High Dynamic Range Imaging by Fusing Multiple Raw Images and Tone Reproduction

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Abstract — *This paper presents an integrated color imaging system for taking images in extremely high dynamic range scenes. The system first fuses several differently exposed raw images to acquire more intensity information. The effective dynamic range of the image raw data can be extended to 256 times if five differently exposed images are fused. Then it runs edge detection iterations to extract the image details in different luminance levels. The proposed tone reproduction algorithm equalizes the histogram of the extracted fine edges which tends to assign larger dynamic range for highly populated regions. Finally, the local contrast enhancement is performed to further refine the image details. The experimental results show that the proposed high dynamic range imaging system has good performance on both tone and color reproduction[1].*

Index Terms — High dynamic range imaging, tone reproduction, image fusion, and contrast enhancement.

I. INTRODUCTION

The capability of taking images in extremely high dynamic range (HDR) scenes has become generally necessary for a modern digital still camera (DSC) [1]-[6]. The real world shows the scenes with light intensities ranging from starlit to white snow in sunlight. Although high quality image sensors have a larger dynamic range, most consumer imaging systems have narrower exposure latitude than color negative films. Hence DSCs highly rely on auto exposure control algorithm to determine the right exposure for covering the light intensity range of the scene being taken. However, it is still impossible to obtain an adequate representation with image sensors in some scenes. The dynamic range of a camera system is limited by the noise of the sensor as well as the precision of the analog-to-digital converter. A good approach to remedying the problem is taking multiple images in the same scene with different exposure settings to acquire more luminance intensities information and then fuse them into a single one [7]-[12]. On the other hand, the standard image file format only supports the intensity data (*RGB* or *YCbCr*) for each color channel in the range of 0 to 255. Attempting to scale or map high dynamic range image data in such a way that the resulting image has preserved the visual brightness and contrast impression of the original scene is called tone reproduction [13]-[16].

Most of the published tone reproduction algorithms are developed based on two common techniques: histogram equalization [17]-[25] and local contrast enhancement [26]-[27]. A good HDR imaging system in a DSC should improve contrast, brightness, and visibility while maintaining right color reproduction [28]-[29]. These systems have generally met one of these criteria at the expanse of the others. Global histogram equalization gains the advantage of low complexity and preserves the overall impression of brightness, but condensing the data range in global view may also reduce the visibility of fine image textures. This is because it uses histogram information over the whole image which limits the ratio of contrast stretching. Local contrast enhancement efficiently improves visibility of the fine textures. But it usually results in the problem of visible gradient reversal or generates undesired halos and other artifacts. On the other hand, previous HDR image systems may sacrifice the color constancy for preserving visibility. Reproducing correct color may not be the first criterion for the applications on medical imaging or surveillance systems, but it would be the top priority for a consumer DSC. In our previous works, we have addressed the related issues and also proposed a robust tone reproduction system with the reproduced colors maintained [30]-[31]. The key features of this system include two ideas: acquiring more light intensity data by fusing two images and applying tone reproduction with macro edge equalization. The resulting image keeps more visible details in entire dynamic range and further improves the quality of color reproduction in general scenes.

In this paper, we present an integrated approach to further improve the performance of our previous works. The key concept of the new system is acquiring more intensity data by fusing three or five differently exposed images and preserving feature visibility based on both fine edges histogram equalization and local contrast evaluation. Through systematically executing the image fusing tool we developed, which can fuse two differently exposed images in one time, the dynamic range of the fused image can be extended to 256 times of the original raw image. Since the fine image details located in different luminance levels are well preserved in the fused raw image, it is much easier to extract the image details in different luminance levels. The noise level is also significantly reduced. The final image is reproduced by simultaneously applying both global histogram equalization and local contrast enhancement based on those extracted fine edges.

In the remaining sections, the signal processing flow of the proposed HDR imaging system is described in Section II. The details of the image fusion process and the new tone

[1] This work was supported in part by the National Science Council, R.O.C., under Grants NSC 95-2221-E-003-018-MY2.

