HDR Imaging Based on Image Interpolation and Motion Blur Suppression in Multiple-Exposure-Time Image Sensor

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SUMMARY We aim at HDR imaging with simple processing while preventing spatial resolution degradation in multiple-exposure-time image sensor where the exposure time is controlled for each pixel. The contributions are the proposal of image interpolation by motion area detection and pixel adaptive weighting method by overexposure and motion blur detection.

key words: multiple-exposure-times imaging, HDR imaging, motion blur, overexposure, image interpolation

1. Introduction

High dynamic range (HDR) images are expected to be used in surveillance cameras for traffic and security and industrial equipment cameras for object identification and observation. One of the widely used methods for obtaining HDR images with a fixed camera is the exposure bracketing scheme [1], which continuously captures images with different exposure times. The problems of this method are that a ghost occurs in the reconstructed image due to the displacement of the moving subject between the images at each exposure time, and that the temporal resolution is reduced. There is also a method of performing complicated optimized signal processing to suppress ghosting [2], [3], but it is difficult to implement hardware for surveillance cameras etc. in terms of computational complexity.

The imaging method for controlling the exposure amount for each pixel aims at obtaining an image in which ghost and motion blur are suppressed, and improving DR and time resolution. The method [4], [5] improves the temporal resolution of HDR images by simultaneously obtaining images with different exposures with different sensitivities for each pixel. However, since the exposure time of an image is the same, there is a weak point that motion blur easily occurs. On the other hand, there are several methods of simultaneously obtaining images with different exposure amounts by changing the exposure time for each pixel or line [6]–[9]. These methods can reconstruct an HDR image with small motion blur while suppressing ghosting by simultaneously capturing images with different exposure times (multiple exposure time imaging). However, in the method of controlling the sensitivity and the exposure time for each pixel, defective pixels are generated in the images of each exposure amount, and the number of effective pixels is reduced to half or less than 1/4. Therefore, it is necessary to interpolate defective pixels, which leads to deterioration of high frequency components.

In this paper, we propose a multiple exposure time imaging/interpolation method and an HDR reconstruction method, assuming hardware implementation of HDR reconstruction with fixed cameras such as surveillance cameras. The first proposed method is an imaging/interpolation method for suppressing a decrease in the number of effective pixels in the multiple exposure time imaging method. The second proposed method is an HDR image reconstruction method that suppresses overexposure and motion blur. In the proposed imaging method, we introduce an exposure time control pattern that assumes image interpolation based on moving area detection. Specifically, images of middle and long exposure times are captured simultaneously, and the pixel arrangement that allocates the middle and long exposure times is switched for each frame for HDR reconstruction. Therefore, in a static area where there is no moving subject, the defective pixels of the middle/long exposure time image can be interpolated from the previous frame. In the proposed reconstruction method, the appropriate weight of the pixel value of each exposure amount in a single frame is calculated for each pixel independently for hardware implementation, and HDR reconstruction is performed by a weighted average. The effectiveness of each proposed method is shown by simulation experiments.

2. Proposed Imaging and Reconstruction Methods

2.1 Multiple Exposure Time Imaging/Interpolation

Figure 1 shows the configuration of the multiple exposure time image sensor [8]. This image sensor can control the reset and readout phase of the charge stored in the photodiode in units of up to 4×4 pixel blocks. The control in block units is realized by using the skipping selection and skipping reset functions of the vertical and horizontal scanning circuits.

In the proposed imaging method, short-exposure-time imaging of all pixels and then middle- and long-exposure-time imaging of half of all pixels are performed for each frame \( f \) (dashed line) of the HDR image in Fig. 2. The ghost of the HDR image can be suppressed because the imaging timing is the same for the middle and long expo-
sure time in Fig. 2 are defective pixels. Each defective pixel moving region because the amount of incident light changes zero in the static region where the amount of incident light amount are the same. Equation (1) approaches the output pixel value characteristics with respect to the in-

defective pixels, \( x^{(f-1)}_S \) and \( x^{(f-1)}_L \) with the same effective pixel position are used to calculate Eq. (1) to determine the moving region.

