COLOR HIGH DYNAMIC RANGE (HDR) IMAGING IN LUMINANCE-CHROMINANCE SPACE

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ABSTRACT

In this paper, we address the issue of color in high dynamic range (HDR) imaging. In contrast to state-of-the-art methods, we propose to move the complete HDR imaging process from RGB to a luminance-chrominance color space. Our aim is to get a more computationally efficient technique and to avoid also any possible color distortions originating from three color channels processed separately. To achieve this, we build a camera response function for the luminance channel only and weight and compose the HDR luminance accordingly, while for the chrominance channels we apply weighting in relation with the saturation level. We demonstrate that our technique yields natural and pleasant to perceive tone-mapped images and is also more robust to noise.

1. INTRODUCTION

The visual representation of natural scenes has reached a point where spatial resolution is no longer an issue and greater realism is achieved by either adding the third dimension or utilizing a more and more realistic gamut of light and color. The HDR imaging approaches the latter problem by capturing multiple images of the same scene with different exposures and then composing them into a single image spanning the whole dynamic range of the scene [1], [2]. The image composition step requires a preliminary calibration of the camera response function [2]. A related problem then is to adequately tone map the so obtained HDR image back to a low-dynamic range (LDR) display. Tone mapping techniques range in complexity from a simple gamma-curve to sophisticated histogram equalization methods and complicated lightness perception models [3], [4], [5].

State-of-the-art techniques for HDR imaging have been developed generically for the RGB color space. Luminance-chrominance color space representations have been neglected. We consider a generic luminance-chrominance color space linearly related to the RGB space. Such a space is composed of an achromatic (gray) luminance component and two chrominance components, which are orthogonal to the achromatic one. Examples of such spaces are YUV/YCbCr and opponent color spaces [6]. We denote the luminance and the two chrominance components by Y, U, and V, respectively. Let $\mathbf{z} = [z^R, z^G, z^B]$ be an image in the RGB space and $\boldsymbol{\zeta} = [\zeta^Y, \zeta^U, \zeta^V]$ is the same image in the luminance-chrominance space (we use Roman letters to denote images in RGB and the corresponding Greek letters to denote images in luminance-chrominance). Transformation of the image from RGB to luminance-chrominance is defined in matrix form as $\boldsymbol{\zeta} = \mathbf{z}\mathbf{A}$, where the matrix $\mathbf{A}$ is normalized in such a way that if $\mathbf{z}(\cdot) \in [0,1]^3$ then $\boldsymbol{\zeta}(\cdot) \in [0,1] \times [-0.5, 0.5]^2$. The hue and saturation can be defined as $H = \arctan\frac{\zeta^U}{\zeta^V}$ and $S = \sqrt{(\zeta^U)^2 + (\zeta^V)^2}$, respectively.

HDR imaging techniques working in luminance-chrominance seem more meaningful and preferable for a number of reasons. *First*, decorrelated color space offers better compressibility. Considering image compression techniques, they all store images in some luminance-chrominance space. When one starts with already-compressed multiple-exposure LDR images, it is more efficient to compose the HDR image directly in the same color space. The resulting HDR image is then better suited for compression and, if to be displayed, it can be mapped to sRGB during the tone mapping stage. *Second*, any HDR technique operating in RGB space requires post-composition white balancing since the three color channels undergo parallel transformations. While the white balancing would yield perceptually convincing colors, they might not be the true ones. For the sake of hue preservation and better compression, it is beneficial to opt for a luminance-chrominance space, even if the input data is in RGB, e.g. uncompressed TIFF. *Third*, the luminance channel, being a weighted average of the R, G, and B channels, enjoys a better signal-to-noise ratio (SNR), which is crucial if the HDR imaging process takes place in noisy conditions.

In this contribution, we address the problem of HDR imaging in a luminance-chrominance space, propose effi-

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cient algorithms for HDR image composition and tone mapping and emphasize the benefits of such an approach. The paper is organized as follows. HDR image composition, including camera response function definition and processing the luminance and chrominance channels, is presented in Section 2. An adapted tone mapping method for luminance-chrominance HDR images is presented in Section 3. Examples demonstrating the viability of our approach are given in Section 4 and finally some conclusions are drawn in Section 5.

