A STATISTICAL DERIVATION OF AN AUTOMATIC TONE MAPPING ALGORITHM FOR WIDE DYNAMIC RANGE DISPLAY

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ABSTRACT

In this paper, we present a modified tone mapping algorithm for displaying wide dynamic range images with good brightness. Our algorithm embeds an automatic computation of the key parameter controlling the brightness of tone mapped images, which make use of statistical analysis of WDR images. This enables to prevent unnecessary or cumbersome manual tuning of parameters as often found in tone mapping algorithms. Experimental results performed on different WDR images show that we are able to get images which are visually pleasant and which have good brightness and contrast. The good performance of our algorithm is also confirmed numerically through the use of the tone mapping quality index (TMQI), an objective image quality measure.

Index Terms— Wide dynamic range images, tone mapping, automatic parameterization, curve fitting.

1. INTRODUCTION

Wide dynamic range (WDR) imaging is becoming more and more popular. The dynamic range is defined as the ratio between the intensity of the brightest point and the intensity of the darkest point in a scene. For natural scenes, this ratio can be of the order of millions. Wide dynamic range images, also called high dynamic range (HDR) images, are images that exhibit a large dynamic range. Nowadays, sophisticated multiple exposure fusion techniques can be used for the construction of WDR images [1]. However, most of today's display devices (such as printers, CRT and LCD monitors, and projectors) have a limited or low dynamic range (LDR). As a result of this, the captured scene of a WDR image on such display devices will either be over-exposed in the lit areas or under-exposed in the dark areas, and details will be lost. Thus, there is a need to compress the dynamic range of a WDR image to the standard and low dynamic range of today's display devices. Tone mapping algorithms perform this compression/adaptation of the dynamic range. In fact, the aim of a tone mapping algorithm is mainly to produce pleasant and good looking images that match the perception of the original scene [2, 3], with high contrast in bright as well as dark areas of the scene. There has been much research in the development of tone-mapping algorithms. Two main categories of tone-mapping algorithms exist: tone reproduction curves [4–8] and tone reproduction operators [9–11]. Tone reproduction curves (TRC), also called global tone mapping operators, apply the same compression function to all pixels of the image, which means that one input value will always be mapped to only one output value. Tone reproduction operators (TRO), also called local tone mapping operators, consist of spatial-location-dependent and varying transformations that are applied to each pixel depending on its surrounding neighborhood. In this case, one input value may correspond to different output values, as a function of the pixel neighborhood. Different TRO-based algorithms were presented by Tumblin and Turk [12], Pattanaik *et al.* [13], Ashikhmin [14], Fairchild *et al.* [15], and Kuang *et al.* [16] to name a few. An algorithm using both global and local operators was introduced by Meylan *et al.* based on a retinal adaptation model [10]. Gu *et al.* introduced a local-edge preserving decomposition algorithm for performing tone mapping [17]. In [18], Ofili *et al.* have proposed a combined global and local tone mapping algorithm for displaying WDR images. It is based on an inverse exponential function and uses a low-pass filter for getting the local information needed for performing tone mapping while preserving details. However, it is prone to false colors and the local contrast is not always good. For solving these issues, we have proposed a slight modification of that tone mapping algorithm that simply adjusts the ratio between the brightness and the contrast components [19]. In this work, we present a specific automatic estimation of the key parameter controlling the brightness of tone mapped images in our algorithm in order to prevent cumbersome manual tunings for rendering visually pleasant tone mapped images. The rest of the paper is organized as follows: in Section 2, we summarize our tone mapping algorithm described in [19]; in Section 3, we describe our model for computing automatically the parameter controlling the brightness of tone mapped images; in Section 4, we present some experimental results, and we end the paper with concluding remarks.

