Demosaicing with The Bayer Pattern

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Abstract

Digital cameras are becoming more and more powerful but even if they are smaller, the CCD sensors still associate only one color to each pixel. This mosaic of color, called The Bayer Pattern, must be processed in order to obtain a high resolution color image. Each pixel of this interpolated image has a full spectrum of color based on the colors of the surrounding pixels. This process is referred as demosaicing or demosaicking. This report presents the work I have done for the final project, which was to implement and compare different commonly used demosaicing methods.

1 Introduction

The resolutions for digital cameras are becoming bigger and bigger but the principle is still the same. These cameras are based on a charge coupled device (CCD) array and each sensor on the CCD captures only one sample of the color spectrum.

Digital color cameras generally use a Bayer mask over the CCD. A Bayer filter mosaic is a color filter array (CFA) for arranging Red Green Blue (RGB) color filters on a square grid of photosensors. [Fig. 1] Each square of four pixels has one filtered red, one blue, and two green. This is because the human eye is more sensitive to green than either red or blue.

We now have a mosaiced image; at each pixel, there is only one spectral measurement, which means that the other colors have to be estimated according to the neighboring colors in order to produce a high resolution color image. This process is referred to as demosaicing. The mosaiced image is the first image, we now will have to perform interpolations on this image. There are many different methods to do this, of which i am going to present four and compare them according to a similarity measurement: the Peak Signal to Noise Ratio (PSNR) in dB. I will present first a nearest neighbor interpolation and then several other methods that involves averaging such as a bilinear interpolation, a Fast High Quality Linear Interpolation and a Gradient based interpolation. The comparison of the different algorithms is based on an image by Kodak. It provides an excellent cross-section of environments and also demosaicing "trouble-spots", such as fine details and picket fences.

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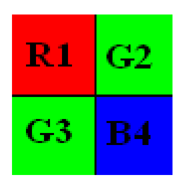
2 Demosaicing methods

2.1 Pixel Doubling Interpolation

Since we need 3 colors for each pixel in order to produce a high resolution color image, we first need to determine 2 colors for each pixel. In this method of interpolation, we only pay attention to the nearest neighbor of the actual pixel. There is no averaging to determine the spectrum of this pixel; instead the demosaiced values are simply copied from one of its nearest neighbors. For instance, the blue value captured at a sensor becomes the blue for every pixel in its 2x2 Bayer pattern block. Since it is the same for the red color and it is a little bit different for the green, we have to choose the color we want between the 2 green pixels in the 2x2 bayer pattern block for a red or blue pixel. This is an arbitrary choice.



2x2 Bayer Pattern block

Top left pixel: (R,G,B) = (R1,G2,B4)
Top right pixel: (R,G,B) = (R1,G2,B4)
Bottom left pixel: (R,G,B) = (R1,G3,B4)
Bottom right pixel: (R,G,B) = (R1,G3,B4)

Noting that there are only two different colors for a 2x2 Bayer pattern block. We can without measuring say that it is a bad method but it can be used as a baseline for comparisons.

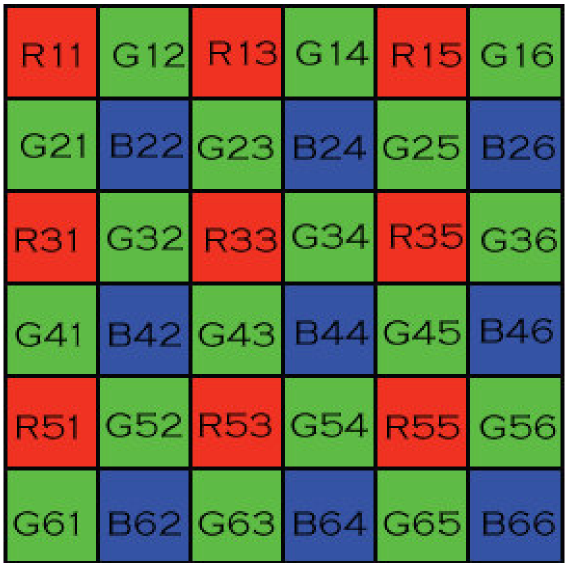


Fig.1 - Bayer Pattern

2.2 Bilinear Interpolation

In this method of interpolation, instead of considering only 4 pixels like the 2x2 Bayer pattern block we actually calculate the average on each pixel depending on its position in the Bayer Pattern in order to determine the spectrum of the particular pixel. For a pixel, we consider its 8 direct neighbors and then we determine the 2 missing colors of this pixel by averaging the colors of the neighboring pixels.
We actually have 4 different cases of averaging which are the red pixel, the blue pixel, the green pixel on a red row and the green pixel on the blue row. On each of them the averaging will be slightly different.