2. HDR IMAGE COMPOSITION

Consider a set of images $\boldsymbol{\zeta}_i = \left[\zeta_i^Y, \zeta_i^U, \zeta_i^V\right], i = 1, \ldots, N$ in the luminance-chrominance space, captured with different exposure times Δt_i and with LDR, assuming $\boldsymbol{\zeta}(\mathbf{x}) \in [0,1] \times [-0.5, 0.5]^2$, where $\mathbf{x} = [x_1, x_2]$ is a pixel coordinate. The goal is to obtain a single HDR image $\tilde{\boldsymbol{\zeta}} = \left[\tilde{\zeta}^Y, \tilde{\zeta}^U, \tilde{\zeta}^V\right]$ in the same color space. In our setting, the luminance and chrominance channels are treated separately. While for the luminance channel, a pre-calibrated camera response function is used, for the chrominance channels a saturation-driven weighting is applied.

2.1. Luminance component composition

The camera response function for the luminance channel is estimated from a set of images of a scene captured with different exposure times. A sufficient number of suitable pixels, i.e. pixels having monotonically increasing values between under- and over-exposure are then chosen. Using these pixels, the camera response function is fitted employing an SVD solver, in a fashion similar to that of [2], [7]. In our experiments, we have found that 100 pixels is a sufficient amount for most cases. The camera response function is estimated (calibrated) only once and then is used for the linearization of the input values in all HDR compositions of the same device.

Similarly to the technique in [2], the HDR luminance component is obtained by a pixelwise weighted average of input luminances. As a weighting function we use a Gaussian function w^Y with a mean of 0.5 and a standard deviation of 0.2 thus ensuring a smaller impact of the under- or over-exposed pixels. The logarithmic HDR luminance is obtained as

$$\ln \tilde{\zeta}^Y(\mathbf{x}) = \frac{\sum_{i=1}^N w^Y(\zeta_i^Y(\mathbf{x}))(g(\zeta_i^Y(\mathbf{x})) - \ln \Delta t_i)}{\sum_{i=1}^N w^Y(\zeta_i^Y(\mathbf{x}))}.$$

In the above equation g is the camera response function. Because of its nature, the HDR luminance is obtained in logarithmic scale. After employing the natural exponential, the resulting values are positive, normally spanning [10^{-4} 10^4] thus being truly high dynamic range.

2.2. Chrominance components composition

For the chrominance components we define no camera response. Instead, we weight the chrominances in relation to the level of color saturation. The higher the color saturation, the more the pixel contains valuable chromatic information, and thus the higher the weight. This is motivated by the fact that when a pixel is over- or under-exposed it is always less saturated than it would be at the correct exposure. More specifically, $w^{UV}(S) = S^\alpha$, where $\alpha > 1$. In our experiments, we have found that $\alpha = 1.5$ is a good choice. To guarantee the color preservation, we use the same weights for both chromatic components and compose any chromatic component $C \in \{U, V\}$ as

$$\tilde{\zeta}^C(\mathbf{x}) = \frac{\sum_{i=1}^N w^{UV}(S_i(\mathbf{x}))\zeta_i^C(\mathbf{x})}{\sum_{i=1}^N w^{UV}(S_i(\mathbf{x}))},$$

where S_i denotes the saturation of $\boldsymbol{\zeta}_i$. We remark that being a convex combination of the input chrominances, the range of $\tilde{\zeta}^C(\mathbf{x})$ is again in $[-0.5, 0.5]$. However, because of averaging, the possible number of distinct pixel values is remarkably higher than in the original source sequence.

3. TONE MAPPING FOR LUMINANCE-CHROMINANCE HDR IMAGES

Tone mapping is an HDR imaging technique used to approximate the visibility of the tones of an HDR image on an LDR media, such as LCD and CRT displays or print-outs [8]. Essentially, tone mapping compresses the contrast of a scene to fit into the displayable range of a media while preserving details and color.

