High Dynamic Range image capturing by Spatial Varying Exposed Color Filter Array with specific Demosaicking Algorithm

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Abstract

High Dynamic Range (HDR) imaging is a future trend for digital imaging. With excessive spatial resolution in digital cameras nowadays, plenty of spaces remain in the dynamic domain to enhance the image quality. In order to produce HDR image using conventional devices, multiple captures with different exposure settings are performed and combined. However, multiple exposure systems requires static photo scene. In this paper, a Spatial Varying Exposure (SVE) system is proposed. By altering the exposure settings in spatial domain, it is possible to capture HDR image from instantaneous scene by trading-off spatial resolution. Moreover, a specific demosaicking algorithm is designed to conceal the color pixels assigned to different exposure fields.

1. Introduction

Digital imaging is an essential part of multimedia applications. In the technology of digital image capturing, spatial resolution and color bit-depth remains the main criterion of image quality. Recent consumer-level digital cameras offer 1000 mega-pixel and 24 bits RGB color depth. This is more than enough for most photography applications such as displaying on PC monitors and printing in 3R size.

Dynamic Range is a different angle to improve the visual quality of the captured image. Photo scenes to be captured may have high variety in luminance. As a result, some regions in the captured picture become over-exposed or under-exposed. Pixels with intensity higher than the maximum or lower than the minimum in the dynamic range of the digital camera will be truncated to the maximum or minimum values instead. This effect is shown in Fig. 1.

Figure 1. Over-exposure (left) and Under-exposure (right)

High Dynamic Range (HDR) Imaging is a research topic to extend the captured dynamic range of digital devices. There are several ways to achieve this. Without requiring higher-ended sensors, the simplest way to achieve high dynamic range is to combine multiple images captured in different exposure settings. A method to combine multiple exposure images into HDR image is proposed in [1]. This method achieves good results by applying least mean square algorithm to evaluate the real scene radiance values.

Multiple exposure images of a photo scene can be taken independently. As higher precision pixel value is produced by pixel-wise calculations, static image scene and fixed camera position are required. Thus, this is not efficient to be used in mobile capture devices such as digital cameras and mobile phone cameras. To improve the mobility of HDR imaging, Spatial Varying Exposure (SVE) is proposed [2]. By trading off spatial resolution, multiple-exposure is achieved in single shuttering.

In this paper, a HDR capturing system is introduced. A SVE array based on Bayer Color Filter Array [3] is proposed in Section 2. In Section 3, a specific demosaicking algorithm for the SVE array is explained. In Section 4, results of the system are given. Finally a conclusion is given in Section 5.

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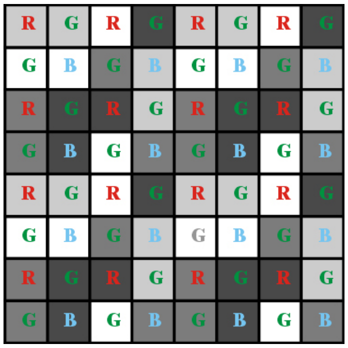

Figure 2. SVE Color Filter array [2]

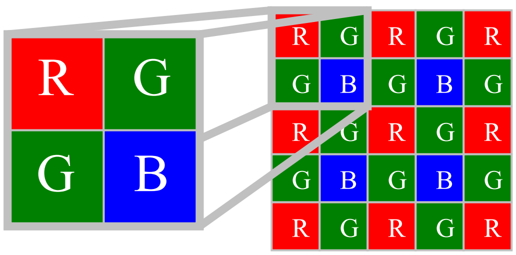

Figure 3. Bayer color filter array

2. Spatial Varying Exposure Array

Spatial Varying Exposure (SVE) in color filter array is suggested in [2]. By assigning pixels to different exposure settings, wider dynamic range can be covered. In CMOS sensors, SVE can be archived by controlling the exposure time of individual pixels. By doing so, the exposure time difference can be tuned as an additional photo setting. For CCD sensors, however, the circuits of individual pixels cannot be modified separately. Thus, the only way to achieve SVE is to use filters of different opacity for different exposure planes. In this case, the exposure difference is fixed for CCD cameras.

An example SVE array with four exposure plane as suggested in [2] is shown in Fig. 2. By combining information from different exposure planes, a high-dynamic range image is produced. The SVE method increases the captured dynamic range by trading off spatial resolution. This requires that the multiple exposure pictures are identical in capture time and camera position. Therefore, using SVE to capture HDR image is more suitable for mobile device and moving photo scenes. However, some pixels in the SVE sensor surface is used for different exposures, some spatial information is lost leading to blurring and false color at edge positions.

