REFINING A BAYER FILTER TO IMPROVE PHOTOGRAMMETRIC MEASUREMENT QUALITY AND REDUCE IMAGE ARTEFACTS

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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.

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 (Hubel et al. 2004). 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.

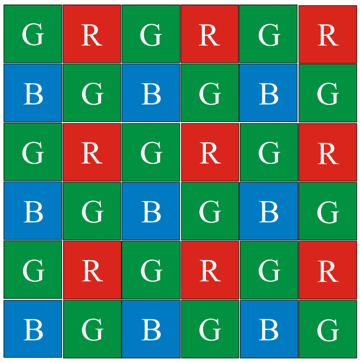

Figure 1: Bayer Colour Filter Pattern

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 (Go et al. 2000). 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 (Lukac et al. 2003, Hubel et al. 2004).

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 (Go et al. 2000, Malvar et al. 2004). 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 (Cai et al. 2001), methods that adapt to local image edge directions (Adams 1995, Kimmel 1999, Lukac et al 2003, Lukac et al. 2004), and data dependant triangulations (Su and Willis 2003). In general, bilinear interpolation has been favoured because it is simple, fast and robust (Cai et al. 2001).

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.

Camera system

The Bayer filter reported in this paper was specifically developed to improved 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 (Harvey and Shortis 1995, 1998). Typical accuracy of fish measurement is better than 1% of the overall fish length.

Images from the CVM7+ cameras are transmitted to the surface computer in Bayer format. The surface 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 Imaging Technology Incorporated's 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').

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 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 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 (Gunturk et al 2002).

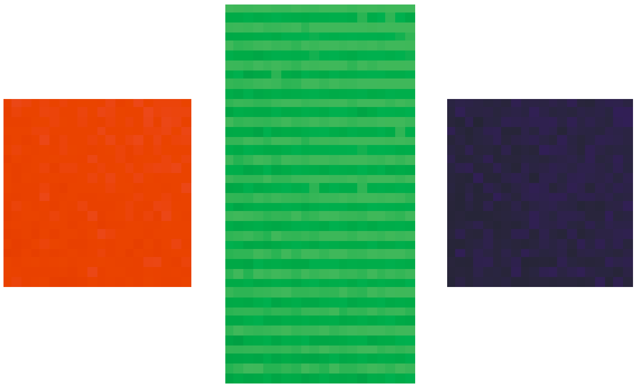

Figure 2: Raw Bayer image data of a constant background showing variation (banding) in the green data

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 preserved 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:

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

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 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 $\alpha_r, \alpha_g, \alpha_b$ and $\sigma_r, \sigma_g, \sigma_b$ 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:

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

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

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

where:

$$r_0 = f(1,\sigma_r) \qquad r_1 = f(\sqrt{5},\sigma_r)$$

$$g_0 = f(0,\sigma_g) \qquad g_1 = f(\sqrt{2},\sigma_g) \qquad g_2 = f(2,\sigma_g) \qquad g_3 = f(\sqrt{8},\sigma_g)$$

$$b_0 = f(1,\sigma_b) \qquad b_1 = f(\sqrt{5},\sigma_b)$$

$$r_{norm}^{-1} = 2r_0 + 4r_1 \qquad g_{norm}^{-1} = g_0 + 4g_1 + 4g_2 + 4g_3 \qquad b_{norm}^{-1} = 2b_0 + 4b_1$$

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 the same 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.

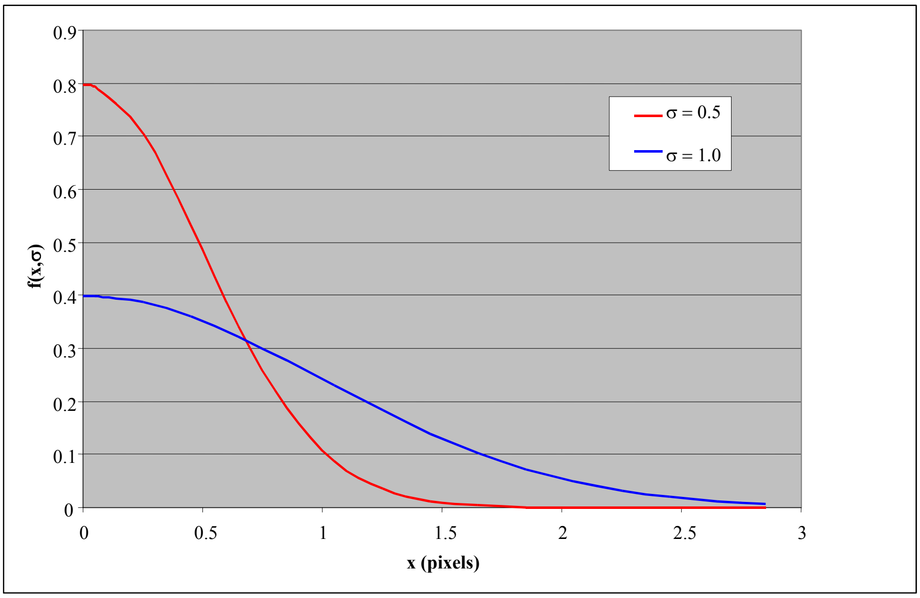

Figure 3: Filter curves generated with equation (1)

For efficiency, all filter parameter are precomputed 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 filter speed.