<u>Pixel R33 (red pixel):</u> Red = R33
Green = (G23+G34+G32+G43) / 4
Blue = (B22+B24+B42+B44) / 4

<u>Pixel B44 (blue pixel):</u> Blue = B44
Green = (R33+R35+R53+R55) / 4
Red = (R33+R35+R53+R55) / 4

<u>Pixel G43 (Green in a blue row):</u> Green = G43
Red = (R33+R53) / 2
Blue = (B42+B44) / 2

<u>Pixel G34 (Green in a red row):</u> Green = G34
Red = (R33+R35) / 2
Blue = (B24+B44) / 2

Like the pixel doubling interpolation, this method allows us to determine the red, green and blue color for each pixel. We also expect better results than the pixel doubling interpolation because we calculate the average of the neighbor pixels instead of just copying the values. The missing component will then be closer to the true values.

2.3 Gradient Based Interpolation

This is the method proposed by Laroche and Prescott. There are 3 steps in this method: the first is to compute the luminance on each pixel, and then the second and the third are the interpolation of the color differences: Red minus Green and Blue minus Green. We will need those two interpolations in order to determine the red and blue channel for each pixel. This is a direct consequence of the fact that the human eye is sensitive to luminance changes.
In the first step, we have only to determine the luminance for the red and blue channel. The lumiance is the green channel so we consider, on the green pixel, that the luminance is actually the intensity of the pixel. On a red or blue pixel, the luminance of this pixel is determined by knowing if the pixel is on a vertical edge or on a horizontal one. In order to know if we have an edge, we can calculate 2 parameters: α and β, which depends on whether we are on a red or blue pixel.
If we are on a blue pixel, for example B44, we have
$\alpha = abs[(B42 + B46) / 2 - B44]$ (vertical edge)
$\beta = abs[(B24 + B64) / 2 - B44]$ (horizontal edge)
Then using those 2 values, we can estimate the missing green value.

If $\alpha < \beta$ (vertical edge), G44 = (G43+G45) / 2
If $\alpha > \beta$ (horizontal edge), G44 = (G34+G54) / 2
If $\alpha = \beta$ (no edge), G44 = (G43+G45+ G34+G54) / 4

Similarly, for R33, we have
$\alpha = abs[(R31 + R35) / 2 - R33]$ (vertical edge)
$\beta = abs[(R13 + R53) / 2 - R33]$ (horizontal edge)

If $\alpha < \beta$ (vertical edge), G33 = (G32+G34) / 2
If $\alpha > \beta$ (horizontal edge), G33 = (G23+G43) / 2
If $\alpha = \beta$ (no edge), G33 = (G32+G34+ G23+G43) / 4

At this point we know exactly the luminance values for each pixel (green channel), we just have to determine the blue and red channel by computing the differences between those channels and the luminance channel. Let's note: Dxy = Cxy - Lxy. (C: Red or Blue depending on which one is to be computed, L: Luminance)
We have for red and blue:
Red: R34 = G34 + (D33 + D35)/2
R43 = G43 + (D33 + D35)/2
R44 = G44 + (D33 + D35 + D53 + D55)/4
Blue: B34 = G34 + (D24 + D44)/2
B43 = G43 + (D42 + D44)/2
B33 = G33 + (D22 + D24 + D42 + D44)/4
In this method, we determine the missing color values by averaging and by considering the different edges that we

encounter in the image and also by computing the luminance. We can expect to have more accurate colors in output especially on the edges. When we find an edge, we consider the pixels along the edge instead of considering all the neighbors.

