An Introduction of HDR Image Printing Oriented Technology

Bongsun LEE*, Wei MING*

Abstract

In recent years, the development of high dynamic range (HDR) imaging has attracted great attentions among researchers and developers. HDR images used to be the exclusive of photographers, but now they have walked into the lives of ordinary people. While many vendors have been focusing on HDR monitors or the technology of displaying HDR images on standard monitors, no products on market has yet targeted for printing HDR images. The technology presented in this report provides the complete solution from HDR image creation to HDR image transformation for printing. We expect that this technology could bring the first HDR printing product from Konica Minolta (KM) onto market. The experiments have indicated that the proposed technology could provide excellent image quality for HDR image printing from both perceptual and quantitative evaluations.

Compared with existing solutions in the field, which is based on display or viewing oriented HDR image processing, the proposed technology targets on how to ensure the high quality of HDR image printing directly. The technology of using extended RGB image and image-based gamut mapping has made great success on HDR image printing.

1 Introduction

Human eye is able to adapt to wide range of luminance in real scene. Overall range that human can perceive is the order of magnitude around 10^8 to 10^{14} and the simultaneous range is about 10^4 (10^{-1} to 10^3)[1]. However, the current displays can only achieve the dynamic range of around 1000 due to its limitation of producing maximum and minimum luminance. With this reason, it is impossible to represent all the luminance ranges observed in a scene on the current display system. The same analogy applies to printing system. Printers have more limited dynamic range than displays. Its brightest region comes from paper white and the darkest area is represented by black ink or toner. The measurement of typical printer shows that the ratio of the brightest to the darkest level is less than 100 or two orders of magnitude.

Here comes the need of compression of dynamic range of real scenes to fit into the range of display and printing devices. In this process, the compressed scenes should preserve the details and colors observed in the real scenes as much as possible. There are many tone mapping operators (TMO) for this purpose. They are performing significant contrast reductions of high dynamic range images to be displayable and printable on the low dynamic range displays and printers. At the same time, they try to produce visually pleasing outputs on those media by preserving details in both highlight and shadow areas. In the case of printers, shrinking of lightness and chroma is added to the tone mapping in order to compensate for their smaller color gamut compared to the display gamut or the gamut of camera images. During the printing, the much greater range of colors captured by the input device must be fitted into the smaller range that is possible to print. The process of fitting colors from the input device into the range of the output device is generally referred to as a gamut mapping.

A special problem exists when the input range is extremely large compared to the output range. If the

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* Konica Minolta Laboratory U.S.A., Inc. (HLUS)

straightforward approach of simply scaling the input values to within the smaller range is attempted, many colors will become too de-saturated and much of the subtle gradations between colors will be also lost. Another possible approach is clipping out-of-range colors or a combination of clipping of extreme colors and scaling of less extreme colors. For some HDR images, the clipping of some mid-range colors would result in problematic renderings that appear unrealistic, and the clipping of high-range colors may require more time to process.

For the compression of lightness and contrast of HDR images, many TMOs have been introduced. One particular TMO is an algorithm known as iCAM06[2]. In this algorithm, colors are tone-mapped to roughly within the range of an intermediate destination device, and then scaled and clipped to the specific contours representing the color capabilities of the output device. However, the process of scaling and clipping can suffer from similar problems as noted above.

To print HDR image, the conventional workflow is to first tone-map the HDR image into sRGB color space, and then use the standard ICC or WCS (Windows Color System on Windows 7 and Vista) color management scheme to convert RGB image to CMYK image for printing. However, since the conversion to sRGB space involves the scaling and clipping to its predefined format, all the useful information about high-range data beyond the sRGB boundary is lost. This loss cannot be recovered in the following gamut mapping process. Our approach is to preserve this extended range data in both highlight and shadows during the tone mapping stage, and use those information in gamut mapping stage. To fully use the preserved information, our original WCS plugins are applied to dynamically control the color conversion for each single image. This method will improve the reproduction of contrast, saturations, and brightness on target printers over the conventional tone mapping or gamut mapping approaches.

