Perception Motivated Hybrid Approach to Tone Mapping

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ABSTRACT

We propose a general hybrid approach to the issue of reproduction of high dynamic range images on devices with limited dynamic range. Our approach is based on combination of arbitrary global and local tone mapping operators. Recent perceptual studies concerning the reproduction of HDR images have shown high importance of preservation of overall image attributes. Motivated by these findings, we apply the global method first to reproduce overall image attributes correctly. At the same time, an enhancement map is constructed to guide a local operator to the critical areas that deserve enhancement. Based on the choice of involved methods and on the manner of construction of an enhancement map, we show that our approach is general and can be easily tailored to miscellaneous goals of tone mapping. An implementation of proposed hybrid tone mapping produces good results, it is easy to implement, fast to compute and it is comfortably scalable, if desired. These qualities nominate our approach for utilization in time-critical HDR applications like interactive visualizations, modern computer games, HDR image viewers, HDR mobile devices applications, etc.

Keywords: Tone mapping, HDRI, dynamic range reduction.

1 INTRODUCTION

Merits of high dynamic range imaging (HDRI) are currently widely recognized in computer graphics, high-quality photography, computer vision, etc. However, HDRI becomes popular in interactive and real-time applications as well. Data visualization, computer games and other interactive applications gain new qualities thanks to HDRI. The reproduction of high dynamic (HDR) data on the low dynamic (LDR) output devices requires the reduction of dynamic range, commonly referred to as a tone mapping.

Many so-called tone mapping operators were proposed in history [Dev02, Rei05]. We can classify the existing approaches according to the transformation they apply to convert input luminances to the output values. *Global* tone mapping methods apply a tone reproduction curve - e.g. a function. Therefore, they transform particular value of the input luminance to one specific output value. *Local* tone mapping operators may on the other hand reproduce particular input luminance to different output values depending on the surrounding pixels.

Although many sophisticated local tone mapping operators were published, these are typically not very generic approaches and just a few of these methods is suitable for interactive and computationally weak applications. Even worse, hardly any of them can be marked as general and scalable. Besides, recent perceptual studies concerning the reproduction of HDR images [Yos05, Led05, Cad06, Cad07] have shown high importance of preservation of global image attributes (overall brightness, overall contrast).

Generally speaking, global methods reproduce overall image attributes well, they are fast to compute, and easy to implement, but may wash away important details. Local approaches excel in reproduction of local contrast (details), but they are computationally intensive and may reproduce overall image attributes poorly, see Figure 1. Motivated by the mentioned findings we present a fast and simple yet powerful general hybrid approach to tone mapping issue. This approach takes advantages of both global and local tone mapping approaches to overcome mentioned limitations. Moreover, since the aims of tone mapping can differ among particular applications, the proposed approach can be easily tailored to the miscellaneous goals.

The paper is organized as follows. In Section 2, we overview the previous work and we focus particularly on linear tone mapping methods. In Section 3, we introduce and describe generally the new hybrid tone mapping idea. In Section 4, we present two exemplary implementations of hybrid tone mapping approach and show the results. Finally, in Section 5, we conclude and give suggestions for future work.

2 RELATED WORK

The areas of high dynamic range imaging and the tone mapping are currently quite complex. Refer to the state of the art by Devlin [Dev02] or to the book by Reinhard et al. [Rei05] for an overview. Since we concentrate mainly on interactive applications and computationally

Figure 1: Global methods reproduce overall image attributes well, but wash away important details (left). Local approaches excel in reproduction of details, but may reproduce overall image attributes poorly (right).

efficient methods, we survey briefly the time-dependent methods suitable for interactive applications.

2.1 Time-dependent Tone Mapping

Adaptation mechanisms of human visual system show time-dependency. Human needs some time to adapt to low luminance levels after entering the dark cinema from the sunlit street, for example. However, involvement of time-dependency is profitable also for non-perceptual applications of tone mapping, since it avoids flickering and other time-dependent artifacts.