2.4 High Quality Linear Interpolation

Malvar et al proposed a method to demosaic an image using a Bayer Pattern. This is actually a set of 8 kernels [fig.2] that we need to normalise and then apply to the mosaiced image in order to demosaic it. The choice of the kernel depends on the position of the pixel.
There are 8 cases:
2 - To determine the red and green values on a blue pixel,
2 - To determine the blue and green values on a red pixel,
4 - To determine the red and blue values on a green pixel.
(2 for a green pixel in a "red row" and 2 in a "blue row")

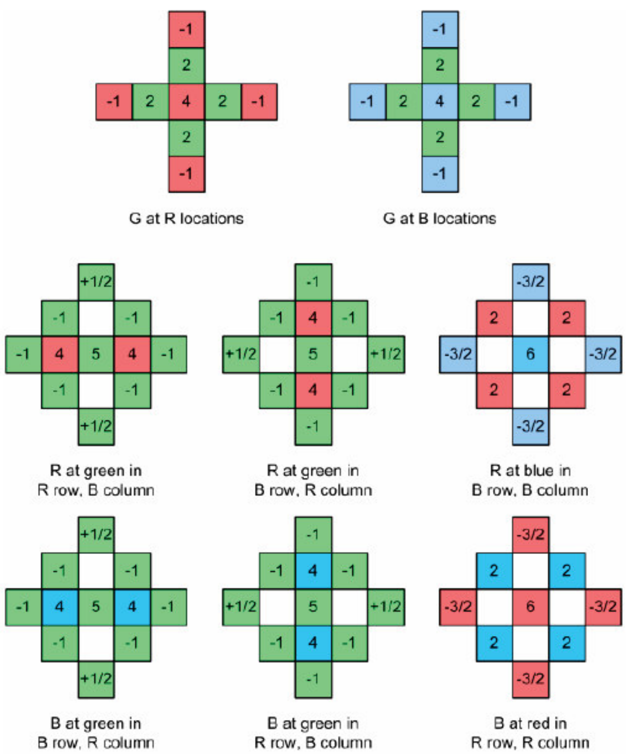


Fig.2 - 8 kernels for a High quality linear interpolation

By looking at the different kernels, we can see that this is similar to the previous method with the gradient based interpolation. To determine a color, we calculate the average of the neighbor with the same color, but we also incorporate the green channel into each of them. This creates a link between the channels, and thus the rendering of the edges should be better than a basic linear interpolation (nearest neighbor or bilinear)

3 Results

To determine if the results are good, we use the Peak Signal to Noise Ratio (PSNR). We will measure the quality difference in dB.

$$PSNR = 20 \log_{10} \frac{255}{RMSE}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i \in everyPixel} (demosaicedValue_i - actualValue_i)^2}$$

When we compute the RMSE, we use only one channel, the red. The higher the PSNR is, the better the results are. Basically it compares the value of a red pixel and the value of the same pixel on the ground truth image.

By applying the different interpolation methods to the original mosaiced image we have the following results:

Interpolation method	PSNR
Pixel doubling	24.15
Bilinear Interpolation	27.67
Gradient based Interpolation	28.69
High Quality Linear Interpolation	33.39

Those results show that the high quality linear interpolation has the better results on this particular original image. This difference is obvious when we look at the demosaiced images [Fig.3]. The pixel doubling approach is definitely not the right one. The other approaches have pros and cons.
Those algorithms are going to be intergrated into a digital camera so we don't have to consider only the the demosaiced image, we have to be concerned about the speed of execution and also the memory usage. We don't want to wait for 10 seconds between each pictures...
Concerning the speed of those interpolations, the High Quality Linear Interplation is powerful with great results but it's time consuming due to all the calculus we need to do for a single pixel. It's even worse for the Gradient based interpolation because we first need to calculate all the green pixels, then compute the other colors and the results are not that good compare to the High Quality Linear Interpolation. Finally, the bilinear filter is very fast but the results are not really good.
The digital cameras can take pictures that are becoming bigger and bigger and so in order to do treatments on those pictures we need memory. For all the interpolation methods, we need to have a memory to store the image and also a memory to store the information about the kernel.