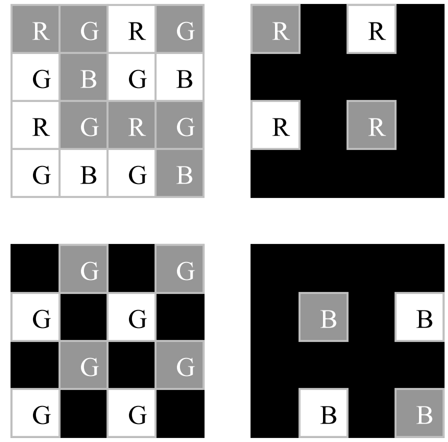

Figure 4. Proposed SVE Array and the three color planes

In our proposed HDR capturing system, a new SVE array is designed based on the Bayer Color Filter Array [3]. Conventional digital cameras nowadays use Bayer array to capture different color components as shown in Fig. 3. On the Bayer filtered image sensors, a new SVE color filter array is implemented by adjusting the exposure time of CMOS sensors or adding alpha filters on top of the sensors. Therefore, the proposed system is cost effective as it requires least modification to the current digital capture devices.

The Bayer color filter array is a 2x2 color filter pattern consisting of 1 red, 1 blue and 2 green pixel. This pattern repeats throughout the capturing surface as shown in Fig. 3. In the proposed system, the color pixels in the Bayer pattern are divided into two exposure fields. The exposure fields are distributed evenly in each color channels. This gives a repeating 4x4 pattern as shown in Fig. 4. In the Red and Blue color planes, the distance between two effective pixels in each exposure plane is 3 pixels. For the Green color plane, there is unit distance between two effective pixels. Therefore, the green color plane is used as a luminance reference to reconstruct the two exposure images. Detailed operation is explained in the next section.

In this SVE array, there exist available pixels in every column and every row for each exposure fields. Knowing that horizontal and vertical edges are least robust to color aliasing, this design can preserve color information in every horizontal and vertical edge to prevent false color. As a result, the loss in spatial resolution is minimized.

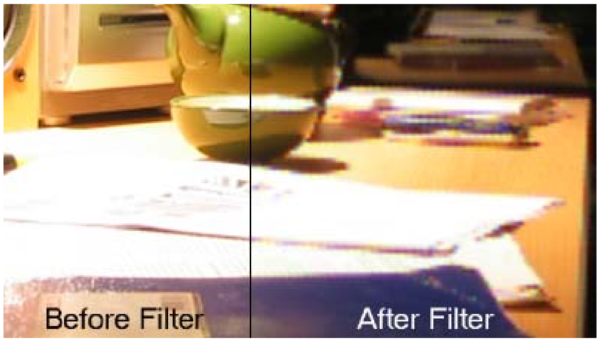

Figure 5. False Color effect in edges

3. Demosaicking

Demosaicking is a research topic to reconstruct lost spatial information in images captured by color filter arrays. In the conventional Bayer Filter array, each sensor pixel captures one single color component as shown in Fig 3. To reconstruct the missing color information, the simplest way is to perform bilinear interpolation. However, this may lead to blurring and false color in edge positions. It is shown in Figure 5. Several algorithms are proposed to solve this problem. Among these algorithms, the Primary-Consistent Soft-Decision [4] and the Direction Categorization [5] method gives good results in concealing the color information to reduce color aliasing.

In our proposed SVE array, as shown in Fig 4, the effective pixels for each exposure plane are halved camparing to the Bayer array. As a result, the demosaicking algorithms for standard Bayer array are not applicable. Therefore, a specific demosaicking algorithm is designed. With less information available, it is necessary to design a reconstruction function for each color pixel locations. In each exposure plane, two intermediate images H and V are constructed by manipulating the horizontal and vertical neighboring pixels. By doing so, the horizontal and vertical edges can be preserved in corresponding intermediate images. After that, the two intermediate images are combined by identifying the direction characteristics of each pixel. Detailed operation is explained follow.

3.1. Green component reconstruction

In the proposed SVE array, the Green channel has shortest distance between neighboring effective pixels in each exposure plane. Therefore, the Green channel is reconstructed first as it contains least unknown locations to be filled.

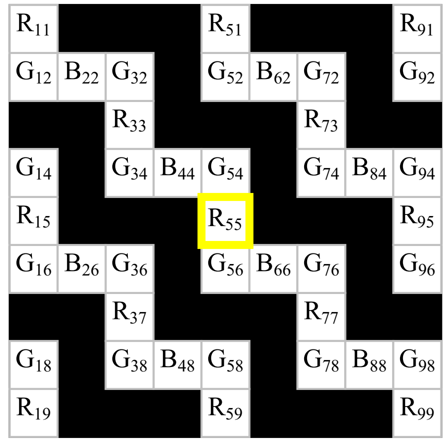

Figure 6. Location of red pixel in same exposure plane

In Blue and Red pixel positions, the regional color difference is calculated to reconstruct the missing Green component value. Taking the Red pixel positions as an example, the Reconstructed G_{55} is located at the R_{55} positions as shown in Fig. 6.