A number of tone mapping methods working in RGB space exist. These techniques can easily be adapted for the luminance range reduction, however the term 'tone mapping' would be questionable in this context, as tone is usually used in connection with color. We denote such a luminance range reduction operator as $\mathcal{T}$ and define its output, the reduced-range luminance image, as $\mathring{\boldsymbol{\zeta}}(\mathbf{x}) \in [0,1]$. As for the chromatic channels, we suggest a simple, yet effective approach.

The sRGB gamut does not allow for the rendering of very dark or very bright vivid and saturated colors which exist in real scenes and which are captured in HDR images. Therefore there is need for a chromatic tone mapping. In our approach, in order to get faithful colors that fit into the sRGB gamut we keep the hue intact while sacrificing saturation. Introducing a scaling factor δ for the two chrominances will not then change the hue, but will scale down the saturation. The scheme we use to guarantee legal sRGB values is embedded in the color space transformation itself and described as follows.

Let $\mathbf{B} = \mathbf{A}^{-1}$ be the luminance-chrominance to RGB transformation matrix and define the gray (achromatic) image and its chromatic complement image in RGB space by

$$\mathring{\mathbf{z}}_{\text{gray}}(\mathbf{x}) = \left[\mathring{z}^{R}_{\text{gray}}(\mathbf{x}) \;\; \mathring{z}^{G}_{\text{gray}}(\mathbf{x}) \;\; \mathring{z}^{B}_{\text{gray}}(\mathbf{x})\right] = \left[\begin{array}{c} \mathcal{T}\left(\tilde{\zeta}^{Y}\right)(\mathbf{x}) \\ 0 \\ 0 \end{array}\right]^{T} \mathbf{B},$$

$$\mathbf{z}_{\text{chrom}}(\mathbf{x}) = \left[z^{R}_{\text{chrom}}(\mathbf{x}) \;\; z^{G}_{\text{chrom}}(\mathbf{x}) \;\; z^{B}_{\text{chrom}}(\mathbf{x})\right] = \left[\begin{array}{c} 0 \\ \tilde{\zeta}^{U}(\mathbf{x}) \\ \tilde{\zeta}^{V}(\mathbf{x}) \end{array}\right]^{T} \mathbf{B}.$$

We remark that $\mathring{\mathbf{z}}_{\text{gray}}(\mathbf{x})$ is truly a gray image because in RGB to luminance-chrominance transforms $b_{1,1} = b_{1,2} = b_{1,3}$. We look for a map $\delta \geq 0$ such that

$$\mathring{\mathbf{z}}\left(\mathbf{x}\right) = \mathring{z}_{\text{gray}}(\mathbf{x}) + \delta\left(\mathbf{x}\right) z_{\text{chrom}}(\mathbf{x}) \in \left[0,1\right]^{3}. \tag{1}$$

We can define it by $\delta\left(\mathbf{x}\right) = \min\left\{1, \delta_R\left(\mathbf{x}\right), \delta_G\left(\mathbf{x}\right), \delta_B\left(\mathbf{x}\right)\right\}$ where

$$\delta_R\left(\mathbf{x}\right) = \begin{cases} \frac{\mathring{z}^{R}_{\text{gray}}(\mathbf{x})}{-z^{R}_{\text{chrom}}(\mathbf{x})} & \text{if } z^{R}_{\text{chrom}}(\mathbf{x}) < 0 \\ \frac{1-\mathring{z}^{R}_{\text{gray}}(\mathbf{x})}{z^{R}_{\text{chrom}}(\mathbf{x})} & \text{if } z^{R}_{\text{chrom}}(\mathbf{x}) > 0 \\ 1 & \text{if } z^{R}_{\text{chrom}}(\mathbf{x}) = 0 \end{cases}$$

and δ_G and δ_B are defined analogously. Thus, δ is the largest one (not larger than 1) which allows the condition (1) to hold. It is easy to realize that the hue of $\mathring{\mathbf{z}}\left(\mathbf{x}\right)$ is not influenced by δ, whereas the saturation is scaled proportionally to it. Roughly speaking, the low dynamic range image $\mathring{\mathbf{z}}\left(\mathbf{x}\right)$ has colors which have same hue as those in the HDR image $\tilde{\boldsymbol{\zeta}}$ and which are desaturated a little as it is needed to fit within the sRGB gamut.