Probably the first time-dependent tone mapping method was presented by Pattanaik et al. [Pat00]. The method is based on statical color model by Hunt that is extended of time adaptation. Authors use global s-shaped curve for mimicking the response of both direct and inverse models of visual perception.

Durand and Dorsey [Dur00] used the global tone mapping operator by Ferwerda et al. [Fer96] for interactive tone mapping. Authors model visual adaptation course over the time for rods and cones.

Fairchild and Johnson [Fai03] adapted the iCAM model [Fai02] to account for time-dependent adaptation effects. The time-dependency provide two exponential filters that modify adaptation level. The used model is local (filtering using wide gaussian curve) and therefore computationally intensive. Since the filtering kernel is very large, the properties of the iCAM outputs resemble global tone mapping results.

Ledda [Led04] proposed strictly local time-dependent approach. The method is based on initial effort by Pattanaik, but adds local processing using bilateral filter. Time-dependency is modeled using exponential filters for rods and cones.

The above surveyed time-dependent approaches apply either global curves and thus they destroy subtle details or they apply local methods and thus they are computationally demanding. Moreover, interactive applications often need to do some sort of load balancing, however there is an unanswered question, how to scale the time-dependent methods properly.

2.2 Linear Tone Mapping

As we have noticed, global methods reproduce overall image attributes well, see Figure 1. The group of global methods comprise a subset of linear tone mapping curves. Despite of the simplicity of *linear* tone mapping curves, the approaches utilizing linear (or close-to linear) mapping have many advantages that deserve our attention.

Since the linear methods scale image intensities by a constant (scale factor), they do not change scene contrasts for display. This is probably the reason why these methods show [Cad06, Cad07] to perform well in perceptual reproduction of the overall image attributes.

Linear tone mapping methods transform the input HDR image to the output image values using the scale factor, $L_d = m \cdot L_w$, where m is the *scale factor*, L_w is the input luminance, and L_d is the output value in the interval of [0, 1].

The simplest linear approach is the *maximum luminance* mapping, where we map the maximal input luminance to the maximal output value (e.g. to 1): $m = \frac{1}{L_{wmax}}$, where L_{wmax} is the maximal input luminance. Since the maximal luminance is usually enormous in case of HDR images, this approach produces typically too dark and valueless results. *Mean value* mapping approach gives more reasonable outputs by mapping the *average* input luminance to the average output scale: $m = 0.5 \cdot \frac{1}{L_{avg}}$, where L_{avg} is the average input luminance.

Ward's contrast based scale factor [War94] focuses on the preservation of *perceived contrast*. The computation of the scaling factor is based on Blackwell's [CIE81] psychophysical contrast sensitivity model. Almost the same principle of contrast preservation is exploited also in the work of Ferwerda et al. [Fer96].

Another linear approach was introduced by Neumann et al. [Neu98]. They propose the minimum *information loss* method that tries to mimic the photographer's practice to lose a minimum amount of information. The method automatically selects ideal clipping interval to obtain a minimum of detail-lost areas. The automatic selection of the interval is done by means of logarithmic image histogram.

Mapping using *s-shaped curve* [Pat00] is formally not a linear approach, but practically it can produce results that are very close to the linearly mapped results. S-shaped curves resemble transfer curves of classical photographic media.

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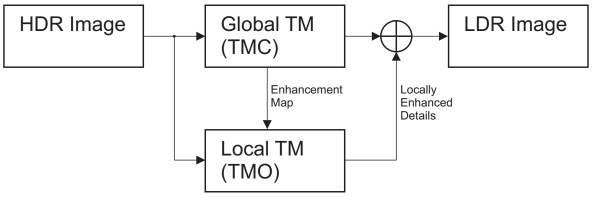

Figure 2: Overview of the hybrid tone mapping approach.

