Journal of ELECTRICAL ENGINEERING, VOL 69 (2018), NO4, 261–269

Temporal adaptation control for local tone mapping operator

Dragomir El Mezeni, Lazar Saranovac*

High dynamic range (HDR) imaging has gained great popularity over the past twenty years. Tone mapping operator (TMO) is the key component that enables reproduction of HDR images on the standard low dynamic range (LDR) display devices. When it comes to the HDR video, design of the TMO becomes especially challenging since temporal control of TMO parameters is needed in order to avoid possible artifacts. Since temporal and spatial contrast cannot be met simultaneously, existing solutions are usually designed to optimize one of these two requirements. We present novel local tone mapping operator that preserves details and simultaneously provides good local and global contrast of processed images. Tunable temporal control enables trade-off between spatial and temporal contrast of a tone mapped video. Flexible control presented in this paper ensures that both requirements can be met with a single operator just by using different tuning of the control block. When compared to the state-of-the-art TMOs, proposed solution exhibits better results regarding overall image quality.

K e y w o r d s: high dynamic range imaging, local tone mapping, video tone mapping, temporal coherency

1 Introduction

Light intensity variations in natural scenes have a high dynamic range (HDR) which can span several orders of magnitude. Evolution has adjusted human visual system (HVS) so it can simultaneously perceive dynamic range up to four orders of magnitude. Therefore, to enjoy images that exploit a full potential of the HVS, at least equally good cameras and display devices are needed. Today, HDR scenes can be efficiently captured using high end cameras, new sensor technologies, or computational photography methods that can extract a HDR image from several differently exposed low dynamic range (LDR) images. However, display technology is lagging behind and the majority of displays today have moderate contrast rates and is unable to faithfully reproduce HDR content.

Tone mapping algorithms enable efficient contrast reduction of HDR images, which is needed for reproduction on a standard LDR display, without significant loss of important features and details. Over the past two decades, many TMOs were introduced and they can be roughly divided in two categories: global and local. The global operators apply the same mapping function to all pixels in the image, while local operators adapt mapping function to the pixels local neighborhood. Therefore global operators are faster and easier to control, while local operators provide better detail preservation.

Although all these operators more or less successfully solve the problem of still image tone mapping, many of them fail at HDR video sequences. Namely, since the TMOs intend to maximally use the output dynamic range, small changes in the input HDR image, such as introduction or removal of a light source, can lead to a significant change of the LDR output. This behavior is highly undesirable in a video since it can lead to the large light intensity jumps between successive LDR frames which is perceived as flickering in the output video sequence. The main requirements for TMOs used in HDR video solutions are simplicity, robustness and controllability. Hence, global tone mapping operators are usually used in these kind of applications. Local TMOs were usually avoided in earlier video HDR solutions, although they provide much better still image quality compared to the global ones. This is due to their local adaptability, which poses a great challenge when designing a robust control algorithm.

Regarding temporal characteristics, video TMOs can be roughly divided into two additional categories: temporally coherent (TC) and temporally adaptive (TA). Temporally coherent TMOs preserve brightness relationship between any two frames in the HDR sequence. This enables temporal contrast preservation during the tone mapping process. Unfortunately, this comes at the price of reduced spatial contrast. Temporally adaptive TMOs adapt their output to the each frame, providing the best spatial contrast. Spatial and temporal contrast are different sides of the same coin and cannot be achieved simultaneously.

Recently, significant effort has been put into design of the video tone mapping algorithms and many new solutions emerged [1]. Although there are solutions with sufficiently good image quality they are putting priority on either spatial or temporal contrast. In order to meet both requirements with a single TMO in this paper we propose temporal adaptation control for local tone mapping operator. The main targets of our algorithm are robustness and flexibility making it suitable for consumer elec-

University of Belgrade, School of Electrical Engineering, Department of Electronics, Bulevar Kralja Aleksandra 73, Belgrade, Serbia, 11000, elmezeni@etf.rs

DOI: 10.2478/jee-2018–0037, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

tronics applications. For this reason, we have chosen to extend our previous work and provide temporal control of ELTM operator [2]. ELTM has shown robust performance on various type of HDR scenes. Also, it can be tuned for desired appearance using several globally defined parameters. Temporal control algorithm enables its usage in the HDR video tone mapping. Control algorithm is also flexible providing users with ability to set desired temporal vs spatial contrast trade-off.

