The influence of Bayer filters on the quality of photogrammetric measurement

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ABSTRACT

Bayer colour filter arrays (CFA) are commonly used to obtain digital colour imagery from a single-chip CCD or CMOS camera. Colour information is captured via a regular array of colour filters placed over the image sensor, and the full colour image is reconstructed in a demosaicing process. Colour imagery derived in such a way is prone to visual artefacts including false colours, poor edge definition and a loss of image and colour sharpness. Such artefacts are suspected of degrading the quality of photogrammetric measurements made from demosaiced images. An approach to demosaicing based on the use of tuneable Gaussian filters is proposed. The new approach is designed to minimise image artefacts and is specifically aimed at improving the quality of photogrammetric measurements made with the demosaiced imagery. Results are given for a specific application of Bayer CFA cameras to underwater stereo length measurement of fish. The results show a reduction in visual artefacts and an improvement in the quality of stereo measurements.

Key words: colour image, Bayer, colour filter array, demosaicing, image quality, photogrammetry

1. INTRODUCTION

Digital colour cameras frequently employ a Bayer CFA to derive colour imagery from a single image sensor. To enable the generation of a colour image a colour filter is placed on top of each photodiode, making it sensitive to a particular colour. The typical Bayer CFA pattern consists of repeated lines of red/green and green/blue sensitive pixels, and is shown in figure 1. There are twice as many green sensitive pixels as there are red and blue sensitive pixels. This is an intentional design feature aimed at maximising luminance information that is primarily contained in the green channel[1]. Since the image is effectively under sampled, the missing colour information has to be interpolated for each pixel position. The interpolation is variously known as CFA interpolation, Bayer conversion, Bayer filtering, or demosaicing.

Most digital cameras use a single sensor CFA to obtain colour imagery in favour of a three-sensor solution (a sensor for each of the red, green and blue channels) because it reduces both camera size and cost[2]. However, the Bayer CFA approach to obtaining colour images has several disadvantages. Since each pixel has been made sensitive to a specific spectral band the overall sensor sensitivity is lower than an equivalent sized panchromatic sensor. Also, due to colour under sampling, the recovered colour images tend to lose sharpness, and visual artefacts in the form of blurred edges and false colours are introduced[1,3].

There are many established Bayer demosaicing algorithms. Most of these make some attempt to overcome the inherent problems of blurred edges and aliasing in the recovered colour image. In general, the demosaicing algorithms fall into two classes. The first class is based on interpolation and includes approaches such as nearest neighbour replication, bilinear and cubic spline interpolation, and neural networks[2,4]. The second class includes approaches that consider image content in the filtering process, for example colour correlation approaches that consider the correlation between image colour channels[5], methods that adapt to local image edge directions[3,6,7,8], and data dependant triangulations[9]. In general, bilinear interpolation has been favoured because it is simple, fast and robust[5].

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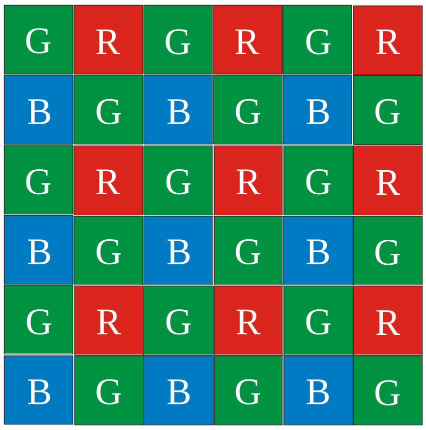


Figure 1: Bayer colour filter pattern

The complexity of the demosaicing algorithm is, in part, dependent on the type of camera. Frame rate cameras are much more likely to have relatively straightforward algorithms because of the necessity to process the images very rapidly. In contrast, digital still cameras may have more sophisticated algorithms due to the relatively slow read out rate of images, and the possibility of on board storage to accommodate "burst" mode shooting. Anecdotal evidence suggests that image artefacts are clearly associated with frame rate cameras whereas digital still cameras do not exhibit visible image degradation.

