# Demosaicing using Human Visual Properties and Wavelet Interpolation Filtering

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## Abstract

New color signal demosaicing algorithms in digital cameras are introduced by using properties of the human visual system, and by analyzing the desired frequency response of the interpolation filters. A color transformation of the RGB signal is used to obtain new signals on which interpolation is performed. The transformation corresponds to the signal processing steps within the human visual system. Wavelet filters are used for interpolation. Both objective measure and subjective testing show that the proposed algorithm achieves advantages over a previously published algorithm.

## Introduction

Solid-state digital cameras are experiencing fast growth today. They are becoming an indispensable component in a multimedia world. The digital camera market is currently dominated by cameras based on CCD arrays. Due to difficulties in optics and the need for reducing the size of the camera, the single CCD has dominated over the three CCD configuration in the consumer market.[1,2]

In a 1-CCD camera, a color filter is attached to each pixel element of the CCD array. The color filters alternate in a mosaiced fashion. One such example is shown in 0 for RGB cameras. This pattern is known as the Bayer pattern[3] and is adopted by many cameras. After capturing the image using a mosaiced pattern, the camera generates a full RGB image by interpolating this mosaiced data. This process is called *demosacing*.

Many demosaicing algorithms have been published in the past.[4,5,6] These algorithms typically interpolate the mosaiced data in the RGB space by using linear filtering. Many of them are edge-adaptive to increase the sharpness of the picture. However, there are two important shortcomings for these methods.

The first shortcoming is the choice of the color space. Since the mosaiced data is captured in the RGB space, it is thus natural to perform interpolation in this space. Unfortunately, the RGB space is not perceptually uniform. Intuitively speaking, it is inferior to interpolating in a perceptually uniform color space. The other shortcoming of the current algorithms is their choice of the interpolation filters. This filter should be chosen according to the filtering and/or sampling process performed by both the lens and the CCD, which requires the interpolation filter to have good frequency response and to be smooth, among various other properties. Furthermore, the filter choice should also take into account the compression process that follows.

| | | | | | |
|---|---|---|---|---|---|
| G | R | G | R | G | R |
| B | G | B | G | B | G |
| G | R | G | R | G | R |
| B | G | B | G | B | G |
| G | R | G | R | G | R |
| B | G | B | G | B | G |

*Figure 1. The Bayer pattern CCD array.*

In this work we propose a new demosaicing method by addressing the above two problems. We solve the first problem by first transforming the RGB data. The transformation mimics the retinal processing[7] and has certain similarities to perceptually uniform color space transforms. The second problem is solved by using wavelet interpolation filters. In one scheme, two different wavelet filters are used, with one for the G signal and the other one for R and B signals. Furthermore, the filter can be so chosen that if wavelet compression is used (as in a JPEG2000 encoder), the high-frequency coefficients will be zero, thus making the demosaiced image highly compressible. The methods proposed in this paper can be applied to other color signal interpolation problems too.

## Demosaicing using Human Visual Properties

Most of the demosaicing algorithms for RGB cameras interpolate in the RGB space for various reasons, one of

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which being the computational efficiency since the 1-CCD raw data is readily available in this space. Furthermore, they often treat each color plane separately. However, this is not the way our visual system works.

On one hand, it is conceivable that the human visual system does some sort of demosaicing since the photoreceptors in our visual system are interleaved and yet we see a continuous colorful world [7]. On the other hand, it has been demonstrated that demosaicing in the human visual system is done by treating all color planes simultaneously and thus practical algorithms have been developed using this property [4][8].

The approach in [4] exploits the correlation between different color planes statistically by using the tool of joint distribution. On the other hand, the center/surround representation is used in [8]. For example, for a pixel with known R, the unknown G value is computed by dictating that the center/surround difference is the same for both G and R components.

In this work, we rather propose to separate the RGB signal such that the resulting component planes are decorrelated. We then interpolate each plane separately before applying the inverse transform to bring them back to RGB. It is intuitively clear that if the 1-CCD raw data is available in a color space corresponding well to human color vision, the demosaicing process can achieve higher color accuracy and consistency. Therefore, in our algorithm the decorrelating color transformation mimics retinal processing.

Two important characteristics of the human visual response are the power-law contrast response and opponent color processing. The power-law contrast response is given by

$$y = x^{\alpha} \tag{1}$$

where x is the input stimulus to the human visual system and y is the response, and $\alpha$ is typically chosen to be 1/3. On the other hand, the opponent color theory basically says that the human visual system processes the input signal in opponent color directions. Roughly speaking, the three directions are luminance, red-green and yellow-blue.

Our algorithm works by first computing the power-law response to the R,G and B input signals. Let us call the new signals $R'$, $G'$ and $B'$. Then the missing $G'$ signal is interpolated. Next, the opponent color is computed and the missing $R'$-$G'$ and the missing $B'$-$G'$ signal are interpolated. The demosaiced image is then brought back to RGB space by performing inverse opponent color transformation and power law with exponent $1/\alpha$.

