High Dynamic Range Image Acquisition from Multiple Low Dynamic Range Images Based on Estimation of Scene Dynamic Range

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Abstract. To acquire a high dynamic range (HDR) image of a scene, several low dynamic range (LDR) images acquired from a digital camera with different exposure times are generally fused into one HDR image to cover the entire dynamic range of the scene. However, when capturing a scene, the scene dynamic range (SDR) is unknown. Consequently, the exposure times for the LDR images need to be as varied as possible to cover the unknown SDR. This paper proposes a method to estimate the SDR using two LDR images. Using the SDR information, SDR-adaptive exposure times can then be selected to achieve the optimal HDR image. The SDR is defined as two exposure times when captured LDR images are marginally clipped to black and white, indicating the lower and upper limits of the SDR, respectively. To identify these times, two LDR images, an overexposed and an underexposed image, are captured. Using the opto-electronic conversion function of the camera used, the minimum gray level in the overexposed image is then used to estimate the exposure time to make the minimum gray level of the image just black, while the maximum gray level in the underexposed image is used to estimate the exposure time to make the maximum gray level of the image just white. By evaluating the acquired HDR image error according to the exposure times of fused LDR images for various scenes, SDR-adaptive exposure times to acquire an optimal HDR image with the minimal error are selected. Experiments confirm that the quality of an HDR image based on fusing LDR images with the proposed SDR-adaptive exposure times is similar to that of an HDR image based on fusing LDR images with conventionally chosen exposure times, even though the number of LDR images used to acquire the HDR image with the proposed method is much smaller than that used by the conventional method. © 2009 Society for Imaging Science and Technology. [DOI: 10.2352/J.ImagingSci.Technol.2009.53.2.020505]

INTRODUCTION

While improvements are consistently being made to the resolution, image quality, design, and convenience of digital cameras, the dynamic range of the image sensors in digital cameras remains limited. Thus, when using a digital camera to take a picture of a scene that includes both bright and dark regions, the bright regions are often converted to white, while the dark regions are sometimes converted to black, as image sensors with a low dynamic range (LDR) cannot simultaneously sense bright and dark information in an image with a high dynamic range. Thus, to overcome these limitations of the image sensors in digital cameras, research on the acquisition and reproduction of high dynamic range (HDR) images has attracted recent attention.

The dynamic range that can be acquired using most digital cameras is limited, yet an HDR image can almost express the dynamic range of the real world, which is about 10^8, whereas the dynamic range that the human eye can accommodate in a single view is about 10^3, and the dynamic range of the image sensors in most digital cameras is about 10^3, representing only 1/100 000 of the real world. The overall brightness information of the real world with a high dynamic range cannot be expressed using the normal 24-bit RGB image format with 8 bits per channel. Therefore, a new image format suitable for HDR images is required, such as 32-bit RGE image format with additional 8-bit exponent information. In addition, the reproduction of HDR images on a normal display with a low dynamic range is one of the most important challenges for high dynamic range imaging. As the dynamic range of a normal display is about 10^3 and such displays can only show image files with a 24-bit RGB format, HDR images need to be converted to a 24-bit RGB format using tone mapping or tone reproduction.

In general, there are two ways to acquire an HDR image: using a special HDR camera system that can accommodate the entire scene dynamic range or fusing several LDR images with multiple exposure times taken using a regular digital camera. Mann, Debevec et al., Robertson et al., and Mitsunaga et al. 4–7 already proposed various HDR image acquisition methods using LDR images captured using a regular digital camera, where a number of LDR images with multiple exposure times are fused to cover a broad range of both bright and dark regions, as the dynamic range of a real scene cannot be expressed by a single image taken using a regular LDR digital camera. An LDR image captured with a short exposure time can express bright areas, whereas a long exposure time can express dark areas. Therefore, capturing various images with different exposure times to cover the entire scene dynamic range (SDR) is important in all these methods.

However, when a photographer captures a series of LDR images to acquire an HDR image of a scene, if the SDR is
unknown, consecutive LDR images ranging from the longest exposure time to the shortest exposure time of the LDR camera are needed to make sure the entire SDR is covered, resulting in a quite inefficient process. Conversely, if the SDR is known, the proper exposure times can be selected for the efficient capture of LDR images for a particular scene.

