LOW COMPLEXITY IMAGE FUSION IN BAYER DOMAIN USING A MONOCHROME SENSOR AND BAYER SENSOR

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ABSTRACT

Mobile cameras have come a long way since their evolution and have replaced digital still cameras. However, their low-light photography performance needs significant improvement. Dual camera systems consisting of a monochrome sensor and a Bayer sensor offer us a way to improve the low-light photography. The existing dual camera systems use post-processing methods after Image Signal Processor (ISP) for image fusion which are computationally intensive and use two ISPs. We propose a novel architecture in which the image fusion can be done in Bayer domain prior to the ISP. This helps us realize image fusion using only one ISP and also reduces power consumption, making it a viable solution for smart phones. The proposed system also gives better quality images than existing systems.

***Index Terms*—** Dual sensor system, Bayer image fusion, Low light photography

1. INTRODUCTION

Camera is one of the key USPs of modern smartphones. Most of the high-end smartphones have cameras which are comparable to DSLRs in day-light scenarios. However smartphones have a physical limit on the size of sensors and hence have a large number of pixels in a small area. So their low-light photography is significantly inferior compared to DSLRs which have huge sensors. This has led to the advent of dual-sensor camera configurations which can tackle the issue of low-light photography.

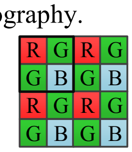


Fig. 1. Bayer Sensor (RGGB)

One of the popular configurations is to use a monochrome sensor and a Bayer sensor [1]. Bayer sensor has primary color filters on each pixel. One such pattern RGGB is shown in Fig. 1. Since there are no color filters, the monochrome sensor captures about 3x light and produces better contrast for crisper images. Using these two sensors and a combination of hardware/software techniques, we can generate a final image that has more detail than that would be possible using a single sensor, especially in low-light conditions.

The conventional method of image fusion [2] happens after pre-processing and ISP as shown in Fig. 2. Image fusion may consist of color domain transform, feature extraction, image registration and various means to combine two or more images. Bayer image of resolution $W\ x\ H$ processed through ISP produces image data of $3\ x\ W\ x\ H$ as it will have all three colors for each pixel.

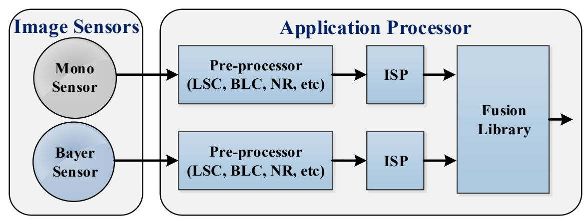


Fig. 2. Conventional dual sensor system

The disadvantage with conventional approach is that image registration, warping, fusion related operations in fusion library happen for all 3 channels (RGB/YUV). Another drawback is that it makes use of two ISPs. Limitation also comes from image processing blocks like white balance which affect the fused output as these operations cannot be done on single channel mono sensor data.

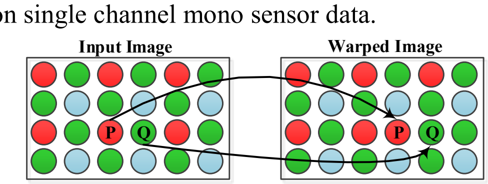


Fig. 3. Warping problem in Bayer image

We can overcome these limitations if we perform the image fusion in Bayer domain. However this method presents two major challenges.

1) It is not possible to do warping of Bayer image while retaining Bayer pattern. For example, Image registration might result in a warping matrix which changes location of pixel P and Q from (x, y) to (x+1, y) as shown in Fig. 3. In such case, warped image loses its Bayer pattern and demosaicing process [3] will generate artifacts.

2) In case of conventional system, once image registration is done, fusion involves replacement of Y

channel by mono sensor data. However extracting and fusing luma from mono sensor in Bayer image poses another challenge as it has no direct Y component which can be replaced or blended with mono sensor data.

We propose a novel architecture which overcomes these challenges and performs image fusion in Bayer domain. We introduce a new Bayer domain transformation which transforms Bayer quad to $YC_bC_rD_g$ quad. We also propose a method of splitting the monochrome signal into phase-aligned $Y_{G1}Y_{G2}Y_RY_B$ before the inverse Bayer domain transformation.

Rest of the paper is organized as follows. In Section 2, our proposed image fusion system is described. We explain the advantages of our system in Section 3. We demonstrate our experimental results in Section 4. Conclusion and future scope are given in Section 5.

2. PROPOSED SYSTEM

We propose to do image registration and image fusion in Bayer domain as shown in Fig. 4. This results in requirement of only one ISP, saving significant area and power.