2 Related work

For many years, TMO of choice for the video HDR applications was the global version of Reinhard's photographic tone reproduction operator [3]. This is due its simplicity of implementation and control. To avoid flickering Kang *et al* [4] used input log average luminance calculated over a fixed number of previous frames. Ramsey *et al* [5] extended this idea by using a flexible window for temporal averaging, allowing a fast adaptation to the sudden light changes and a smooth operation otherwise. Kiser *et al* [6] suggested that better control of the Reinhard's tone mapping operator can be achieved by using IIR filtering to smooth maximal/minimal luminance, and the key value.

Instead of the usual approach of filtering scene parameters, Mantiuk *et al* [7] temporally filter the tone mapping curve to prevent sudden changes in its shape, thus providing a smooth transition between successive frames. Similar approach for dynamic range reduction and temporal coherence is used in [8]. Local contrast preservation is enabled by using base/detail decomposition, while selective scaling of a detail layer imposes noise awareness.

There are several operators developed directly from HVS models [9–13]. They employ spatio-temporal adaptation process that imitates response of rod and cone cells in retina. Operators which include spatially local adaptation [10] produce strong ghosting artifacts. To avoid ghosting artifacts, some operators [14, 15] employ spatio-temporal edge-aware filtering during local processing.

Boitard *et al* [16] concluded that besides flickering, there is an issue of temporal brightness and object coherency in HDR video. This means that the brightness relations in a sequence should be preserved during the tone mapping process. Boitard proposed frame based post-processing method which forces temporal coherency. To resolve very limited spatial contrast produced with the original algorithm, a new solution is proposed in [17], which includes segmentation of the scene into regions with similar illuminations and then imposes coherency to each region separately. However, this concept cannot be used for real-time tone mapping since it requires video analysis as one of the first steps.

The first comprehensive evaluations of the state-of-the-art solutions for video tone mapping were presented in [18–20]. In these studies Mantiuk's display adaptive tone mapping (DA-TM) [7] and Boitard's temporal coherence tone mapping (TC-TM) [16] are designated as the best performing solutions. In the most recent evaluation of the state-of-the-art video HDR TMO algorithms [1] DA-TM and TC-TM are once again designated as the best performing algorithms regarding temporal coherence, and we will compare our temporal results to these two solutions. In the same study two new tone mapping algorithms Motion path filtering (MPF-TM) [15] and Noise aware tone mapping (NA-TM) [8] stood out regarding local contrast preservation.

3 Local tone mapping operator

Block diagram of the ELTM algorithm [2] is in Fig. 1.

Input R, G, B values are linearly correlated with the light intensity falling on the camera sensor, and they are normalized to fit the range [0,1]. To separate illumination form reflectance input luminance (Y) is transferred to the logarithmic scale (Λ), where it is decomposed into a base (Λ_B) and two detail parameters (Λ_C, Λ_F) using edge-aware filters. Full description of decomposition process and details manipulation can be found in [2]. Coarse details (Λ_C) contain information about local contrast while fine details (Λ_F) are reflecting the image sharpness. The base parameter (Λ_B) reflects input images high dynamic range, since it contains information about scene illumination. Hence, to reduce dynamic range of the image, the base parameter is adjusted in logarithmic scale, to fit the predefined target dynamic range (τ_R)

$$k = \eta(\Lambda_B + \lambda), \tag{1}$$

$$\eta = \frac{\tau_R}{\Lambda_M - \Lambda_m}. \tag{2}$$

where, k is the adjusted dynamic range base parameter, with η and λ being the base parameter scaling ratio and the base parameter offset. To increase robustness the minimal (Λ_m) and maximal (Λ_M) values of the original base parameter (Λ_B), used in (2) are calculated as 0.06-th and 99.9-th percentiles from rather than simple minimal and maximal Λ values.