Accordingly, this paper proposes an SDR estimation method using just two LDR images. The SDR is defined based on two exposure times, where the minimum gray level in one captured LDR image is marginally clipped to black, while the maximum gray level in the other captured LDR image is marginally clipped to white, thereby indicating the lower and upper limits of the SDR, respectively. To determine the lower limit of the SDR, namely, the exposure time required to make the minimum gray level of the image just black, an overexposed LDR image is captured first. Using the previously obtained opto-electronic conversion function (OECF) of the camera, the minimum gray level in the overexposed LDR image is then converted to the exposure time required to make the minimum gray level of the image just black. Similarly, the upper limit of the SDR is estimated from the maximum gray level in an underexposed LDR image using the previously obtained OECF of the camera.

To choose the optimal exposure times for a scene, the errors in the acquired HDR images are evaluated according to the exposure times of the fused LDR images for various scenes. To calculate the error in the resultant HDR image, an HDR image, for a given scene, is first designated as the original HDR image, then virtual LDR images are made from the original HDR image by applying an inverse camera response curve to acquire a new HDR image and a new HDR image is reproduced from several virtual LDR images with varied exposure times. The difference between the original HDR image and the HDR image reproduced by the virtual LDR images is then defined as the error of the HDR image. The number of LDR images used to acquire an HDR image is fixed to three, considering the relative size of the dynamic range of an individual LDR image to the entire size of the dynamic range covered by the LDR images from the longest to the shortest exposure time. When three exposure times are chosen, where the dynamic range of the LDR images is located at the center of the SDR and about nine steps outside the lower and upper limits of the SDR, respectively, the resulting HDR image has the minimal error for all types of scene.

HDR IMAGE ACQUISITION

Estimation of Camera Response Curve

The relationship between the scene radiance value and the gray level in an LDR image captured by a regular digital camera is nonlinear and is called the camera response curve or camera characteristic curve. It can be shown as follows:

\[ r \cdot t = f(z), \]

where \( r \) is the scene radiance value, \( t \) is the exposure time, \( z \) is the gray level, and \( f \) is the function of the camera response curve. Mann et al.\(^4\) addressed the nonlinear relationship between the gray level and the radiance, yet were unable to estimate the camera response curve. Subsequently,Debevec et al.\(^5\) estimated the camera response curve by solving the problem of the least-squared error minimization using a singular value decomposition method for the relationship among the gray level, radiance, and exposure time. Robertson et al.\(^6\) also estimated the camera response curve using the Gaussian relaxation method, while Mitsunaga et al.\(^7\) simply modeled the camera response curve as a polynomial expression based on the fact that the ratio of the time-scaled radiances is equal to the ratio of the exposure times between two LDR images with different exposure times. The polynomial is given as follows:

\[ I = f(z) = \sum_{n=0}^{N} c_n z^n, \]

where \( I \) is the time-scaled radiance, \( z \) is the gray level, \( N \) is the degree of the polynomial, and \( c_n \) is the coefficient for each term in the polynomial. The ratio of the time-scaled radiances is assumed to be equal to the ratio of the exposure times as follows:

\[ \frac{I_{p,q}}{I_{p,q+1}} = \frac{t_q}{t_{q+1}} = R_{q,q+1}, \]

where \( p \) is a pixel in an LDR image, \( q \) is an LDR image, \( t \) is the exposure time, and \( R_{q,q+1} \) is the ratio of the exposure time between the \( q \)th and \( q+1 \)th LDR image. Using Eqs. (2) and (3), we can express \( R_{q,q+1} \) as follows:

\[ R_{q,q+1} = \frac{f(z_{p,q})}{f(z_{p,q+1})} = \frac{\sum_{n=0}^{N} c_n z_{p,q}^n}{\sum_{n=0}^{N} c_n z_{p,q+1}^n}, \]

where \( R_{q,q+1} \) is known because the exposure times are already known. The function of the camera response curve can be estimated by solving Eq. (4), namely, finding the optimal \( c_n \) coefficients. In the current paper, the camera response curve is estimated using the Mitsunaga method mentioned above.