The color transformation described above is independent of the specific interpolation algorithms. This has been confirmed through experiments in which we observed improved demosaicing results for each and all of several different interpolation kernels including two wavelet schemes with results given in Table 1 and an ad-hoc linear interpolation filter.

*(a)*

*(b)*

*Figure 2. Original images used to generate Bayer pattern data for experiments. Image (a) is from Kokak PhotoCD and (b) is from Kodak FlashPix CD.*

## Demosaicing using Wavelet Interpolation Filtering

Both the optical lens and the CCD perform low-pass filtering of the image. For the lens, its frequency response is also known as its modulation transfer function, while for CCD, its spatial integration can be modeled as a square-window filter with sinc frequency response. The low-pass filtered scene is subsequently sub-sampled by CCD.

The demosaicing process can be modeled as multi-scale synthesis. When implemented using filter banks, it is achieved by upsampling followed by low-pass filtering. The interpolation filter used for demosaicing has to take into account the filtering and sub-sampling processes performed by the lens and the CCD in order to retain as much high-frequency component as possible while avoiding aliasing effects. For the Bayer pattern, this means that the interpolation filter for the $G'$ signal should have diamond-shape frequency response, while the filter for $R'$–$G'$ and $B'$-$G'$ should have square-shape frequency response. In our approach, we use a 2-D non-separable quincunx wavelet filter [9] to interpolate the $G'$ signal and the so-called 7/9 1-D separable synthesis filter [10] to interpolate the $R'$-$G'$ and $B'$-$G'$ signals. We call this method wavelet scheme 1 in the rest of the paper.

Another advantage of using wavelet filters for demosaicing is that, if wavelet-based image compression algorithm is used as in the forthcoming JPEG2000 standard, the demosaicing interpolation filter can be so chosen that the demosaiced image has all its high-frequency coefficients to be zero, thus making it highly compressible as discussed previously.

At the time when this paper is written, it looks almost certain that 1-D separable wavelet filtering is going to be adopted by JPEG2000 with several options of the filter set, one of which being the popular 7/9 filter pair. When the demosaiced image is compressed with such encoders in a space that is a linear transformation of the space ($G'$, $R'$-$G'$, $B'$-$G'$), we further propose wavelet scheme 2. In this scheme, we use the corresponding synthesis filter to interpolation all three color components. Thus, $R'$-$G'$ and $B'$-$G'$ components are interpolated in the same way as in scheme 1. But for $G'$ component, this means that the signal is further downsampled into two parts, with each part being as if it is subsampled by 2 in each direction from the original image. Then each part is interpolated and the two resulting $G'$ signals are averaged to obtain the final $G'$ image.

## Experimental Results

We synthesized a number of Bayer pattern raw images from full RGB images by either direct sub-sampling or low-pass filtering followed by sub-sampling. The results are shown in this section♠. Two of the original images are given in 0.

### Objective Measurements

To show the effectiveness of color transformation for demosaicing, we first compare the results obtained with and without color transformation by using both wavelet scheme 1 and scheme 2. The root mean square error in CIE$L^*a^*b^*$ space is given in 0. The error is computed by first transforming both the original image and the demosaiced image into CIEXYZ space. The transformation from sRGB to XYZ is used.[0]

The results in 0 clearly indicates that demosaicing with color transformation achieves lower chromatic error. Furthermore, it confirms that this gain is independent of the choice of the interpolation kernel. For image 0 (a) the average gain for chromatic components $a^*$ and $b^*$ is 2.55dB, while the gain for image 0 (b) is 2.32dB on average.

♠ All images in the CD-ROM proceeding are color images.

**Table 1. Root mean square error for $L^*$, a* and b* components. Each pair of numbers in a cell is the demosaicing error with and without color transformation, in that order. Two interpolation kernels (Interp 1 and Interp 2) are used. Results in (a) and (b) correspond to images 0 (a) and 0 (b), respectively.**

| | ΔL | Δa | Δb |
|---|---|---|---|
| Interp 1 | 9.11/9.12 | 7.96/15.1 | 11.44/16.31 |
| Interp 2 | 10.88/11.21 | 8.13/8.55 | 11.63/13.23 |

*(a)*

| | ΔL | Δa | Δb |
|---|---|---|---|
| Interp 1 | 2.74/2.68 | 2.64/4.49 | 3.38/5.05 |
| Interp 2 | 3.16/3.36 | 2.79/2.58 | 3.51/4.35 |

*(b)*

**Table 2. Root mean square error for L, $a^*$ and $b^*$ components given by the Sanyo algorithm. Results (a) and (b) correspond to images 0 (a) and 0 (b), respectively.**

| | ΔL | Δa | Δb |
|---|---|---|---|
| Result (a) | 10.09 | 8.74 | 12.42 |
| Result (b) | 3.77 | 4.34 | 5.62 |

One can also compare wavelet scheme 1 with scheme 2 using the object measurements above. The results are mixed. However, when judged subjectively, the images given by scheme 1 tend to be sharper as will be demonstrated later.