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Manuscript received January 15, 2008 0098 3063/08/$20.00 © 2008 IEEE

reproduction algorithm are stated in Section III and IV. In Section V and VI, the experimental results and conclusions are presented.

II. The Proposed High Dynamic Range Imaging System

The proposed HDR imaging system simultaneously deals with the issues of both tone reproduction and color reproduction. The basic design concepts of this system include: (a) maintaining linear color image processing in the image fusion as well as the remaining color image processing stages, (b) leaving the nonlinear processing stage such as tone reproduction and gamma correction in the last one.

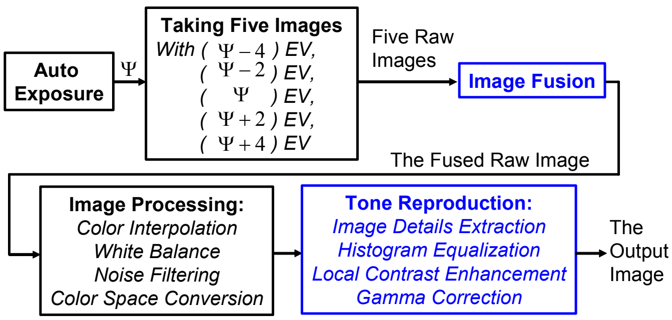


Fig. 1. The proposed high dynamic range imaging system.

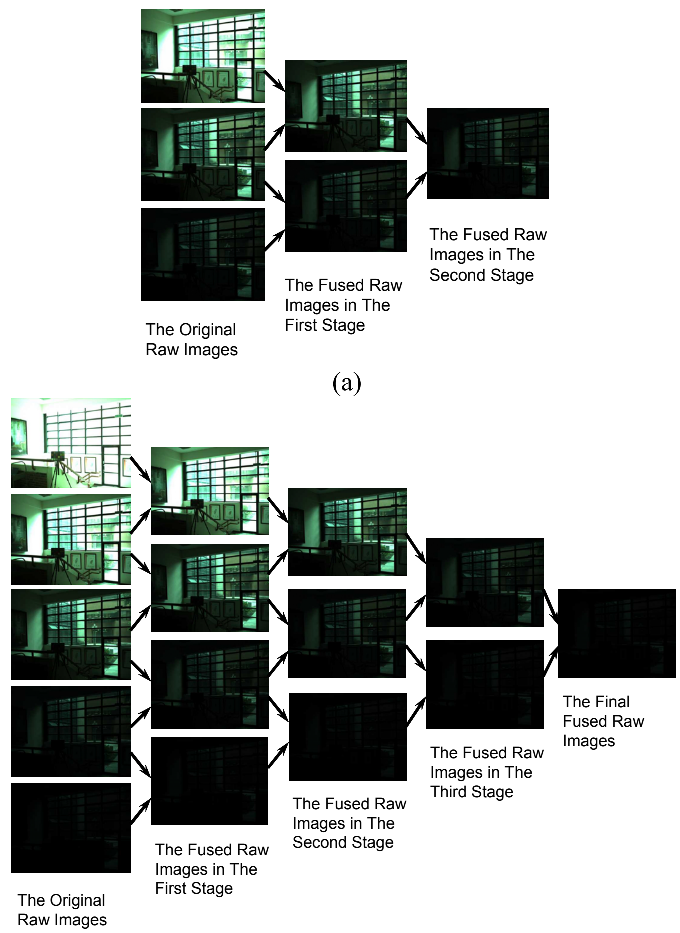
Fig. 1 shows the proposed signal processing flow for taking pictures in high dynamic range scenes. The system first runs a typical auto exposure algorithm to determine the initial guess (Ψ) of exposure setting, and then it takes five differently exposed still images. Note that the number of fused images can be changed according to the requirement of image quality, hardware platform performance, and available system memory.

Unlike most of fusion algorithms that fuse some processed images, the proposed image fusion algorithm directly works on raw image data before performing any color image processing. This is because the images taken by a commercial camera are typically processed by an unknown image processing pipeline. Several nonlinear operators such as tone curve transformation and gamma correction have been applied to produce these images. Without compensating for the nonlinear signal processing before executing image fusion, it is quite difficult to maintain color constancy.