HDR Image Fusion

Several LDR images with different exposure times are used to acquire one HDR image. In conventional HDR images, the wide-range scene radiance information is stored using a 32-bit image format instead of the normal 24-bit image format.\(^1\) The radiance value of each pixel in the HDR image is obtained from the gray level of each pixel in the LDR image using the camera response curve with the exposure time used to capture the LDR image. The radiance values from several LDR images with different exposure times for each pixel are then fused into one radiance value as follows:

\[ r = \frac{\sum_{q=1}^{Q} w(z_q) r_q}{\sum_{q=1}^{Q} w(z_q)}, \]

where \( w(z_q) \) is the weight for each pixel.
where \( r \) is the radiance value of each pixel in the HDR image, \( w(z) \) is the weight function of variable \( z \), \( z \) is the gray level, and \( r_q \) is the radiance value obtained from LDR image \( q \). Thus, the radiance value in the HDR image is fused based on a weighted sum of the radiance values from the series of LDR images. Debevec’s weight function\(^5\) is maximized at 128 for gray levels with an 8-bit format and becomes linearly smaller toward 0 and 255. Robertson et al.\(^6\) also proposed a similar weight function to Debevec’s, yet the shape is a Gaussian curve. Plus, Mitsunaga et al.\(^7\) used the camera response curve divided by the derivative of itself as the weight function, and assumed that if the slope of the camera response curve is steeper, the noise level in the time-scaled radiance value is increased. Despite the methodical differences, the general shapes are similar to each other. This study uses Mitsunaga’s weight function to fuse the LDR images into one HDR image. Figure 1 shows the typical procedure for the HDR image acquisition.

**SDR ESTIMATION**

Conventionally, to cover an unknown SDR using several LDR images, the LDR images are captured with varied exposure times from the longest to the shortest, where the ratio between adjacent exposure times is two. As a result, in some cases, the number of captured LDR images can be more than ten. Plus, as the number of LDR images increases, the time taken to capture them also increases and the process involved in fusing them becomes more computationally complex. This is obviously an inefficient way to acquire an HDR image; if the SDR is known, the number of LDR images required to cover the SDR can be effectively reduced by choosing SDR-adaptive exposure times. Therefore, in this paper, the SDR is estimated using just two images, an overexposed and an underexposed LDR image.

When the camera exposure time is varied, the gray levels in the captured LDR image are also varied. Thus, an LDR image captured using a longer exposure time is brighter, namely, the gray levels in the image are increased; conversely, a shorter exposure time means the image becomes darker, namely, the gray levels in the image are decreased. When an LDR image is captured with the proper exposure time, the LDR image can appear like a real view, and the gray levels in the image are distributed from black to white. However, when pixels are clipped to black or white, this means the LDR image does not cover the entire SDR, as shown in Figure 2(b). With a longer exposure time, the captured LDR image becomes brighter and the number of black pixels is decreased. At a certain point, when there are no more black pixels in the image, this means the minimum gray level is no longer black, indicating that the LDR image includes the lower limit of the SDR, as shown in Fig. 2(a). Figure 3 shows an example of the change in the minimum gray level in LDR images captured with various exposure times for a particular scene.

![Figure 1. Typical procedure for HDR image acquisition.](image1)

![Figure 2. Variation of maximum and minimum gray levels in LDR images with different exposure times: (a) LDR image including lower limit of SDR, (b) LDR image within SDR, and (c) LDR image including upper limit of SDR.](image2)

![Figure 3. Change of minimum gray level in LDR images with various exposure times for a particular scene.](image3)
image includes the upper limit of the SDR, as shown in Fig. 2(c). In this paper, to connect the SDR with the exposure time, the lower limit of the SDR is defined as the exposure time when the maximum gray level of the captured LDR image is just clipped to black, while the upper limit of the SDR is defined as the exposure time when the minimum gray level of the captured LDR image is just clipped to white. In the 8-bit digital format, the black gray level is set to 0, while the white gray level is set to 255.

