GEOMETRICAL ACCURACY OF BAYER PATTERN IMAGES

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ABSTRACT

Modern digital still cameras sample the color spectrum using a color filter array coated to the CCD array such that each pixel samples only one color channel. The result is a mosaic of color samples which is used to reconstruct the full color image by taking the information of the pixels' neighborhood. This process is called demosaicking. While standard literature evaluates the performance of these reconstruction algorithms by comparison of a ground-truth image with a reconstructed Bayer pattern image in terms of grayscale comparison, this work gives an evaluation concept to asses the geometrical accuracy of the resulting color images. Only if no geometrical distortions are created during the demosaicking process, it is allowed to use such images for metric calculations, e.g. 3D reconstruction or arbitrary metrical photogrammetric processing.

Keywords

Bayer pattern demosaicking, Geometrical accuracy, Evaluation

1 INTRODUCTION

Commercially available digital still cameras are based on a single CCD sensor overlaid by a color filter array (CFA) which gives the possibility to capture a color image with only one CCD sensor. Several types of color mosaics have been implemented in the past, whereat the most common CFA is called the Bayer pattern [Bayer76] and is shown in figure 1. The scheme results in 25% red and blue and 50% green coverage of the array. A real example of an image captured by a CCD sensor that is equipped with a Bayer pattern filter is shown in figure 2. It results in an image mosaic of three colors, where the missing color pixels have to be interpolated to get a complete full RGB color image. This reconstruction is called *demosaicking*.

The paper is structured as follows. First, the state

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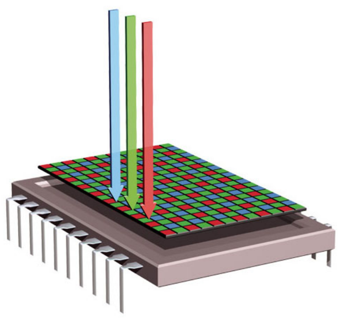
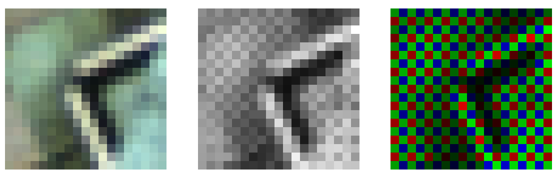


Figure 1: Concept of color acquisition using Bayer pattern (image from © 2003 Foveon, Inc. Used with permission). Digital sensor equipped with a color filter array, where every pixel only records one color instead of three.



(a) (b) (c)

Figure 2: Principle of Bayer pattern images. (a) Small detail of a conventional color image with 19×19 pixels. (b) This image is captured by a single CCD sensor equipped with a Bayer pattern filter. The mosaic is strongly visible. (c) Image (b) where each sample is plotted with the color from the Bayer pattern.

of the art of Bayer pattern demosaicking is presented in section 2. Next, the standard accuracy evaluation method is described in section 3. In section 4 the novel geometrical accuracy evaluation method and results are given. Finally, concluding remarks are made in section 5.

2 STATE OF THE ART

The Bayer color filter was patented in 1976 by [Bayer76]. To interpolate color values at each pixel, Bayer proposed simple bilinear interpolation. At the beginning of the development of digital still cameras, [Cok87] suggested to use a constant hue-based interpolation, since pixel artifacts in the demosaicking process are caused in sudden jumps in hue. [Freem88] then proposed to use a median-based interpolation of the color channels to avoid color fringes. In 1993 Hibbard filed a patent to adaptively interpolate a full color image by using an edge-based technique. The patent was approved two years later [Hibba95]. Meanwhile, [Laroc94] got their edge-based method approved, which can be seen as an extension to Hibbard's approach. [Hamil97] used the concepts of both edge-based methods and created a combination and extension of these approaches. [Chang99] proposed a simple, however promising method using a bigger local neighborhood to define the gradients. The difficulty of Bayer pattern demosaicking is still a hot topic in the computer vision community, e.g. see [Malva04]. A good survey is found in the review article [Raman02].

3 EVALUATION

The standard evaluation concept for Bayer pattern demosaicking methods is to start with a color image I_{ref}. This image is converted to a Bayer pattern image I_{BP}, that is then reconstructed to a full color image I_{res} by using a demosaicking method. This image can now be compared with the reference image I_{ref}. Figure 3 illustrates the evaluation setup.

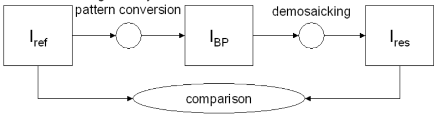


Figure 3: Concept of Bayer pattern demosaicking evaluation setup.