Fusing images with raw data is much easier than with the data through several nonlinear processing steps. This is because the raw image is linear proportional to the intensity of the incident light after passing image sensor calibration [32]. Since the difference of 1 EV is equivalent to changing the shutter time by two times, the effective intensity range is extended 8 EV = 2^8 = 256 times by fusing five images. The following stage includes several linear signal processing steps like a traditional image processing pipeline for color reproduction. After that, the proposed tone reproduction, which combines global edge histogram equalization and local contrast enhancement, is executed to further enhance the contrast of the image details without destroying the color constancy that has been done in the previous image processing steps. To keep the signal processing accuracy, the data path or data structure should be designed with 32 or more bits resolution through the entire pipeline. It significantly reduces noise level and maintains color constancy while applying tone reproduction.

III. Image Fusion Algorithm

In our previous work, we have proposed a robust image fusion algorithm which combines global and local stabilization for fusing two raw images [30]. The image fusion tool can fuse two images that are taken with 2 EV exposure difference. The global stabilization algorithm automatically detects and bypasses saturation pixels and uses the median motion vectors of all macro blocks. The local stabilization algorithm detects those misaligned pixels corresponding to moving objects and selects the non-saturation ones into the final images.



(b)

Fig. 2. The process of image fusion. (a) fusing three differently exposed images, (b) fusing five differently exposed images.

As shown in Fig. 2, fusing three ((Ψ-2), Ψ, (Ψ+2)) or five ((Ψ-4), (Ψ-2), Ψ, (Ψ+2), (Ψ+4)) images can be achieved by invoking this fusion tool three or ten times, respectively. In Fig.2-(a), there are three image fusion steps. Any two images that have 2 EV difference are fused into a single one in each step. The fused image has similar brightness as the image with shorter exposure, but it drastically increases available information compared to the original shorter exposure one. For example, the two images that are taken with (Ψ+2) EV and Ψ EV are fused in the first stage. The equivalent brightness of the fused image is similar to the image with the shorter exposure one (Ψ EV), but the effective color depth has been extended more 2 bits. In this case, the number of overexposed pixels is almost the same as the image with Ψ EV. Assume the color depth of a raw image is 10 bits, the effective color depth of the fused images has been extended to 12 bits in the fusion result. This is because the darker regions of the image can refer to the intensity information of the brighter one and they are scaled down to the lower 2 bits of the raw data.

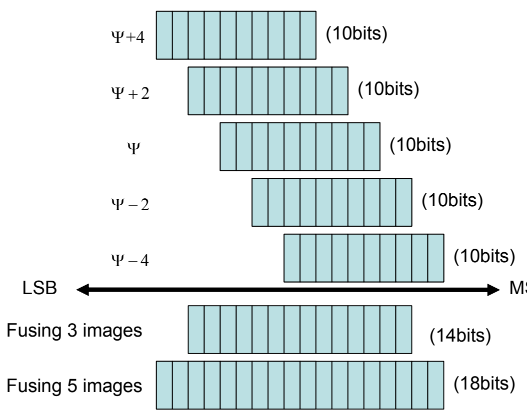


Fig.3 The effective color depth extension through image fusion.

Through the fusion process shown in Fig. 2, the effective color depth in the fused image has been extended. The fused image looks darker than normal exposure one. However, it keeps more information in the lower data bits that may not be visible before tone reproduction. As shown in Fig. 3, the effective numbers of bits for fusing three and five images are extended from 10 bits to 14 and 18 bits, respectively. The remaining issue is how to fully utilize the available intensity information and represent them efficiently such that the final picture has better visual quality.