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2. THE EXPONENT-BASED TONE MAPPING ALGORITHM OF OFILI *ET AL.*

Our tone mapping algorithm, which is an improvement of the tone mapping algorithm of Ofili *et al.* [18] is defined by [19]:

$$\begin{cases} y(p) = x_{max} \times \frac{1-e^{-\frac{x(p)}{x_0(p)}}}{1-e^{-\frac{x_{max}(p)}{x_0(p)}}} \\ x_0(p) = k_1 \times \mu_x + \frac{(x*h)(p)}{2} \end{cases} \quad (1)$$

where x is the original WDR image, y the final LDR image, p a pixel, x_{max} the maximum value for the display device (for example, for an 8-bit display device, $x_{max} = 2^8 - 1 = 255$). x_0 is the adaptation factor and it is computed as the sum of a global component $k_1 \times \mu_x$ and a local component $\frac{x*h}{2}$. In the global component part, k_1 is a parameter varying between 0 and 1 that plays a major role in brightening an image, and μ_x is the average intensity (mean intensity) of WDR image x. Regarding the local component that is used to extract the local information, $*$ denotes the convolution operation and h is for example a 2D Gaussian filter.

3. AUTOMATICALLY ADJUSTING THE BRIGHTNESS

3.1. Automatic estimation of the parameter k_1

The parameter k_1 is used to modulate the amount of brightness for the tone mapped images: when k_1 increases, the tone mapped image becomes darker, while it becomes brighter when k_1 decreases, as can be seen in Fig. 1. To clearly illustrate numerically the impact of k_1 on the brightness, we plot in Fig. 2 the variation of the brightness with respect to k_1 for the WDR image that was tone mapped in Fig. 1. The brightness is estimated numerically here as the mean value of the tone mapped image. As we can see, the mean value decreases as k_1 increases. To derive the automatic k_1-equation, a mathematical model based on the properties of images needs to be obtained experimentally. To simplify the model, the initial hypothesis is that there exists a one-dimensional interpolation function for computing the k_1 value. Based on this hypothesis, the k_1-equation can be described as shown in Eq. (2):

$$k_1 = f(\lambda) \quad (2)$$

where k_1 is the dependent variable which varies from 0 to 1, and λ is an independent property of the WDR image. Since the function needs to be derived experimentally, the next step is to obtain the data samples used in modeling the function. An outline of the steps taken in designing the automatic estimation algorithm is shown in Fig. 3. First, more than 200 WDR images are tone-mapped with k_1 varying from 0.05 to 1.0 in order to manually select and store for each image the optimal k_1 value which yields a good quality display. Then, the same WDR images are analyzed and various independent

Fig. 1: Effect of k_1 on tone mapping: (a) $k_1 = 0.10$ (b) $k_1 = 0.25$ (c) $k_1 = 0.50$ (d) $k_1 = 0.75$ (e) $k_1 = 1.0$.

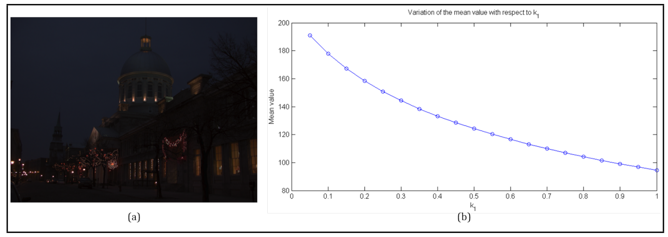

Fig. 2: Effect of k_1 on the brightness. (a) Original WDR image (b) Variation of the mean value of the resulting tone mapped images with respect to k_1.

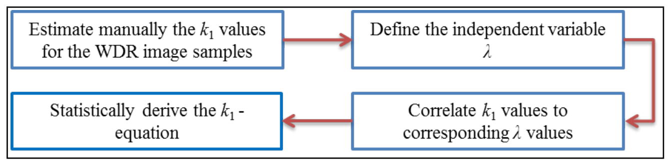

Fig. 3: Outline of the steps taken in deriving the mathematical model for estimating the k_1 value needed for the tone mapping operation.

variables λ (mean, max, min, variance, etc.) can be proposed and computed for each WDR image. Finally, the optimal k_1 values as well as each of the different proposed independent variables are used in determining if a one-dimensional relationship exists between them. This is made so that an equation can be derived for automatically estimating the value k_1 needed for producing good quality tone-mapped images.