2.2 Reconstruction Method

In the proposed method, HDR reconstruction is performed using a weighted average of \( x^{(f)}_S \), \( y^{(f)}_M \), and \( y^{(f)}_L \) where all pixels are effective pixels. In order to control the weight so as to suppress overexposure and motion blur, the position and intensity of overexposure and motion blur are estimated by calculating the rate of change of pixel values in the \( f \) frame. We calculate the rate of change of the pixel value between the short exposure time image and the longer exposure time image in the same frame by applying a digital gain in the same manner as in Eq. (1). Then, the change rate of the pixel value becomes large in the region where overexposure or motion blur occurs. In the proposed method, the pixel value change rates \( D_M \) and \( D_L \) are calculated between \( x^{(f)}_S \) and \( y^{(f)}_M \), between \( x^{(f)}_S \) and \( y^{(f)}_L \), respectively, and the weights are calculated based on these. Since the change rates are different for each pixel, the weight is calculated for each pixel accordingly.

Define a normal distribution function

\[
f(D) = \frac{1}{\sqrt{2\pi \sigma}} \exp\left(-\frac{(D - \mu)^2}{2\sigma^2}\right)
\]

and let the functions whose average \( \mu \) is 1 and 0 be \( f_1(D) \) and \( f_0(D) \). Here, the average value of \( f_1(D) \) is set from the upper limit of \( D \). In preliminary experiments, when \( g \) was set to three times, the value of \( D \) was within a little more than 1 even for pixels with large motion blur and overexposure.

For this reason, in this paper the upper limit of \( D \) is simply set as \( 0 \leq D_M, D_L \leq 1 \). Using these functions \( f_1(D) \) and \( f_0(D) \) and the two change rates \( D_M \) and \( D_L \), the weights \( w_S \), \( w_M \), and \( w_L \) of \( x^{(f)}_S \), \( y^{(f)}_M \), and \( y^{(f)}_L \) are calculated as follows.

\[
w_S = f_1(D_L) f_1(D_M)
\]

\[
w_M = f_1(D_L) f_0(D_M)
\]

\[
w_L = f_0(D_L)
\]

According to this formula, a large weight is set to \( x^{(f)}_S \) for pixels where overexposure or motion blur occurs in both \( y^{(f)}_L \) and \( y^{(f)}_M \). The weight of \( y^{(f)}_M \) is set larger for pixels with large overexposure and motion blur only in \( y^{(f)}_L \). The weight of \( y^{(f)}_L \), which is the highest S/N, is set to a large value for pixels in which no whiteout or motion blur occurs even in \( y^{(f)}_L \).

After normalization so that the sum of the independently calculated weights becomes 1, the HDR image is reconstructed by the weighted average of the following equation.

\[
y^{(f)}_{HDR} = w_S \left(x^{(f)}_S \cdot g_{SL}\right) + w_M \left(y^{(f)}_M \cdot g_{ML}\right) + w_L y^{(f)}_L
\]

Here, the input and output characteristics are adjusted to \( y^{(f)}_L \)
by applying known digital gains $g_{SL}$ and $g_{ML}$ to $x^{(f)}_S$ and $y^{(f)}_M$, respectively. When the upper limit of $D$ is reduced, the weight of the short exposure becomes relatively large, so that the local image-quality degradation due to overexposure and motion blur is reduced for the reconstructed image. On the other hand, because short exposure is more likely to be used, the whole image quality is likely to deteriorate. As described above, in the proposed reconstruction method, HDR reconstruction can be performed only with the rate of change of pixel value between each exposure time image and the normal distribution function, and real-time operation can be expected sufficiently.

3. Performance Evaluation

We confirm the effectiveness of the proposed interpolation imaging method and reconstruction method by simulating the imaging of a scene with a contrast and a moving subject based on a real image. We confirm the effectiveness of the proposed interpolation imaging method and reconstruction method by simulating the imaging of a scene with a contrast and a moving subject based on a real image. Figure 3 shows an image example. These images were taken with Canon EOS 50D at each exposure time (1/90, 1/30 and 1/10 seconds) with blackout and whiteout. Thereafter, the subject (Train) cut out from another photograph was translated at a rate of 4 pixels per short exposure time and superimposed on the image at each exposure time. As a result, each image has motion blur corresponding to each exposure time.