For the vertical intermediate value G_{55V}, the function is simply interpolation as shown in (1).

$$G_{55V} = \frac{G_{54} + G_{56}}{2} \tag{1}$$

For the horizontal intermediate value G_{55H}, it is necessary to consider the situation of horizontal edges. So, the luminance information is highly dependent on the only available R_{55} value in the specific row. The median color differences between Green and Red channel are calculated. For Red positions in same exposure plane, R_{53} and R_{57} are not present. So, interpolated values (2) are used instead.

$$\begin{aligned} \hat{R}_{53H} &= \frac{R_{33} + R_{73}}{2} \\ \hat{R}_{57H} &= \frac{R_{37} + R_{77}}{2} \end{aligned} \tag{2}$$

The color differences between the Green and Red color planes for the upper and lower regions are calculated by (3).

$$\begin{aligned} Diff_{UP} &= median\left(G_{52}, G_{54}, G_{56}\right) - \hat{R}_{53H} \\ Diff_{DOWN} &= median\left(G_{54}, G_{56}, G_{58}\right) - \hat{R}_{57H} \end{aligned} \tag{3}$$

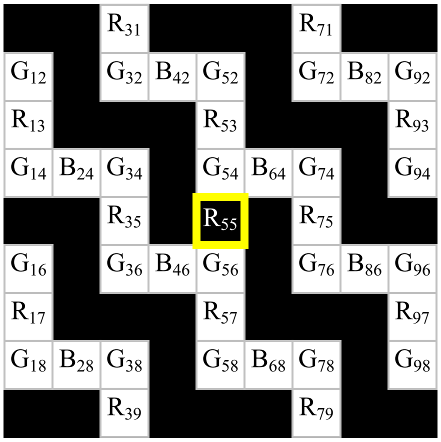

Figure 7. Location of red pixel in different exposure plane

Weighting factors are calculated in (4) by measuring the similarity of the current pixel and the neighboring pixels in the upper and lower region.

$$\begin{aligned} w_{UP} &= \left|\hat{R}_{57H} - R_{55}\right| \\ w_{DOWN} &= \left|\hat{R}_{53H} - R_{55}\right| \end{aligned} \tag{4}$$

The reconstructed G_{55H} value is given by (5)

$$G_{55H} = \frac{Diff_{UP} \times w_{UP} + Diff_{DOWN} \times w_{DOWN}}{w_{UP} + w_{DOWN}} + R_{55} \tag{5}$$

For Red positions of different exposure plane, as shown in Fig. 7, R_{55} is not present. Interpolated value (6) is used instead.

$$\hat{R}_{55H} = \frac{R_{35} + R_{75}}{2} \tag{6}$$

To reconstruct Green component at Blue positions, similar operation is performed. The only difference is that the horizontal and vertical directions are reversed. After that Green component in Green position of different exposure plane is calculated in (7).

$$\begin{aligned} G_{55V} &= \frac{G_{54V} + G_{56V}}{2} \\ G_{55H} &= \frac{G_{45H} + G_{65H}}{2} \end{aligned} \tag{7}$$

Finally, fully populated Green color plane is available for reference by the other two color planes.

3.2. Red & Blue component reconstruction

For Red and Blue components, the reconstruction operations are much simpler. This is done by weighted interpolation of the color difference between the Red or Blue components with the Green components. Taking the Red components as an example, Red position of different exposure plane as shown in Fig. 7 is first processed. To reconstruct the R_{55H} value, two weighting factors are calculated as shown in (8).

$$\begin{aligned} w_1 &= \left|G_{35} - G_{55}\right| \\ w_2 &= \left|G_{75} - G_{55}\right| \end{aligned} \tag{8}$$

The reconstructed R_{55H} value is given by (9).

$$R_{55} = \frac{(R_{75} - G_{75}) \times w_1 + (R_{35} - G_{35}) \times w_2}{w_1 + w_2} + G_{55} \tag{9}$$

The operation for R_{55V} is similar with reversed vertical and horizontal directions. For other positions of the Red and Blue planes, similar operations are performed by weighted interpolation of the closest neighboring pixels in the target direction. Finally, the Green and Blue color planes of the two intermediate images are fully filled.

