefore, a method to reconstruct the red and blue images is to use low-frequency information from the red and blue images and high-frequency information from the green image. The green image is interpolated using the diamond-shaped, lowpass filter, H_{ds}.

$$R = G + k_R \qquad B = G + k_B \quad (4)$$

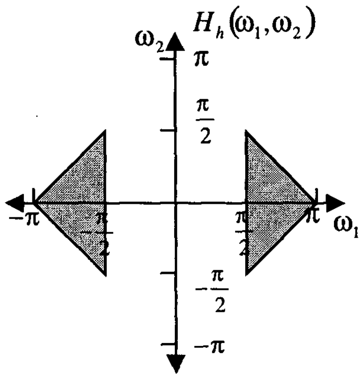
A horizontal highpass filter, H_h, and a vertical highpass filter, H_v, are designed to pass the horizontal high frequencies and vertical high frequencies, respectively, from the green image. The output of these filters can be added to the output of the red and blue interpolation filters, increasing the sharpness in the reconstructed red and blue images. The ideal response of these filters is shown in Fig. 3.

The aliasing in the red and blue images is due to components of the input image outside the rectangular Nyquist region. The sampling process replicates the input high frequencies in the low frequency region of the spectrum. By modulating the output of the horizontal highpass filter back to horizontal low frequencies, the horizontal aliasing in the red/blue images caused by the sampling process can be estimated. For the red image, this modulated signal needs to be added to the output of the red interpolation filter but subtracted from the output of the blue interpolation filter since $R(-z_1, z_2)$ has a negative sign in (1) and $B(-z_1, z_2)$ is positive in (3). An estimate of the aliasing caused by high vertical frequencies can be produced by modulating the output of the vertical highpass filter to low vertical frequencies. Here, the modulated signal is added to the blue output but subtracted from the red output. Using this process, the reconstructed red image and the reconstructed blue image can be expressed as (5) and (6), respectively. A block diagram outlining this approach is presented in Fig. 4.

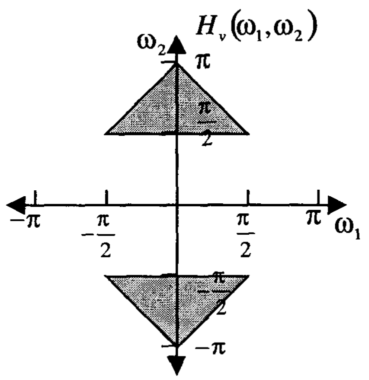
$$\begin{aligned} \hat{R}(z_1,z_2) &= R_s(z_1,z_2)H_r(z_1,z_2) \\ &\quad +G_h(z_1,z_2) + G_h(-z_1,z_2) \\ &\quad +G_v(z_1,z_2) - G_v(z_1,-z_2) \quad (5) \\ \hat{B}(z_1,z_2) &= B_s(z_1,z_2)H_b(z_1,z_2) \\ &\quad +G_h(z_1,z_2) - G_h(-z_1,z_2) \\ &\quad +G_v(z_1,z_2) + G_v(z_1,-z_2) \quad (6) \\ &\textit{where} \\ G_h(z_1,z_2) &= G_s(z_1,z_2)H_h(z_1,z_2) \\ G_v(z_1,z_2) &= G_s(z_1,z_2)H_v(z_1,z_2) \end{aligned}$$

3. EFFICIENT IMPLEMENTATION

An efficient implementation for the block diagrams in Fig. 4 can be derived easily. From Fig. 4, the filtered red signal is

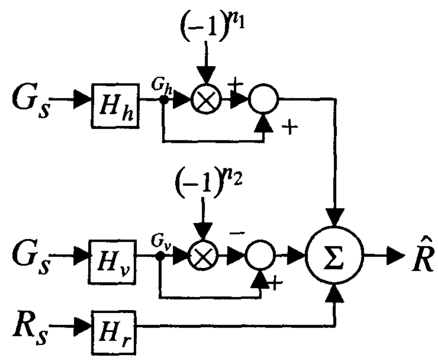


(a) Ideal horizontal highpass filter.