It is now obvious that the tone mapped LDR image can be defined in luminance-chrominance space as

$$\mathring{\boldsymbol{\zeta}}(\mathbf{x}) = \left[\mathcal{T}\left(\tilde{\zeta}^{Y}\right)(\mathbf{x}) \;\; \delta\left(\mathbf{x}\right)\tilde{\zeta}^{U}(\mathbf{x}) \;\; \delta\left(\mathbf{x}\right)\tilde{\zeta}^{V}(\mathbf{x})\right].$$

The tone mapped luminance-chrominance image $\mathring{\boldsymbol{\zeta}}$ can be compressed and stored directly with an arbitrary method (for example, DCT-based compression, as in JPEG), and for display transformed into RGB using the matrix $\mathbf{B}$. We demonstrate that this approach yields lively, realistic colors.

4. RESULTS

We compare the proposed HDR imaging approach in luminance-chrominance space against established techniques working in the RGB space. In particular, Debevec's HDR Shop v.1.0.3 software [9] has been used for the HDR composition in RGB space. Figure 1 shows the source LDR sequence $\left\{\mathbf{z}_i\right\}_{i=1,2,3}$ used in the experiments. There are a number of tone mapping techniques, most of them requiring careful tuning of a set of input parameters. We have opted for the *photographic tone reproduction operator* [8] as it is a global tone mapping technique with fully automatic parameter estimation. The tone mapped result of processing in RGB space is shown in Figure 2. In our approach, we first transform the sequence $\left\{\mathbf{z}_i\right\}_{i=1,2,3}$ to the opponent color space. The operator $\mathcal{T}$ we use for reducing the range of $\tilde{\zeta}^{Y}$ is an adaptation of the method developed in [3]. Our result is shown in Figure 3. Beside some obvious differences in brightness, chromatic distortions which can arise from the RGB processing can be seen when the tone-mapped images are compared with the source sequence in Figure 1. Overall, the colors obtained by processing in luminance-chrominance space are much more faithful, as the hue has been preserved.

A further notable advantage of our approach appears when the source sequence is degraded by noise. In our simulations we added zero-mean Gaussian noise with standard-deviations $\sigma = \frac{5}{255}, \frac{15}{255}$, and $\frac{25}{255}$ to the original source sequence from Figure 1. The HDR images obtained from the original sequence were used as reference in order to measure the errors in the HDR images composed from the noisy sequences. In order to obtain meaningful and comparable results, we calculate the SNR only on the luminance component of the HDR images. This is based on the fact that the image content is differently distributed among the three channels of different color-space representations and the luminance is the most informative one. For the RGB HDR images this component is simply the average of the R, G, and B channels. The results are summarized in Table 1. As can be seen from the table, the inherent noise-attenuation properties of the luminance-chrominance representations alone give strong support to our approach.

5. CONCLUSIONS

In this contribution we have presented an efficient method for composing HDR images in luminance-chrominance color spaces along with a method for tone mapping images acquired in this fashion. Our approach yields more realistic colors with better noise suppression qualities compared to the traditional RGB methods, and does so in a computationally efficient manner. It is our belief, that the advantages of

σ	SNR$_{RGB}$	SNR$_{lum-chrom}$
5/255	25.8	26.3
15/255	13.8	18.2
25/255	10.9	14.6

Table 1. SNR (dB) comparison between processing in a luminance-chrominance space vs. RGB.

Fig. 1. Three-image source sequence used to compose the HDR images.

Fig. 2. HDR image composed and tone mapped by processing in RGB color space.

Fig. 3. HDR image composed and tone mapped by our approach in luminance-chrominance space.

the proposed approach shall motivate the migration of the process from RGB to luminance-chrominance space.

6. REFERENCES

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