Several metrics are defined, to allow a quantitative comparison. The root mean square error (RMSE) counts the gray value differences of the images in DN and is defined as follows

$$RMSE(I_{\text{ref}}, I_{\text{res}}) = \sqrt{\frac{1}{|\mathcal{N}|}\sum_{i\in\mathcal{N}} (I_{\text{ref}}(i) - I_{\text{res}}(i))^2} \tag{1}$$

where $\mathcal{N}$ is the neighborhood containing all pixels of the image and $i = (x, y)$ is the index for one single pixel. The RMSE is calculated for each color channel and the total RMSE is defined by the sum of the single RMSE values. [Raman02] suggests to use the RMSE in the L*a*b* color model, which has the advantage that color differences in this color model match with human perception. This error metric is defined as

$$RMSE_{\text{L}^*\text{a}^*\text{b}^*}(I_{\text{ref}}, I_{\text{res}}) = \sqrt{\frac{1}{|\mathcal{N}|}\sum_{i\in\mathcal{N}} (\Delta L^*(i))^2 + (\Delta a^*(i))^2 + (\Delta b^*(i))^2} \tag{2}$$

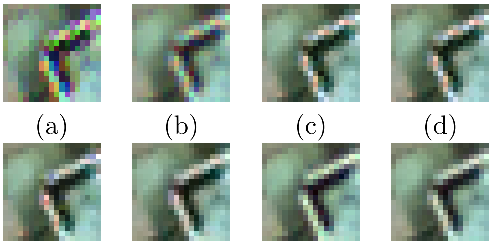
where $\Delta L^*(i) = L^*_{I_{\text{ref}}}(i) - L^*_{I_{\text{res}}}(i)$, $\Delta a^*(i) = a^*_{I_{\text{ref}}}(i) - a^*_{I_{\text{res}}}(i)$ and $\Delta b^*(i) = b^*_{I_{\text{ref}}}(i) - b^*_{I_{\text{res}}}(i)$.

All these error metrics are defined globally for the whole image. Therefore, a small total RMSE may not be directly related to a good demosaicking results. In homogenous image areas the RMSE is near to zero, whereas it is larger near edges. Therefore, an additional error metric is introduced, which calculates the RMSE per color channel only in the neighborhood of Canny edges [Perko04]. In the evaluation this error metric is called RMSE at edges.
The results of the discussed demosaicking methods are given in table 1 for an aerial image.

Approach	RMSE					RMSE at edges		
	red	green	blue	total	L*a*b*	red	green	blue
nearest neighbor	7.0	5.4	6.1	18.5	9.9	22.8	17.1	19.5
bilinear	3.8	2.5	3.0	9.3	4.7	11.5	7.4	8.8
Cok logarithmic	2.6	2.5	2.1	7.2	4.1	7.6	7.4	5.8
Cok linear	2.5	2.5	2.1	7.1	4.0	7.2	7.4	5.7
Hibbard	2.5	2.4	2.2	7.1	4.0	7.0	6.7	5.9
Laroche	2.2	2.1	2.0	6.3	4.2	6.1	5.9	5.5
Hamilton	2.1	1.4	1.7	5.2	3.5	5.9	3.5	4.5
Chang	1.9	1.3	1.5	4.7	3.3	5.2	3.5	3.9

Table 1: Demosaicking results for an aerial image with 1500×480 pixel. A part of this image is shown in figure 2 (a). Given are RMSE in DN for all color channels and total RMSE, the RMSE at edges in DN for all color channels and the RMSE in L*a*b* color space.

In figure 4, the color fringes occurring at the edges are visible, above all for the simple demosaicking approaches (a) and (b). Visually the methods by Hamilton and Chang perform best. The numerical evaluation is not very surprising: As



(a) (b) (c) (d)

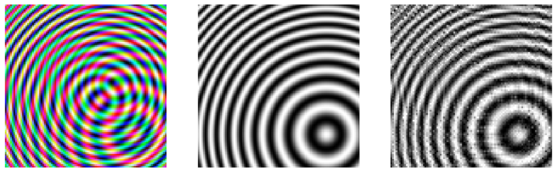
(e) (f) (g) (h)

Figure 4: Demosaicking results for different methods. A detail with 19×19 pixel is used. (a) Nearest neighbor (b) Bilinear (c) Cok logarithmic (d) Cok linear (e) Hibbard (f) Laroche (g) Hamilton (h) Chang. Simple methods like (a) and (b) produce color fringes at edges, whereas edge-base approaches (e)-(h) converges more and more to the original image.

expected the nearest neighbor methods perform worst, followed by the bilinear and constant hue-based interpolation. The edge-based approaches outperform the non-adaptive ones and give better results according to their complexity. The algorithm of Chang gives the best results.
Of course the green color channel is reconstructed with the smallest error, since already 50% of the green data is available in the mosaic. Also worth to mention is that, as expected, the RMSE at edges is significantly higher (about a factor of 3) than over the whole channel.