The following section describes the workflow of the HDR image printing we have developed. Section 3 provides the detail information about the major functions and procedures in the workflow. The experimental results from running our application software are presented in Section 4. The conclusion is summarized in Section 5.

2 Workflow of HDR image printing

Fig. 1 shows the workflow of HDR image printing. Application software is the core processing module which takes input images, applies tone mapping, performs gamut mapping by WCS plugin, transforms to CMYK, and then prints on a target printer. Input image to the software is either HDR image or multiple exposure images taken by a digital camera. One of methods to obtain HDR images is to take several images of the same scene at the different exposure values, and combine them with weighted average of each image. Tone mapping is performed on the HDR image to compress the range. In the software, modified and customized iCAM06 was used for the tone mapping and its algorithm will be explained in more detail in Section 3. The result of the tone mapping is not scaled or clipped, but is preserved to be saved as the extended range data. WCS plugin module transforms the extended range data to the CMYK image by performing the gamut mapping. During this conversion process, predefined settings for Color Device Model Profile (CDMP) plugin and Gamut Mapping Model Profile (GMMP) plugin are used. The resulting CMYK image is ready to be printed on the target printer and expected to reproduce the faithful colors, contrast, and details of the original scenes as closely as possible.

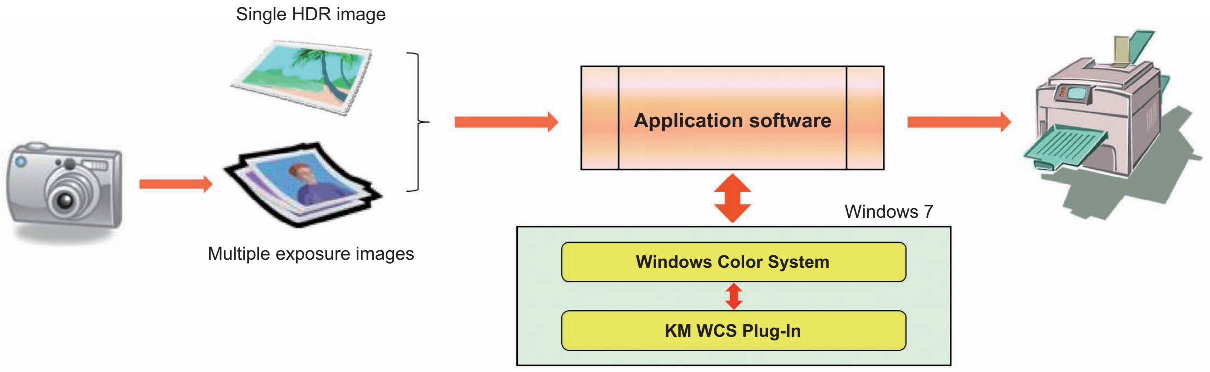

Fig. 1 Workflow of HDR image printing

3 Major functions in the application software

There are three major functions implemented in the application software,that is, HDR image creation, Tone mapping, and Gamut mapping.

3. 1 HDR image decoding and creation

Input image to the application software is either HDR image or several images taken by a digital camera at different exposures. Those different exposure images are combined to create single HDR image.

3. 1. 1 HDR Image Decoding

The HDR encoding format is defined to use a scene referred standard in order to represent the original, captured scene values as closely as possible. In our application software, two widely used HDR formats, OpenEXR and RGBE were supported. They are evaluated as the best encodings with the capability of fidelity as close to perfect as to human eyes 3).

3. 1. 2 HDR Image Creation

Three core technologies, Image alignment, Noise reduction and Image combining, are used in image creation process.