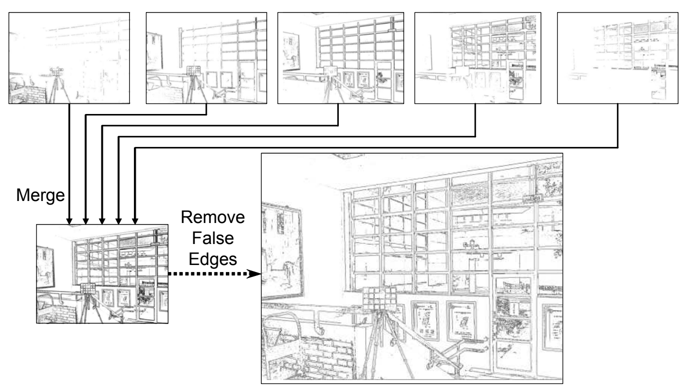
IV. TONE REPRODUCTION

The tone reproduction aims at enhancing the contrast ratio for fine image details/textures while maintaining color constancy. It can be further decomposed into four steps: fine image details extraction, image edges histogram equalization, local contrast calculation, *RGB* gain setting, and gamma correction. Since gamma correction is a standard step of an image pipeline, in the following subsections, we will only describe the algorithm details for the other three steps.

A. Fine Image Details Extraction

Fig. 4-(a) shows an image that has passed the image processing but without being enhanced by tone reproduction. As shown in Fig. 4-(b), the proposed tone reproduction algorithm first extracts the image details in different luminance levels. The fused image is scaled up four times ($4\times$) and the pixel values are clipped to the saturation value in each iteration. The popular edge detector called Sobel operator is applied for detecting all possible image details in different luminance levels. All false edge points in the merged edge map are further filtered out such that the final edge map only keeps the most important image details/textures that should be visible in the final image.

(a)



(b)

Fig. 4. The extracted edges maps in each luminance level and the final edge map.

B. Image Edges Histogram Equalization

To have better visual quality, the proposed tone production system is operated on *CIELAB* color space which is recommended by Commission Internationale de l'Eclairage (CIE). *CIELAB* is a relatively uniform color space that has better separation between luminance and chrominance components. It is much easier to evaluate the luminance of the image textures in human perception than other spaces.

The design concept is to expand the contrast of more image details by assigning larger dynamic range for highly populated regions. Assuming the entire dynamic range of luminance value L^* with *CIELAB* space is normalized to the range of 0 to 100, all extracted edges are first assigned to the M histogram bins $HB_k,\ 1 \le k \le M$, according to their original L^* luminance values. The cumulative frequency distribution function ($t(j),\ 1 \le j \le M$) is constructed as (1), where $h(k),\ 1 \le k \le M$, denotes the histogram value for the bin k.

$$t(j) = \sum_{i<j} h(i) \ / \ \sum_{1 \le i \le M} h(i) \tag{1}$$

For a pixel x with luminance value $L_x, j \times (100/M) \le L_x < (j+1) \times (100/M)$, it is initially assigned in the j-th bin. The target luminance value of pixel x should be moved to the p-th bin, where $p = M \times t(j)$ after histogram equalization. Hence the gain corresponding to global histogram equalization, which is denoted as ω_G, can be derived in (2).

$$\omega_G = p / j = M \times t(j) / j \tag{2}$$

C. Local Contrast Enhancement

Incorporating local contrast enhancement is particularly useful for further improving the contrast of the image details in HDR imaging. The major drawback of local contrast enhancement is that it may have brightness reversal problem or generate some undesired artifacts. These problems may not be so important for medical imaging or surveillance systems, but for consumer digital cameras, having a beautiful picture without artifacts would be a basic requirement. If an image taken by a digital camera has some artifacts or the contrast of the image details becomes too harsh, the camera is always unacceptable in consumer market.

In the proposed system, we incorporate the local contrast enhancement into tone reproduction. The weight regarding to local contrast is defined in (3), where the function f_N is used for data normalization which is defined in (4)-(6). $L_{x,AVG}$ is the average L^* values of the neighboring pixels for the pixel x.

$$\omega_L = f_N(\log(L_x) - \log(L_{x,AVG})) \tag{3}$$

$$f_N(u) = (u - \Delta_{\min})/(\Delta_{\max} - \Delta_{\min}) \tag{4}$$

$$\Delta_{\min} = \arg\min_x(\log(L_x) - \log(L_{x,AVG})) \tag{5}$$

$$\Delta_{\max} = \arg\max_x(\log(L_x) - \log(L_{x,AVG})) \tag{6}$$

The integrated gain ω for a pixel x in L^* component is determined by (7), where L_x^T denotes the target L^* value of the pixel x. It simultaneously performs global and local contrast enhancement.