Prominent image artefacts were noted in a specific application that uses Bayer CFA cameras in an underwater stereo measurement system. The artefacts resulted in poor colour and horizontal edge definition, and it was suspected that such artefacts were leading to degradation in the quality of stereo measurements made with the camera system. This paper proposes an approach to demosaicing based on independent Gaussian filters for each of the red, green and blue channels. The approach aims to reduce the displeasing visual nature of image artefacts and improve the quality of stereo measurements made with the camera system.

2. CAMERA SYSTEM

The Bayer filter reported in this paper was specifically developed to improve imagery derived from an underwater stereo measurement system. The system is primarily used to measure fish and consists of two JAI CVM7+ cameras mounted on a base bar, approximately 800mm apart, inwardly converging at approximately 7.5 degrees. Images from the underwater cameras are sent to the surface via 70 metres of fibre optic cable. At the surface a computer program controls image acquisition based on the detection of motion, externally triggers the camera system for exact stereo synchronisation, and logs digital stereo image pairs directly to computer hard disk drives. The camera system is calibrated in-water using a calibration cube and commercially available software[10,11]. Typical accuracy of fish measurement is better than 1% of the overall fish length.

Images from the CVM7+ cameras are transmitted to the computer in Bayer format. The computer has the task of demosaicing the imagery to recover colour images (performing the demosaicing at the host computer reduces by a factor of three the amount of data that is transmitted between the cameras and computer since the image is effectively transmitted as greyscale rather than colour). Demosaicing is performed on the host computer using Software Development Kit Imaging Foundation Classes, version 5.5 (the Bayer filter provided in this library is henceforth referred to as the 'IFC Bayer filter') bundled with the camera from Imaging Technology Incorporated.

Imagery from the CVM7+ cameras demosaiced using the IFC Bayer filter displays significant artefacts that effect definition of horizontal edges and are visually displeasing. A sample of such imagery is seen in the left hand image of figure 4. An investigation into the artefact source considered the camera itself, as well as the IFC Bayer filter used to recover the colour image. Due to the proprietary nature of the library used, the exact algorithm used for Bayer filtering could not be determined. However, it was observed that green levels on adjacent image lines in the raw Bayer image suffered quite large variations. The variations are consistent between every second image row, resulting in a pattern of horizontal banding in the green data.

Figure 2 shows a 40x40 pixel region of a raw Bayer image separated into red, green and blue components. The image is of a constant background scene, so no significant variation in colour should be observed. The banding that occurs in the green data is visibly obvious, and the intensity level variation results in a standard deviation (SD) of the green data approximately three times worse than for the red and blue (SD red = 5.5, SD green = 15.9, SD blue = 5.1). The noted noisiness of the green channel is unfortunate since many demosaicing algorithms rely on the dominantly sampled green channel to be less susceptible to aliasing and preserve most of the image information[12].

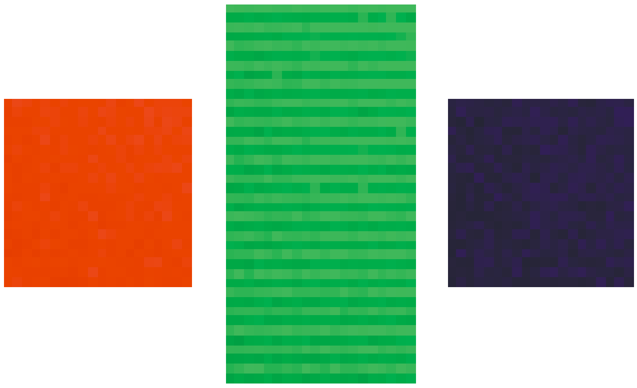


Figure 2: Raw Bayer image data of a constant background showing variation (banding) in the green data

3. PROPOSED BAYER FILTER

It was suspected that banding of the green pixel data was the major cause of artefacts observed in the demosaiced colour images. One approach to reducing the artefacts is to apply a Gaussian type filter to the raw image during the colour image recovery. Using a different Gaussian filter for each of the red, green, and blue channels allows for different levels of filtering to be achieved for each channel. In this case the red and blue channels could be lightly filtered to preserve image sharpness, whereas the green channel could be more heavily filtered to remove the effect of banding.
The proposed demosaicing filter is based the equation of a Gaussian curve:

$$f(x,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{\frac{-x^2}{2\sigma^2}\right\} \tag{1}$$

Where x represents the distance in pixels from the pixel that is being demosaiced, and σ is the standard deviation, or effective region of influence of the filter. Figure 3 shows the effect on filter coefficients of different values of σ. The demosaicing is computed over a 5x5 window since this was found during experimental tests to be the minimum window required to remove the effect of green banding in the demosaiced image.