For several different scenes, LDR images were captured with varied exposure times using a Canon EOS 10D. Figure 4 shows graphs of the change in the minimum gray level of the LDR images with various exposure times, from when the minimum gray level in the captured LDR image was just clipped to black, namely, the lower limit of the SDR, to when the minimum gray level in the image became white. The number 0 on the horizontal axis in Fig. 4 signifies the lower limit of the SDR, while the number on the horizontal axis represents the number of steps for the exposure time away from the lower limit of the SDR. Here, a larger number of steps means a longer exposure time. The ratio of the exposure time between adjacent steps was $2^{1/3}$. As shown in Fig. 4, the OECFs for the lower limit of the SDR for the different scenes were similar to each other.

Likewise, Figure 5 shows graphs of the change in the maximum gray level of the LDR images with various exposure times, from when the maximum gray level in the captured LDR image was just clipped to white, namely, the upper limit of the SDR, to when the maximum gray level in the image became black. The number 0 on the horizontal axis in Fig. 5 signifies the upper limit of the SDR, while the number on the horizontal axis represents the number of steps for the exposure time away from the upper limit of the SDR. Here, a larger number of steps means a shorter exposure time. Fig. 5 also shows that the OECFs for the upper limit of the SDR were similar, regardless of the scene. Thus, based on the data for the two OECFs for the lower and upper limits of the SDR, a polynomial regression method was used to model two inverse OECFs for the lower and upper limits of the SDR as follows:

$$E_{L}(z_{\min}) = l_3z_{\min}^3 + l_2z_{\min}^2 + l_1z_{\min} + l_0, \tag{6}$$

$$E_{U}(z_{\max}) = u_3z_{\max}^3 + u_2z_{\max}^2 + u_1z_{\max} + u_0, \tag{7}$$

where $E_{L}(z_{\min})$ and $E_{U}(z_{\max})$ are the inverse OECFs for the lower and upper limits of the SDR, respectively, $z_{\min}$ and $z_{\max}$ are the minimum and maximum gray level in the captured LDR image, respectively, and $E$ represents the number of steps for the exposure time away from the upper or lower limit of the SDR. The values for the coefficients $l_i$ and $u_i$, $i = 0, 1, 2, \text{and } 3$, after modeling are shown in Table I and their modeled curves are shown in Figure 6.

After modeling the inverse OECFs for the lower and upper limits of the SDR, the lower and upper limits of the SDR can be estimated using an overexposed and an underexposed LDR image. To estimate the lower limit of the SDR, an overexposed LDR image needs to be captured first. Then, based on the minimum gray level in the overexposed LDR image, the number of steps for the exposure time away from the lower limit of the SDR can be calculated using the inverse OECF for the lower limit of the SDR. As such, the lower limit of the SDR can be estimated by adding the calculated number of steps for the exposure time to the steps for the exposure time used to capture the overexposed LDR image. The lower limit of the SDR then becomes the exposure time corresponding to the resultant number of steps. Similarly, to estimate the upper limit of the SDR, an under-

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Figure 4. OECFs of lower limit of SDR for various scenes.

Figure 5. OECFs of upper limit of SDR for various scenes.
exposed LDR image needs to be captured. Then, based on the maximum gray level in the underexposed LDR image, the number of steps for the exposure time away from the upper limit of the SDR is calculated using the inverse OECF for the upper limits of the SDR. As such, the upper limit of the SDR can be estimated by subtracting the calculated number of steps for the exposure time from the steps for the exposure time used to capture the underexposed LDR image. The upper limit of the SDR then becomes the exposure time corresponding to the resulting number of steps. Figure 7 shows an example of estimating the SDR for a scene.

When capturing LDR images with multiple exposure times, the aperture value needs to be fixed. Thus, it is important to choose the appropriate aperture value, as the aperture value has an overall effect on the gray levels of the LDR images. The appropriate condition is that the SDR is located at the center of the whole range of camera exposure times. As shown in Figure 8, when capturing several scenes, most of the exposure times were automatically chosen under the auto exposure time mode (fixed aperture value) of the camera, which corresponded to about 1/3 of the SDRs. Therefore, based on this tendency, a proper aperture value was chosen for a scene. First, the exposure time was fixed at 1/3 of the possible range of exposure times for the camera. In the case of the Canon EOS 10D this was 0.8 s, as shown in Figure 9. The aperture value was then chosen automatically for a particular scene according to the half-shutter of the camera under the auto aperture mode (fixed exposure time). As a result, when the aperture value used to capture the LDR images with varied exposure times was fixed at the aperture value obtained above, the SDR for a particular scene was found to be centered in the possible range of exposure times for the camera.

