Fuzzy Logic Supported High Dynamic Range Image Reproduction Techniques

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Abstract: The high dynamic range of illumination may cause serious distortions and problems in the view and further processing of digital images. In this paper a new fuzzy based tone reproduction pre-processing algorithm is introduced which may help in developing the hardly or non viewable features and content of the images making easier the further processing.

Keywords: high dynamic range images, image reproduction, lightness perception, segmentation, image processing, fuzzy reasoning

1 Introduction

Digital processing can often improve the visual quality of real-world photographs, even if they have been taken with the best cameras by professional photographers in carefully controlled lighting conditions. This is because visual quality is not the same as accurate reproduction of the scene. In image processing most of the recently used methods apply a so called preprocessing procedure to obtain images which guarantees – from the point of view of the concrete aims – better conditions for the processing. For example, if we eliminate the noise from the images to be processed, we can obtain much better results than else. There are many kinds of image properties to which the certain methods are more or less sensitive [1][2]. It is known that certain regions of images have different features in most of the cases. Usually, the parameters of the processing methods are functions of the image features. E.g. the light intensity at a point in the image is the product of the reflectance at the corresponding object point and the intensity of illumination at that point. The amount of light projected to the eyes (luminance) is determined by a number of factors: the illumination that strikes visible surfaces, the proportion of light reflected from the surface, and the amount of light absorbed, reflected, or deflected by the prevailing atmospheric conditions (such as haze or other partially transparent media) [3]. Only one of these factors, the proportion of light reflected (lightness), is associated with an intrinsic property of surfaces and hence is of special interest to the visual system. If a visual system only made a single measurement of luminance, acting as a photometer, then there would be no way to distinguish a white surface in dim light from a black surface in bright light. Yet, humans can usually do so and this skill is known as lightness constancy [3]. The constancies are central to perception. An organism needs to know about meaningful world properties, such as color, size, shape, etc. These properties are not explicitly available in the retinal image and must be extracted by visual processing. A gray patch appears brighter when viewed against a dark background and darker when viewed against a bright background. This effect, known as "simultaneous contrast," is one of many brightness effects that are commonly attributed to simple visual processes, such as the lateral inhibition that occurs in the retina, whereby cells in one region inhibit cells in adjacent regions.

In this paper we will deal with the reproduction of images when the high dynamic range of the lightness causes distortions in the appearance and contrast of the image in certain regions e.g. because a part of the image is highly illuminated looking plain white or another is in darkness. Using such an algorithm in preprocessing phase of the images, we can make attainable the information hided in the picture, we can avoid the information loose, and we can improve the performance of different image processing algorithms, e.g. corner and edge detectors.

The paper is organized as follows: Section 2 deals with the background of the tone reproduction, in Section 3 a new anchoring based reproduction algorithm is described, while in Section 4 another new and promising concept, the so called tone mapping function based algorithm is introduced. Section 5 is devoted to the examples and Section 6 reports conclusions.

2 Background

Everybody knows the phenomena: if we switch off the lights at night, at first we cannot see anything at all. But the eye adapts to the new lighting situation and after one minute we begin to detect first objects and after about twenty minutes most of the features became visible again (although they lost their color). The same happens if the illumination suddenly changes from dark to bright, but this time the process of adaptation is less noticeable, because it happens much faster: in the first two seconds more than 80 percent of the adaptation is done [4].

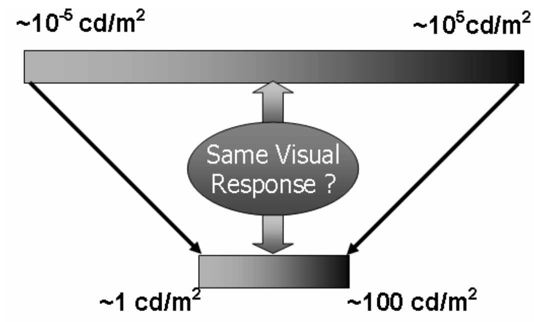

Figure 1
Illustration of the mapping the high dynamic scale to a displayable range

The task of a tone reproduction operator is to present the global illumination solution for a scene on the display (monitor, print, etc.) such that it closely matches the impression of an observer of the corresponding real world's scene. The tone reproduction operator has to face two major problems when fulfilling this task:

- It must mimic how the eye would see the real world and the displayed image and find a match between the two impressions.
- It must compress the high dynamic range of the real world to the small dynamic range of the display (e.g. for monitors 1 - 120 cd/m2).