Target dynamic range (τ_R) is set to the value of 5, which is sufficient for currently available displays. In the current implementation logarithm with base 2 is used, for different logarithm base value τ_R should be adjusted accordingly. Purpose of the offset parameter λ is to adapt tone mapping process to a changing lighting conditions. Using the offset value $\lambda = -\Lambda_M$ ensures that maximal pixel value of the current frame will be mapped to the maximal display value, thus achieving full adaptation. To achieve particular adaptation level, adapted offset value λ in (1) should be chosen as will be explained further (Section 4).

All output parameters in Fig. 1 are calculated using the statistics of the currently processed frame and represent the inputs to the control block.

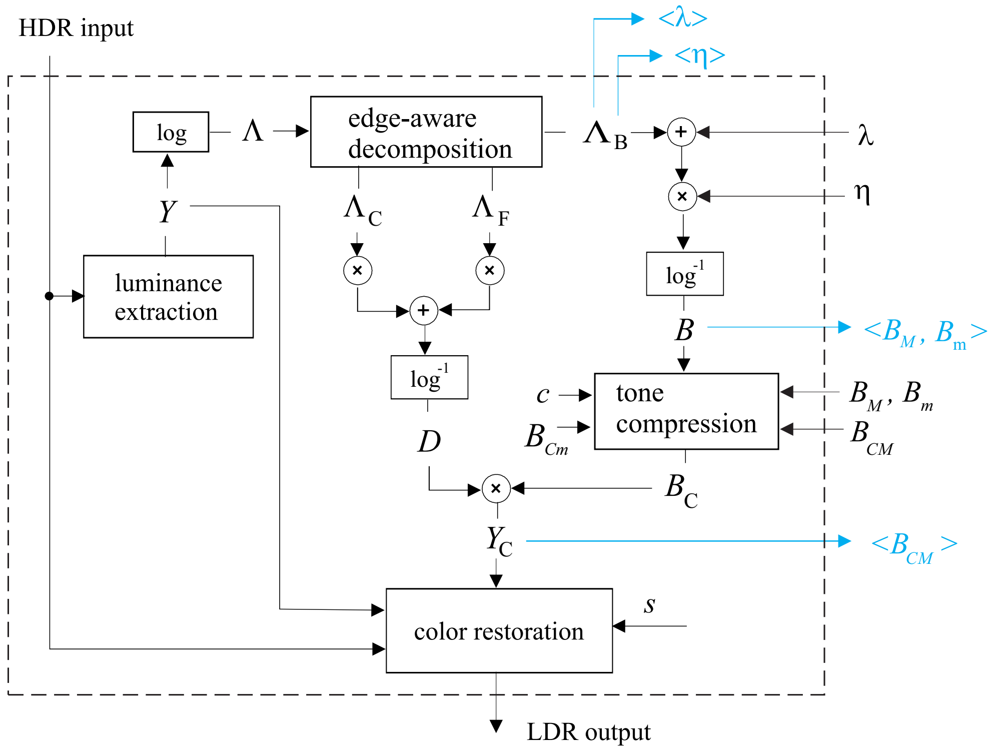

Fig. 1. Block diagram of the ELTM algorithm

After partial adjustment (done in logarithmic scale) the base parameter (B_C) the HDR compression is completed in linear scale, using adaptive logarithm mapping, [2]

$$B_C = (B_{CM} - B_{Cm}) \frac{\log\left(\dfrac{B - B_m}{B_M - B_m} + c\right) - \log c}{\log(1+c) - \log c} + B_{Cm}. \tag{3}$$