3 HYBRID TONE MAPPING

We propose a general idea of new hybrid tone mapping approach in this section, while two exemplary implementations are described in the next section. We do not concern the inherent physically-induced issues of real output devices (gamma correction, etc.), in this paper.[1] In the further text, we assume (without the loss of generality) that the output device range is linear and is limited to the interval of [0, 1]. Moreover, we do not concern the reproduction of colors here. All of our proposed methods aim to reduce dynamic range of the input image and the color information is left untouched. However, there is no obstacle to involve any method with a specific color processing into hybrid tone mapping approach if desired.

The overview of general hybrid tone mapping framework is shown in Figure 2. The process consists of three steps. First, the input high dynamic range image is transformed using global tone mapping curve. This mapping produces the base of the output low dynamic range image and (if necessary) outputs desired values for the construction of an *enhancement map*. In the second step, the enhancement map is constructed considering the aim of the tone mapping (see Figures 3, 6). Finally, the enhancement map is used to guide a local tone mapping method to reconstruct subtle details. The locally enhanced details are then added back to the globally transformed image to improve the final image while maintaining good overall reproduction of image attributes. Due to the enhancement map, the local tone mapping method is applied merely to the critical areas of the original image and therefore a lot of computational resources are saved.

3.1 Construction of Enhancement Map

Besides the choice of the involved methods, the manner of the construction of the enhancement map is an essential heart of the hybrid tone mapping. The enhancement map therefore has a profound effect on the properties of the hybrid tone mapping approach as a whole.

The enhancement map is generally a map of float numbers with the same dimensions as the original HDR image. In the examples shown in section 4, the enhancement map is constructed using a sort of thresholding of input luminance values. However, there is no obstacle to construct the enhancement map in a different way (for example based on input gradients, etc.). When we use a linear transform function in a global part of hybrid mapping, the construction of the enhancement map is very simple and effective. Since we know the analytical equation of the transfer curve, the clipping values are then directly known and the enhancement map is constructed effortlessly by thresholding. For the other approaches (s-shaped curves, log scaling, etc.), we propose to use the clip values of 5th and 95th luminance percentiles. However, the manner of the enhancement map construction can reflect a special goal of implemented method, as we show in section 4.3.

[1] Nevertheless, all the tone mapping results presented in this paper have been gamma corrected finally, using the value of $\gamma = 2.2$ as usual.

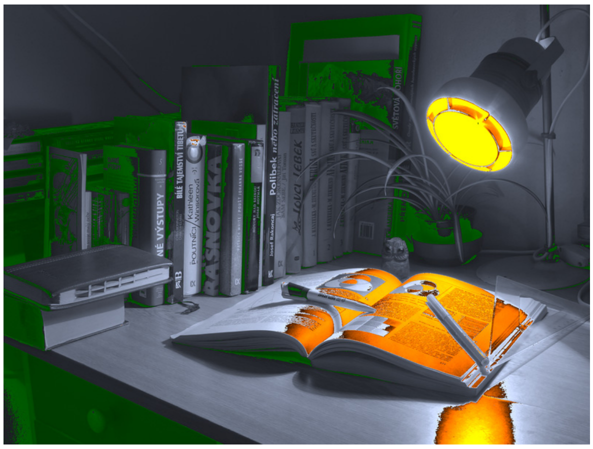

Figure 3: Example of an enhancement map (orange and green areas) for perceptually plausible hybrid approach. The luminances in orange-colored areas are potentially clipped due to linear mapping, while the details in dark parts, green-colored areas, are lost due to insufficient numerical precision.

Due to the abrupt changes of the global mapping to the local mapping (and vice versa), artifacts might appear on the borders of the enhancement map. To avoid the artifacts, we propose to construct and apply the enhancement map as follows (we show the process for only one clipping value L_{clip}):

$$EM(x,y) = \begin{cases} 0 & if\ TMC(L_w) < L_{clip} \\ \min(1, TMC(L_w) - L_{clip}) & otherwise, \end{cases}$$

where $EM(x,y)$ is the enhancement mask value, $TMC()$ is a global tone mapping method, L_w is the input luminance, and L_{clip} is the clipping luminance. The final output value L_d is then computed as a weighted sum of a global method and a local method outputs: $L_d(x,y) = EM(x,y) \cdot TMO(L_w) + (1 - EM(x,y)) \cdot TMC(L_w)$, where $TMO()$ is the involved local method.