3. 1. 2. 1 Image Alignment

Three different exposures (EV −2.0, 0.0, +2.0) were used to take three images using Canon PowerShot G12 digital camera 5). Those EV values represent underexposed, normal, overexposed images, respectively. The camera features the HDR shooting mode which takes three exposures, combine them, and tone-map the created HDR image inside the camera. Similar operations are performed in our software, and the resulting images will be compared with those of the camera. Before combing the images, image alignment is performed to avoid any misalignment caused by camera shakings or slight shift of objects in a scene. Among the techniques of image alignment and registrations, Greg Ward's median threshold bitmap (MTB) approach 6) was used. This is a very fast algorithm since it performs the alignment operation on binary images rather than 8-bit grayscale images.

The algorithm selects one of the images as the reference image and computes the offsets or shift amounts of the remaining images relative to the reference image. This offset is used to compensate for the misalignment. The algorithm computes MTBs which are the bi-level bitmaps of the original images. Taking the difference of these two bitmaps with an exclusive-or (XOR) operator generates x and y offsets that need to be shifted in the given image relative to the reference image. The shift amounts show how much misalignment occurred in the two images.

3. 1. 2. 2 Noise Reduction

Images taken by digital cameras tend to be noisy under low light or underexposed conditions. These noises are often amplified during the HDR image creation process. In our development, noise reduction technique which is similar to the blending mode in the Photoshop was implemented. 'Screen' mode is one of the blend modes in the Photoshop which is lightening the images by blending subsequent duplicate layers of the original image 7). This operation effectively brightens underexposed images while reducing some noise levels presented in those images. It does not compromise the detail since it actually increases the signal to noise ratio (SNR) of the image. Following equation is the mathematical formula which was used for blending the images.

$$\text{Result value} = 255 - [((255 - \text{Top Layer value}) * (255 - \text{Bottom Layer value}))/255]$$

Here, the bottom layer is the base layer and the top layer is the blend layer which will be blended with the base layer. From the formula above, we can see the operation looks at each channel's color information and multiplies the inverse of the base and blend colors. Therefore, the result colors are always lighter than the original base colors. The amount of lightening can be determined by how many layering operations would be performed on those two layers.

3. 1. 2. 3 Image Combining

When three input images are combined, each image is needed to be normalized using its exposure time. This is part of the linearization step in which the inverse response of the camera is applied to the given image pixels. After the linearization, pixels of each image are summed up to calculate the irradiance of the combined image. During this process, pixels with under-exposed or over-exposed should be excluded since they have no useful information. For this reason, weighting functions which give more weight in more important pixels are used. Debevec and Malik's algorithm 8) satisfies all those requirements described above, so it was implemented in our application software.

3. 2 Tone mapping

Among various TMOs, iCAM06 has shown the top performance[9]. Since it is using chromatic adaption model (CIECAM02) and improved opponent channel space (IPT), it shows more accurate and faithful reproduction of real-world scenes. One drawback of the algorithm to be used for practical application is that its image layer decomposition filter (*Bilateral filter*) is protected by US patent[10]. For the replacement of the filter, several candidates have been identified and tested. Among those, a *Guided filter* (GF)[11] has been chosen since it showed comparable image quality to the *Bilateral filter* (BF) with significantly reduced computation time. The GF uses a guidance image or the original image itself to extract its structural information and performs the linear transformation to that information. The result is the edge-preserved and smoothed image which is used as the base layer in the iCAM06. The detail layer is obtained by subtracting the base layer from the original image.

Chromatic adaptation and tone compression are done on the base layer. Adopting CIECAM02[12] as the chromatic adaptation model, iCAM06 can predict how human eye adapts to the change of illuminants and viewing conditions. Subsequent tone compression uses the simulation of photoreceptor responses, i.e. cones and rods, to estimate the nonlinear tone compression responses of human visual system.

After the tone-compressed image is combined with the detail layer, it is transformed to the IPT space. Here, many significant image attributes and visual effects (e.g. Hunt effect and Stevens effect) are identified and simulated to reproduce better color appearance (e.g. saturation, colorfulness, contrast, etc.) of the original scene.