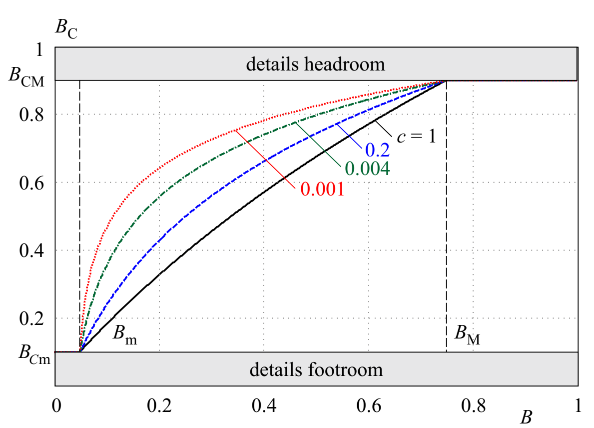

Fig. 2. Adaptive logarithm-based tone compression curve

Here, B_m and B_M are minimal and maximal values of the base parameter (B) after previous adjustment (done in logarithmic scale), and B_{Cm}, B_{CM} are their limits, both in a linear scale. Tone compression curve (4) is adjusted according to the base parameters statistics (taking into account data from previously processed frames), thus preventing flat-looking output images. Constrained range of the compressed base parameter reduce clipping of details in highlighted and shadow image areas. Notice that, although tone compression curve adapts to the each base parameter, there is still flexibility of setting desired level of output brightness by adjusting tone compression parameter c. Family of adaptive tone compression curves for different values of parameter c is shown in Fig. 2.

The low output base limit B_{Cm} is user defined parameter and it defines local contrast in shadow regions. The high output base limit B_{CM} is an internally controlled parameter which is adapted throughout the video to prevent detail clipping in the highlighted regions. Values of B_m and B_M are base parameter statistics used for adjustment of the tone compression curve in the linear scale. When ELTM is used in HDR video, parameter B_M should be fixed at the value of 1 to enable different adaptation levels. The control is achieved using Y_{CM} - the maximal value of the tone compressed luminance plane (Y_C) before its clipping into the range $[0,1]$:

$$B_{CM} = \max\left(\frac{1}{Y_{CM}}, 1\right). \tag{4}$$

Tone compressed luminance is calculated as:

$$Y_C = B_C\, D. \tag{5}$$

Using compressed luminance Y_C, final LDR values are calculated as

$$C_{LDR} = Y_C \left(\frac{C_{HDR}}{Y}\right)^{\frac{s}{\gamma}}, \quad C \in \{R, G, B\}. \tag{6}$$

Parameter s is used to control color saturation of the output LDR image, while γ is a constant which represents sRGB gamma with the value of 2.2.

Although almost all existing TMOs use either logarithmic scaling of the base parameter or some kind of scaling using logarithm-based function, it is their combination that provides the robustness to the ELTM. Namely, ELTM use logarithmic scaling of the base parameter to fit widely varying tone values of input images into predefined constrained dynamic range, decoupling the later processing stages from the input variations. The final look of the output image is determined by the adaptive logarithm-based function in the linear scale. This function adapts to the statistics of each frame providing the good global contrast and significantly reduce detail clipping in the extreme bright and dark regions.

4 Tone mapping operator control

All parameters used in the tone mapping process can be divided into two groups: tuning and statistical. Tuning parameters are user defined and do not change during the tone mapping process. An example of tuning parameters are coarse and fine detail gains (η_C and η_F), which control the amount of detail enhancement, and parameter c, which controls the brightness of the output frame. Other parameters for a current frame are calculated from previous frames statistics. These parameters are denoted as $< . >$ in Fig. 1 and in equation (8) and are processed in the control block before used in the tone mapping process as depicted in Fig. 3.

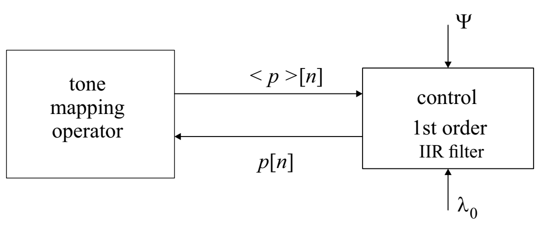

Fig. 3. Control of the proposed tone mapping operator

All control parameters denoted in Fig. 1, used for processing the n-th frame, are calculated in the control block as the output of the first order IIR filter

$$p[n] = \alpha \ < p > [n] + (1-\alpha)\, p[n-1] \,. \tag{7}$$

The base parameter shifting in the logarithm scale, by the value of λ, adapts each frame to maximally use available output dynamic range and thus breaks temporal coherency. To achieve temporal coherence one frame from the video sequence is used as the reference one and its value is denoted as λ_0. The offset values for all other frames in a video sequence are compressed around this reference value