We further compared our algorithm with an edge-adaptive algorithm developed by Sanyo.[5] The algorithm works in the RGB space. Basically, for each color component, it computes the gradient, and uses the gradient to determine the direction of interpolation (e.g. horizontal, vertical or a mix of them). Details of this algorithm can be found in [5].

The root mean square error given by the Sanyo algorithm is given in 0. Comparing the results with those in 0, it is seen that our demosaicing schemes with color transformation outperforms the Sanyo algorithm. This will be confirmed through subjective comparison in the following as well.

### Subjective Comparison

For subjective tests, we compared our algorithm using color transformation and wavelet scheme 1 with the Sanyo algorithm. Four subjects looked at the print-outs side-by-side. They all rated higher the demosaiced images given by our new algorithm.

For the ease of readers, a number of cuts from the demosaicing images are shown in 0, 0 and 0. In each figure, a pair of image cuts is shown, given by our algorithm using color transformation and wavelet scheme 1 and the Sanyo algorithm, respectively. It is seen that the results given by our algorithm are sharper with more vivid color.

*(a)*

*(b)*

*Figure 3. Demosaicing results given by (a) our algorithm using color transformation and wavelet scheme 1 and (b) the Sanyo algorithm.*

*(a)*

*(b)*

*Figure 4. Demosaicing results given by (a) our new algorithm using color transformation and wavelet scheme 1 and (b) the Sanyo algorithm.*

*(a)*

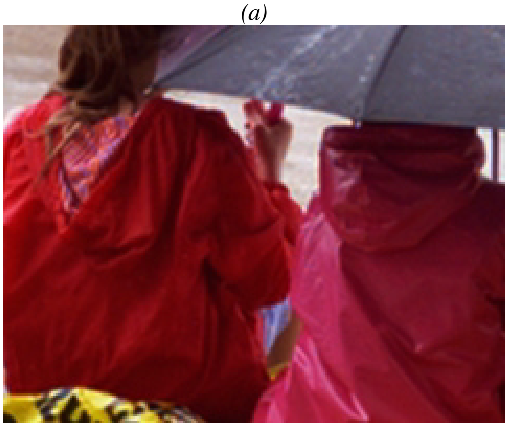
*(b)*

*Figure 5. Demosaicing results given by (a) our algorithm using color transformation and wavelet scheme 1 and (b) the Sanyo algorithm.*

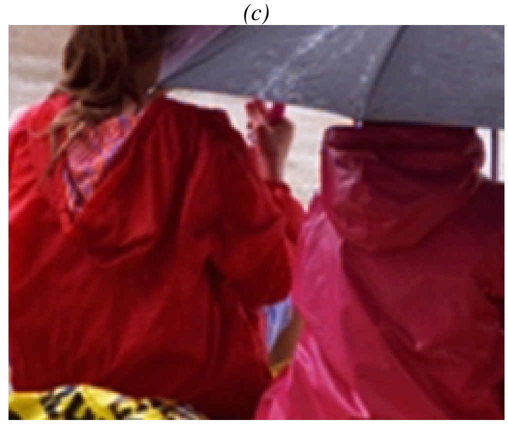
We next look at the benefits of using color transformation before interpolation and the difference between wavelet scheme 1 and scheme 2. Shown in 0 are demosaicing results (cuts) given by four different combinations of color transformation and wavelet interpolation, including (a) color transformation with wavelet scheme 1, (b) color transformation with wavelet scheme 2, (c) wavelet scheme 1 without color transformation and (d) wavelet scheme 2 without color transformation. By comparing Fig. 3 (a) and (c), and Fig. 3 (b) and (d), it is seen that applying color transformation before interpolation does make the images look sharper. On the other hand, by comparing Fig. 3 (a) and (b) and Fig. 3 (c) and (d), it seems that wavelet scheme 1 gives better results. However, when wavelet compression using separate 1-D wavelets is applied after demosaicing, the wavelet scheme 2 may have a better overall result. This needs to be verified in future works.

*(a)*

*(c)*



*(b)*



*(d)*

*Figure 6. Demosaicing results using (a) color transformation and wavelet scheme 1, (b) color transformation and wavelet scheme 2, (c) wavelet scheme 1 without color transformation and (d) wavelet scheme 2 without color transformation.*

## Conclusions

We have proposed a new demosaicing algorithm for 1-CCD digital cameras. The algorithm consists of two independent components: color transformation and wavelet interpolation. Color transformation process implements power-law contrast response and opponent color extraction in a pragmatic way. It is demonstrated that the gain in chromatic component accuracy is large and independent of the particular interpolation kernel used.

The use of wavelet interpolation is conceptually appealing. Furthermore, it may have great advantage in the presence of wavelet-based compression. It is seen that wavelet interpolation gives sharper images than the Sanyo algorithm. In the future, we will further investigate the actual gain of using wavelet interpolation together with JPEG2000 compression.

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