In computer graphics, the dynamic range of a scene is expressed as the ratio of the highest scene luminance to the lowest scene luminance. Photographers are more interested in the ratio of the highest and lowest luminance regions where details are visible. This can be viewed as a subjective measure of dynamic range. Fig. 1 illustrates the main task of high dynamic range image reproduction, i.e. the mapping of the scale of a high dynamic range image to the displayable domain. The high dynamic scale can be divided into two main parts, the first of which contains displayable luminance values and the second one contains such high luminance values, which are not displayable by nowaday's devices. As we know, images may contain different parts having different illumination characteristics. Therefore, it is expected that the image will contain regions, which are highly illuminated and can contain much less illuminated parts, as well. The highly illuminated regions can contain non displayable luminance values, which means that from the point of view of the observer the image data falling into such luminance intervals are lost. Thus, to avoid the image information loosing it is necessary to map these high luminance values to a displayable range.

There are several known methods in the literature addressing these problems. Each of them tries to compress the high dynamic range of luminance values to a displayable range. Just to mention two of them, Kawahito's method [5] is based on multiple exposure time signals while Reinhards in [6] applies a so called zone system.

In this paper we are going to introduce two new concepts for tone reproduction: the first is based on the so called anchoring theory and image segmentation, while the basis of the second one is the modified form of the so called tone mapping function.

3 The Anchor Based Algorithm

3.1 Anchoring Theory

Although, the ambiguous relationship between the luminance of a surface and its perceived lightness is widely understood, there has been little appreciation of the fact that the relative luminance values are scarcely less ambiguous than absolute luminance values [7]. For instance, consider a pair of adjacent regions in the retinal image whose luminance values stand in a five to one ratio. This five to one ratio informs the visual system only about the relative lightness values of the two surfaces, not their specific or absolute lightness values. It informs only about the distance between the two gray shades on the gray scale, not about their specific location on that scale. There is an infinite family of pairs of gray shades that are consistent with the five to one ratio. For example, if the five represents white then the one represents middle gray. But the five might represent middle gray as well, in which case the one will represent black. Indeed, it is even possible that the one represents white and the five represents an adjacent self-luminous region. So the solution is not even restricted to the scale of the gray surface. To derive specific shades of gray from relative luminance values in the image, one needs an anchoring rule. An anchoring rule defines at least one point of contact between luminance values in the image and gray scale values along our phenomenal black to white scale. Lightness values cannot be tied to absolute luminance values because there is no systematic relationship between absolute luminance and surface reflectance, as noted earlier. Rather, lightness values must be tied to some measure of relative luminance. The relative lightness of two regions in an image can remain fully consistent with the luminance ratio between them, even though their absolute lightness levels depend on how the luminance values are anchored [7].

Highest Luminance Rule: The value of white is assigned to the highest luminance in the display and serves as the standard for darker surfaces [8]. Average Luminance Rule: The average luminance rule derives from the adaptation level theory and states that the average luminance in the visual field is perceived as middle gray. Thus, the relative luminance values have to be anchored by their average value to middle gray [7].

There is a tendency of the highest luminance to appear white and a tendency of the largest area to appear white [3]. Therefore the highest luminance rule was redefined based on this experimental evidence. As long as there is no conduct, i.e. the highest luminance covers the largest area, the highest luminance becomes a stable anchor. However, when the darker area becomes larger, the highest luminance starts to be perceived as self-luminous. Thus, the anchor is chosen as a weighted average of the luminance proportionally to the covered area.

3. Segmentation of the Image into Frameworks

The anchoring rule, described in the previous section, cannot be applied directly to complex images in an obvious way. The main concept is based on the decomposition of the image into so called frameworks or segments and then on the application of the anchoring rule in the individual segments, separately.

By the segmentation we have to find the so called centroids of the segments using e.g. the K-means clustering algorithm [9]. The K-means algorithm is initialized by values ranging from the minimum to maximum luminance in the image with a luminance step equal to one order of magnitude and we execute the iterations until the algorithm converges. We operate on a histogram in the log10 of luminance. After the K-means algorithm has finished, the centroids we have got are merged according to the following criteria: when the difference between two centroids is below a certain threshold, e.g. one then these centroids have to be merged. This is also done iteratively. In each iteration step the two closest centroids are merged together and the new centroid value is calculated as the weighted average of the two merged centroids proportional to their area:

$$c_{ij} = \frac{c_i a_i + c_j a_j}{a_i + a_j} \tag{1}$$

where c_i and c_j are the values corresponding to the centroids with indices i and j, a_i and a_j stand for the number of pixels in the ith and jth frameworks, i.e. they represent the number of pixels corresponding to the ith and jth centroid. It is not an ambiguous step to assign a concrete border to the certain frameworks. We can get better results if we look at the frameworks as fuzzy sets, which means that to each pixel a fuzzy membership value is assigned to define the membership of the pixels belonging to the frameworks [10]. Starting from this reasoning as next step we have to estimate the membership functions corresponding to the frameworks. For this purpose we use the centroids determined in the previous step by the K-means clustering algorithm.