$$\omega = L_x^T / L_x = \omega_G \times \omega_L \tag{7}$$

D. RGB gain setting

After the gain in L^* domain for a pixel x has been determined, we can change the luminance of a pixel accordingly. However, directly adjusting the luminance value (L^*) in *CIELAB* color space may not get good color reproduction. This is because the chrominance of a pixel highly depends on the illuminant. An object in a daylight scene appears more colorful, but the same object becomes grayish in the night. Adjusting only the L^* component for pixels may improve the contrast. But it is not helpful for enhancing or recovering the right colors that it should be under a better illuminant condition. Changing the chrominance components (a^* and b^*) may enhance the colors, but it must use different scaling factors for the pixels according to their luminance levels. Systematical methods are not derived yet in the field.

Our tone reproduction system aims at recovering colors for the image area whose exposure is not good in original raw images. The system always adjusts the stimulus values by scaling the data in linear *sRGB* color space and the scaled output tends to equal the target luminance value L_x^T determined in previous steps. The improvement with the proposed approach comes from the fact that using linear *sRGB* color space to represent the stimulus values of a pixel has better linearity in radiometry point of view. *CIELAB* color space is defined by the human perception which is inherently nonlinear response to original light intensity. Dealing with the data in a nonlinear space to recover the poor exposed pixels is much more difficult than with linear one. Hence using *sRGB* would be a better solution than in *CIELAB* color space, if we want to recover the right intensity values for those objects under poor exposure conditions.

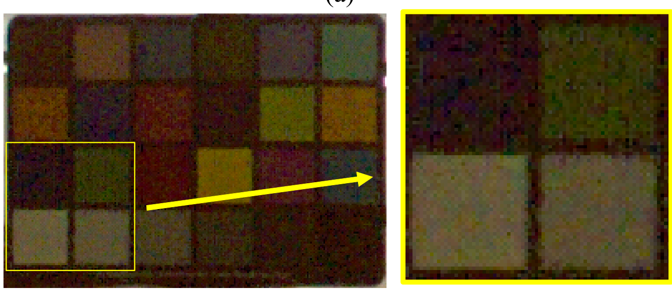
Based on the objective mentioned above, the gain setting problem of tone reproduction can be formulated as follows: Given the original values R_x, G_x, and B_x of a pixel x in linear *sRGB* space and its luminance value (L^*) in *CIELAB* space is L_x, find the scaling factor α such that the luminance value can be mapped to $L_x^T = \omega \times L_x$ if their *RGB* values R_x, G_x, and B_x are scaled to αR_x, αG_x, and αB_x, respectively. As stated in [31], the scaling factor α can be derived as (8), where Y_x and Y_0 are the Y components of the input pixel x and reference white point, respectively.

$$\alpha = \begin{cases} \left(\omega + (16/116)\sqrt[3]{Y_0/Y_x}\,(1-\omega)\right)^3 & Y_x/Y_0 > 0.008856 \\ \omega & Y_x/Y_0 \le 0.008856 \end{cases} \tag{8}$$

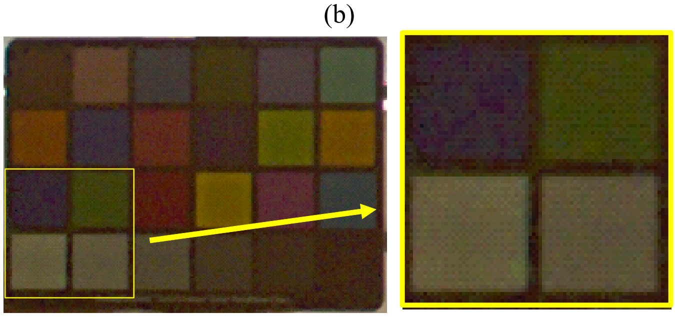
After applying the gain α for a pixel in linear *sRGB* color space, the luminance (L^*) of that pixel has been moved to L_x^T. However, the entire image is typically unexposed in global and local contrast enhancement after processed by (7). This is because ω is usually much lower than 1. Most of data are scaled down through such data processing. To have better visual quality for a picture, we apply auto-level stretching before gamma correction.