All those interpolations are similar concerning the memory usage, the only difference between those interpolations about the memory is the space they need to store the kernels. For the bilinear and the gradient based interpolation, they almost do not need any additionnal memory because it’s only some small calculus. The high quality linear interpolation need a bit more storage because it needs to store the 8 kernels in addition to the memory needed for the calculus.

Fig.3-a Pixel Doubling interpolation

Fig.3-b Bilinear Interpolation

Fig.3-c Gradient Based Interpolation

Fig.3-d High Quality Linear Interpolation

About the performances of all those algorithms, we can notice that the weakness appears when we have to deal with edges. [Fig4] presents the influence of those demosaicing algorithms on another image.

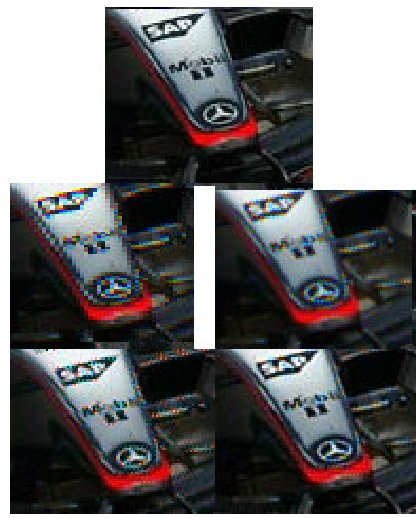


Fig.4 top: original image, middle left: pixeldoubling
middle right: bilinear, bottom left: gradient,
bottom right: High Quality

Interpolation method	PSNR
Pixel doubling	23.35
Bilinear Interpolation	27.3
Gradient based Interpolation	28.47
High Quality Linear Interpolation	33.08

By looking at those results, it seems that the High Quality Interpolation filter is the one who produces the better results.

Finally [Fig5] presents the influence of those demosaicing algorithms on an image where there is only one edge.

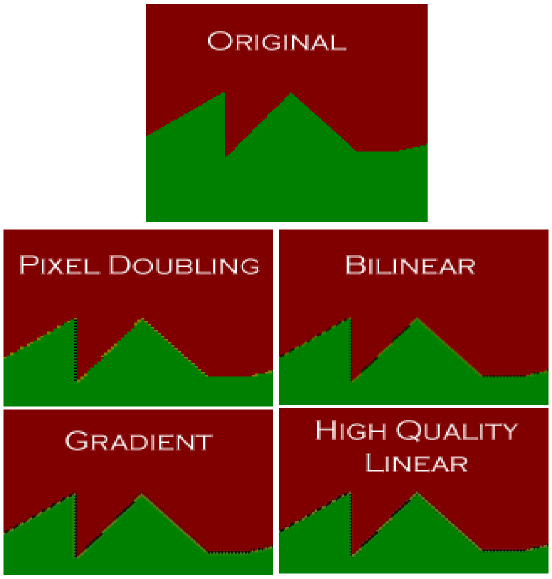


Fig. 5 one edge image

Interpolation method	PSNR
Pixel doubling	27.87
Bilinear Interpolation	31.89
Gradient based Interpolation	27.75
High Quality Linear Interpolation	28.93

By looking at those results, it seems that the bilinear filter is the one who handles the better the edges in this image. But we have to be careful because this is not the kind of image that are supposed to be handled by those interpolations. That is why the results cannot be compared to the previous ones.

4 Conclusion

In conclusion we can say that demosaicing is not a trivial problem, because we have to interpolate a lot of information, and that there are many solutions to process mosaiced images. I tested 4 of them and compare them on 3 images. Those 4 methods have produced some results that can definitely be improved especially on the edges.
We also have to consider that this is a theorical model because in digital cameras the CCD array is not really in focus and so each pixel knows a bit about its neighbors. Thus some other algorithms can do a better interpolation depending on measurments on the focus of the camera.

References

1. Ramanath et al., "Demosaicking Methods For Bayer Color Arrays" (2002)
2. Malvar et al., "High Quality Linear Interpolation for Demosaicing of Bayer-Patterned Color Images" (2004)