As an example of filter coefficient derivation, consider a green pixel on a green/blue image line. Let p(i, j) represent the Bayer image value for a particular location in the image (in this case the green pixel on a green/blue line). Pixels in a 5x5 window surrounding p(i, j) are considered in the computations. Let α_r, α_g, α_b and σ_r, σ_g, σ_b represent gains and filter standard deviations for each colour channel respectively. The gains can be used to control the mixture of colours in the demosaiced image.

The interpolated pixel values are:

$$\text{red} = \alpha_r r_{norm} \begin{Bmatrix} r_0\{p(i-1,j)+p(i+1,j)\}+ \\ r_1\{p(i-1,j-2)+p(i-1,j+2)+p(i+1,j-2)+p(i+1,j+2)\} \end{Bmatrix}$$

$$\text{green} = \alpha_g g_{norm} \begin{Bmatrix} g_0\{p(i,j)\}+ \\ g_1\{p(i-1,j-1)+p(i-1,j+1)+p(i+1,j-1)+p(i+1,j+1)\}+ \\ g_2\{p(i-2,j)+p(i,j-2)+p(i,j+2)+p(i+2,j)\}+ \\ g_3\{p(i-2,j-2)+p(i-2,j+2)+p(i+2,j-2)+p(i+2,j+2)\} \end{Bmatrix}$$

$$\text{blue} = \alpha_b b_{norm} \begin{Bmatrix} b_0\{p(i,j-1)+p(i,j+1)\}+ \\ b_1\{p(i-2,j-1)+p(i-2,j+1)+p(i+2,j-1)+p(i+2,j+1)\} \end{Bmatrix}$$

where:

$$r_0 = f(1,\sigma_r) \qquad r_1 = f(\sqrt{5},\sigma_r)$$
$$g_0 = f(0,\sigma_g) \qquad g_1 = f(\sqrt{2},\sigma_g) \qquad g_2 = f(2,\sigma_g) \qquad g_3 = f(\sqrt{8},\sigma_g)$$
$$b_0 = f(1,\sigma_b) \qquad b_1 = f(\sqrt{5},\sigma_b)$$
$$r_{norm}^{-1} = 2r_0 + 4r_1 \quad g_{norm}^{-1} = g_0 + 4g_1 + 4g_2 + 4g_3 \qquad b_{norm}^{-1} = 2b_0 + 4b_1$$

Filter parameters for the remaining line and pixel combinations (blue pixel on a green/blue line, and blue and green pixels on blue/green lines) are computed in a similar manner. This results in a set of filter values for each combination of pixels and lines. Note that all colour channels are interpolated at each image position even though one channel value will always be directly available from the Bayer image.