3.1 Imaging/Interpolation Method Only

We simulated the proposed imaging and interpolation method, the previous study [9] shown in Fig. 1, and the exposure bracketing imaging method [1]. After that, we compared the image quality of HDR images reconstructed with 17 bits for each RGB color using the same method [4]. Figure 4 shows the outline of each method and the moving area and high frequency region in each HDR image. The reference HDR image shown in Fig. 4 (a) was reconstructed after being superimposed on the image of Fig. 3 without blurring the moving region. The upper parts of Fig. 4 (b)–(d) show the exposure timing and the short/middle/long exposure time pixel pattern for each imaging method. We have determined that the moving area is the same position in the short exposure time images of each method and the reference. Therefore, motion blur occurs in the middle-long exposure time image according to the translation of the moving subject and the exposure order. Each exposure time image in the proposed method and [9] is a downsampled Fig. 3 according to the pixel pattern shown in Fig. 4 (b)–(d). Defective pixels in each exposure time image of the previous study [9] were interpolated by the bicubic method. The same applies to the moving region of the proposed imaging method.

In the moving regions shown in the Fig. 4 and the Table 1, low and high image quality can be obtained by the methods [1] and [9] in which the displacement of the moving subject in each exposure image is maximum and mini-
Table 1  PSNR of Fig. 4.

|                | Mertens et al. [1] | Kosaka et al. [9] | proposed |
|----------------|---------------------|-------------------|-----------|
| whole image    | 32.82               | 31.35             | 34.15     |
| moving area    | 18.44               | 24.81             | 19.85     |
| static area    | 44.45               | 32.10             | 44.41     |

The proposed imaging method has the image quality between them. In the high-frequency region, the previous study [9] has a color shift due to the reduced spatial resolution, while the proposed imaging method has the same image quality as the method [1] that does not require interpolation. Therefore, the proposed method improved the image quality of the moving area as well as the previous study while maintaining the high image quality in the static area, and the effectiveness of the proposed method was confirmed.

3.2 Imaging/Interpolation and Reconstruction Methods

We evaluate the performance of the proposed method including the above-mentioned imaging/interpolation and reconstruction method. Since spatial regularization is not applied to the value of \( D \), a small \( \sigma \) makes the weights discontinuous, so that a pseudo contour is easily generated in the reconstructed image. Therefore, it is necessary to determine an appropriate \( \sigma \) value. In the case of \( g = 3 \) in this experiment, \( \sigma = 0.3 \) was set so that \( w_L \) was less than 0.1 when both medium and long exposures were overexposed in the static region. With this weight control, it is possible to suppress contamination due to overexposure without detecting it.

Figure 5 shows the HDR image reconstructed from Fig. 3. The dynamic range was improved because the high illuminance area and other areas were clearly obtained.

In order to evaluate the motion blur suppression, we compared the image quality with the reference HDR image. In the method [4], the exposure time was set to 1/10 second, and the images with the exposure amount equivalent to 1/30 and 1/90 seconds were generated using the same dimming filter pattern as in Fig. 6 (c), respectively. Figure 6 and Table 2 show the HDR image and its PSNR for each method. From these results, the motion blur was suppressed and the image quality was improved and the effectiveness of the proposed method was clarified.

4. Conclusion

In this paper, we propose an HDR image reconstruction method that suppresses spatial resolution degradation and motion blur in multiple exposure time imaging, and clarifies the effectiveness of the proposed method by performance evaluation. Future tasks include implementing the proposed imaging/reconstruction method using an image sensor [8] and FPGA capable of multiple exposure time imaging, and confirming the operation in real time. The limitations of this study are that the detection sensitivity of overexposure and motion blur depends on the upper limit of \( D \) in Eq. (2) and the scene. In the future, the upper limit of \( D \) and \( \sigma \) should be determined adaptively depending on the scene and \( g \).

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