$$\lambda_A = \Psi\lambda + (1-\Psi)\lambda_0, \tag{8}$$

where adaptation parameter Ψ defines the strength of offset value compression and it takes values from 0 to 1. For $\Psi = 0$ constant offset is used in all frames, which disables adaptation, but preserves temporal coherency. On the other hand, for $\Psi = 1$ the original value λ is used enabling maximal adaptation. This increases spatial at the expense of temporal contrast. Any frame in the sequence can be chosen as the reference frame, and the value if referent offset λ_0 can be extracted from it. Reference frame will then have the best utilization of the output dynamic range and spatial contrast, while offset for the other frames will be calculated using (9). When it comes to real time operation, information on future frames is not available, so the first frame in the sequence is usually designated as the reference.

Flexible adaptation enables that both good temporal and spatial contrast can be achieved with a single tone mapping operator by tuning adaptation parameter value. To the best of our knowledge this is not a case with currently available solutions which are designed to meet either good spatial or temporal contrast but not both.

5 Results

Regarding temporal coherence, proposed temporal control of ELTM was tested using HDR video sequences from [18], and the results of the *Hallway* and *Exhibition area* sequences are presented in this section.

It can be noticed from timing diagrams in Fig. 4(a),(b) and (g) that Virtual exposure TMO [14], Retina model TMO [11] and Color appearance TMO [13] have significant problem with flickering artifacts, represented in rapid change of the luminance value which is not present in the original HDR video. Local adaptation TMO [10] solves flickering artifacts through temporal filtering. On the other hand, this produces strong ghosting artifacts, as it is evident in Fig. 4(d).

Good global contrast without flickering artifacts is achieved with Display adaptive TMO [7]. Since this operator tends to optimize contrast for each frame, temporal contrast is lost and average brightness is larger in indoor in comparison to outdoor areas. Also this operator is global and there is no option for spatially variable processing. Temporal coherency is achieved by Temporal coherent TMO [16], but this processing severely reduce contrast of each frame. Tone mapping algorithm proposed in this paper Fig. 4(i j) is free of flickering artifacts apart of small fluctuations from 100^{th} to 130^{th} frame. These fluctuations also exist in the original HDR sequence as it is shown in Fig. 6 and are not introduced by the proposed algorithm. Combined local and global processing ensure good local and global contrast of each frame. If temporal control is tuned for full adaptation, as in Fig. 4(i) each frame is optimized for the best usage of the output dynamic range, and maximal spatial contrast is achieved. This, however, alters temporal contrast, which can be noticed from timing diagrams. For preserving temporal