Once the tone mapping is done, the original iCAM06 algorithm normalizes the output using the 1st and 99th percentile of the image data in order to remove any extremely dark or bright pixels. The resulting data is then clipped to 0 to 255 range and converted to sRGB standard color space. However, this normalization and clipping are not desirable operation for the HDR image since the operations will lose all the detail information in highlights and shadows in the original image. In addition, the normalization produces negative RGB values especially for very dark color pixels, which will produce unwanted artifacts during WCS gamut mapping. For this reason, we performed the tone mapping without the normalization and clipping. The resulting data was called as *extended RGB data*, which were normalized (scaled) in a device independent visually uniform space, *Jab*. This color space is defined in CIECAM02 specification, which is used in WCS.

3. 3 Gamut mapping using WCS plugin

Our gamut mapping algorithm finds the first J value (referred to as J_{01}) for which 1% of all colors in the HDR image gamut have equal or lower J values, and a second J value (referred to as J_{99}) for which 99% of all colors in the HDR image gamut have equal or lower J values. The HDR image gamut is shifted in the J direction and expanded or contracted uniformly in all directions so that after the operations, the J_{01} point is placed at a first normalized J value J_{norm1}, and the J_{99} point is placed at a second normalized J value J_{norm2}. In our algorithm, the first normalized value J_{norm1} is at the origin of the Jab space. Scaling factor using J_{norm1} and J_{norm2} is greater than 1 in our algorithm. This makes the gamut larger, which increases lightness (or darkness) and saturation.

As compared to performing scaling in the sRGB space, performing scaling in the perceptually uniform Jab space can put the color brightness in a more appropriate place. The resulting colors are more saturated. Negative color values may still occur, but those values can be processed with no problems in WCS workflow. Although the percentile values 1% and 99% are used to define the first and second J values in the above example, other percentile values may be used for this purpose, such as 2% and 98% , etc. depending on the overall lightness level and gamut volume/shape of the input images.

The next step is image-based gamut mapping which performs transformation from the gamut of the normalized image data to the gamut of the output device. In WCS GMM, both the source gamut and the destination gamut are device-dependent, i.e., they are characteristic of the color capabilities of the source and destination devices, but are not image-dependent, i.e., they are not specific to the color gamut of the individual images being processed. In our gamut mapping algorithm, the gamut mapping is image-based, i.e., the color gamut of the image being processed is mapped to the destination gamut. The color gamut of the image can sometimes be smaller than the source gamut used in the WCS GMM. Thus, by using image-based gamut mapping, the destination gamut can be more fully utilized.

The image-based gamut mapping step includes clipping (i.e. moving points to the surface of the destination gamut), scaling (i.e. scaling the colors to within the destination gamut), or a combination of clipping and scaling. Fig. 2 shows how the gamut mapping is performed. The HDR image gamut (G3), generated by the normalization step above, is mapped to the destination gamut (G1). The colors in the HDR image gamut fall into three categories which are treated differently. First, colors that are within the destination gamut (e.g. point C1) are compressed (i.e. scaled down). Second, colors that are outside of the destination gamut but within a predefined boundary (G2) (e.g. point C2) are compressed to within the destination gamut (G1). Generally, colors in the second category are compressed by greater amounts than colors in the first category, and the compression factors for the first and second categories of colors affect each other. Third, extreme outlying colors located outside of the boundary (G2) (e.g. point C3) are mapped to the surface of the destination gamut (G1).