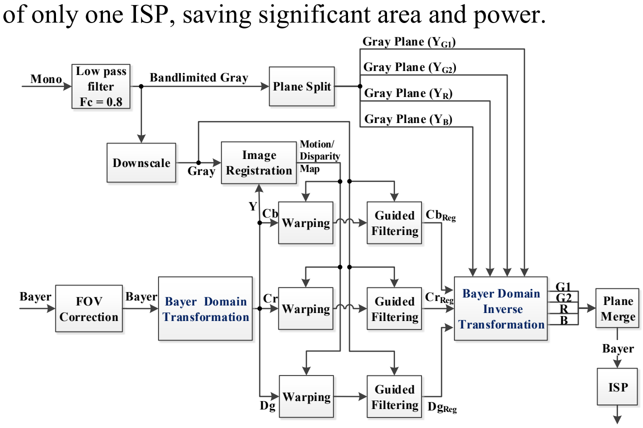


Fig. 4. Proposed dual camera system

Both the challenges explained above in case of Bayer domain image fusion can be addressed if Bayer image is transformed into a new domain. The transformed domain should be such that it allows image warping to be done without having any effect on original Bayer pattern when it is again inverse transformed. It should also allow merging mono sensor data on to one of the channels of transformed domain.

Existing Bayer domain transforms have limitations. Transform given in [4] generates 2 Y (luminance data), 1 C_b and 1 C_r data which is not suitable for doing fusion with mono sensor data as it has only 1 Y. Another transform given in [5] inspired from popular YC_oC_g doesn't extract true luma and chroma as its focus is on compression and not on image fusion.

We propose a novel Bayer domain transform $YC_bC_rD_g$ inspired from RGB domain transform YC_bC_r [6]. It transforms Bayer image into four channels, each of ¼th the original resolution. A quad of {R, G_1, G_2, B} generates one pixel for each of these four channels as shown in Fig. 5.

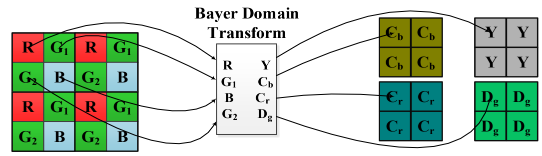


Fig. 5. Proposed Bayer domain transformation to map original Bayer quad into four channels {Y, Cb, Cr, Dg}, each of ¼th the original resolution

Bayer Domain Transformation:

$\mathbf{Y} = 0.299*\mathbf{R} + 0.2935*\mathbf{G_1} + 0.2935*\mathbf{G_2} + 0.114*\mathbf{B}$

$\mathbf{C_b} = - 0.169*\mathbf{R} - 0.1655*\mathbf{G_1} - 0.1655*\mathbf{G_2} + 0.5*\mathbf{B}$

$\mathbf{C_r} = 0.5*\mathbf{R} - 0.2095*\mathbf{G_1} - 0.2095*\mathbf{G_2} - 0.081*\mathbf{B}$

$\mathbf{D_g} = 0.5*\mathbf{G_1} -0.5*\mathbf{G_2}$

Image registration may involve steps like feature detection, feature matching, motion/disparity map estimation. One can choose from various algorithms available for image registration depending on the required image quality and complexity trade off. We have used optical flow with combined local-global (CLG) approach with total variation regularization [7].

As shown in Fig. 4, motion/disparity map is obtained from Y channel of transformed Bayer and luma channel of mono sensor. This map is used to perform image warping on Cb, Cr and Dg channels. As these three channels do not have any pattern like Bayer, warping poses no problems.

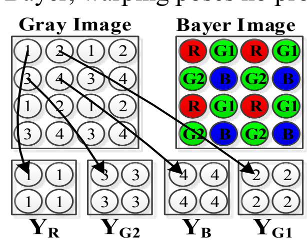


Fig. 6. Interleaving of Mono sensor data for dual sensors (Mono + Bayer) with same resolution

To improve the image registration of these warped images, guided filtering is performed on them using mono sensor's luma as a guide image. Bi-lateral filtering [8], guided filtering [9], fast global smoothing (FGS) [10] etc. are widely used guided filtering algorithms. Our final system uses FGS for guided filtering of warped C_b, C_r and D_g.

Fusion of mono sensor data into Bayer happens during proposed inverse Bayer domain transformation. We propose a method of splitting the monochrome signal into phase-aligned {Y_{G1}, Y_{G2}, Y_R, Y_B} as shown in Fig. 6.

Proposed Bayer domain inverse transformation transforms these phase aligned channels along with warped/filtered Cb, Cr and Dg into Bayer image as shown in Fig. 7. If we use downscaled mono for inverse transform, the fused output image would not be sharp as shown in Fig. 8 (a). So we use phase-aligned mono for inverse transform to get sharper images as shown in Fig. 8 (b). Fused Bayer image can then be processed using conventional ISP to get RGB/YUV image.