If the computational time is not an issue, we can involve more sophisticated criteria to the construction of an enhancement map, e.g. the human visual system properties. Using the visual attention model, for example, we can pass the computational resources to the visually important areas of the image. Another possi-

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bility is the usage of contrast sensitivity function (CSF) during the construction of the enhancement map. In this case, the effort of local method will be directed to the areas, where the detail is (at least potentially) visible for a human observer.

4 USE CASES AND RESULTS

The proposed idea of hybrid tone mapping is general – virtually any combination of existing (and potentially forthcoming) methods is possible. However, the choice of the involved methods has to reflect the intent of the resultant combination (f.e. an aesthetic view, a cognitively rich depiction, or a perceptually plausible reproduction). A combination of methods that is excellent in reproducing details can fail miserably when we aim in reproducing the perceptual experience of an observer. In this section, we show two different examples of the hybrid approach: perceptually plausible approach and cognitively rich approach. We show and discuss actual outputs of these methods and we also exhibit the performance values comparing to original local methods.

4.1 Fast Perceptually Plausible Approach

For such an interactive applications where the perceptually convincing reproduction is desired and where the computational resources are limited (e.g. in computer games), we propose fast and simple implementation of hybrid tone mapping approach as follows.

At the post of global method, we use the linear mapping by Ward [War94]. This method was proven to give reasonable results for natural scenes [Cad06, Cad07], and the computational demands of the method are minimal. Since the global part is purely linear, we can construct the enhancement map directly by thresholding of input luminance values. The exact clipping values are known: $L_{clipLO} = 0$ and $L_{clipHI} = 1$ for an original method. We can modify the approach by shifting the transform curve if desired (to allow the user to adjust brightness or contrast), but even in this case, the clipping values are easily found analytically. Pixels with luminance values outside of the linear interval would be clipped and therefore the information would be lost there. Therefore, these pixels form the enhancement map.

Having the enhancement map, we run the bilateral filtering method [Dur02] just on the areas marked in the map. Bilateral filter separates the original luminance map to the base layer and the detail layer. We use the detail layer to enhance the result of the global tone mapping method. For acceleration of the local filtering, we utilize graphics hardware (GPU) [Fia06]. Figure 4 compares the transforms of the original methods and the hybrid approach and Figure 5 shows the results in the form of output images.

4.2 Time-Dependent Hybrid Mapping

It is usually advantageous to model the course of visual adaptation over the time for interactive applications. Time-dependency of tone mapping is twofold profitable: it increases the perceptual quality on one hand, and it also avoids temporal image artifacts on the other hand.

The way of implementation of time-dependency is influenced by the goal of the whole tone mapping method and it is not necessary to realize it at all, in some cases. In accordance with other authors [Dur00, Pat00] we use an exponential decay function in our perceptually plausible hybrid approach (described in Section 4.1) to model the light adaptation. We omit the simulation of long-term dark adaptation due to its subtle and slow effect and due to efficiency reasons. We modulate the adaptation level $L_{a(w)}$ in the Ward's method [War94] by the exponential function for smooth transitions when tone mapping a dynamic environment:

$\frac{dL_{a(w)}}{dt} \approx \frac{L_{a(w)} - L_{a(w)(t)}}{\tau}$,

where $L_{a(w)}$ is the visual adaptation for static image, $L_{a(w)}(t)$ is the actual adaptation and $\tau = 0.1$ is a time constant that mimics the speed of adaptation.

Similar approach is amenable in many other hybrid tone mapping implementations, since we can usually smoothen the response of particular parameter of involved global tone mapping method. If the computational cost is the main limitation, the time-dependency may be omitted temporarily with reasonable loss of reproduction quality.

4.3 Cognitive Approach

As an example of cognitive (e.g. detail-oriented) hybrid tone mapping approach, we propose the combination of histogram adjustment global tone mapping operator [War97] enhanced by locally applied bilateral filtering [Dur02].