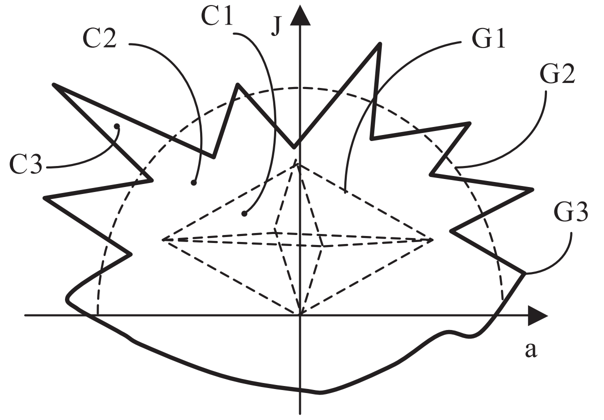

Fig. 2 Gamut mapping for different points in HDR images

In our application software, the image-based gamut mapping is realized by using our original WCS GMM plugin. As explained in Fig. 2, in-range colors (C1 and C2) are converted using a WCS optimized transform which is described in the WCS documentation [13]. WCS performs the transformation to calculate the colors by interpolation. The out-of-range colors (C3) are converted using a WCS sequential transform.

Using this two step approaches, we were able to preserve more detail of the image, avoid too dark colors, and prevent artifacts, when compared with using an optimized transform for all conversions.

4 Experimental results

Canon PowerShot G12 digital camera has been used to obtain 25 pictures from different scenes – daylight, shadow, night, inside, etc. The camera outputs both three exposure images and their tone-mapped image for each scene. 50 more HDR images were collected from various sources available in public domain. Following three mapping methods were tested:

M1: Use Canon's tone mapping results, then perform conventional gamut mapping using our WCS plugin

M2: Use Canon's three exposure images, perform tone mapping to sRGB space (with normalization) using customized iCAM06, then perform conventional gamut mapping using our WCS plugin

M3: Use Canon's three exposure images, perform tone mapping to extended range RGB space using customized iCAM06, then perform image-based gamut mapping using our WCS plugin

Each CMYK image which was converted using those three methods was printed on the target printer, Konica Minolta's bizhub C353 [14]. Table 1 and 2 show the results of image quality evaluation among three methods. For the image quality criteria, five image attributes were tested; Color, Contrast, Saturation, Sharpness, Detail. These are important attributes which greatly affect the overall perceived image quality. In the tables, the numbers indicate which method showed better image quality than the other for the given criteria. For example, in the Table 1, the method M3 showed better sharpness for 24 images, and the method M1 showed better sharpness only for 1 image. From Table 1, we can see that the method M3 outperformed the method M1. Similarly, in Table 2, we observe that the method M3 showed better image quality than the method M2 in all five criteria. In general, Canon's tone mapping (M1) showed good colors and saturations, but poor quality on sharpness and detail representation. Our method M3 showed very good sharpness and detail representation for most images and relatively good reproductions in terms of color, saturation, and contrast. For this reason, overall image quality was perceived better with our method.

Table 2 shows how good it is to use extended range data with its normalization done in gamut mapping stage for the image-based gamut mapping. As we can see, for every criteria, our method M3 outperformed the method M2 for all 50 test images. This proves the superiority of tone mapping to the extended range data and performing the image-based gamut mapping over the conventional tone mapping and gamut mapping.

Table 1 Comparison of image quality evaluation (M1 vs. M3 for 25 images)

Methods	Color	Contrast	Saturation	Sharpness	Detail	Overall
M1	13	10	12	1	0	7
M3	12	15	13	24	25	18

Table 2 Comparison of image quality evaluation (M2 vs. M3 for 50 images)

Methods	Color	Contrast	Saturation	Sharpness	Detail	Overall
M2	13	10	11	5	6	13
M3	37	40	39	45	44	37

5 Conclusion

In this report, the development of HDR image printing oriented technologies has been described. Three major functions, HDR image creation, customized iCAM06 tone mapping, and WCS plug-in gamut mapping were presented in detail, respectively. Performing the normalization and scaling in *Jab* space during gamut mapping not only prevented artifacts, but also preserved brighter and more saturated colors in the output image. Image-based gamut mapping on the extended range data also utilized the source image gamut more effectively, thus performed the gamut mapping which makes better fit into the destination printer gamut. Experimental results showed that our mapping method of HDR image produced superior image quality in most image attributes compared to the Canon's tone mapping and conventional tone and gamut mapping methods.

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