CHOICE OF OPTIMAL EXPOSURE TIMES
Evaluation of HDR Image Using Virtual Images
To choose the optimal exposure times for a scene, a method is needed to evaluate the HDR images resulting from LDR images captured using certain exposure times. Therefore, this paper uses the error of the HDR image as the criterion for this evaluation. In fact, it is almost impossible to obtain the radiance error between the radiance values of an HDR image and the real radiance values of a scene, as it is impossible to measure the exact radiance value for each pixel in a scene. Thus, instead of using the real radiance values for a
scene, the radiance values stored in an HDR image of a scene are considered as the original radiance values for that scene. Namely, the HDR image of a scene is designated as the original HDR image, and then virtual LDR images with varied exposure times are generated from the original HDR image. The gray level of a pixel in a virtual LDR image with a certain exposure time can then be calculated from the radiance value of the corresponding pixel in the original HDR image using the inverse function of the already modeled camera response curve. As a result, a new HDR image is reproduced from several virtual LDR images with varied exposure times, and the HDR image can be evaluated by calculating the error between the original HDR image and the reproduced HDR image as follows:

\[
\text{Error}_{\text{HDR}} = \frac{1}{3n} \sum_{i=1}^{n} \left( \frac{|O_{rp} - R_{rp}|}{O_{rp}} + \frac{|O_{gp} - R_{gp}|}{O_{gp}} + \frac{|O_{bp} - R_{bp}|}{O_{bp}} \right),
\]

where \( O \) is the radiance value of the original HDR image, \( R \) is the radiance value of the reproduced HDR image, \( r, g, \) and \( b \) mean the red, green, and blue channels for a pixel, respectively, \( n \) is the total number of pixels in the image, and \( p \) is the index for each pixel. The difference in the radiance values for each channel between the original and reproduced HDR images is divided by the original radiance value, then the error for the HDR image is calculated by averaging these values for all the pixels. As the difference between higher radiance values becomes higher, to avoid a dependence on the amount of the radiance value, the difference is divided by the original radiance value. The error of an HDR image is thus based on the concept of the averaged noise to signal ratio of the radiance of the HDR image. Therefore, a smaller \( \text{Error}_{\text{HDR}} \) means the HDR image is reproduced more exactly.

![Figure 9. Example of exposure times located at 1/3 of entire range of exposure times.](image)

**SDR-Adaptive Exposure Times**

To identify the optimal exposure times for LDR images to acquire an HDR image with a minimal error, only three LDR images are used per scene, as the entire dynamic range of the LDR images, from the longest to the shortest exposure time, can be covered by three dynamic ranges of LDR images with multiple exposure times, as shown in Figure 11. As demonstrated, the entire dynamic range of LDR images with 52 different exposure times can be covered based on three dynamic ranges of LDR images with three different exposure times. Each vertical bar with the same length represents the dynamic range of an LDR image with a certain exposure time. The dynamic range of the LDR image with a longer exposure time is located in the lower part on the log-scaled radiance axis, while the dynamic range of the LDR image with a shorter exposure time is located in the upper part on this axis. If the exposure times are so long or short that the dynamic range of the LDR image is located beyond the SDR (long vertical bar), the minimum or maximum gray level in the LDR image does not become black or white, respectively, as represented by the shorter bar in Fig. 11.

![Figure 10. Flowchart of evaluation method for HDR image using virtual images.](image)