V. The Experimental Results

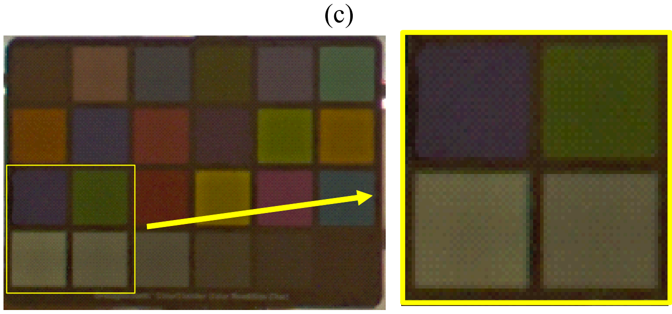
(a)



(b)



(c)



(d)

Fig. 5. The experimental results. (a) The final output image, (b) The cropped area of the image without fusion, (c) The cropped area of the image with fusing three images, and (d) The cropped area of the image with fusing five images.

Fig. 5 shows the experimental results of the proposed system for taking a picture in an extremely high dynamic range scene. Compared to Fig. 4-(a), the visual quality of Fig. 5-(a) is much better than the one without tone reproduction. In Fig.4-(a), many important image details are assigned into a narrow dynamic range such that they are invisible in the original image. Through the processing of the proposed tone reproduction, the dynamic range corresponding to these image details are stretched out more evenly. It is also worthy noting that the taken picture with the proposed system has much lower noise level compared to the normal exposed one as demonstrated in Fig. 5-(b), 5-(c), and Fig. 5-(d).

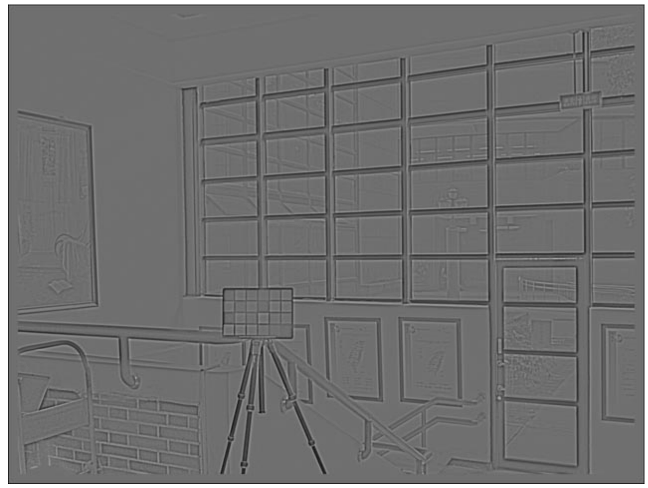


Fig. 6 The local contrast map for an HDR image

Fig. 6 shows the estimated local contrast map of an HDR image. It is obvious that the local contrast map can have better representation in image textures even if the image textures are in darker or brighter regions. Hence it is quite helpful to enhance the contrast for those regions that may not assign wide enough data range to represent their contrast in darker and brighter regions.

Fig. 7 Some other cases: the images without tone reproduction (left) and the images with tone reproduction (right).

Fig. 7 shows the experimental results of taking images in other HDR scenes. The objects under the back light condition may not be observed before tone reproduction. After tone reproduction, the brightness, contrast, and colors for the objects with poor exposure can be significantly improved.

VI. Conclusions

In this paper, we proposed a robust high dynamic range imaging system. The main improvements compared to other systems are that the system systematically fuses available raw images to extend the color depth and combines global histogram equalization and local contrast enhancement into a single gain setting step. The color constancy of the final image is also significantly improved after tone reproduction.

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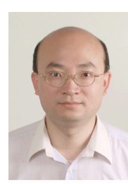

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