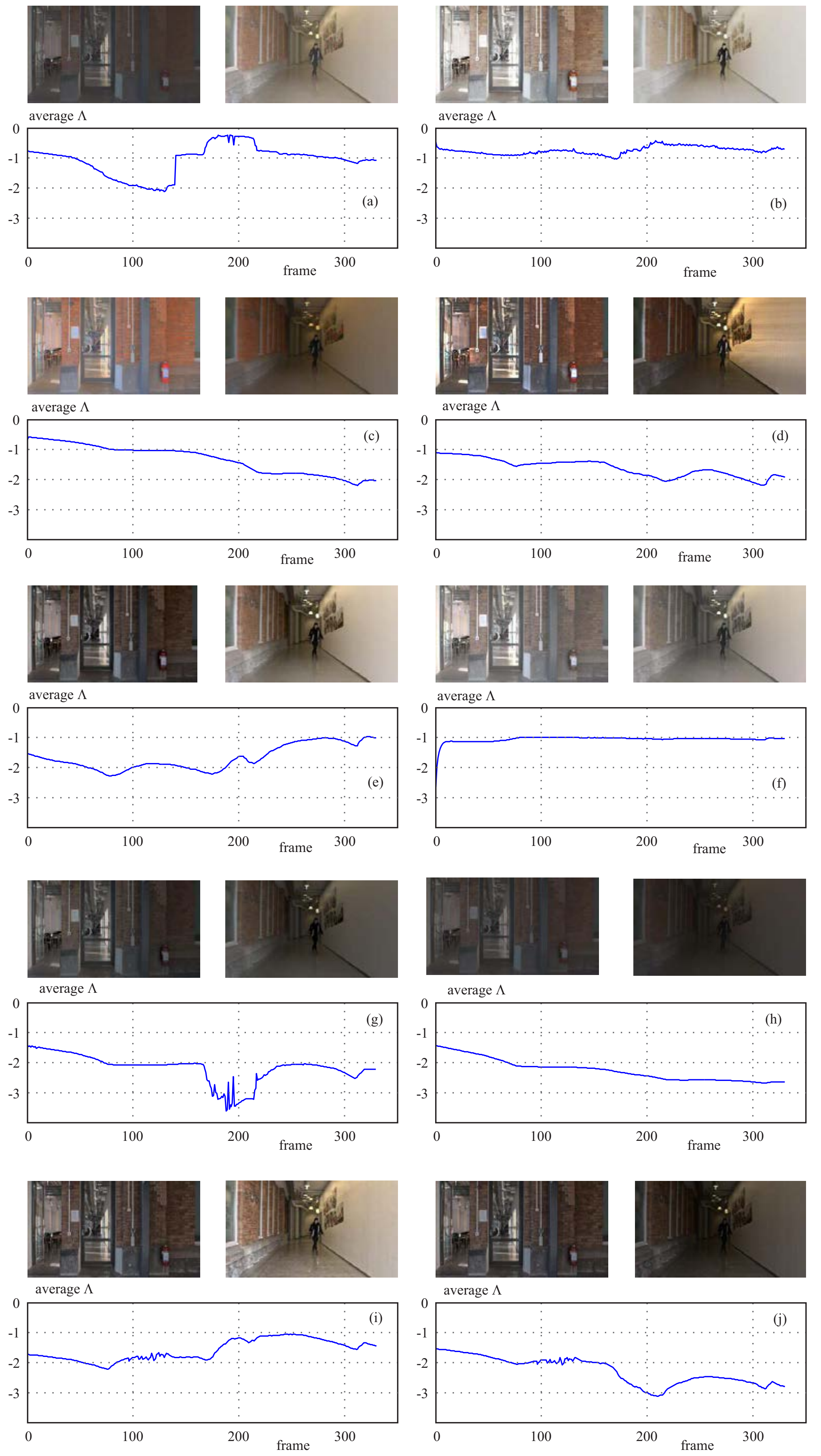

Fig. 4. Comparison of different video tone mapping operators.For each method, average logarithm luminance is presented along with two frames representing outdoor and indoor part of the scene

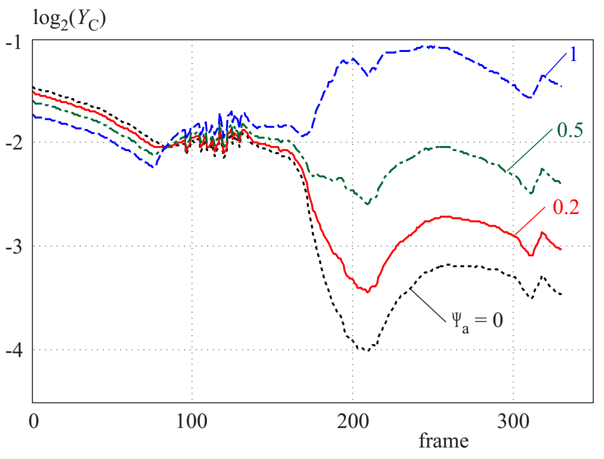

Fig. 5. Average logarithm luminance for the Hallway video sequence for different values of adaptation parameter