The histogram adjustment method grants most of the available device contrast to the areas of abundant luminance values in the input HDR image. Generally speaking, large areas in an input image are given more contrast (thus subtle details present at these areas may become visible) at the expense of tiny areas. This advanced 'distribution of contrast' is achieved thanks to cumulative function derived from formerly constructed image histogram. The cumulative function is then used as a tone reproduction curve to transform input luminance to output values.

In accordance with the choice of involved methods, we propose to construct also the *enhancement map* seeking the same goal of cognitively rich (detailed) output image. We detect the areas of small local contrast on the chart of cumulative function constructed in the previous step – these areas represent pixels, where the detail is potentially vanished. We use the second derivative of cumulative function for this detection (note that

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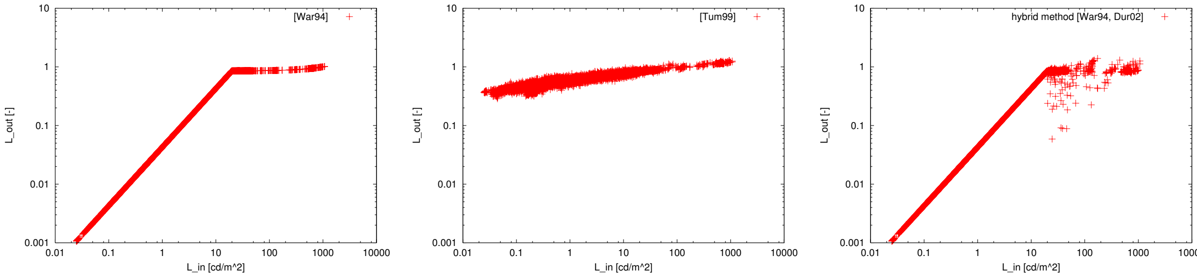

Figure 4: Tone mapping transforms, left: global method [War94] maps input HDR values via linear function – note the clipping of high luminances, middle: local method [Tum99] applies different transform to different pixels – the reproduction of overall image attributes is poor, right: hybrid approach [War94, Dur02] combines merits of both the global and local approaches.