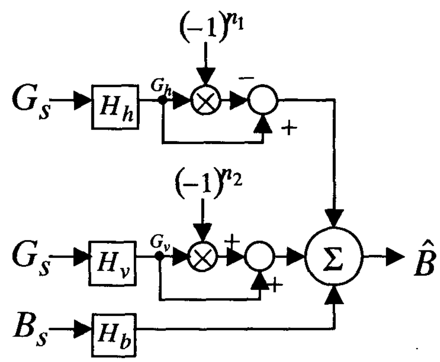


(b) Ideal vertical highpass filter.

Fig. 3. Ideal green highpass filters.



(a) Block diagram for interpolating the red image.



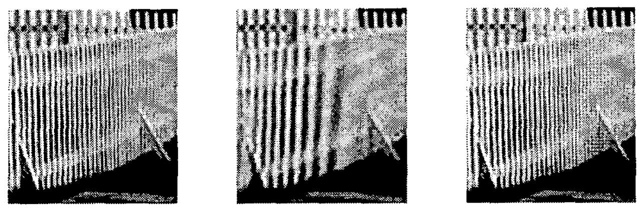
(b) Block diagram for interpolating the blue image.

Fig. 4. Block diagram for proposed CFA interpolation method.

combined with horizontal information from the green image and vertical information from the green image. Because G_h is modulated and added to itself, the signal containing the horizontal information is non-zero only on the even columns (left-most column indexed as zero). Similarly, G_v is modulated and subtracted from itself. Thus, this signal is non-zero only on the odd rows (top-most row indexed as zero). The sum of these two signals will be used as a correction signal for the interpolated red image. Thus, referring to Fig. 1, the correction signal at a G_r pixel (even row, even column) will be $2 \cdot G_h$. The correction signal for an R pixel (even row, odd column) is zero. The correction signal for a B pixel (odd row, even column) will be $2 \cdot G_h + 2 \cdot G_v$. Finally, the correction signal for a G_b pixel (odd row, odd column) will be $2 \cdot G_v$. Correction values at G_r (green pixels in a row containing red pixels), R, B, and G_b (green pixels in a row containing blue pixels) pixels will be computed by filtering the green samples with the coefficient sets $2 \cdot H_h$, 0, $2 \cdot (H_h + H_v)$, and $2 \cdot H_v$, respectively. Thus, this algorithm can be implemented with a periodic, spatially-varying filter, where the coefficients for the filter change for the different types of pixels.

4. RESULTS

In order to test the proposed algorithm, 15x15 filters were designed to approximate the ideal filters: H_r, H_b, H_{ds}, H_h, and H_v. A sample image, *Lighthouse* (Kodak PhotoCD Color Image Database), was resampled according to the Bayer CFA and reconstructed using the designed filters. In this image, the fence provides an increasingly high spatial frequency that causes aliasing in the undersampled red image. The results from a small region of the image are presented in Fig. 5. To illuminate the effects of the algorithm without full-color printing, only the red image is presented. Fig. 5(a) is the original image and Fig. 5(b) is the result using only a filter designed to approximate the ideal filter, H_r, to interpolate the image. Fig. 5(c) shows the effect of using the method from Fig. 4(a). This result shows that not only has the information from the green image been able to restore the sharpness in the red image but it can also effectively reduce the appearance of the aliasing.



(a) Original image.

(b) Using an approximation of the ideal interpolation filter, H_r.

(c) Using the proposed alias cancellation method.

Fig. 5. Interpolation results on example image.

5. CONCLUSIONS

This article outlined a new technique for performing CFA interpolation. In the algorithm, information from the green image was used to add high-frequency information to the lower-sampled red and blue images. The green high-frequency information was also used to estimate the aliasing present in the insufficiently sampled red and blue images. With an example image, the method was able to significantly improve the interpolation result over standard interpolation techniques.

One other advantage of this algorithm is that its implementation involves only the use of linear filters. Thus, it can be programmed efficiently on any DSP architecture, making it a suitable algorithm for today's cameras.

More research needs to be performed to determine the best method to combine the green and red/blue information. Currently, the green information is added without scaling to the red and blue images. However, in some cases, it may be necessary to attenuate or amplify the green information before adding it to the red and blue images.

Also, more work needs to be done to define methods of designing the filters for this problem. Metrics of performance need to be defined so that optimization techniques can be defined. One such metric could be the amount of alias rejection the filters provide. The design technique should probably consider the filters as a set and provide the best set of filters rather than individually designing each filter to meet some criterion.

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