To identify the three optimal exposure times for LDR images of a scene, the errors for HDR images acquired based on LDR images using various groups of exposure times were checked for several scenes. A group of exposure times was composed of three exposure times, where one placed the dynamic range of the LDR image at the center of the SDR,
while the other two placed the dynamic ranges of the LDR images symmetrically below and above the center of the SDR, respectively, as shown in Fig. 11. Figure 12 then shows the tendencies of the errors for the HDR images acquired according to the group of exposure times used for the LDR images. The horizontal axis represents the difference in the exposure time step from the lower and upper limits of the SDR to the longest and shortest exposure times in a group of exposure times. A negative number on the horizontal axis means the longest and shortest exposure times in the group of exposure times are located between the lower and upper limits of the SDR, 0 on the horizontal axis means the longest and shortest exposure times in the group of exposure times are located on the lower and upper limits of the SDR, and a positive number on the horizontal axis means the longest and shortest exposure times in the group of exposure times are located beyond the lower and upper limits of the SDR. As such, the HDR image error according to the group of exposure times used for several scenes exhibited a U-shaped curve, and the minimal error was at about nine steps. Namely, when the exposure times of the three LDR images for a scene were chosen at the middle of the SDR and nine steps apart from the lower and upper limit of the SDR, respectively, the resultant HDR image from the LDR images had the minimum error. Therefore, these exposure times were considered as the SDR-adaptive exposure times for the LDR images to acquire an HDR image with the minimal error for a scene.

This result can be explained by the shape of the camera response curve. For the same amount of error on the gray level axis, the time-scaled radiance value is seriously affected on the steep slope of the camera response curve and less affected on the gentle slope of the camera response curve, as shown in Figure 13. A gray level error in an LDR image generally occurs due to camera noise, such as quantization noise. Thus, the derivative of the camera response curve, as shown in Figure 14, can be considered as a noise-sensitivity function for the resultant radiance value. Using a similar approach, Mitsunaga’s weight function, which fuses the radiance values calculated from the LDR images, sets a high weight value for the gentle slope of the camera response curve. In Figure 15, the distribution of regions that are less sensitive to noise in the dynamic range of an LDR image is shown for three groups of exposure times. An arrow in the dynamic range of an LDR image indicates a region that is less sensitive to noise, as shown in Fig. 15(a). The right sides of Figs. 15(b)–15(d) show the distribution of regions that are less sensitive to noise in the dynamic range of the result-
ant HDR image after fusion. The arrow distribution in Fig. 15(b) is so close together that overlapping occurs. In contrast, the arrow distribution in Fig. 15(d) is so extended that some parts of the arrows are outside the dynamic range of the HDR image. However, in both cases, the arrows do not cover the entire dynamic range of the HDR image efficiently, thus the error for the HDR image becomes larger. Therefore, Fig. 15(c) shows properly distributed arrows across the dynamic range of the HDR image. The arrows cover the entire dynamic range efficiently, resulting in a smaller error for the HDR image. Consequently, the tendency of the HDR image error according to the group of exposure times was a U-shaped curve.

**EXPERIMENTAL RESULTS**

For several scenes, LDR images were captured, the SDRs estimated, and the HDR images acquired. The digital camera used in the experiments was a Canon EOS 10D DSLR camera. Figure 16 shows an example of the SDR estimation for a scene. A scene of a bright window in a dark corridor, as shown in Fig. 16(a), was captured using various exposure times. Figure 16(b) shows the exposure times used, and the
The overexposed and underexposed LDR images were captured using exposure times of $13\,\text{s}$ and $1/2580\,\text{s}$, respectively. The minimum gray level in the overexposed LDR image was 45, while the maximum gray level in the underexposed LDR image was 60. Using Eqs. (6) and (7), $E_L(45)=9$ and $E_L(60)=13$ were obtained. The lower and upper limits of the SDR were then estimated as exposure times of $1.6\,\text{s}$ and $1/128\,\text{s}$, respectively. This was an accurate estimation of the SDR, as the real lower and upper limits of the SDR were the same, as shown in Fig. 16(b). Here, due to the noise in the camera system, up to gray levels 5 and 250 were considered as black and white, respectively.

HDR images were obtained for three scenes: a window in a classroom, a basement parking lot, and a night view, as shown in Figures 17–19 respectively. Each figure shows the original HDR image and three reproduced HDR images when using the LDR images with the conventionally chosen exposure times, practically chosen exposure times, and proposed SDR-adaptive exposure times, respectively. In addition, the SDR of the scene and position of the selected LDR images are indicated in a graph of the dynamic ranges. The HDR images were tone-mapped and transformed into 24-bit RGB images using the program HDR Shop. The HDR images reproduced using the conventional and proposed choices of LDR images were almost identical to the original HDR image for each scene, making it difficult to distinguish between them with the naked eye. In addition, the dynamic ranges of the LDR images chosen using the conventional and proposed methods were also able to cover the whole SDR for each scene as shown in Figs. 17(e), 18(e), and 19(e).