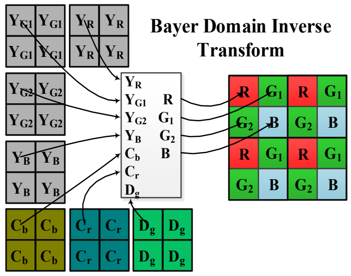


Fig. 7. Proposed Bayer domain inverse transformation

Bayer Domain Inverse Transformation:

$\mathbf{R} = \mathbf{Y_R} + 1.4*\mathbf{C_r}$

$\mathbf{G_1} = \mathbf{Y_{G1}} - 0.343*\mathbf{C_b} - 0.711*\mathbf{C_r} + \mathbf{D_g}$

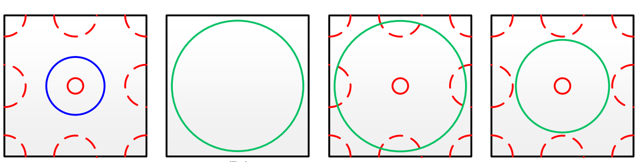
$\mathbf{G_2} = \mathbf{Y_{G2}} - 0.343*\mathbf{C_b} - 0.711*\mathbf{C_r} - \mathbf{D_g}$

$\mathbf{B} = \mathbf{Y_B} + 1.765*\mathbf{C_b}$

(a) (b)

Fig. 8. Effect of phase-aligned splitting of mono (a) Fusion with downscaled mono (b) Fusion with phase-aligned mono

If we use the mono-sensor image directly for image fusion, it may result in chroma aliasing as shown in Fig. 10 (b). The cause for this artifact can be understood by the analysis of 2D-Fourier Transform of these images. Fig. 9 shows idealized frequency spectrum of Bayer, mono and fused image. In each figure {(a), (b), (c), (d)}, both axes span [-π, π), DC is located at the center of figure. Red line corresponds to chrominance of image while blue/green corresponds to luminance of image. If mono image is fused directly into Bayer with proposed Bayer domain transformation, it may create aliasing [11] in chrominance spectra as shown in Fig. 9 (c). To tackle this problem, mono image is passed through a very high frequency cut-off (Fc=0.8) low pass filter (LPF). Fig. 9 (d) shows spectra of fused Bayer image which uses low pass filtered mono image. If we pass the mono image through a high frequency cutoff LPF and then use it for image fusion, the fused image does not exhibit any color aliasing artifacts as shown in Fig. 10 (c).



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

Fig. 9. Idealized frequency spectrum of images from 2D-FFT of (a) Bayer image (b) mono image (c) fused image without low pass filtering of mono image (d) fused image with low pass filtering of mono image.

If one uses single lens dual sensor camera [12] then image registration, warping and guided filtering are not required. This kind of dual sensor camera inherently gives aligned images and our Bayer domain transform can be used directly to perform Bayer domain image fusion.

(a) (b) (c)

Fig. 10. Chroma aliasing (all are ISP processed) (a) Bayer input image (b) Fused image without low pass filtering of mono image (c) fused image with low pass filtering of mono image

Field of View (FOV) correction and downscale are optional blocks required based on dual camera sensor resolutions.

3. ADVANTAGES OF PROPOSED SYSTEM OVER CONVENTIONAL SYSTEM

As image registration, warping, guided filtering and fusion are happening in Bayer domain, it requires only one ISP as compared to requirement of two ISPs in conventional system.

The proposed system also reduces required computations. If the width of both mono and Bayer sensor is W and height is H then RGB to YUV color transform for conventional system will have three channels of resolution $W\ x\ H$ while Bayer to $YC_bC_rD_g$ color transform for proposed system (Fig. 5) will have four channels of resolution $\frac{W}{2}\ x\ \frac{H}{2}$. In both systems, processing blocks like feature detection, feature matching, motion/disparity map generation etc. are applied to only one channel (Y channel). Warping and guided filtering are performed on two channels (C_b and C_r) in conventional system whereas on three channels (C_b, C_r and D_g) in proposed system. Table 1 shows the total pixel operations required by both systems. Based on it, we can observe that the proposed system reduces required computations in fusion library by **~66.67%** compared to conventional system.