3.3. Direction Categorization

The final step is to categorize each pixel location by their directionality. This is done by the Direction Categorization method proposed in [5]. Gradients in horizontal and vertical directions are calculated by (10).

$$\begin{aligned} Grad_V &= \left|R_{53} - R_{55}\right| + \left|G_{54} - G_{56}\right| + \left|R_{55} - R_{57}\right| \\ Grad_H &= \left|R_{35} - R_{55}\right| + \left|G_{45} - G_{65}\right| + \left|R_{55} - R_{75}\right| \end{aligned} \tag{10}$$

The pixel locations are categorized to vertical, horizontal or smooth by comparing the two gradients calculated in (10). Further refinements can be performed to ensure consistence of the directions along edges. Detailed operations can be found in [5]. Finally, the resulting pixel values are mapped by (11).

$$R_{55} = \begin{cases} R_{55V} & ,Vertical \\ R_{55H} & ,Horizontal \\ \dfrac{R_{55V} + R_{55H}}{2} & ,Smooth \end{cases} \tag{11}$$

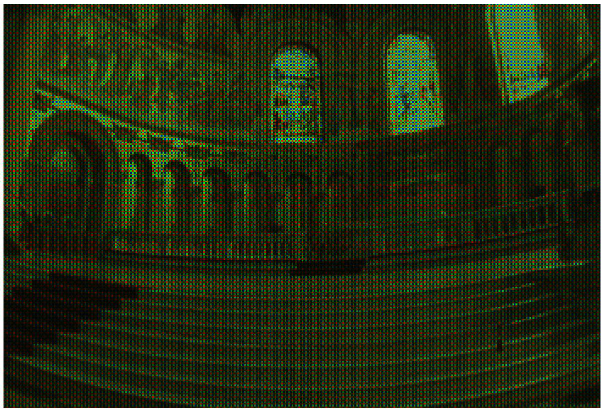

Figure 8. Pseudo-captured image segment of the *Memorial* Sequence

Figure 9. Pseudo-captured image segment of the *Room* Sequence

Figure 10. Demosaicked image segment of the *Memorial* Sequence by bilinear interpolation

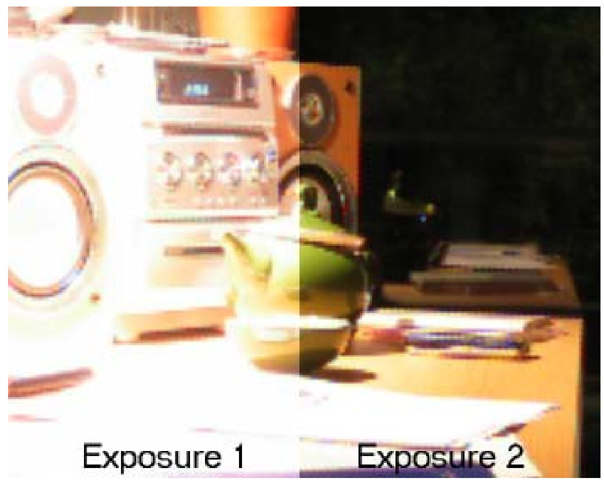

Figure 11. Demosaicked image segment of the *Room* Sequence by bilinear interpolation

Figure 12. Demosaicked image segment of the *Memorial* Sequence by the proposed method

Figure 13. Demosaicked image segment of the *Room* Sequence by the proposed method

Figure 14. Tone-mapped result of *Memorial*

Figure 15. Tone-mapped result of *Room*

Table 1. PSNR comparison of the demosaicked exposure images

	Proposed	Interpolation
Memorial exp1	30.71dB	29.62 dB
Memorial exp2	28.76 dB	27.62 dB
Room exp1	32.38 dB	29.62 dB
Room exp2	30.03 dB	29.22 dB

4. Results and Discussion

The proposed system is tested with multiple exposure sequences. Two exposure images are picked as the two exposure plane of the SVE array. A pseudo-captured image is generated by copying the pixel values of the two exposure images according to the exposure plane each pixel location belongs to. The pseudo-captured images are shown in Fig. 8, 9.

After performing demosaicking on the pseudo-images, the results are compared to bilinear interpolation. As shown in Fig. 10-13. It is obvious that the image generated by the proposed method gives sharper edges and more consistent edge color. PSNR measurement is done to the two reconstructed exposure images referencing the two original exposure images. The bilinear interpolated images are compared. In the tested cases, the PSNR of the proposed method is much higher.

Having the two reconstructed exposure images in full resolution, the HDR image can be generated using existing HDR synthesis algorithms for multiple exposure images [1]. The resulting HDR images are tone mapped to 24-bit color-depth for display. The results are displayed in Fig. 14, 15. As shown in the figures, some of the details are restored in the over-exposed and under-exposed regions.

5. Conclusion

A High Dynamic Range image capturing system is proposed. By applying Spatial Varying Exposure on the capture sensor surface, two exposure planes with different exposure settings are captured. Two exposure images are reconstructed by applying a specific demosaicking algorithm to the captured SVE image. The result images and PSNR results shows good performance of the demosaicking algorithm. Existing HDR synthesis and tone-mapping method is applied to the two intermediate image giving high quality HDR images as the system output.

6. References

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