Table II shows the HDR image errors between the original HDR image and the reproduced HDR images for each scene. The conventional method used 18 LDR images to cover the unknown SDR, where the captured LDR images had exposure times ranging from $32\,\text{s}$ to $1/4096\,\text{s}$, and the ratio between the adjacent exposure times was 2. Meanwhile, the proposed method only used two LDR images to estimate the SDR, and three LDR images were used to acquire the HDR image. Of course, for these two cases, it was assumed that the camera response curve had already been obtained. Overall, the errors for the HDR images acquired using LDR images with SDR-adaptive exposure times were larger than those for the HDR images acquired using LDR images with conventionally chosen exposure times. However, both of them were too small to be perceptible to the naked eye, even though the number of LDR images used to acquire the HDR image with the proposed method was much smaller than that used by the conventional method.

As a practical choice, to acquire an HDR image, photographers generally use three LDR images: one with the normal exposure time, and the others with twice and half as long as the normal exposure time, respectively. Thus, as an additional comparison, the reproduced HDR images and positions of the LDR images related to the "practical choice" are also presented and compared with those of the other methods for the three scenes, as shown in Figs. 17–19. The positions of the LDR images selected according to the practical choice were fixed, despite the scene variation, as shown in Figs. 17(e), 18(e), and 19(e), as the normal exposure time for each scene was fixed at $0.8\,\text{s}$ when choosing the proper...
aperture value under the auto aperture mode (fixed exposure time). In addition, since the dynamic ranges of the LDR images selected according to the practical choice were located in the lower part of the SDR, they were unable to cover the upper part of the SDR. As a result, the bright regions in the HDR images reproduced using the practical choice of LDR images were incorrectly expressed for each scene, as shown in Figs. 17(c), 18(c), and 19(c), making the HDR image errors with the practical choice much larger than those with the other choices, as shown in Table II.

CONCLUSIONS
This paper proposed an efficient method for acquiring an HDR image using a regular digital camera based on SDR estimation. First, two LDR images, an overexposed and an underexposed image, are captured for a scene. Next, two inverse OECFs are used to estimate the lower and upper limit of the SDR from them. SDR-adaptive exposure times for LDR images to acquire an HDR image with the minimal error are then determined by evaluating the HDR image error according to the exposure times used. Several experi-
ments confirmed that both of the errors of an HDR image based on the fusion of three LDR images with the proposed SDR-adaptive exposure times and an HDR image based on the fusion of 18 LDR images with conventionally chosen exposure times are so small that they are not perceptible to the naked eye. Therefore, the proposed method can help reduce the number of LDR images required for the acquisition of an HDR image, although it does not consider any other problems when capturing an LDR image, such as motion blur problems in the case of a moving scene or shaken camera. Under these situations, additional image processing procedures for compensation would be required with the proposed method.

Table II. HDR image errors between original and reproduced HDR images.

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<th>Scene</th>
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<th>Practical choice (No. of images used = 3)</th>
<th>Proposed SDR-adaptive choice (No. of images used = 5(2 + 3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window in classroom</td>
<td>0.005 82</td>
<td>0.086 67</td>
<td>0.008 20</td>
</tr>
<tr>
<td>Basement parking lot</td>
<td>0.003 47</td>
<td>0.028 61</td>
<td>0.005 35</td>
</tr>
<tr>
<td>Night view</td>
<td>0.006 13</td>
<td>0.012 31</td>
<td>0.008 95</td>
</tr>
</tbody>
</table>

Figure 18. HDR image comparison of basement parking lot: (a) original HDR image, (b) reproduced HDR image when using conventional choice of LDR images, (c) reproduced HDR image when using practical choice of LDR images, (d) reproduced HDR image when using proposed SDR-adaptive choice of LDR images, and (e) indication of used LDR images.
REFERENCES


Figure 19. HDR image comparison of night view: (a) original HDR image, (b) reproduced HDR image when using conventional choice of LDR images, (c) reproduced HDR image when using practical choice of LDR images, (d) reproduced HDR image when using proposed SDR-adaptive choice of LDR images, and (e) indication of used LDR images.