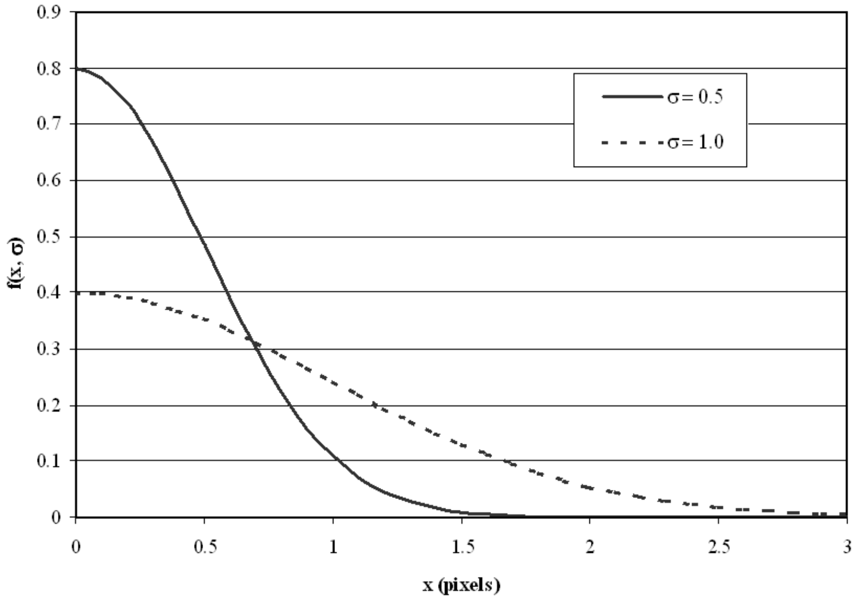


Figure 3: Filter curves generated with equation (1)

For efficiency, all filter parameters are pre-computed and normalised. During the demosaicing process the raw image is cached through a rotating buffer to decrease the number of memory access operations in order to optimise the computation speed of the filter.

4. RESULTS

Figure 4 shows various results of the proposed filter. The imagery was collected in an out of water environment, and three different sub scenes were chosen to highlight vertical and horizontal edges as well as texture. The left hand image was demosaiced using the IFC Bayer filter. This image exhibits false colouring and noticeable vertical artefacts (stripes through the image) that lead to poor horizontal edge definition.

The remaining three images in figure 4 were demosaiced with the proposed filter. In the image second from left, filter settings of σ_r= 0.1, σ_g= 0.1, σ_b= 0.1 were used. With this setting little smoothing is seen and the demosaiced image still contains artefacts, although they are considerably reduced compared with the IFC Bayer filter. The image third from left was generated with σ_r= 2.0, σ_g= 2.0, σ_b= 2.0. This setting removes all artefacts, but results in an image that is over-smoothed and has a distinct de-focussed appearance. The right hand image was generated with filter settings σ_r= 0.5, σ_g= 1.0, σ_b= 0.5, in order to smooth the green channel more than the red and blue. These settings provide an optimum trade off between removing the artefacts and over smoothing image detail.

The vertical striping in the demosaiced image appears to be inconsistent with the horizontal striping in the green channel image shown in figure 2. However the demosaicing process filters or interpolates the Bayer image into different visual patterns, such as the apparent checkerboard pattern in the second example in figure 4. The quality of the demosaicing is evident in the removal of such patterns in uniform areas such as those in the image used in figure 4, and this criterion supports the chosen filter settings.

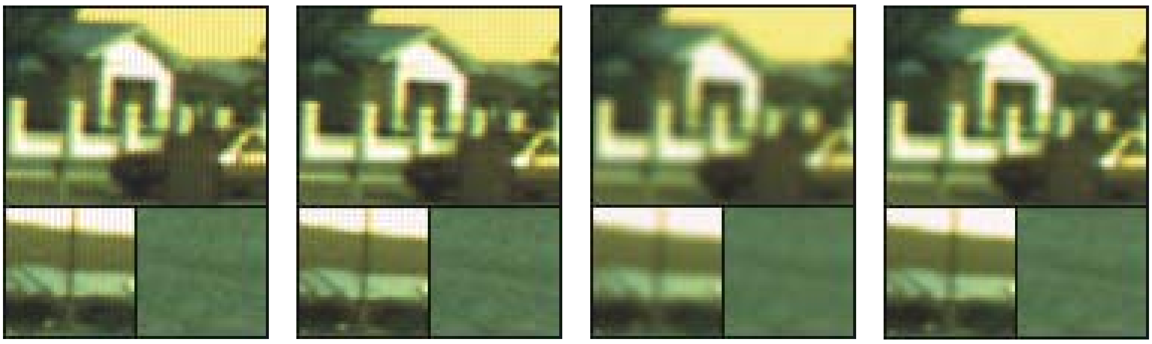


Figure 4: Image reconstruction with various filters. From left, IFC Bayer filter, proposed filter σ_r= 0.1, σ_g= 0.1, σ_b= 0.1, proposed filter σ_r= 2.0, σ_g= 2.0, σ_b= 2.0, proposed filter σ_r= 0.5, σ_g= 1.0, σ_b= 0.5

To evaluate the effect of the proposed filter on stereo measurement accuracy a series of measurements were performed on imagery captured in an underwater environment. The stereo camera system was deployed underwater, and footage of a known test object was captured. On the test object three distances were identified for measurement: one distance between vertical edges, one distance between horizontal edges, and one distance between two well defined dots. Measurements between vertical and horizontal edges were chosen specifically because of the poor horizontal edge definition seen in images recovered with the IFC Bayer filter. Such measurements serve to highlight any benefits of the proposed Bayer filter. The test object and measured distances are shown in figure 5.