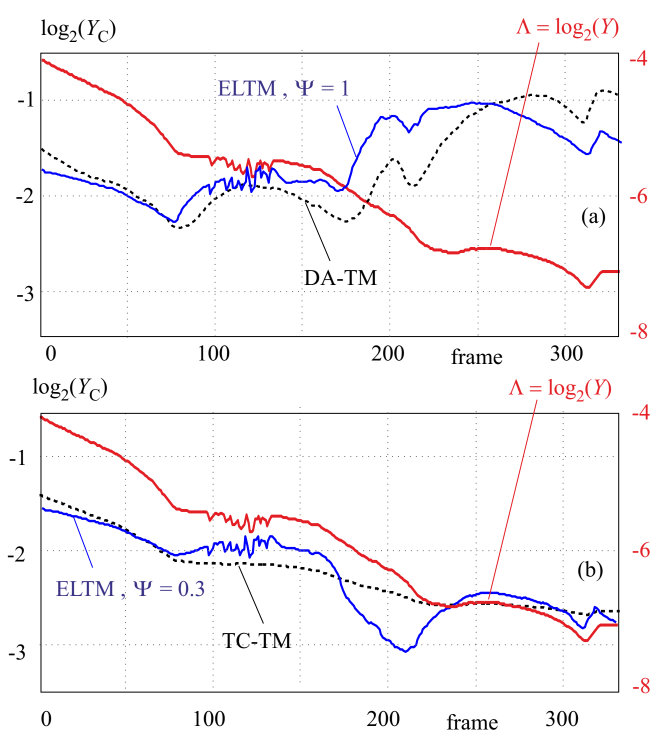

Fig. 6. Average logarithm luminance for the Hallway video sequence: HDR video (a) – DA-TM *vs* proposed operator with full adaptation (b) – TC-TM *vs*(c) – proposed operator with partial adaptation

contrast, adaptation should be constrained by lowering value of parameter Ψ. The timing diagram of average brightness of the *Hallway sequence*, for different values of adaptation parameter is shown in Fig. 5. Even in the partial adaptation scenario, where adaptation parameter was set to $\Psi = 0.3$, Fig. 4(j), proposed tone mapping operator shows better local contrast compared to other, temporally coherent, tone mapping solutions.

In the next few figures, proposed tone mapping algorithm is compared to the two representative state-of-the-art tone mapping algorithms. Display adaptive tone mapping (DA-TM) [7] is shown to produce the best results regarding spatial contrast while Temporal coherence tone mapping (TC-TM) [16] ensures temporal coherency. These tone mapping operators are chosen base on evaluation studies presented in [18–20].

The 98$^{\text{th}}$ and 256$^{\text{th}}$ frame from the *Hallway* sequence, and 10$^{\text{th}}$ and 150$^{\text{th}}$ frame from the *Exhibition area* sequence are used to demonstrate temporal coherency. These frames depict outdoor and indoor areas. The results presented in Fig. 7(a) and Fig. 10(a) were generated using DA-TM, while Fig. 7(b) and Fig. 10(b) provide results of the proposed algorithm with adaptation parameter set to $\Psi = 1$.

Spatial contrast is very good and details are visible in both cases, since DA-TM is designed to preserve spatial contrast for each frame. It can be seen in Fig. 7 that proposed algorithm is better at detail preservation in highlighted areas, especially noticeable in the face regions. However, temporal coherency is not preserved since in Fig. 7(b) and Fig. 10(b) the indoor is now brighter than the outdoor area. In this sequence the proposed algorithm provides similar results as DA-TM.

The results of TC-TM are presented in Fig. 8(a) and Fig. 11(a). Temporal contrast is preserved as shown in Fig. 6(c) but spatial contrast is seriously compromised. Fig. 8(b) and Fig. 11(b) show results of the proposed algorithm using small adaptation factor $\Psi = 0.3$. It shows that coherency is mostly preserved, except in the transition region, while spatial contrast is much better than in the TC-TM result. This inconsistency in the transition region is consequence of the η and $B_{\min}$ adaptations which are still left in the algorithm, although the adaptation value is low. Fast variations in the output log average luminance between the 100$^{\text{th}}$ and 130$^{\text{th}}$ frame are not artefacts of the tone mapping process since the same variations exist in the input HDR video sequence in Fig. 6(a). Proposed algorithm is also compared to Motion-path filtering TMO [15] and results are presented in Fig. 9. Although this operator has local processing, proposed TMO provides better local and global contrast. In Fig. 12 we have provided results of the proposed tone mapping operator for the frames used in the most recent evaluation study [1]. Original HDR videos are from [21], and they are made for video HDR TMO evaluations. It shows that proposed TMO preserves details in both highlight and shadow regions, without significant noise amplifications. The main advantage over already exiting solutions is its flexibility to adapt to the various user requirements regarding spatial/temporal contrast trade-off.