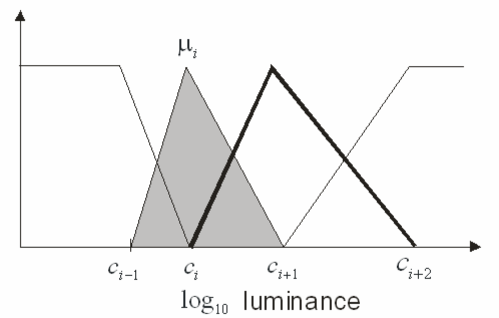

Figure 2
Illustration of the membership function μ_i, which defines the membership of the luminance values in the *i*th framework

Let μ_i be the membership function corresponding to the *i*th centroid (framework) defined as follows (see Fig. 2):

$$\mu_i(x,y) = \frac{I(x,y) - c_{i-1}}{c_i - c_{i-1}}, I(x,y) < c_i, \tag{2}$$

$$\mu_i(x,y) = \frac{c_{i+1} - I(x,y)}{c_{i+1} - c_i}, I(x,y) \geq c_i, \tag{3}$$

where $\mu_i(x,y)$ is the membership function corresponding to the *i*th framework.

The c_i values are the centroids estimated by the K-means clustering algorithm and $I(x,y)$ stands for the luminance value in the log10 space of the pixel at position $[x, y]$. The membership depends also on the articulation of the certain frameworks [11], i.e., frameworks with low variance have less influence on the global lightness. As next step we have to determine an articulation factor for each framework independently. Frameworks with wider intensity range will have a greater weighting factor in the determination of the final luminance value of the output pixel. A framework whose dynamic range is higher than one order of magnitude has a maximum articulation and as the dynamic range goes down to zero, the articulation reaches the minimum:

$$F_i = 1 - e^{-\frac{(\max \log I_i - \min \log I_i)}{2s}}. \tag{4}$$

Here F_i denotes the articulation factor of the *i*th framework, s stands for a parameter by which the influence of F_i on the final membership value can be set. After the articulation factors have been estimated, we have to multiply these factors by the corresponding μ_i values to get the final membership value in the frameworks (see eq. (4)).

$$\mu_i(x, y) := \mu_i(x, y)F_i, \quad (5)$$

where i=1..n, n is the number of frameworks.

3.3 Anchor Estimation

After the decomposition into frameworks has been done (see Section 3) we have to estimate an anchor within each framework independently. For this purpose we use the highest luminance rule, described above (see Section 3), that is, we need to find the luminance value that would be perceived as white. Although, we apply the highest luminance rule, we cannot directly use the highest luminance in the framework as an anchor. Seemingly, there is a relation between what is locally perceived as white and the relative magnitude of its area. If the highest luminance covers a large area it becomes a stable anchor. However, if the highest luminance is largely surrounded by darker pixels, these pixels have a tendency to appear white and the highest luminance to appear as self-luminous. Therefore, we estimate the local anchor by removing 5% of all pixels in the framework's area that have the highest luminance and then take the highest luminance of the rest of the pixels as the anchor (the 5% is an experimental factor) [11].

3.4 Merging Frameworks

As the final step we compute the global lightness of the pixels by merging the frameworks. For this purpose, the following fuzzy rulebase is used:

IF (I(x,y), fw1) THEN LM=L1,

IF (I(x,y), fw2) THEN LM=L2,

IF (I(x,y), fw3) THEN LM=L3,

…

IF (I(x,y), fw$n$) THEN LM=Ln,

where (I(x,y),fw$i$) denotes that the luminance I(x,y) is the member of the ith framework (fw$i$) with nonzero membership value, i=1..n, n stands for the number of frameworks. Li represents the estimated anchor corresponding to the ith framework while LM stands for the lightness modification value, which is used for shifting the original luminance values to achieve a displayable range of luminance. This value is got after evaluation of the above defined fuzzy rulebase, i.e. as the weighted sum of the local lightness values, where the membership values serve as weighting factors. Finally, the lightness values of the output image can be got according to