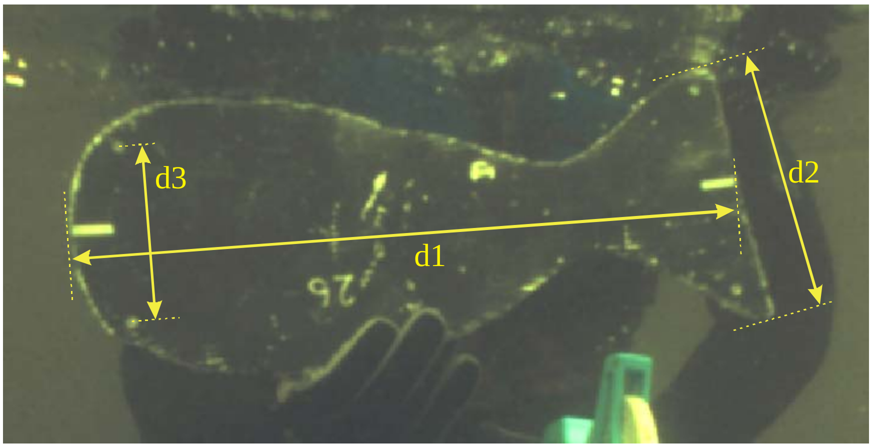


Figure 5: Test object for underwater measurement validation showing dimensions measured

Footage of the test object was captured at two different object distances from the camera system. At each object distance, 10 stereo pairs were captured in Bayer format. The 10 stereo pairs make up a movie sequence recorded at approximately 10 frames/second. The imagery was then converted to colour format using the IFC Bayer filter and the proposed Bayer filter (σ_r= 0.5, σ_g= 1.0, σ_b= 0.5). Distances d1, d2 and d3 were then manually measured for both sets of imagery at both object distances. At each object distance and for each Bayer filter the mean, range and standard deviation of the sets of distance measurements were computed. Results are summarised in tables 1 and 2.

Measured Distance	IFC Bayer filter			Proposed Bayer filter		
	Mean Error	Range	SD	Mean Error	Range	SD
d1 (455)	-0.5	4.6	1.8	-0.2	4.9	1.8
d2 (180)	0.6	4.5	1.3	-0.1	4.0	1.4
d3 (113)	-0.6	2.6	0.7	-0.3	1.6	0.6

Table 1: Summary of 10 distance measurements with test object 1100mm from the stereo camera system (all values in millimetres)

Measured Distance	IFC Bayer filter			Proposed Bayer filter		
	Mean Error	Range	SD	Mean Error	Range	SD
d1 (455)	-1.3	4.2	1.6	-0.5	2.6	1.1
d2 (180)	1.3	30.0	11.4	0.0	7.0	2.6
d3 (113)	-1.4	8.0	3.2	0.0	1.8	0.7

Table 2: Summary of 10 distance measurements with test object 2600mm from the stereo camera system (all values in millimetres)

With the test object at a distance of 1100mm from the stereo camera system there is little difference between the distance measurements obtained from imagery derived using the IFC Bayer filter compared with the proposed Bayer filter, although the average error is improved for the proposed Bayer filter. At an object distance of 2600mm the proposed Bayer filter significantly out-performs the IFC Bayer filter, especially on the distance d2, measured between two horizontal edges. Although the means of the IFC Bayer filter distances are still close to the true values, the range and standard deviation of the distances increases significantly in comparison to the proposed Bayer filter. Again, this is particularly noticeable in distances measured between substantially horizontal edges.