3.1.1. Manually estimating the values of k_1

Through the experiments performed on more than 200 WDR images and by varying k_1 between 0.05 and 1.0 (with a step of 0.05), we have noticed that tone mapped images with a mean intensity value around 120 have good brightness and contrast. Thus, we select as the "optimal" k_1 (among the values ranging from 0.05 to 1.0), for each of the tested images, the value which produces a tone mapped image that has a mean intensity value around 120.

3.1.2. Determining the independent variable λ

After performing the previous experiment where the optimal k_1 values for more than 200 WDR images are obtained, the next step is to find a variable that correlates with these k_1 values so that the value of k_1 can be predetermined before the actual tone mapping process. An approach based on deriving an independent variable from a coarsely compressed WDR image is proposed. A simple tone mapping algorithm is used for computing the coarsely compressed tone mapped image. We acknowledge that at first sight it may appear hazardous to derive the parameter k_1 of our tone mapping from the image produced using a different tone mapping algorithm. In fact, we cannot use our tone mapping algorithm for computing the parameter k_1 of our tone mapping algorithm since we will end up with a *chicken or the egg causality dilemma*: we need k_1 to perform our tone mapping algorithm, and we also use the same algorithm for computing k_1. Consequently, the idea for avoiding this kind of causality dilemma is to use another tone mapping algorithm for computing k_1. Since we do not want any analytical computation of k_1 to be more computationally expensive than our tone mapping algorithm itself, we propose to use for the simpler tone mapping algorithm a simplified version of the tone mapping Eq. (1) where the denominator factor is removed:

$$\begin{cases} y^i(p) = x_{max} \times \left(1 - e^{-\frac{x(p)}{x_0^i(p)}}\right) \\ x_0^i(p) = 0.5 \times \mu_x + 0.5 \times (x * h)(p) \end{cases} \tag{3}$$

where $y^i(p)$ is the tone mapped image used for estimating k_1, x_{max} is the maximum pixel intensity of the display device, and $x_0^i(p)$ is the adaptation factor. For standard display devices such as computer monitors, $x_{max} = 255$ (8 bits). For the filter h, we have used a 5×5 Gaussian filter in the simulations, which is a reasonable size for getting good performance. Using the compressed images from the simplified tone mapping algorithm, we have investigated the mean intensity value as a potential independent variable for automatically computing k_1. We note that variables such as the maximum intensity, minimum intensity or the standard deviation of the images obtained with the simplified tone mapping algorithms are not relevant since they do not enable to derive by interpolation a one-dimensional relationship with k_1 because of their unstable variation with respect to k_1.

3.1.3. Correlation between k_1 and the proposed independent variable

The approximation model that we have designed for computing k_1 works as follows: for each WDR image, we choose as our experimental k_1 the value that gives a mean value of the tone mapped image around 120. For each WDR image, we also compute the image (called simplified tone mapped image) obtained with the simplified tone mapping Eq. (3), and for each of the simplified tone mapped image obtained we compute its mean intensity value λ. After that, we plot the graph between the experimental k_1 values and the mean values given by the simplified tone mapping algorithm. Results showed that there is a correlation between the mean intensity value λ computed from each simplified tone mapped images and the k_1 value used in the actual tone mapping operation

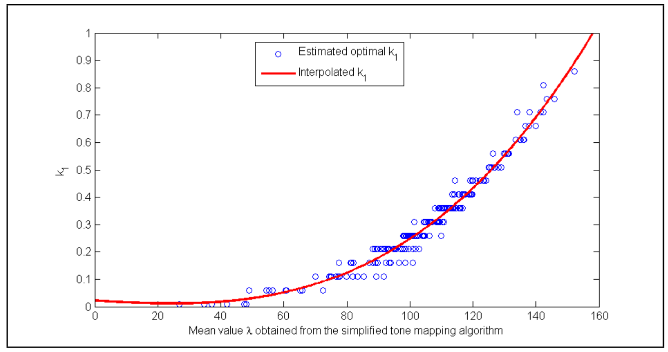

Fig. 4: Graph of k_1 vs. the mean intensity value λ computed from the simplified tone mapping algorithm.