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 $\sigma_r = 0.1$, $\sigma_g = 0.1$, $\sigma_b = 0.1$ 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 $\sigma_r = 2.0$, $\sigma_g = 2.0$, $\sigma_b = 2.0$. This setting removes all artefacts, but results in an image that is over-smoothed. The right hand image was generated with filter settings $\sigma_r = 0.5$, $\sigma_g = 1.0$, $\sigma_b = 0.5$, making an attempt to smooth the green channel more than the red and blue. These settings provide a reasonable trade off between removing the artefacts and over smoothing image detail, and were adopted for the following stereo measurement tests.

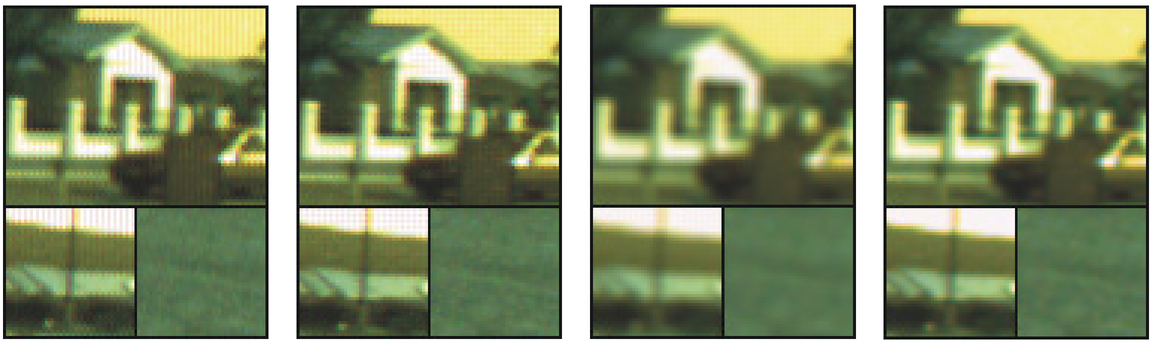

Figure 4: Image reconstruction with various filters. From left, IFC Bayer filter, proposed filter $\sigma_r = 0.1, \sigma_g = 0.1, \sigma_b = 0.1$, proposed filter $\sigma_r = 2.0, \sigma_g = 2.0, \sigma_b = 2.0$, proposed filter $\sigma_r = 0.5, \sigma_g = 1.0, \sigma_b = 0.5$

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.

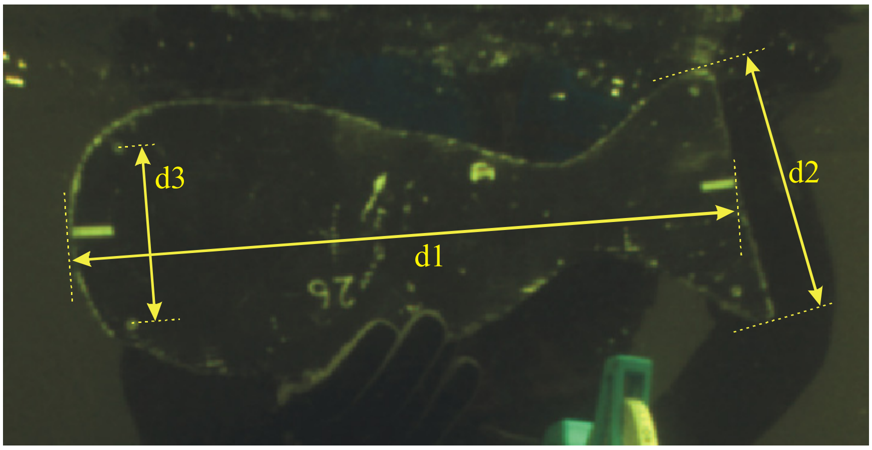

Figure 5: Test object for underwater measurement validation showing dimensions measured

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 ($\sigma_r = 0.5, \sigma_g = 1.0, \sigma_b = 0.5$). 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.

	IFC Bayer filter			Proposed Bayer filter			True
Distance	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Distance**
d1	454.5	4.6	1.8	454.8	4.9	1.8	455
d2	180.6	4.5	1.3	179.9	4.0	1.4	180
d3	112.4	2.6	0.7	112.7	1.6	0.6	113

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

	IFC Bayer filter			Proposed Bayer filter			True
Distance	Mean	Range	SD	Mean	Range	SD	Distance
d1	453.7	4.2	1.6	454.5	2.6	1.1	455
d2	181.3	30.0	11.4	180.0	7.0	2.6	180
d3	111.6	8.0	3.2	113.0	1.8	0.7	113

Table 2: Summary of distances measured 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 distance measurements obtained from imagery derived using the IFC Bayer filter compared with the proposed Bayer filter. Mean distances compare equally well with the true distances, and ranges and standard deviations are near to identical. At an object distance of 2600mm the proposed Bayer filter significantly outperforms 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 are measured between substantially horizontal edges. This result is significant when the system is used to measure fish in a dynamic environment since it is usually possible to measure each fish only once, or twice at best. The opportunity to increase distance accuracy by averaging over 10 consecutive frames does not exist. In this case the proposed Bayer filter offers a significant measurement performance increase.

Discussion

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: reduction of image artefacts, and improvement in the quality of stereo measurements made from the demosaiced images.

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 interesting 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.

Acknowledgements

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