This result is significant when the system is used to measure large fish, such as Southern Bluefin Tuna[13] in a dynamic environment such as transfers between aquaculture cages. Estimation of the biomass of SBT requires measurement of both body length and depth to optimise the known correlation between fish size and weight, therefore requiring measurement of both horizontal and vertical edges of the silhouette. In addition, it is usually possible to measure these rapidly swimming fish no more than twice as they passes through the field of view of the stereo-cameras. The opportunity to increase distance accuracy by averaging over 10 consecutive frames is not possible and in this case the proposed Bayer filter offers a significant measurement performance increase.

5. DISCUSSION AND CONCLUSIONS

The proposed demosaicing algorithm based on Gaussian filters was shown to provide better performance than the commercially available IFC Bayer filter. Performance was judged in two key areas: improvement in the quality of stereo measurements made from the demosaiced images, and reduction of image artefacts.

The proposed filter works effectively in the presented case where there is a problem with banding in the green channel of the unconverted Bayer image. This issue is effectively dealt with by allowing independent tuning of the filter in each image channel. This allows the red and blue channels to be lightly smoothed and retain detail while the green channel is more aggressively smoothed to remove the artefacts introduced to the demosaiced image by banding in the original Bayer image.

The only disadvantage of the proposed filter is that it takes approximately 1.5 times longer to execute than the IFC Bayer filter. Without working knowledge of the IFC Bayer filter algorithm, it is assumed that the proposed filter is slower because it uses a larger window to interpolate values at each pixel position.

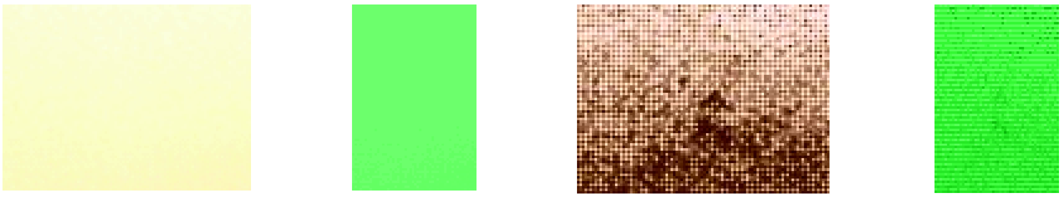
The perceived sharpness of edges and reduction of artefacts within the images was used to visually choose the optimum settings for the proposed filter. This method produced a significant improvement in stereo measurement accuracy. However, it would be informative to repeat the stereo measurement experiment using various different settings of the proposed filter, and then choose the optimum filter settings based on the accuracy and repeatability of the stereo measurements.

6. POSTSCRIPT

Subsequent to the conclusion of this research, a number of technical problems were identified with the hardware. The source of the essential problem was isolated to one of the fibre optic modem pairs, which were transmitting a degraded LVDS signal despite satisfactory self-testing at start-up. During the investigations to isolate the problem, significant power and data signal losses were measured between the computer and the cameras over the copper and fibre optic cables, and across the marine grade connectors that link the different segments of the cables.

As a part of this investigation, one camera was connected over a standard 10m copper LVDS connector to check signal loss and evaluate the imagery. A section of uniform background from a captured image is shown in figure 6. The full colour image was demosaiced using the IFC Bayer filter. Also shown is the green band of the sub-image from the same area, prior to demosaicing. In comparison, figure 6 also shows similar sub-images from the system with the full set of copper and fibre optic cables plus the connectors. All sub-images have been subjected to a histogram equalisation to emphasize the detail.

The impact of the additional cable length and connectors on image quality is clearly evident in this comparison. The full colour image and the green band show image artefacts whereas the equivalent sub-images transmitted over the 10m LVDS cable are free of the artefacts. Comparison of the red and blue bands showed no significant artefacts or additional noise.



Full colour Green band Full colour Green band
10m copper LVDS cable Full cable and connector set

Figure 6: Comparison of demosaiced full colour and raw Bayer green band sub-images of uniform areas from frames captured using a 10m LVDS cable and the full cable and connector set.

It is apparent from these images that the demosaicing based on the Gaussian filters is compensating more effectively for the image degradation induced by the signal losses. However removing or minimising the signal losses would substantially improve the image quality and further investigation of these affects will be undertaken in the future.

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