$$I_{res}(x,y) = I(x,y) - L_G \,. \tag{6}$$

4 The Tone Mapping Function Based Algorithm

As mentioned in the previous section it is necessary to map the high dynamic range of luminance values to a displayable one. The method presented in this section solves the task by maintaining the complexity so low, that the real time processing can be achievable, as well. The main idea lies on defining a simple mapping function, which maps the wide range of luminance values to a displayable one. Besides it, the simple and easily evaluable mapping function (having low complexity) can be combined with a nonlinear scaling of the vertical axis (the axis of displayable luminance values), as well thus extending the mapping possibilities. The nonlinear vertical axis on one hand enables to keep the image data, which should not be modified invariable while on the other hand the high or less illuminated areas can be corrected without having an influence on the areas containing correct image data. Furthermore, the nonlinear mapping function makes possible to compress regions where unimportant or sparse information is stored thus offering a way to keep wider parts of the displayable or viewable domain for the important (dense) regions. The mapping will keep the relativity of the luminance i.e. lighter regions will remain lighter while darker regions darker. Fig. 3 illustrates a possible mapping function and a nonlinear vertical axis of the displayable luminance values. It can be seen that the nonlinearity of the vertical axis is influenced by a set of linear functions.

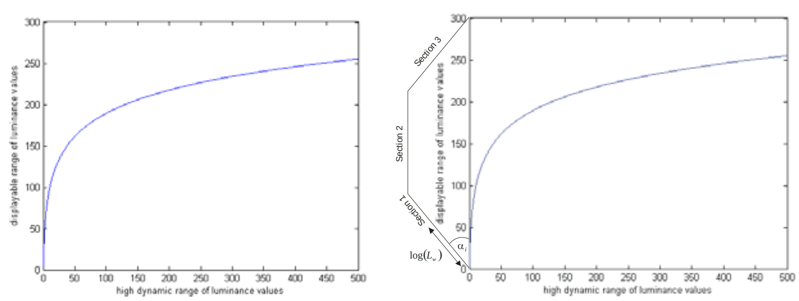

Figure 3
Example of the most frequently used logarithmical mapping function (left) and a function with nonlinear vertical axis used by the proposed algorithm (right)

By changing the linear functions the nonlinear characteristics of the vertical axis can also be modified. The used mapping function in Fig. 3 has the form of:

$$\text{if } 0 \le \log(L_w) \le SW1 \text{ then } L_d = \log(L_w)\cos\alpha_1$$

$$\text{if } SW1 < \log(L_w) \le (SW1 + SW2) \text{ then } L_d = \log(L_w)\cos\alpha_2$$

$$\text{if } (SW1 + SW2) < \log(L_w) \le (SW1 + SW2 + SW3) \text{ then}$$
$$L_d = \log(L_w)\cos\alpha_3$$

where L_w stands for a wide range luminance value, SW*i* represent the width of the *i*th section, L_d denotes the displayable luminance value (luminance value in the resulted image) and α_i is the angle between the side of the *i*th section and the original vertical axis. Another promising concept for choosing the nonlinear scaling function of the vertical axis can be the following: We know that the information (seen or hided) is represented by the intensity changes (e.g. by the edges). Thus, the magnitude of the mapped domains corresponding to certain parts of the original, high dynamic ranges can be chosen proportional to the number of intensity changes within the corresponding parts (this can easily be measured e.g. by the density of characteristic edges within the domains).

5 Examples

Fig. 4 shows an image where a part of the scene is highly illuminated while another part is in the shadow and the details can be badly recognized. Fig. 5 shows the result after applying the anchoring based tone reproduction algorithm. In Fig. 6 the result got by the new fuzzy based tone reproduction algorithm using anchoring can be followed (see section 4.) Fig. 7 illustrates the processed image when simply applying a logarithmic mapping function with linear vertical axis, while in Fig. 8 the result of the combination of logarithmic mapping function and non-linear scaling can be seen.

Conclusions

In this paper new algorithms have been introduced for the reproduction of images when the high dynamic range of the lightness causes distortions. The highly illuminated regions of the images may contain corners, edges, or other important information, as well. Using the algorithms we can reconstruct the highly illuminated regions and obtain an image which can be processed more effectively by other algorithms. The computational complexity of the techniques can be kept low thus making possible their use in real-time applications.

Figure 4
Original image

Figure 5
Processed image using the anchoring based reproduction algorithm

Figure 6

Processed image using the fuzzy based tone reproduction algorithm using anchoring

Figure 7

Processed image using logarithmic mapping function

Figure 8
Processed image using the combination of logarithmic mapping function and non-linear scaling

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