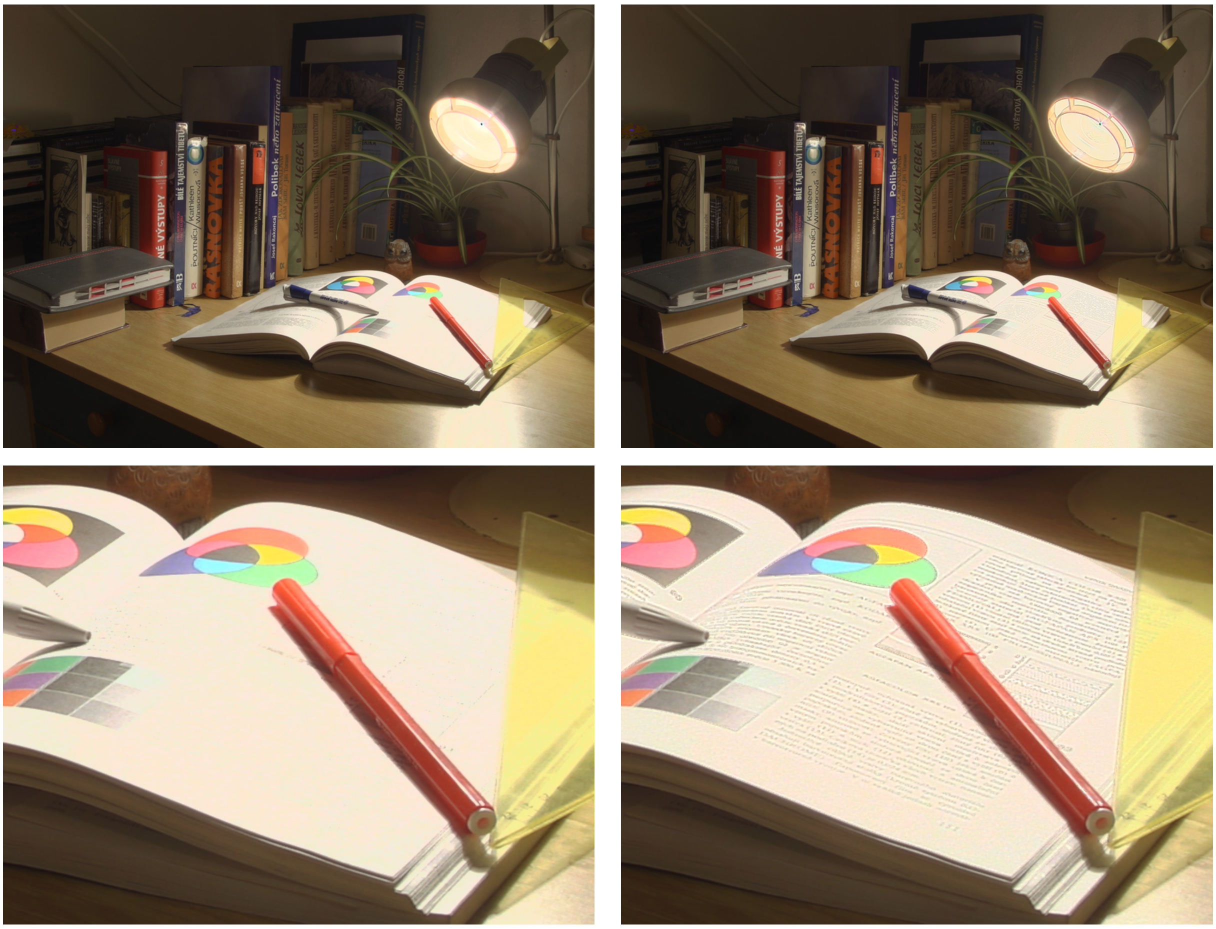

Figure 5: top left: result of purely global method [War94] exhibits well reproduced overall contrast, however shows the lack of subtle details, top right: result of the new hybrid approach [War94, Dur02] preserves the overall contrast accurately, and adds the lost details. Bottom: close-ups of the book, note the reproduced details in the hybrid approach result (bottom right).

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Perceptual method (Sec. 4.1)		Cognitive method (Sec. 4.3)	
Enhancement map [% of image pixels]	Speedup [-]	Enhancement map [% of image pixels]	Speedup [-]
1.4e-3%	**118,5**	0.132 %	**41,74**

Table 1: Comparison of performances of two different implementations of hybrid tone mapping (average results over 10 HDR images). The speedup value shows the acceleration of hybrid approach against the original, completely local approach.

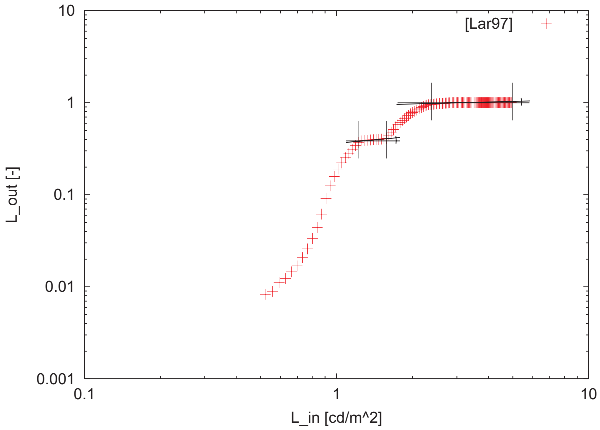

Figure 6: Cognitive hybrid approach. Left: cumulative function [War97] with detected areas for local enhancement. We use the threshold of 0.1 for detection, e.g. $L'_{out} < 0.1$. Right: corresponding enhancement map constructed from the cumulative function.

the the derivative is never a negative number in our case). Sections that show low slope (low values of the second derivation) are selected to construct the enhancement map (see Figure 6) – each pixel with the luminance value within the boundary of a selected section becomes a member of enhancement map.