(see Fig. 4). Using MATLAB's curve fitting tool [20] for interpolating k_1 as a function of the mean value λ obtained from the simplified tone mapping algorithm, we get the following cubic k_1-equation:

$$k_1 = 2.4\times10^{-7}\lambda^3+5.9\times10^{-6}\lambda^2-7.3\times10^{-4}\lambda+2.4\times10^{-2} \tag{4}$$

As shown in Fig. 4, the trend of the values of k_1 selected for the varying images correlate with the description of the rendering parameter k_1. As expected, low k_1 values are required for images with a low mean intensity value (dark images) while high k_1 values are needed for WDR images with high mean intensity value (bright images). To evaluate the fit of the interpolated curve for the k_1-equation, the goodness of fit for the curve is computed. Two criteria are used in the analysis of this curve: the root mean squared error (RMSE) and the coefficient of determination (R-square). The RMSE is used to measure the difference between the model's predicted values and the experimentally-derived values [20]. A better fit is indicated by an RMSE value closer to 0. The R-square is used to measure how well the curve fit explains the variations in the experiment data [20, 21]. It can range from 0 to 1 where a better fit is indicated by a score closer to 1. Results show that good RMSE and R-square scores are obtained for the fit of the k_1-equation: RMSE=0.0273 and R-square=0.9736. This indicates that the automatic k_1-equation for computing k_1 is reliable and precise enough, and thus can be used in Eq. (1) for automatically performing tone mapping. This removes the need to manually set the parameter k_1 for performing tone mapping.

4. SIMULATION RESULTS

For evaluation purposes, our automatic exponential-based tone mapping algorithm is applied to different WDR images. The resulting tone mapped images are compared with two other tone mapping operators: the retinal display algorithm of Meylan *et al.* [10] and the display adaptive tone mapping algorithm of Mantiuk *et al.* [22]. Due to page limitations, we only show in Fig. 5-6 two WDR images tested as well as the resulting tone mapped images obtained from the different tone mapping algorithms. All image results were obtained from software implementations of the different tone mapping algorithms. In the figures, we also show the k_1 value that has been automatically computed through the statistical model that we have described in the previous section. Manual tunings were used for the other algorithms. As can be noticed in the figures, our improved tone mapping algorithm gives images with good colors and good contrast as well as good brightness. In general, the algorithm of Meylan *et al.* create blurred images, while the algorithm of Mantiuk *et al.* produces images that exhibit faded colors. For an objective comparison of the different tone mapping algorithms, a tone mapping quality index (TMQI) proposed by Yeganeh and Wang [23] is used, which assesses the effectiveness of the different tone mapping operators. TMQI scores range from 0 to 1, where 1 is the highest in terms of image quality. The TMQI scores for the three tone mapping algorithms and for the two images used in the tests are shown in Table 1. As can be seen, the TMQI values from our tone mapping system are in the high score range that can be attained using this objective test. We have obtained the highest values for the images tested in comparison to the two other tone mapping algorithms, which highlights the good performance of our automatic tone mapping algorithm.

Table 1: TMQI scores for the three tone mapping operators.