4 GEOMETRICAL ACCURACY

For metric digital cameras the geometrical accuracy of the resulting images is essential. The higher the frequencies in an image, the more artifacts will occur after demosaicking. Since non-linear interpolation is used in the edge-based approaches, the question is, whether the geometry is changed by this procedure. The motivation for this evaluation comes from the observation sketched in figure 5. Strong image artifacts occur caused by non-linear interpolation. Therefore, several algorithms based on the image geometry are performed to answer this question. In this evaluation, the following test setup is used: A color image I_{RGB} is converted to grayscale using standard YIQ color model yielding to the reference grayscale image I_{ref}. On the other side, the color image I_{RGB} is converted to a Bayer pattern image I_{BP}, which is then reconstructed to the full color image $I_{\mathrm{RGB'}}$ and also converted to grayscale, resulting in I_{res}. If the demosaicking process does



(a) (b) (c)

Figure 5: Hypothesis that the demosaicking process may introduce geometrical distortions. (a) Synthetic color image containing high frequencies. Each color channel contains concentric circles with varying center and frequencies. (b) Red color channel of the input image. (c) Red color channel of reconstructed Bayer pattern image using method by Hamilton.

not change the geometry, the grayscale images I_{ref} and I_{res} should now have a very similar geometry. This concept is illustrated in figure 6. Two tests are performed to determine the geometrical aspects:

(i) Subpixel matching: According to this concept two images are generated where one of them is subpixel translated by a given subpixel shift (e.g. $(-0.3, -0.2)$ pixel). These resulting images are then matched using the algorithm by [Gleas90]. Now, if there are differences in the geometry, the image pair based on the Bayer pattern should give a bigger error than the pair based on the input image.

(ii) Subpixel corner detection: The image pairs are generated as in the subpixel matching test. Then subpixel Harris corners are extracted in both images and matched using nearest neighbor assignment.

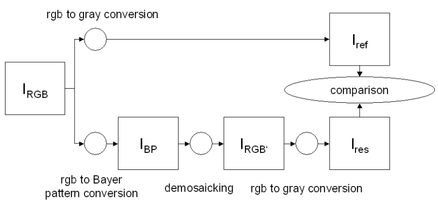


Figure 6: Concept of geometrical Bayer pattern demosaicking evaluation setup.

Both tests are performed on ten different images and the average results are chosen. Figure 7 shows the mean and the standard deviation of the errors in x and y coordinates for the subpixel matching test and figure 8 for the corner detection test. The errors are given in pixel for the original image and for eight demosaicking methods. As expected the nearest neighbor method introduces the largest errors and should not be used. The seven other methods give errors comparable to the original image, however the method by Hibbard performs worse. Standard methods like Hamilton and Chang perform very good by producing no additional error in comparison to the original image.

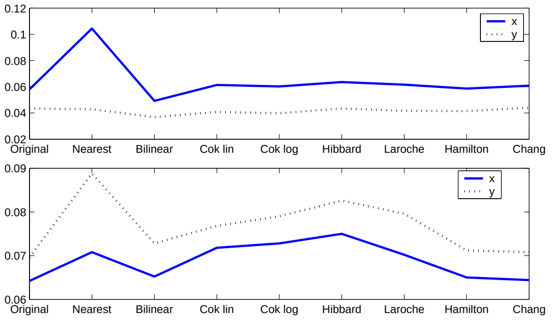


Figure 7: Results of the subpixel matching test in pixel. The mean error values are shown on the top and the standard deviation on the bottom for the original image and for eight Bayer Pattern demosaicking methods.

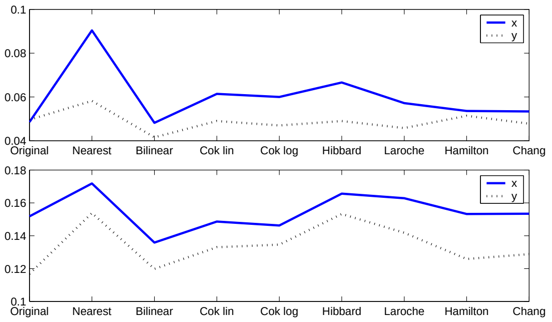


Figure 8: Results of the subpixel corner detection test in pixels. The mean error values are shown on the top and the standard deviation on the bottom for the original image and for eight Bayer Pattern demosaicking methods.

5 CONCLUSION

This paper describes the difficulty of reconstructing the missing color samples of a Bayer pattern image. The presented results lead to two basic conclusions: First, there are algorithms for demosaicking which give very good results and are computationally not very expensive, namely the algorithms by Hamilton and Chang. Second, the demosaicking process does not create geometrical distortions, so that e.g. stereo matching produces the same results as on true color images. Both aspects are very important for metric computer vision, consequently a camera equipped with a Bayer pattern filter for color image sensing is a useful approach.

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