6 Conclusion

In this paper we propose temporal control of ELTM operator, which is shown to preserve and enhance details, thus providing good global and local contrast of output images. Temporal control, presented in this paper, enables its usage in HDR video applications, by avoiding

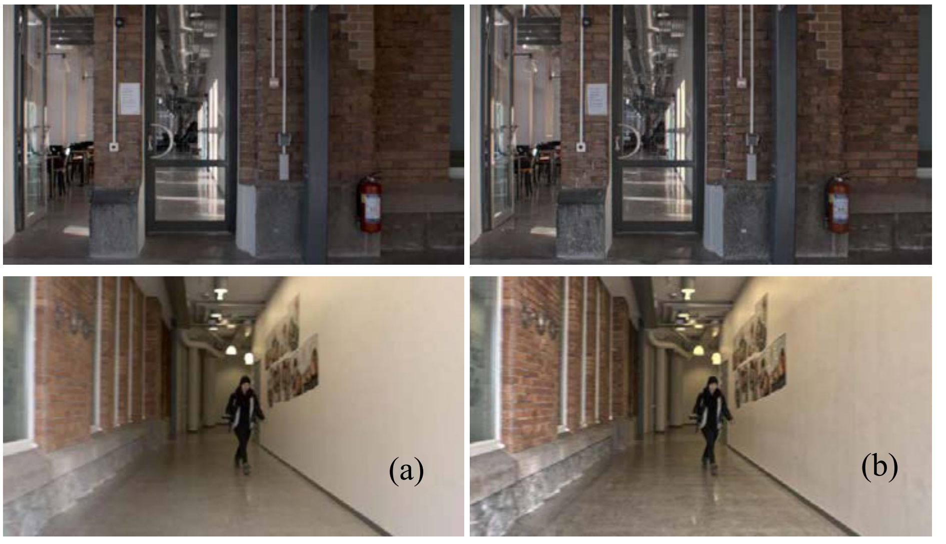

Fig. 7. Comparison between (a) – DA-TM, and (b) – proposed TM

Fig. 8. Comparison between (a) – TC-TM, and (b) – proposed TM

Fig. 9. Comparison between (a) – MPF-TM, [15], and (b) – proposed TM

Fig. 10. Comparison between (a) – DA-TM, and (b) – proposed TM

Fig. 11. Comparison between (a) – TC-TM, and (b) – proposed TM

Fig. 12. Results of proposed TMO for various video sequences used in [1]

flickering artefacts. In addition, provided control is adaptive and enables that both temporal coherency and maximal spatial contrast can be achieved, by different tuning of the proposed control block. To the best of our knowledge, none of the currently available tone mapping operators offers this kind of flexibility. The results clearly show that the described video tone mapping operator outperforms current state-of-the-art video tone mapping operators regarding image quality and flexibility.

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Received 30 March 2018

Dragomir M. El Mezeni was born in Belgrade, Serbia in 1985. He received the BSc degree in electrical engineering from the University of Belgrade in 2008, MSc degree in electronics in 2010 and is currently pursuing PhD degree at the same University. He is currently teaching and research assistant of electrical engineering at the University of Belgrade. His research interests include digital image/video processing, computational photography and very large scale integration architectures for digital signal processing.

Lazar V. Saranovac (associate professor) was born in Sremska Mitrovica, Serbia in 1961. He received the BS degree in electrical engineering from the University of Belgrade in 1987, MS degree in electronics in 1993 and PhD degree from the same University in 2001 He is currently an Associate Professor of electrical engineering at the University of Belgrade. His research interests include embedded systems, methods for measuring electric power, digital signal processing and design of digital systems.