Tone mapping algorithm	Image 1	Image 2
Our algorithm	**0.9536**	**0.8752**
Meylan *et al.*'s	0.8125	0.7603
Mantiuk *et al.*'s	0.8559	0.8347

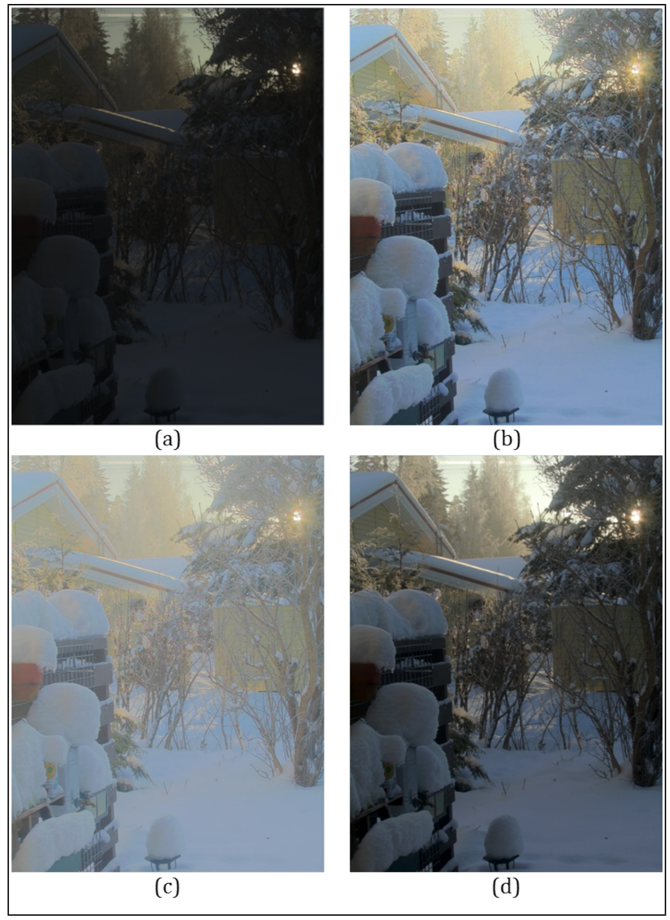

Fig. 5: Tone mapping results: (a) Original WDR image (b) Our automatic algorithm ($k_1 = 0.4249$) (c) Meylan *et al.*'s algorithm (d) Mantiuk *et al.*'s algorithm

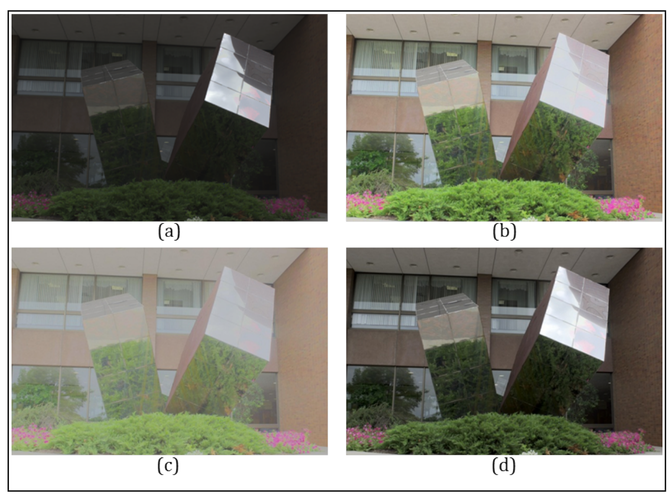

Fig. 6: Tone mapping results: (a) Original WDR image (b) Our automatic algorithm ($k_1 = 0.3595$) (c) Meylan *et al.*'s algorithm (d) Mantiuk *et al.*'s algorithm

5. CONCLUSION

In this paper, we have presented an enhanced automatic tone mapping algorithm that exploits both global and local image information for producing low dynamic range images with high brightness and good contrast. Our algorithm does not require manual tuning of parameters for increasing the brightness of images, which makes it efficient and well fit for implementation on hardware devices (cameras, smart phones, system-on-a-chip, etc.). Experimental tests performed with different WDR images have shown that high objective quality measure values are attainable using our algorithm, and it is also able to produce visually pleasant images.

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