Finally, we apply the local trilateral filtering method [Cho03] on the original input pixels that are present (or masked) in enhancement map. Similarly to the bilateral filter, the trilateral filter produces blurred image, but preserves significant luminance edges. We obtain local details by dividing the original image by the blurred image. Finally, we enrich the result of histogram adjustment method by these details. See Figure 7 (bottom line) where two renditions of one input image are shown to compare the two presented hybrid implementations.

4.4 Performance Results

Since one of the goals of the hybrid approach is the reduction of computational complexity, we present here the numerical performance results, see the Table 1[2]. The table shows average values measured at the group of 10 input HDR images. The perception-targeted fast hybrid approach is on average 3 times faster than the cognitive method and more that 118 times faster than the original bilateral filtering method. The reported speedup is gained thanks to the enhancement map. Since the enhancement map contains usually just a small portion of the original image pixels (as shown in the table), the time-demanding local approach is applied locally, to the small (necessary) part of the image.

Generally speaking, our technique places very small additional load to the system leaving large space for other computations. This is very profitable in interactive applications like the computer games, etc. However, note that besides the performance improvement, hybrid tone mapping can enhance the quality of the output image as well (see Figure 5).

In the imminent future, we can expect the need of dynamic range reduction even on various portable devices and on small and computationally elementary machines. The hybrid tone mapping will be reasonable in this case as well, thanks to its *good scalability*. If we face the lack of computational power, we can modify (soften) the criteria of the construction of the enhancement map. Depending on these criteria, we are able to continuously balance the computational load spanning from the complete locally enhanced method up to the factual omitting of the local enhancement (e.g. purely global tone reproduction). Finally, the other possibility to decrease the time consumption is to omit the time-dependent processing, as noted in Section 4.2.

[2] The performance values strongly depend on the selection and the implementation of the involved methods and we therefore present the average values for an overview.

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Figure 7: Further results of the new hybrid approach. Top left: pure global method [War94] without enhancement washes away details seen through the window. Top right: hybrid approach [War94, Dur02] enhances the image (note the revival of the birch twigs) without affecting the overall image attributes. Bottom left: hybrid approach [War94, Dur02] – perceptually plausible reproduction of well-known Memorial church image, bottom right: cognitive rendition of the same input image by hybrid combination of histogram adjustment and trilateral filtering [War97, Cho03].

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5 CONCLUSIONS AND FUTURE WORK

We presented a novel hybrid approach to the issue of reproduction of high dynamic range images on devices with limited dynamic range of luminance (e.g. tone mapping issue). In our approach, we combine results of arbitrary global and local tone mapping operators. Recent perceptual studies concerning the reproduction of HDR images have shown high importance of preservation of overall image attributes. Motivated by these studies, we apply the global method first to reproduce overall image attributes correctly. At the same time, we construct an enhancement map to guide a local operator to the critical areas that deserve enhancement.

We do not invent another complex tone mapping method, but we rather propose a general framework that utilizes already known ideas and combines existing and potentially forthcoming methods. We have shown that the presented hybrid approach can be easily tailored to miscellaneous potential goals of tone mapping (e.g. to get perceptually plausible images, to get detail-rich depictions, etc.). Our experiences indicate that an implementation of proposed hybrid tone mapping approach typically produces reasonable results, it is easy to implement, fast to compute and it is comfortably scalable, if desired. These qualities nominate our approach for utilization in time-critical HDR applications like interactive visualizations, modern computer games, HDR image viewers on mobile devices, etc.

The perception of image attributes depends partially on the semantics of the input image or scene. Therefore every, even a subtle modification of an image can affect the quality of reproduction of an attribute (in both positive and negative sense). In the future, we will conduct subjective perceptual experiments to uncover and to quantify the effect of particular local enhancement method (in relation to the manner of enhancement map construction) on the quality of reproduction of image attributes.

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