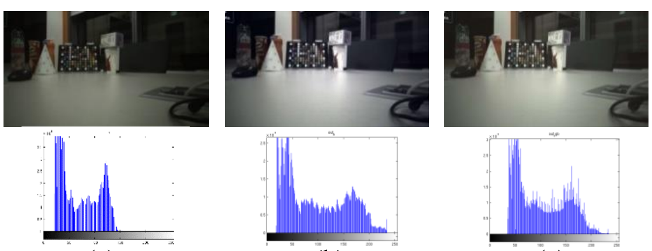
Table 1. Pixel operation requirement in both system

	Pixel operation required	
	Conventional System	**Proposed System**
Feature Detection & Matching, Motion map generation etc.	$W\ x\ H$	$\frac{W\ x\ H}{4}$
Warping & guided filtering	$2\ x\ W\ x\ H$	$(3\ x \frac{W\ x\ H}{4})$
Total	$\mathbf{3\ x\ W\ x\ H}$	$\mathbf{W\ x\ H}$

Some of the ISP processing blocks are not channel independent i.e. processing being done on R channel is dependent on G and/or B channel. Processing done by these blocks in conventional system becomes undone when image fusion happens i.e. Y channel is replaced by mono sensor data. One such processing block is white balance. Gains for white balance are derived using all 3 channel data. Once luma is replaced during fusion, these gains are no longer correct. Due to this reason, our proposed system generated better quality images than conventional system. To achieve similar quality image using conventional system, we need to perform white balance operation again. This would require significant extra computations, additional hardware resources and would lead to additional power consumption.

4. EXPERIMENTAL RESULTS

Our experimental dual camera setup has 16 MP mono and 3.7 MP Bayer sensor with different FOV and 9 mm of baseline. Fig. 11 shows the result for a test image. Each image is presented with its histogram to evaluate effect of image fusion. Fig. 12 shows zoomed-in images of test image and result. Upper left part of input image is dark with not clear details which are enhanced by image fusion with mono sensor data. We have shown lower resolution images in Fig. 11 for illustrative purpose. The visual quality difference is best observed at higher resolutions. Results have been verified and holds true for various test images which includes depth variation of objects from camera, big/small check box pattern, objects of different size and colors.



(a) (b) (c)

Fig. 11. Experimental Results for test image with its histogram. (a) ISP processed Bayer sensor image, (b) Proposed system output, (c) Conventional system output

Our software ISP is modeled using demosaicing, white balance, gamma correction & color correction processing blocks. Fused images clearly show contrast and brightness improvement over single Bayer sensor images processed through our model ISP.

The histograms also validate our proposition that fused image from proposed system is having better contrast than the conventional system given no additional post processing is done in conventional system after image fusion. For the conventional system, the white-balance operation performed in ISP loses its effect after the fusion and results in a poor quality image as explained in Section 3. This can be clearly observed in Fig. 11 and Fig. 12.

Power measurement of Samsung Galaxy S6 device for rear camera shows that single ISP consumes 0.24 W while total power consumption of S6 device at that time is 2.72 W.

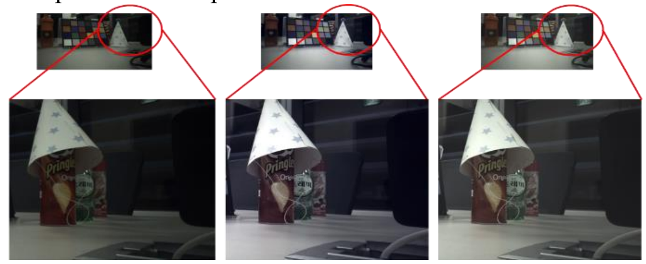


Fig. 12. Test image set (a) ISP processed Bayer sensor image, (b) Proposed system output, (c) Conventional system output

As conventional system uses two ISPs simultaneously and proposed system uses single ISP, Table 2 shows comparison of power consumption estimate for both the systems. This data shows that using our approach one can achieve **~8.8% power saving** in total power consumption of dual camera device while camera is being used.

Table 2. Power consumption comparison

Galaxy S6 device	Conventional system	Proposed system
Power consumed by ISPs	0.48 W	0.24 W
Total power consumed	2.96 W	2.72W

5. CONCLUSION

A low complexity image fusion system in Bayer domain using a monochrome and Bayer sensor is presented. We have used a novel Bayer domain transform for performing the image fusion. Proposed system requires only one ISP and is computationally less intensive which reduces the hardware resources significantly and still gives better quality fused images. **Our analysis shows that proposed system reduces device power by ~8.8%. It also reduces required computations in fusion library by ~66.67% which translates into additional power savings. (On top of ISP power savings of ~8.8%).**

As future work, we will work on quantitative comparison of image quality of the proposed method against existing methods. We will also make an effort to further enhance the image quality by studying the impact of better image registration algorithms. We will also work on quantitative analysis of the reduction in power consumption and execution time due to the reduced computations in the fusion library of the proposed system.

We believe that our system makes improved low light photography more accessible on smart phones as mobile devices are always constrained by battery power and our system significantly reduces hardware resources and power consumption. This translates into increased Days of Usage for the user. Also it makes this improved photography accessible to low-tier and mid-tier smart phones which have only one ISP in their SOC.

6. REFERENCES

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